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# Supply Chain Management

*Edited by Pengzhong Li*

# SUPPLY CHAIN MANAGEMENT

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# Meet the editor

Dr. Pengzhong Li, born in 1968, associate Professor of Sino-German College of Postgraduate Studies (CDHK) of Tongji University, received his Ph.D. in Mechanical Engineering from Tongji University in 2004. From 1995 to 2001 he served as Manager of Business Department in Guilin Daewoo Bus Co., LTD. As a visiting scholar financed by DAAD, he worked in Ruhr University Bochum in 2006 and 2008. He is a member of International Association of Computer Science and Information Technology (IACSIT) and the editor of International Journal of Computer and Electrical Engineering. His research interests include manufacturing system engineering, quality management, simulation application and environmentally conscious manufacturing.

# Contents

# Preface

With gradually recognized significance of supply chain management, it attracts extensive attention from businesses and academic scholars. Many important research findings and results had been achieved. This book presents a collection of recent contributions from the worldwide researchers in the field of supply chain management. It is aimed at providing new ideas, original results and practical experiences regarding this highly up-to-date area.

Research work of supply chain management involves all activities and processes including planning, coordination, operation, control and optimization of the whole supply chain system. To make it convenient for readers to find interesting topics, content of this book was structured into three technical research parts with total of 27 chapters written by well recognized researchers worldwide. In part one, Management Method and Its Application, the editor hopes to give readers new methods and innovative ideas about supply chain management. Chapters about supply chain coordination were put into part two, Coordination. The third part, Modeling and Analysis, is thematically more diverse, it covers accepted works about description and analysis of all supply chain management areas.

I am very honored to be editing such a valuable book, which contains contributions of a selected group of researchers presenting the best of their work. The editor truly hopes the book will be helpful for researchers, scientists, engineers and students who are involved in supply chain management. Although it represents only a small sample of the research activity on supply chain management, the book will certainly serve as a valuable tool for researchers interested in getting involved in this multidisciplinary field. Further discussions on the contents of this book are warmly welcome.

Finally, the editor would like to thank all the people who contributed to this book, in particular Ms. Iva Lipovic, for indispensable technical assistance in book publishing.

**Pengzhong LI**

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# Part 1

## Management Method and Its Application

# 1

# Supply Chain Optimization: Centralized vs Decentralized Planning and Scheduling

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## 1. Introduction

In supply chain management manufacturing flow lines consist of two or more work areas, arranged in series and/or in parallel, with intermediate storage areas. The first work area processes raw items and the last work area produces end items or products, which are stored in a storage area in anticipation of future demand. Firstly managers should analyze and organize the long term production optimizing the production planning of the supply chain. Secondly, they have to optimize the short term production analyzing and organizing the production scheduling of the supply chain and finally taking under consideration the stochasticity of the real world, managers have to analyze and organize the performance of the supply chain adopting the best control policy.

In supply chain management production planning is the process of determining a tentative plan for how much production will occur in the next several time periods, during an interval of time called the planning horizon. Production planning also determines expected inventory levels, as well as the workforce and other resources necessary to implement the production plans. Production planning is done using an aggregate view of the production facility, the demand for products and even of time (ex. using monthly time periods). Production planning is commonly defined as the cross-functional process of devising an aggregate production plan for groups of products over a month or quarter, based on management targets for production, sales and inventory levels. This plan should meet operating requirements for fulfilling basic business profitability and market goals and provide the overall desired framework in developing the master production schedule and in evaluating capacity and resource requirements.

In supply chain management production scheduling defines which products should be produced and which products should be consumed in each time instant over a given small time horizon; hence, it defines which run-mode to use and when to perform changeovers in order to meet the market needs and satisfy the demand. Large-scale scheduling problems arise frequently in supply chain management where the main objective is to assign sequence of tasks to processing units within certain time frame such that demand of each product is satisfied before its due date.

For supply chain systems the aim of control is to optimize some performance measure, which typically comprises revenue from sales less the costs of inventory and those associated with the delays in filling customer orders. Control is dynamic and affects the rate of accepted orders and the production rates of each work area according to the state of the system. Optimal control policies are often of the bang-bang type, that is, they determine when to start and when to stop production at each work area and whether to accept or deny an incoming order. A number of flow control policies have been developed in recent years (see, e.g., Liberopoulos and Dallery 2000, 2003). Flow control is a difficult problem, especially in flow lines of the supply chain type, in which the various work and storage areas belong to different companies. The problem becomes more difficult when it is possible for companies owning certain stages of the supply chain to purchase a number of items from subcontractors rather than producing these items in their plants.

In general, a good planning, scheduling and control policy must be beneficial for the whole supply chain and for each participating company. In practice, however, each company tends to optimize its own production unit subject to certain constraints (e.g., contractual obligations) with little attention to the remaining stages of the supply chain. For example, if a factory of a supply chain purchases raw items regularly from another supply chain participant, then, during stockout periods, the company which owns that factory may occasionally find it more profitable to purchase a quantity immediately from some subcontractor outside the supply chain, rather than wait for the delivery of the same quantity from its regular supplier. Although similar policies (decentralized policies) can be individually optimal at each stage of the supply chain, the sum of the profits collected individually can be much lower than the maximum profit the system could make under a coordinated policy (centralized policies).

The rest of this paper is organized as follows. Section 2 a literature review is presented. In section 3, 4 and 5 three cases studies are presented where centralized and decentralized optimization is applied and qualitative results are given. Section 5 draws conclusions.

## 2. Literature review

There are relatively few papers that have addressed planning and scheduling problems using centralized and decentralized optimization strategies providing a comparison of these two approaches.

(Bassett et al., 1996) presented resource decomposition method to reduce problem complexity by dividing the scheduling problem into subsections based on its process recipes. They showed that the overall solution time using resource decomposition is significantly lower than the time needed to solve the global problem. However, their proposed resource decomposition method did not involve any feedback mechanism to incorporate "raw material" availability between sub sections.

(Harjunkoski and Grossmann, 2001) presented a decomposition scheme for solving large scheduling problems for steel production which splits the original problem into sub-systems using the special features of steel making. Numerical results have shown that the proposed approach can be successfully applied to industrial scale problems. While global optimality cannot be guaranteed, comparison with theoretical estimates indicates that the method produces solutions within 1–3% of the global optimum. Finally, it should be noted that the general structure of the proposed approach naturally would allow the consideration of other types of problems, especially such, where the physical problem provides a basis for decomposition.

(Gnoni et al., 2003) present a case study from the automotive industry dealing with the lot sizing and scheduling decisions in a multi-site manufacturing system with uncertain multi-product and multi-period demand. They use a hybrid approach which combines mixed-integer linear programming model and simulation to test local and global production strategies. The paper investigates the effects of demand variability on the economic performance of the whole production system, using both local and global optimization strategies. Two different situations are compared: the first one (decentralized) considers each manufacturing site as a stand-alone business unit using a local optimization strategy; the second one (centralized) considers the pool of sites as a single manufacturing system operating under a global optimization strategy. In the latter case, the problem is solved by jointly considering lot sizes and sequences of all sites in the supply chain. Results obtained are compared with simulations of an actual reference annual production plan. The local optimization strategy allows a cost reduction of about 19% compared to the reference actual situation. The global strategy leads to a further cost reduction of 3.5%, smaller variations of the cost around its mean value, and, in general, a better overall economic performance, although it causes local economic penalties at some sites.

(Chen and Chen, 2005) study a two-echelon supply chain, in which a retailer maintains a stock of different products in order to meet deterministic demand and replenishes the stock by placing orders at a manufacturer who has a single production facility. The retailer's problem is to decide when and how much to order for each product and the manufacturer's problem is to schedule the production of each product. The authors examine centralized and decentralized control policies minimizing respectively total and individual operating costs, which include inventory holding, transportation, order processing, and production setup costs. The optimal decentralized policy is obtained by maximizing the retailer's cost per unit time independently of the manufacturer's cost. On the contrary, the centralized policy minimizes the total cost of the system. An algorithm is developed which determines the optimal order quantity and production cycle for each product. It should be noted that the same model is applicable to multi-echelon distribution/inventory systems in which a manufacturer supplies a single product to several retailers. Several numerical experiments demonstrate the performance of the proposed models. The numerical results show that the centralized policy significantly outperforms the decentralized policy. Finally, the authors present a savings sharing mechanism whereby the manufacturer provides the retailer with a quantity discount which achieves a Pareto improvement among both participants of the supply chain.

(Kelly and Zyngier, 2008) presented a new technique for decomposing and rationalizing large decision-making problems into a common and consistent framework. The focus of this paper has been to present a heuristic, called the hierarchical decomposition heuristic (HDH), which can be used to find globally feasible solutions to usually large decentralized and distributed decision-making problems when a centralized approach is not possible. The HDH is primarily intended to be applied as a standalone tool for managing a decentralized and distributed system when only globally consistent solutions are necessary or as a lower bound to a maximization problem within a global optimization strategy such as Lagrangean decomposition. The HDH was applied to an illustrative example based on an actual industrial multi-site system as well as to three small motivating examples and was able to solve these problems faster than a centralized model of the same problems when using both coordinated and collaborative approaches.

(Rupp et al., 2000) present a fine planning for supply chains in semiconductor manufacturing. It is generally accepted that production planning and control, in the make-to-order environment of application-specific integrated circuit production, is a difficult task, as it has to be optimal both for the local manufacturing units and for the whole supply chain network. Centralised MRP II systems which are in operation in most of today's manufacturing enterprises are not flexible enough to satisfy the demands of this highly dynamic co-operative environment. In this paper Rupp et al. present a distributed planning methodology for semiconductor manufacturing supply chains. The developed system is based on an approach that leaves as much responsibility and expertise for optimisation as possible to the local planning systems while a global co-ordinating entity ensures best performance and efficiency of the whole supply chain.

## 3. Centralized vs decentralized deterministic planning: A case study of seasonal demand of aluminium doors

### 3.1 Problem description

In this section, we study the production planning problem in supply chain involving several enterprises whose final products are doors and windows made out of aluminum and compare two approaches to decision-making: decentralized versus centralized. The first enterprise is in charge of purchasing the raw materials and producing a partially competed product, whereas the second enterprise is in charge of designing the final form of the product which needs several adjustments before being released to the market. Some of those adjustments is the placement of several small parts, the addition of paint and the placement of glass pieces.

We focus on investigating the way that the seasonal demand can differently affect the performances of our whole system, in the case, of both centralized and decentralized optimization. Our basic system consists of two production plants, Factory 1 (F1) and Factory 2 (F2), for which we would like to obtain the optimal production plan, with two output stocks and two external production facilities called Subcontractor 1 and Subcontractor 2 (Subcontractor 1 gives final products to F1 and Subcontractor 2 to F2). We have also a finite horizon divided into periods. The production lead time of each plant is equal to one period (between the factories or the subcontractors). In Figure 1 we present our system which has the ability to produce a great variety of products. We will focus in one of these products, the one that appears to have the greatest demand in today's market. This product is a type of door made from aluminum type A. We call this product DoorTypeA (DTA). The demand which has a seasonal pattern that hits its maximum value during spring and its minimum value during winter as well as the production capacities and all the certain costs that we will talk about in a later stage are real and correspond to the Greek enterprise ANALKO. Factory 1 (F1) produces semi-finished components for F2 which produces the final product. The subcontractors have the ability to manufacture the entire product that is in demand or work on a specific part of the production, for example the placement of paint. Backorders are not allowed and all demand has to be satisfied without any delay. Each factory has a nominal production capacity and the role of the subcontractor is to provide additional external capacity if desirable. For simplicity, we assume that both initial stocks are zero and also that there is no demand for the final product during the first period. All factories have a large storage space which allows us to assume that the capacity of storing stocks is infinite. Subcontracting capacity is assumed to be infinite as well and both the production cost and the subcontracting cost are fixed during each period and proportional to the quantity of products produced or subcontracted respectively. Finally the production capacity of F1 is equal to the capacity of F2.

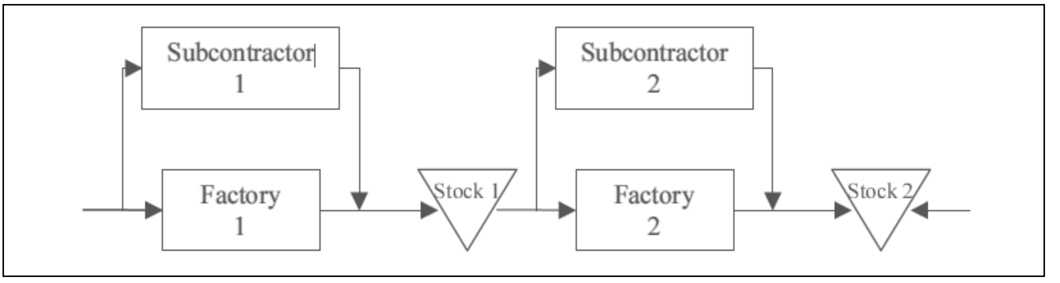


Fig. 1. The two-stage supply chain of ANALKO

On the one hand in the decentralized approach, we have two integrated local optimization problems from the end to the beginning. Namely, we first optimize the production plan of F2 and then that of F1. On the other hand, in centralized optimization we take into account all the characteristics of the production in the F1 and F2 simultaneously and then we optimize our system globally. The initial question is: What is to be gained by centralized optimization in contrast to decentralized?

### 3.2 Methodology

Two linear programming formulations are used to solve the above problems. In appendix A all decision variables and all parameters are presented:

#### 3.2.1 Centralized optimization

The developed model, taking under consideration the final demand and the production capacity of two factories as well as the subcontracting and inventories costs, optimizes the overall operation of the supply chain. The objective function has the following form:

$$Min\ Z = \sum_{i=1}^{2}[cp_i \sum_{t=1}^{T} P_{i,t} + h_i \sum_{t=1}^{T} I_{i,t} + \mathrm{csc}_i \sum_{t=1}^{T} SC_{i,t}] \tag{1}$$

The constraints of the problem are mainly two: a) the material balance equations:

$$I_{1,t} = I_{1,t-1} + P_{1,t} + SC_{1,t} - P_{2,t} - SC_{2,t}\ ,\ \ \forall t \tag{2}$$

$$I_{2,t} = I_{2,t-1} + P_{2,t} + SC_{2,t} - d_t\ ,\ \forall t \tag{3}$$

$$I_{1,t} = I_{2,T} = 0 \tag{4}$$

and b) the capacity of production:

$$P_{i,t} \leq \text{production capacity of factory i during period t} \tag{5}$$

$$P_{1,T} = P_{2,1} = 0 \tag{6}$$

#### 3.2.2 Decentralized optimization

In decentralized optimization two linear mathematical models are developed. The fist one optimizes the production of Factory 2 satisfying the total demand in each period under the capacity and material balance constraints of its level:

$$Min\ Z = cp_2 \sum_{t=1}^{T} P_{2,t} + h_2 \sum_{t=1}^{T} I_{2,t} + \text{csc}_2 \sum_{t=1}^{T} SC_{2,t} \tag{7}$$

subject to balance equations:

$$I_{2,t} = I_{2,t-1} + P_{2,t} + SC_{2,t} - d_t\ ,\ \forall t \tag{8}$$

$$I_{2,T} = 0 \tag{9}$$

and production capacity:

$$\text{P}_{2,\text{t}} \leq \text{production capacity of factory 2 during period t}\ ,\ \forall t \tag{10}$$

$$P_{2,1} = 0 \tag{11}$$

The second model optimizes the production of Factory 1 satisfying the total demand coming from Factory 2 in each period under the capacity and material balance constraints of its level:

$$Min\ Z = cp_1 \sum_{t=1}^{T} P_{1,t} + h_1 \sum_{t=1}^{T} I_{1,t} + \text{csc}_1 \sum_{t=1}^{T} SC_{1,t} \tag{12}$$

subject to balance equations:

$$I_{1,t} = I_{1,t-1} + P_{1,t} + SC_{1,t} - P_{2,t} - SC_{2,t}\ ,\ \forall t \tag{13}$$

$$I_{1,t} = 0 \tag{14}$$

and production capacity:

$$\text{P}_{2,\text{t}} \leq \text{production capacity of factory 2 during period t}\ ,\ \forall t \tag{15}$$

$$P_{1,T} = 0 \tag{16}$$

### 3.3 Qualitative results

We have used these two models to explore certain qualitative behavior of our supply chain. First of all we proved that the system's cost of centralized optimization is less than or equal to that of decentralized optimization (property 1).

***Proof*:** This property is valid because the solution of decentralized optimization is a feasible solution for the centralized optimization but not necessarily the optimal solution ■

In terms of each one factory's costs, the F2's production cost in local optimization is less than or equal to that of global (property 2).

***Proof*:** The solution of decentralized optimization is a feasible solution for the centralized optimization but not necessarily the optimal centralized solution ■

In terms of F1's optimal solution and using property 1 and 2 it is proved that the production cost in decentralized optimization is greater than or equal to that of centralized optimization (property 3).

In reality for the subcontractor the cost of production cost for one unit is about the same as that of an affiliate company. The subcontractor in accordance with the contract rules wishes to receive a set amount of earnings that will not fluctuate and will be independent of the market tendencies. Thus when the market needs change, the production cost and the subcontracting cost change but the fixed amount of earnings mentioned in the contract stays the same. The system's optimal production plan is the same when the difference between the production cost and the subcontracting cost stays constant as well as the difference between the costs of local and global optimization is constant (property 4). Using this property we are not obliged to change the production plan when the production cost changes. In addition, in some cases, we could be able to avoid one of two analyses.

***Proof*:** If for factory $F_2$, $\Delta_2 = \mathrm{csc}_2 - cp_2 = \mathrm{csc}'_2 - cp'_2$ where $\mathrm{csc}_2 \neq \mathrm{csc}'_2$ and $cp_2 \neq cp'_2$ then it is enough to demonstrate that the optimal value of the objective function as well as the optimal production plan are the same when the production cost and the subcontracting cost are $cp_2, \mathrm{csc}_2$ and when the production cost and the subcontracting cost are $cp'_2, \mathrm{csc}'_2$. For $cp'_2, \mathrm{csc}'_2$, we take the following objective function:

$$Min\ Z = cp'_2 \sum_{t=1}^{T} P_{2,t} + h_2 \sum_{t=1}^{T} I_{2,t} + \mathrm{csc}'_2 \sum_{t=1}^{T} SC_{2,t} \tag{17}$$

Subject to:
Balance equations:

$$I_{2,t} = I_{2,t-1} + P_{2,t} + SC_{2,t} - d_t, \ \forall t \tag{18}$$

$$I_{2,T} = 0 \tag{19}$$

Production capacity:

$$P_{2,t} \leq \text{production capacity of factory 2 during period t}, \ \forall t \tag{20}$$

$$P_{2,1} = 0 \tag{21}$$

It is also valid that:

$$\sum_{t=1}^{T} P_{2,t} + \sum_{t=1}^{T} SC_{2,t} = d_t, \ \forall t \tag{22}$$

$$\mathrm{csc}'_2 - cp'_2 = \Delta_2 \tag{23}$$

Using equalities (22), (23) the objective function becomes:

$$Min\ Z = cp'_2 \sum_{t=1}^{T} [d_t - SC_{2,t}] + h_2 \sum_{t=1}^{T} I_{2,t} + \mathrm{csc}'_2 \sum_{t=1}^{T} SC_{2,t} \Rightarrow$$

$$Min\ Z = cp'_2 \sum_{t=1}^{T} d_t + h_2 \sum_{t=1}^{T} I_{2,t} + (\mathrm{csc}'_2 - cp'_2) \sum_{t=1}^{T} SC_{2,t} \Rightarrow (\mathrm{csc}'_2 - cp' = \Delta_2)$$

$$Min\ Z = cp'_2 \sum_{t=1}^{T} d_t + h_2 \sum_{t=1}^{T} I_{2,t} + \Delta_2 \sum_{t=1}^{T} SC_{2,t} \tag{24}$$

Following the same procedure and using as production cost and subcontracting cost $csc_2$, $cp_2$ the objective function becomes:

$$Min\ Z = cp_2 \sum_{t=1}^{T} d_t + h_2 \sum_{t=1}^{T} I_{2,t} + \Delta_2 \sum_{t=1}^{T} SC_{2,t} \tag{25}$$

Objective function (24) and (25) have the same components (except the constant term $cp_2 \sum_{t=1}^{T} d_t$ which does not influence the optimization). This results the same minimum value and exactly the same production plan due to the same group of constraints (13)-(14)■

When the centralized optimization gives an optimal solution for F2 to subcontract the extra demand regardless of F1's plan, the decentralized optimization gives exactly the same solution (property 5).

***Proof*:** In this case F1 obtains the demand curve which is exactly the same to the curve of the final product. In the case of decentralized optimization (which gives the optimal solution for F2) in the worst scenario we will get a production plan which follow the demand or a mix plan (subcontracting and inventory). The satisfaction of the first curve (centralized optimization) is more expensive for F1 than the satisfaction of the second (decentralized optimization) because the supplementary (to the production capacity) demand is greater. For this reason the production cost of F1 in decentralized optimization is greater than or equal to the production cost of the centralized optimization and using property 2 we prove that centralized and decentralized optimal production cost for F1 should be the same ■

Finally, we have demonstrated that when at the decentralized optimization, the extra demand for *F*2 is satisfied from inventory then the centralized optimization has the same optimal plan (property 6).

***Proof*:** In this case of decentralized optimization, F1 has the best possible curve of demand because F2 satisfy the extra demand without subcontracting. In centralized optimization in the best scenario we take the same optimal solution for F2 or a mix policy. If we take the case of mix policy then the centralized optimal solution of F1 will be greater than or equal to the decentralized optimal solution and using property 3 we prove that centralized and decentralized optimal production cost for F1 should be the same■

## 4. Centralized vs decentralized deterministic scheduling: A case study from petrochemical industry

### 4.1 Problem description

Refinery system considered here is composed of pipelines, a series of tanks to store the crude oil (and prepare the different mixtures), production units and tanks to store the raw materials and the intermediate and final products (see Figure 2). All the crude distillation units are considered continuous processes and it is assumed that unlimited supply of the raw material is available to system. The crude distillation unit produces different products according to the recipes. The production flow of our refinery system provided by Honeywell involves 9 units as shown in Figure 2. It starts from crude distillation units that consume raw materials ANS and SJV crude, to diesel blender that produces CARB diesel, EPA diesel and red dye diesel. The other two final products are coker and FCC gas. All the reactions are considered as continuous processes. We consider the operating rule for the storage tanks where material cannot flow out of the tank when material is flowing into the tank at any time interval, that is loading and unloading cannot happen simultaneously. This rule is imposed in many petrochemical companies for security and operating reasons.

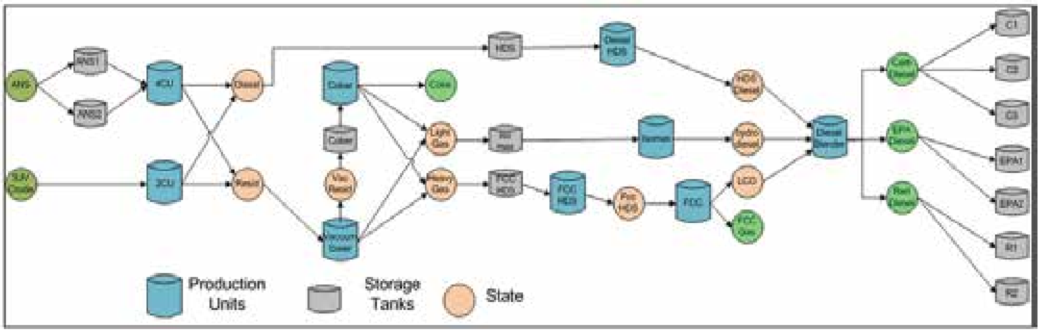


Fig. 2. Flowchat of the refinery system of Honeywell

In the system under study the production starts from cracking units and proceed to diesel blender unit to produce home heating oil (Red Dye diesel) and automotive diesel (Carb diesel and EPA diesel). Cracking unit, 4CU, processes Alaskan North Slope (ANS) crude oil which is stored in raw material storage tanks ANS1 and ANS2, whereas cracking unit 2 (2CU) processes San Joaquin Valley (SJV) crude oil. SJV crude oil is supplied to 2CU via pipeline. The products of cracking units are then processed further downstream by vacuum distillation tower unit and diesel high pressure desulfurization (HDS) unit. The coker unit converts vacuum resid into light and heavy gasoil and produces coke as residual product. The fluid catalyzed high pressure desulfurization (FCC HDS) unit, FCC, Isomax unit produce products that are needed for diesel blender unit. The FCC unit also produces by-product FCC gas. The diesel blender blends HDS diesel, hydro diesel, and light cycle oil (LCO) to produce three different final products. The diesel blender sends final products to final product storage tanks. The byproduct FCC gas and residual product Coke is not stored but supplied to the market via pipeline. The system employs four storage tanks to store intermediate products, vacuum resid, diesel, light gasoil, and heavy gasoil.

### 4.2 Methodology

A mixed integer linear programming (MILP) model is first developed for the entire problem with the objective to minimize the overall makespan. The formulation is based on a continuous time representation and involves material balance constraints, capacity constraints, sequence constraints, assignment constraints, and demand constraints. The long term plan is assumed to be given and the objective is to define the optimal production scheduling. In such a case the key information available for the managers is firstly the proportion of material produced or consumed at each production units. These recipes are assumed fixed to maintain the model's linearity. The managers also know the minimum and maximum flow-rates for each production unit and the minimum and maximum inventory capacities for each storage tank. The different types of material, that can be stored in each storage tank, are known as well as the demand of final products at the end of time horizon. The objective is to determine the minimum total makespan of production defining the optimal values of the following variables: 1) starting and finishing times of task taking place at each production unit; 2) amount and type of material being produced or consumed at each time in a production unit; and 3) amount and type of material stored at each time in each tank. In the following subsections the mathematical formulation of the centralized and decentralized optimization approach is presented as well as the structural decomposition rule developed for the decentralization of the global system. Notice that this decentralization rule is generally applicable in this type of system where intermediate stock areas (eg. tanks) appear and in the same time the production is a continuous process. In the end of this section an analytical mathematical proof is given in order to demonstrate that the application of this structural decomposition rule, for the decentralization of the system, gives the same optimal solution as the centralize optimization.

### 4.2.1 Centralized optimization

In this section the centralized mathematical model is presented. Notice that all parameters of the problem as well as the decision variables are given in appendix B. The objective function of the problem is the minimization of makespan (H). The most common motivation for optimizing the process using minimization of makespan as objective function is to improve customer services by accurately predicting order delivery dates.

$$\min H \tag{26}$$

Constraints (27) to (29) define binary variables *wv, in,* and *out*, which are 1 when reaction, input flow transfer to tanks and output flow transfer from tanks occur at event point n, respectively. Otherwise, they become 0. Variable $in(j, jst, n)$ is equal to 1 if there is flow of material from production *unit (j)* to storage *tank (jst)* at *event point (n)*; otherwise it is equal to 0. Variable $out(jst, j, n)$ is equal to 1 if material is flowing from storage (jst) to unit (j) at event point (n), otherwise it is equal to 0. Equations (28) and (29) are capacity constraints for storage tank. Constraints (28) state that if there is material inflow to tank (jst) at interval (n) then total amount of material inflow to the tank should not exceed the maximum storage capacity limit. Similarly, constraints (29) state that if there is outflow from tank (jst) at interval (n) then the total amount of material flowing out of tank should not exceed the storage limit at event point (n).

$$b_{i,j,n} \le U * wv_{i,j,n} \tag{27}$$

$$\text{inflow}_{j,jst,n} \le V_{jst}^{\max} * in_{j,jst,n} \tag{28}$$

$$\text{outflow}_{j,jst,n} \le V_{jst}^{\max} * out_{j,jst,n} \tag{29}$$

Material balance constrains (30) state that the inventory of a storage tank at one event point is equal to that at previous event point adjusted by the input and output stream amount.

$$St_{jst,n} = St_{jst,n-1} + \sum_{j \in Jprodst_{jst}} \text{inflow}_{j,jst,n} + \text{inflow1}_{jst,n} - \sum_{j \in Jstprod_{jst}} outflow_{j,jst,n} \tag{30}$$

The production of a reactor (31) should be equal to the sum of amount of flows entering its subsequent storage tanks and reactors, and the delivery to the market.

$$\sum_{i \in I_J} \rho_{s,i}^{P} b_{i,j,n} = \sum_{jst \in JSTprodst_j \cap JST_S} \text{inflow}_{j,jst,n} + \sum_{j' \in Jseq_j \cap Junitc_s} \text{unitflow}_{s,j,j',n} + \text{outflow2}_{s,j,n} \tag{31}$$

Similarly, the consumption of a reactor (32) is equal to the sum of amount of streams coming from preceding storage tanks and previous reactors, and stream coming from supply.

$$\sum_{i\in I_J} \rho^C_{s,i} * b_{i,j,n} = \sum_{jst\in Jstprod_j \cap JST_S} outflow_{jst,j,n} + \sum_{j'\in Jseq_j \cap Junitp_s} unitflow_{s,j,j',n} + \inf low2_{s,j,n} \quad (32)$$

Demand for each final product $r_s$ must be satisfied in centralized problem and also in decentralized problem. Constraints (33) state that production units must at least produce enough material to satisfy the demand by the end of the time horizon.

$$\sum_{jst\in JST_s,n} outflow1_{jst,n} + \sum_{j,n} outflow2_{s,j,n} \geq r_s \quad (33)$$

Constraints (34) enforce the requirement that material processed by unit (*j*) performing task (*i*) at any point (*n*) is bounded by the maximum and minimum rates of production. The maximum and minimum production rates multiply by the duration of task (*i*) performed at unit (*j*) give the maximum and minimum material being processed by unit (*j*) correspondingly.

$$R^{\min}_{i,j}(Tf_{i,j,n} - Ts_{i,j,n}) \leq b_{i,j,n} \leq R^{\max}_{i,j}(Tf_{i,j,n} - Ts_{i,j,n}) \quad (34)$$

In the same reactor, one reaction must start after the previous reaction ends. If binary variable *wv* in inequality (35) is 1 then constraint is active. Otherwise the right side of the constraint is relaxed.

$$Ts_{i,j,n+1} \geq Tf_{i',j,n} - U * (1 - wv_{i',j,n}) \quad (35)$$

If both input and output streams exist at the same event point in a tank, then the output streams must start after the end of the input streams.

$$Tsf_{j,jst,n} - U * (1 - in_{j,jst,n}) \leq Tss_{jst,j',n} + U * (1 - out_{jst,j',n}) \quad (36)$$

When a reaction takes place in a reactor, its subsequent reactions must take place at the same time. Constraints (37) and (38) are active only when both binary variables are 1.

$$Ts_{i',j',n} - U * (2 - wv_{i,j,n} - wv_{i',j',n}) \leq Ts_{i,j,n} \leq Ts_{i',j',n} + U * (2 - wv_{i,j,n} - wv_{i',j',n}) \quad (37)$$

$$Tf_{i',j',n} - U * (2 - wv_{i,j,n} - wv_{i',j',n}) \leq Tf_{i,j,n} \leq Tf_{i',j',n} + U * (2 - wv_{i,j,n} - wv_{i',j',n}) \quad (38)$$

Also when one reaction takes place, the flow transfer to its subsequent tanks must occur simultaneously.

$$Tss_{j,jst,n} - U * (2 - wv_{i,j,n} - in_{j,jst,n}) \leq Ts_{i,j,n} \leq Tss_{j,jst,n} + U * (2 - wv_{i,j,n} - in_{j,jst,n}) \quad (39)$$

$$Tsf_{j,jst,n} - U * (2 - wv_{i,j,n} - in_{j,jst,n}) \leq Tf_{i,j,n} \leq Tsf_{j,jst,n} + U * (2 - wv_{i,j,n} - in_{j,jst,n}) \quad (40)$$

Similar constraints are written for the reaction and its preceding flow transfer from tanks to the reactor, as in constraints (41) and (42).

$$Tss_{jst,j,n} - U * (2 - wv_{i,j,n} - out_{jst,j,n}) \leq Ts_{i,j,n} \leq Tss_{jst,j,n} + U * (2 - wv_{i,j,n} - out_{jst,j,n}) \quad (41)$$

$$Tsf_{jst,j,n} - U * (2 - wv_{i,j,n} - out_{jst,j,n}) \leq Tf_{i,j,n} \leq Tsf_{jst,j,n} + U * (2 - wv_{i,j,n} - out_{jst,j,n}) \quad (42)$$

Finally, the following constraints (43) define that all the time related variables are less than makespan (*H*).

$$Tf_{i,j,n} \le H \ , \ Tsf_{j,jst,n} \le H \ , \ Tsf_{jst,j,n} \le H \tag{43}$$

### 4.2.2 Decentralized optimization

The decentralized strategy proposed here decomposes the refinery scheduling problem spatially. To obtain the optimal solution in decentralized optimization approach, each sub-system is solved to optimality and these optimal results are used to obtain the optimal solution for the entire problem. In our proposed decomposition rule, we split the system in such a way so that a minimum amount of information is shared between the sub-problems. This means splitting the problem at intermediate storage tanks such that the inflow and outflow streams of the tank belong to different sub-systems. The decomposition starts with the final products or product storage tanks, and continues to include the reactors/units that are connected to them and stops when the storage tanks are reached. The products, intermediate products, units and storage tanks are part of the sub-system 1. Then following the input stream of each storage tank, the same procedure is used to determine the next sub-system. If input and output stream of the tank are included at the same local problem then the storage tank also belongs to that local problem.

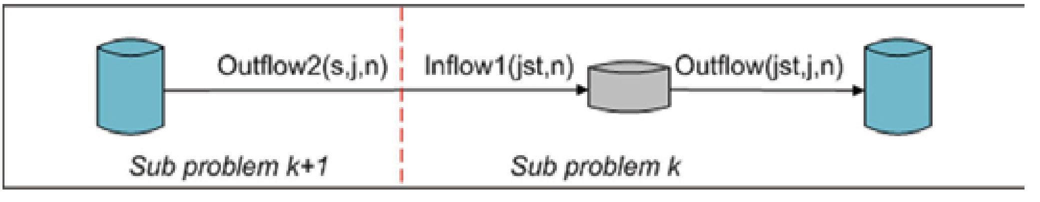


Fig. 3. Intermediate storage tank connecting two sub-systems

When the problem is decomposed at intermediate storage tanks, storage tanks become a connecting point between two sub-systems. The amount and type of material flowing out of the connecting intermediate storage tank at any time interval (n) becomes demand for the preceding sub-system (k+1) at corresponding time interval (see Figure 3).

After decomposing the centralized system, the individual sub-systems are treated as independent scheduling problems and solved to optimality using the mathematical formulation described in previous subsection. It should be also noticed that the operating rules for the decentralized system are the same as those required for the centralized problem. In general the local optimization of sub-system k gives minimum information to the sub-system k+1 which optimizes its schedule with the restrictions regarding the demand of the intermediates obtained by sub-system k. In Figure 4, we present the decomposition of the system under study after the application of the developed decomposition rule. The system is split in two sub-systems where sub-system 1 produces all of the final products and one by-product. The sub-system 1 includes 5 production unit, 7 final product storage tanks, and 3 raw material tanks. Raw material tanks in sub-system 1 are defined as intermediate tanks in centralized system. The sub-system 2 includes 4 production units, 1 intermediate tank, 2 raw material tanks and it produces 4 final products. Except Coke, all other final products in sub-system 2 are defined as intermediate products in centralized system.

The sub-systems obtained using this decomposition rule have all the constraints presented in the basic model but in addition to that the k+1 sub-system has to satisfy the demand of

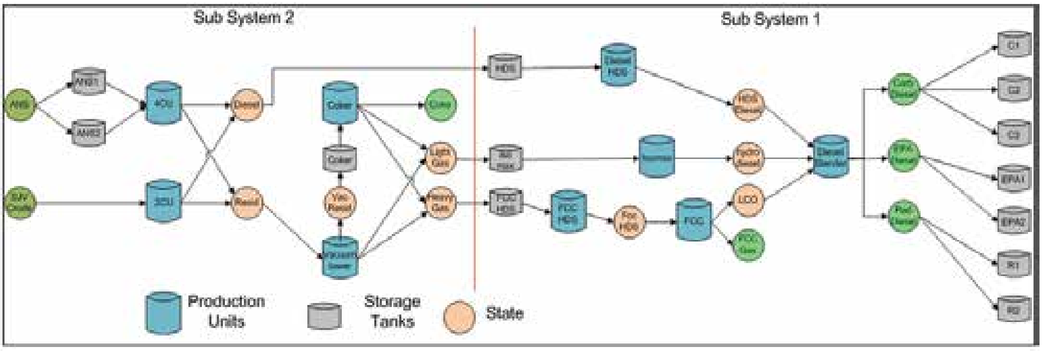


Fig. 4. Decomposition of Honeywell production system

final products produced by this sub-system and also the demand of intermediate products needed by sub-system k. The demand constraints for intermediate final products for sub-system k+1 are given by equation (44).

$$\sum_{j} \text{outflow2(s,j,n)} \geq \text{r(s,n)}, \quad \forall \text{s} \in \text{S}, \text{j} \in \text{Junitp}(s,k+1), \text{n} \in \text{N} \tag{44}$$

When production units in sub-system k+1 supply material to storage tanks located in sub-system k, in order to obtain globally feasible solution, the following capacity constraints are added to sub-system k+1. Constraint in equation (45) is for time interval n=0; sum of the material supplied to storage tank (jst) in sub-system k and initial amount present in the storage tank must be within tank capacity limit. Whereas equations (46) and (47) represents capacity constraints for event point n=1 and n=2 respectively.

$$\sum_{j} \text{outflow2(s,j,n)} + \text{stin(jst)} \leq \text{V}^{\max}\text{(jst)}, \quad \forall \text{s} \in \text{S}, \text{jst} \in \text{Jst(s,k)}, \text{j} \in \text{Junitp(s,k+1)}, n = 0 \tag{45}$$

$$\sum_{j} \sum_{n=0}^{1} \text{outflow2(s,j,n)} + \text{stin(jst)} - r_S(0) \leq \text{V}^{\text{max}}\text{(jst)}, \quad \forall \text{s} \in \text{S}, \text{jst} \in \text{Jst(s,k)}, \text{j} \in \text{Junitp(s,k+1)}, \text{n} \in \text{N} \tag{46}$$

$$\sum_{j} \sum_{n=0}^{2} \text{outflow2(s,j,n)} + \text{stin(jst)} - \sum_{n=0}^{1} \text{r(s,n)} \leq \text{V}^{\text{max}}\text{(jst)}, \quad \forall \text{s} \in \text{S}, \text{jst} \in \text{Jst(s,k)}, \text{j} \in \text{Junitp(s,k+1)}, \text{n} \in \text{N} \tag{47}$$

Constraints (48) and (49) represent lot sizing constraints for sub-system k+1. The demand of intermediate final product s at event point n is adjusted by the amount present in the storage tank after the demand is satisfied at previous event point (n-1). This adjusted demand is then used in demand constraints for intermediate final products.

$$\text{r(s,1)} - \left( \sum_{j} \text{outflow2(s,j,0)} + \text{stin(jst)} - \text{r(s,0)} \right) = \text{r}'\text{(s,1)}, \quad \forall \text{s} \in \text{S}, \text{j} \in \text{Junitp(s,k+1)}, \text{jst} \in \text{Jst(s,k)} \tag{48}$$

$$\text{r(s,2)} - \left( \sum_{j} \sum_{n=0}^{1} \text{outflow2(s,j,n)} + \text{stin(jst)} - \sum_{n=0}^{1} \text{r(s,n)} \right) = \text{r}'\text{(s,2)}, \quad \forall \text{s} \in \text{S,j} \in \text{Junitp(s,k+1)}, \text{jst} \in \text{Jst(s,k)}, \text{n} \in \text{N} \tag{49}$$

The optimal time horizon of global problem is obtained by combining the optimal schedules of sub-systems at each point (*n*) such that the material balance constraints are satisfied for connecting intermediate storage tanks. Since sub-system *k+1* satisfies the demand of sub-system *k,* sub-system *k+1* will happen before the sub-system *k*.

### 4.3 Qualitative results

In this section an analytical proof is presented in order to demonstrate that the decentralization of the system under study using the rule presented in section 4.2.2 gives exactly the same optimal makespam as the one obtained by centralized optimization.

***Proof:*** The makespam ($H_L$: local makespam and $H_G$: global makespam) is defined as follow: $H = \sum_{k,z_k} HH_{k,z_k}$ where $HH_{k,z_k} = \sum_{i,n}(T^f_{i,j,n} - T^s_{i,j,n})$ corresponds to $z^{th}$ group of $k^{th}$ sub-system. The $z^{th}$ group is a group where all the *j* which belong to the $z^{th}$ group happen at the same time due to continuity of process operations. In the system under study applying the decomposition rule, we have 2 sub-systems which means k=2. For the 1st sub-system (k=1), $z_1$=1,2 which means that we have 2 groups of units which do not operate at the same time (because of the coker tank). For the 2nd sub-system (k=2) all the units work at the same time $z_2$=1. For $z_1$=1: Vacum_tower, 2CU and 4CU, for $z_1$=2: Coker and for $z_2$=1: FCC HDS, Isomax, FCC, Diesel HDS and Blender. If all the members of the sum $H = \sum_{k,z_k} HH_{k,z_k}$ in decentralized and centralized optimization are equal then $H_L = H_G$.

Without loss of generality, we are going to prove that for k=2 and $z_2$=1 the centralized and decentralized optimization gives the same optimal makespam. The same procedure can be used to prove the case of k=1 and $z_1$=1, 2.

We have to prove that for *i,j* which belong to $z_2$=1, the equality 50 is valid:

$$\sum_{i,n}(T^f_{i,j,n} - T^s_{i,j,n})_L = \sum_{i,n}(T^f_{i,j,n} - T^s_{i,j,n})_G \tag{50}$$

*Proof* of (50): If $\sum_n b_{i,j,n\,L} = \sum_n b_{i,j,n\,G}$ (51) then the equality (50) is valid ( $HH_{2,1L} = HH_{2,1G}$ for appropriate *i,j*). From constraints (34) we have for the decentralized model (34L) and centralized model (34G):

$$R^{MIN}_{i,j}(T^f_{i,j,nL} - T^s_{i,j,nL}) \le b_{i,j,nL} \le R^{MAX}_{i,j}(T^f_{i,j,nL} - T^s_{i,j,nL}) \tag{34L}$$

$$R^{MIN}_{i,j}(T^f_{i,j,nG} - T^s_{i,j,nG}) \le b_{i,j,nG} \le R^{MAX}_{i,j}(T^f_{i,j,nG} - T^s_{i,j,nG}) \tag{34G}$$

We sum (34L, 34G) over *n* and we get the following:

$$R^{MIN}_{i,j}\sum_n(T^f_{i,j,nL} - T^s_{i,j,nL}) \le \sum_n b_{i,j,nL} \le R^{MAX}_{i,j}\sum_n(T^f_{i,j,nL} - T^s_{i,j,nL}) \tag{34L'}$$

$$R^{MIN}_{i,j}\sum_n(T^f_{i,j,nG} - T^s_{i,j,nG}) \le \sum_n b_{i,j,nG} \le R^{MAX}_{i,j}\sum_n(T^f_{i,j,nG} - T^s_{i,j,nG}) \tag{34G'}$$

We then make the following steps: (31L'-31G') and (31G'-31L') and using (51) we prove (50).

*Proof of (51):* In general only one unit *j* produces a product *s*. Thus, in constraints (33) only one of the two parts exists because a product s is produced by a unique unit or is unloaded from a tank or sum of tanks.

$$\sum_{jst\in JST_s,n} outflow1_{jst,n} \geq r_s \quad s\in\{11,12,13\} \tag{33A}$$

$$\sum_{j,n} outflow2_{s,j,n} \geq r_s \quad s\in\{10,14\} \tag{33B}$$

In decentralized and centralized optimization demand $r_s$ is the same which means that:

$$\left.\sum_{jst\in JST_s,n} outflow1_{jst,n}\right._L = \left.\sum_{jst\in JST_s,n} outflow1_{jst,n}\right._G \quad s\in\{11,12,13\} \tag{52}$$

$$\left.\sum_{j,n} outflow2_{s,j,n}\right._L = \left.\sum_{j,n} outflow2_{s,j,n}\right._G \quad s\in\{10,14\} \tag{53}$$

We can obtain (52) and (53) by subtracting (33AL-33AG) and (33AG-33AL) where (33AL), (33AG) are constraints (33A) for the decentralized and centralized case, respectively for (52) and (33BL-33BG) and (33BG-33BL) (where (33BL), (33BG) are constraints (33B) for the decentralized and centralized case) respectively for (53). It should be pointed out that the sum over *j* in (53) can be eliminated because only one *j* produces the product *s.*
A general constraint of the system is that the production and the storage of a produced product take place in the same time.
That means that: $\sum_{jst\in JST_s,n} outflow1_{jst,n} = \sum_{j_s,n} outflow2_{s,j,n}$ and eliminating the sum over *j* for the same reason as in (53) we take: $\sum_{jst\in JST_s,n} outflow1_{jst,n} = \sum_{n} outflow2_{s,j,n}$ (54) for $s\in\{11,12,13\}$ and $j\in J_s$ which is unique. From (53) and (54) we take: $\left.\sum_{n} outflow2_{s,j,n}\right._L = \left.\sum_{n} outflow2_{s,j,n}\right._G, s\in\{10,11,12,13,14\}$ (55). Let's then consider the problem constraints (31): $\sum_{i\in I_j} p^p_{s,i} b_{i,j,n} = outflow2_{s,j,n} s\in\{10,11,12,13,14\}$. Using constraints (27) only one *i* happens at *j* in a certain period *n*. Then the sum over *i* can be relaxed: $p^p_{s,i} b_{i,j,n} = outflow2_{s,j,n} s\in\{10,11,12,13,14\}$ (56). Equation (56) is for the specific s which is produced from a unique *j* from exact task *i* in a certain period *n*. Using equation (55) we have:

$$\left.\sum_{n} outflow2_{s,j,n}\right._L = \left.\sum_{n} outflow2_{s,j,n}\right._G \Rightarrow \text{ using (56)} \qquad \Rightarrow$$

$$\left.\sum_{n} p^p_{s,i} b_{i,j,n}\right._L = \left.\sum_{n} p^p_{s,i} b_{i,j,n}\right._G \Rightarrow \left.\sum_{n} b_{i,j,n}\right._L = \left.\sum_{n} b_{i,j,n}\right._G \qquad \Rightarrow$$

$$\left.\sum_{n} (T^f_{i,j,n} - T^s_{i,j,n})\right._L = \left.\sum_{n} (T^f_{i,j,n} - T^s_{i,j,n})\right._G \Rightarrow \left.\sum_{i,n} (T^f_{i,j,n} - T^s_{i,j,n})\right._L = \left.\sum_{i,n} (T^f_{i,j,n} - T^s_{i,j,n})\right._G$$

$$\forall i\in I_j, j\in J_s, s\in\{10,11,12,13,14\}.$$

That means that equality (50) is satisfied. Summarizing the presented proof is based on the fact that the total time needed to produce a group of products which are produced in the same period in units *j* of z group is the same in local and global optimization ■

## 5. Centralized vs decentralized control policies: A case study of aluminium doors with stochastic demand

### 5.1 Problem description

In this session, we examine a stochastic supply chain which corresponds at ANALKO enterprise. This supply chain is composed by two manufacturers that produce a single product type. The first manufacturer provides the basic component of the final product, and the second one makes the final product (see figure 4). Factory $F_1$ purchases raw material, produces the basic component of product and places its finished items at buffer 1. The second factory makes final products and stores them in buffer 2 in anticipation of future demand. The processing times in each factory have exponential distributions and demand is a Poisson process with a constant rate. There is ample supply of raw items before the first factory so that $F_1$ is never starved. There are also two external suppliers, subcontractor $SC_1$ and, possibly, subcontractor $SC_2$. $SC_1$ can provide basic components to $F_2$ whenever buffer 1 becomes empty. Thus, $F_2$ is also never starved. $SC_2$ can satisfy the demand during stockouts; if $SC_2$ is not available, then all demand during stockouts is lost. Demand is satisfied by the finished goods inventory, if buffer 2 is not empty, otherwise it is either backlogged or satisfied by $SC_2$. Whenever a demand is backlogged, backorder costs are incurred. Holding costs are incurred for the items held in buffer 1 and buffer 2 as well as for those being processed by $F_1$ and $F_2$. The objective is to control the release of items from each factory and each subcontractor to the downstream buffer so that the sum of the long-run average holding, backordering, and subcontracting costs is minimized. We use Markov chains to evaluate the performance of the supply chain under various control policies.

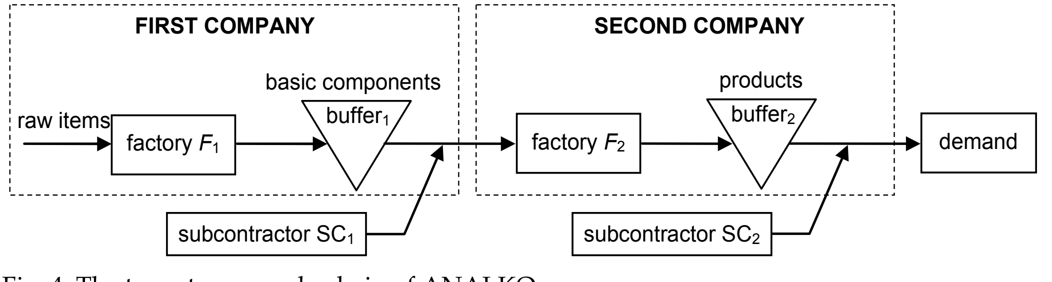


Fig. 4. The tow-stage supply chain of ANALKO

Let $I_1$ denote the number of items in buffer 1 plus the item that is currently being processed by $F_2$, if any. Also, $I_2$ is the *inventory position* of the second stage, that is, the number of finished products in buffer 2 minus outstanding orders. Raw items that are being processed by $F_1$ are not counted in $I_1$. The state variable $I_2$ is positive when there are products in buffer 2; during stockout periods, $I_2$ is negative, if there are outstanding orders to be filled, or zero otherwise. Two production policies are examined: a) *Base stock control* (BS): Factory $F_i$, $i = 1$, 2, produces items whenever $I_i$ is lower than a specified level $B_i$ and stops otherwise. This policy is commonly used in production systems, and b)*Echelon base stock control* (ES): Factory $F_2$ employs a base stock policy with threshold $B_2$ as in BS, while $F_1$ produces items only as long as its echelon (downstream) inventory position, $I_1 + I_2$, is lower than a specified level $E_1$, which will be referred to as the *echelon base stock*.

An order admission policy is also studied (in combination with BS and ES) whereby the arriving orders during a stockout period are accepted until a certain level *C*, called the *base backlog*. An arriving order that finds *C* outstanding orders ahead is subcontracted (or lost if $SC_2$ is not available). This is a *partial backordering policy* (PB). Although it has received little attention in the past, PB is frequently applied in practice because it is more profitable than other policies such as lost sales or complete backordering (Kouikoglou and Phillis 2002; Ioannidis et al., 2008).

### 5.2 Methodology

#### 5.2.1 Performance measures

The overall performance measure of the system is the mean profit rate. This quantity depends on the revenue from sales and the costs of backlog, inventory, production, and subcontracting. The inventory cost typically includes direct costs for storing goods and a loss of opportunity to invest in a profitable way the capital spent for the raw material which resides in the system in the form of semi-finished or end items (see, e.g., Zipkin 2000, p. 34). The backlog cost is in general difficult to measure (Hadley and Whitin 1963, p. 18); it comprises the loss of opportunity to invest an immediate profit, the loss of goodwill when a customer faces a stockout, and a penalty per time unit of delay in filling orders (e.g., discounts offered to customers willing to wait).

We consider the following profit or cost parameters: a) $p_1$ price at which $F_1$ sells a component to $F_2$ (produced by $F_1$ or by $SC_1$), b) $p_2$ selling price of the final product (produced by $F_2$ or by $SC_2$), c) $sc_i$ price at which the external subcontractor $SC_i$ sells finished items to $F_i$, d) $c_i$ unit production cost at $F_i$ ($c_1$ includes the cost of purchasing a raw item), e) $h_i$ unit holding cost rate in $F_i$ (per item per time unit), and f) b backlog cost rate incurred by $F_2$ (per time unit of delay of one outstanding order). If $SC_2$ is not available, then all demand not satisfied by the system (either immediately or after some delay) is lost. This case can be analyzed by setting $sc_2$ equal to the loss of profit $p_2$ plus an additional penalty for rejecting a customer order. For each factory, we assume that it is more costly to purchase an item from a subcontractor than to produce it. Thus, $sc_1 > c_1$ and $sc_2 > p_1 + c_2$. We also assume that production is profitable; hence $p_1 > c_1$ and $p_2 > p_1 + c_2$.

The following quantities are long-run statistics, assuming they exist, of various stochastic processes associated with the performance of the supply chain: a) $TH_i$ mean throughput rate of factory $F_i$, b) $THSC_i$ mean rate of purchasing items from subcontractor $SC_i$, c) $\alpha_I$ stationary probability that $F_i$ is busy, d) B mean number of outstanding orders, i.e., $B = E[\max(-I_2, 0)]$ (57) where E is the expectation operator, and e) $H_i$ mean number of items in $F_i$ (being processed and finished), i.e., $H_1 = \alpha_1 + E(I_1) - \alpha_2$ (58) and $H_2 = \alpha_2 + E[\max(I_2, 0)]$ (59) where $\max(I_2, 0)$ is the number of products in buffer 2. Equations (58-59) follow from the fact that, by definition, $H_1$ includes the item which is being processed by $F_1$ but $I_1$ does not include it; on the contrary, $H_1$ does not include the item that is being processed by $F_2$, which, however, is included in $I_1$ and in $H_2$.

Using the parameters and statistics defined above we can compute performance measures for the individual factories and the whole system. The mean profit rate $J_i$ of $F_i$, $i = 1, 2$, and the overall profit rate $J$ of the system are given by:

$$J_1 = (p_1 - c_1)\mathrm{TH}_1 + (p_1 - \mathrm{sc}_1)\mathrm{THSC}_1 - h_1 H_1 \quad (60)$$

$$J_2 = (p_2 - c_2 - p_1)\mathrm{TH}_2 + (p_2 - \mathrm{sc}_2)\mathrm{THSC}_2 - h_2 H_2 - bB \quad (61)$$

$$J = J_1 + J_2 \quad (62)$$

In equations (57) and (58), the terms involving the throughput rates $\mathrm{TH}_i$ and $\mathrm{THSC}_i$ represent net profits from sales of factory $F_i$. In equilibrium, the mean inflow rate of $F_2$ equals its mean outflow rate, i.e., $\mathrm{TH}_1 + \mathrm{THSC}_1 = \mathrm{TH}_2$, and the mean demand rate equals $\mathrm{TH}_2 + \mathrm{THSC}_2$. If $\mathrm{SC}_2$ is not available, then $\mathrm{THSC}_2$ is the rate of rejected orders.
Along with the policies BSPB and ESPB described in previous subsection, we consider two strategies the companies participating in ANALKO can adopt to maximize their profits: decentralized or local optimization and centralized or global optimization. In both cases, the objective is to determine C, $B_2$, and $B_1$ (under BSPB) or $E_1$ (under ESPB) so as to maximize certain performance measures which are discussed next.
Under decentralized optimization, factory $F_2$ determines C and $B_2$ which maximize its own profit rate $J_2$. Recall that this factory is never starved. Therefore, regardless of the choice of $B_1$ or $E_1$, the second stage of the supply chain can be modeled as a single-stage queueing system in isolation in which the arrivals correspond to finished items leaving $F_2$, the queue represents the products stored in buffer 2, and the departures correspond to customer orders. After specifying its control parameters, $F_2$ communicates these values and also information about the demand to the first stage $F_1$ which, in turn, seeks an optimal value for $B_1$ or $E_1$ so as to maximize $J_1$. Under centralized optimization, the primary objective is to maximize the profit rate J of the system in all control parameters jointly. Intuitively, centralized optimization is overall more profitable than LO, i.e., $J^{GO} \geq J^{LO}$. This can easily be shown by comparing the maximizing arguments (argmax) of profit equations.
A general rule is that each company must benefit from being member of the supply chain. Under decentralized optimization, the second factory maximizes its own profit in an unconstrained manner, so $J_2^{LO} \geq J_2^{GO}$. However, it follows from $J^{GO} \geq J^{LO}$ and (61) that $J_1^{GO} \geq J_1^{LO}$. Thus, centralized optimization is more preferable than decentralized optimization for the first factory, provided that the second factory agrees to follow the same strategy. If the individual profits $J_i^{LO}$ are acceptable for both factories, then LO could be used as a basis of a profit-sharing agreement: a) adopt centralized optimization, so that $F_1$ accumulates more profit, and b) decrease the price $p_1$ at which $F_1$ sells to $F_2$ so that, in the long run, factory $F_i$ has a profit rate equal to $J_i^{LO}$ plus a pre-agreed portion of the additional profit rate $J^{GO} - J^{LO}$. If, on the other hand, $F_1$ is not willing to participate to a supply chain operating under decentralized optimization but it would be willing to do so under centralized optimization, then there are several possibilities for the two companies to reach (or not reach) a cooperation agreement, depending on the magnitude of the extra profit $J^{GO} - J^{LO}$ and the profit margins of the company that owns $F_2$. In general, such problems are difficult and often not well-posed because they are fraught with conflict of interests and subjectivity. In this paper, we assume that both companies are willing to adopt decentralized optimization, as is the case of ANALKO. The problem then is to investigate under which conditions the additional profit rate $J^{GO} - J^{LO}$ would make it worth introducing centralized optimization and how the optimal control parameters can be computed.

### 5.2.2 Centralized and decentralized optimization

We assume that the processing times of $F_1$ and $F_2$ are independent, exponentially distributed random variables with means $1/\mu_i$ and the products are demanded one at a time according to a Poisson process with rate λ. In practice, the processing times often have lower variances than the exponential distribution. The assumption of exponential processing and interarrival times is adopted here in order to facilitate the analysis by Markov chain models. Systems with more general distributions can be evaluated using higher-dimensional Markovian models or simulation. The state of the system is the pair ($I_1$, $I_2$), i.e., the number of components which have not yet being processed by $F_2$ and the inventory position of the second stage. The state variables provide information about the working status of each factory, and form a Markov chain whose dynamics depend on the production control policy as we shall discuss in the next two subsections.

Modeling Base stock control with partial backordering: Factory $F_1$ is working when $I_1 < B_1$. Hence, a transition from state ($I_1$, $I_2$) to state ($I_1 + 1$, $I_2$) occurs with rate $\mu_1$, but these transitions are disabled in states ($B_1$, $I_2$). A transition from state ($I_1$, $I_2$) to ($I_1 - 1$, $I_2 + 1$) occurs with rate $\mu_2$ whenever $I_2 < B_2$. When $I_1 = 1$, $F_2$ is working on one item and buffer 1 is empty; in this case, if this item is produced before $F_1$ sends another one to buffer 1, then the first company is obliged to deliver an item to $F_2$ by purchasing one from $SC_1$. We then have a transition from state (1, $I_2$) to (0, $I_2 + 1$) with rate $\mu_2$, followed by an immediate transition to (1, $I_2 + 1$) which ensures that $F_2$ will continue to produce. However, in state (1, $B_2 - 1$), if $F_2$ produces one item, then it stops producing thereafter since $I_2$ reaches the base stock $B_2$. Hence, there is no need to buy from $SC_1$ and the new system state is (0, $B_2$). Finally, we consider the state transitions triggered by a demand. According to the partial backordering policy, an arriving customer order is rejected when $I_2 = -C$, otherwise it is backordered and the new state is $I_2 - 1$. These transitions occur with rate λ. A diagram showing the state transitions explained above is shown in figure 5.

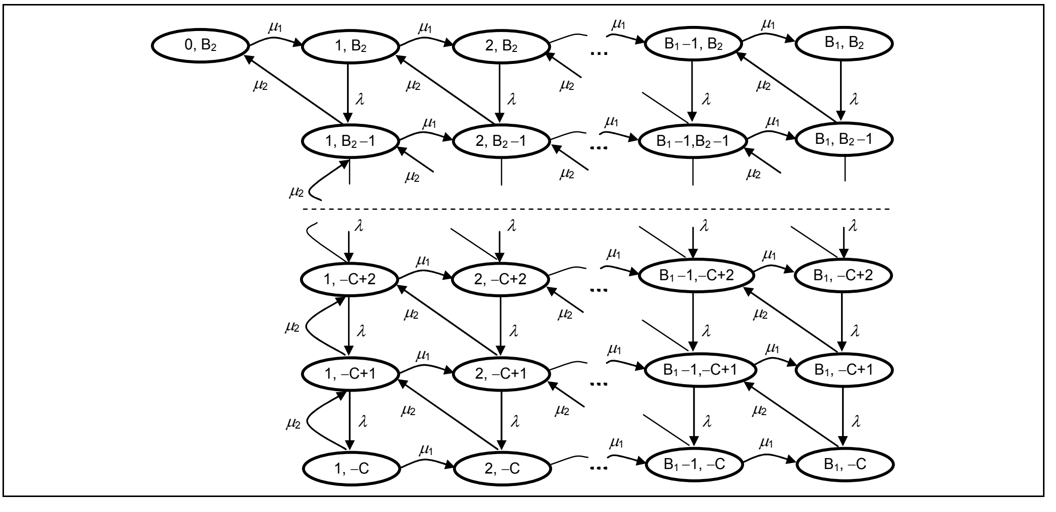


Fig. 5. Markov chain of the supply chain under BSPB.

The Chapman-Kolmogorov equations for the equilibrium probabilities $P(I_1, I_2)$ are

$I_2 = B_2$: $\mu_1 P(0, B_2) = \mu_2 P(1, B_2 - 1)$

$(\lambda + \mu_1)P(I_1, B_2) = \mu_1 P(I_1 - 1, B_2) + \mu_2 P(I_1 + 1, B_2 - 1)\ ,\ 1 \le I_1 \le B_1 - 1,$

$\lambda P(B_1, B_2) = \mu_1 P(B_1 - 1, B_2)$

$B_2 > I_2 > -C$: $(\lambda + \mu_1 + \mu_2)P(1, I_2) = \mu_2[P(1, I_2 - 1) + P(2, I_2 - 1)] + \lambda P(1, I_2 + 1)$

$$(\lambda + \mu_1 + \mu_2)P(I_1, I_2) = \mu_1 P(I_1 - 1, I_2) + \mu_2 P(I_1 + 1, I_2 - 1) + \lambda P(I_1, I_2 + 1),\ 2 \le I_1 \le B_1 - 1,$$

$$(\lambda + \mu_2)P(B_1, I_2) = \mu_1 P(B_1 - 1, I_2) + \lambda P(B_1, I_2 + 1)$$

$I_2 = -C$:

$$(\mu_1 + \mu_2)P(1, -C) = \lambda P(1, -C + 1)$$

$$(\mu_1 + \mu_2)P(I_1, -C) = \mu_1 P(I_1 - 1, -C) + \lambda P(I_1, -C + 1),\ 2 \le I_1 \le B_1 - 1,$$

$$\mu_2 P(B_1, -C) = \mu_1 P(B_1 - 1, -C) + \lambda P(B_1, -C + 1).$$

We solve the first of the equations given above for $P(0, B_2) = (\mu_2/\mu_1)P(1, B_2 - 1)$. We define the column vectors $P_{I_2} = [P(1, I_2)\ \dots\ P(B_1, I_2)]^T$ for $I_2 = B_2, B_2 - 1, \dots, -C$. The Chapman-Kolmogorov equations can be written more compactly as:

$$A_1 P_{B_2} = H_1 P_{B_2 - 1}\ I_2 = B_2 \tag{63}$$

$$AP_{I_2} = GP_{I_2+1} + HP_{I_2-1},\ I_2 = B_2 - 1, \dots, -C + 1 \tag{64}$$

$$A_0 P_{-C} = G_0 P_{-C+1},\ I_2 = -C \tag{65}$$

where A, $A_0$, $A_1$, $H_1$, H, G, and $G_0$ are matrices of suitable dimensions whose elements are the transition rates from and to the states of a given system level $I_2$. This system of equations can be solved sequentially: a) We solve equation (63) for $P_{B_2} = D_{B_2}P_{B_2-1}$, where $D_{B_2} = A_1^{-1}H_1$, b) then, we use the expression found in the previous iteration to solve equations (64) for $P_{I_2} = D_{I_2}P_{I_2-1}$, where $D_{I_2} = (A - GD_{I_2+1})^{-1}$ and $I_2 = B_2 - 1, B_2 - 2, \dots, -C + 1$, c) next, we substitute $P_{-C+1} = D_{-C+1}P_{-C}$ into equation (65) and compute $P_{-C}$ using the normalization condition $P(0, B_2) + \sum_{I_1=1}^{B_1}\sum_{I_2=-C}^{B_2} P(I_1, I_2) = (\mu_2/\mu_1)P(1, B_2 - 1) + \sum_{I_1=1}^{B_1}\sum_{I_2=-C}^{B_2} P(I_1, I_2) = 1$, and d) finally, we compute the remaining probability vectors recursively from $P_{I_2} = D_{I_2}P_{I_2-1}$, for $I_2 = -C + 1, \dots, B_2$. From the equilibrium probabilities we can compute all the terms of equations (60)–(62). We have:

$$TH_i = \mu_i \alpha_i,\quad THSC_2 = \lambda - TH_2,\quad THSC_1 = TH_2 - TH_1,$$

$$\alpha_1 = P(I_1 < B_1) = 1 - \sum_{I_2=-C}^{B_2} P(B_1, I_2),\quad \alpha_2 = P(I_2 < B_2) = 1 - \sum_{I_1=0}^{B_1} P(I_1, B_2),$$

$$E(I_1) = \sum_{I_1=1}^{B_1} I_1 \sum_{I_2=1}^{-C} P(I_1, I_2),\quad E[\max(-I_2, 0)] = -\sum_{I_2=-1}^{-C}\left[I_2 \sum_{I_1=1}^{B_1} P(I_1, I_2)\right],$$

$$E[\max(I_2, 0)] = B_2 P(0, B_2) + \sum_{I_2=1}^{B_2}\left[I_2 \sum_{I_1=1}^{B_1} P(I_1, I_2)\right].$$

Upon substituting these quantities into equations (60)–(62) we compute $J_1$, $J_2$, and J.

Modeling Echelon base stock control with partial backordering: The Markov chain has a similar structure as previously, except that the maximum value of $I_1$ is $E_1 - I_2$; so it is not constant but it depends on the inventory position $I_2$ of the second stage. When $I_2 = B_2$, $I_1$

takes on values from the set {0, 1, …, $E_1 - B_2$}; in all other cases, i.e. $I_2 = B_2 - 1, \ldots, 0, \ldots, -C$, we have $I_1 = 1, 2, \ldots, E_1 - I_2$.

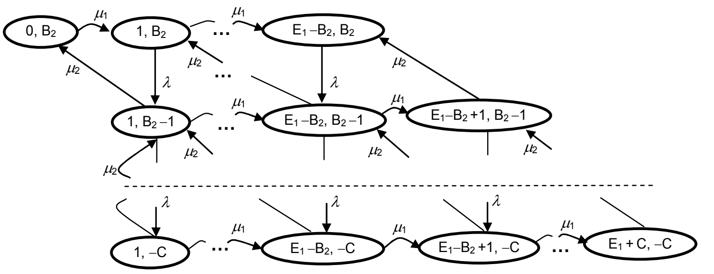

Fig. 6. Markov chain of the supply chain under ESPB

The state transitions of the corresponding Markov chain are shown in figure 6. The equilibrium probabilities, throughput rates, and mean buffer levels at each stage are computed similarly as in the previous case.

### 5.3 Qualitative results

Under a centralized strategy, the simplest method to find the optimal control parameters for BS with PB or ES with PB is to compare the profit rates of the system for all possible combinations of C, $B_2$, and $B_1$ or $E_1$. Similarly, the optimal decentralized policies can be determined by finding the values of C and $B_2$ which maximize $J_2$ and, using these values, the value of $B_1$ or $E_1$ which maximizes $J_1$. Since there are infinite choices for each control parameter, we must determine a finite grid of points (C, $B_2$, $B_1$) or (C, $B_2$, $E_1$) which contains the optimal parameter values. We do this via the following theorem:

**Theorem 1:** Under the assumptions min $(p_1, sc_1) > c_1$ and min $(p_2, sc_2) > p_1 + c_2$ the following hold: a) For both BS with PB and ES with PB, the optimal value of C under centralized optimization is less than $(sc_2 - c_1 - c_2)\mu_2/b$, whereas under decentralized optimization it is less than $(sc_2 - p_1 - c_2)\mu_2/b$, b) Under centralized optimization, the optimal values of $B_1$ and $B_2$ are less than $1 + (sc_1 - c_1)\mu_2/h_1$ and $(sc_2 - p_1 - c_2)\lambda/h_2$, respectively; the optimal value of $E_1$ is less than the sum of the previous two bounds and c) Under centralized optimization, the optimal values of $E_1$, $B_1$, and $B_2$ are bounded from above by $[\max(sc_1 + c_2, sc_2) - c_1 - c_2]\lambda/\min(h_1, h_2)$.

***Proof of part a*:** With C undelivered orders outstanding, the last order in the queue will be satisfied on average after $C/\mu_2$ time units. When this order is delivered to the customer the system (centralized optimization objective) makes profit $(p_2 - c_1 - c_2) - Cb/\mu_2$ if the basic component is made in $F_1$, or $(p_2 - sc_1 - c_2) - Cb/\mu_2$ if the basic component is purchased from $SC_1$. The maximum profit is $(p_2 - c_1 - c_2) - Cb/\mu_2$. Under a decentralized optimization strategy $F_2$ earns $(p_2 - p_1 - c_2) - bC/\mu_2$. Each one of these two profits must be greater than $(p_2 - sc_2)$, for otherwise it would be more profitable to purchase one item from $SC_2$ and sell it to the customer ■

***Proof of part b:*** Under a decentralized BS with PB strategy, a decision to produce one item in $F_1$ and raise the stock level to $I_1 = B_1$ is not profitable for $F_1$ if the profit from selling this item to $F_2$ minus the corresponding holding cost is less than the profit from purchasing one item from $SC_1$ selling it. The holding cost depends on the mean time to sell the item, which is at least $(B_1 - 1)/\mu_2$, assuming that $F_2$, which is currently processing the first of the $B_1$ items, will not idle thereafter. Hence, we must have $(p_1 - c_1) - h_1(B_1 - 1)/\mu_2 > (p_1 - sc_1)$. Using the same argument for the second stage, we obtain $(p_2 - p_1 - c_2) - h_2B_2/\lambda > (p_2 - sc_2)$. From these inequalities we obtain the first two bounds of part (b). Under a decentralized ES with PB strategy, we have $E_1 = \max(I_1 + I_2) \leq \max(I_1) + \max(I_2)$; the right side of the inequality is less than the sum of the previous two bounds and this concludes the proof ■

***Proof of part c:*** Under a centralized strategy, a decision to produce an item in $F_1$ leads to a profit $(p_2 - c_1 - c_2)$ and a holding cost which is greater than $\min(h_1, h_2)(I_1 + I_2)/\lambda$, where $I_1 + I_2$ is the total inventory of the system and $1/\lambda$ is a lower bound on the mean time to sell the item (relaxing the requirement that the item which is produced in $F_1$ will experience an additional delay at $F_2$). The decision to produce the item in $F_1$ is not profitable if the net profit is less than the worst-case outsourcing profit $p_2 - \max(sc_1 + c_2, sc_2)$. So we have $(p_2 - c_1 - c_2) - \min(h_1, h_2)(I_1 + I_2)/\lambda \geq p_2 - \max(sc_1 + c_2, sc_2)$ from which we obtain the bound on $E_1 = \max(I_1 + I_2)$ given in part (c). Moreover, since $\max(I_1 + I_2) \geq \max(I_i) = B_i$, $i = 1, 2$, the same bound is also valid for $B_i$ ■

Concluding, Theorem 1 ensures that the search space of optimal control parameters is bounded. For example, suppose the extra cost for outsourcing from $SC_2$ is $sc_2 - c_1 - c_2 = 10\%$ of the unit selling price, $\min(h_1, h_2) = 1\%$ of the unit selling price per time unit, the mean demand rate is $\lambda = 5$ products per time unit, and it holds that $sc_2 \geq sc_1 + c_2$, i.e., buying products from $SC_2$ is more expensive than buying components from $SC_1$ and processing them in $F_2$ to make products. Then, from part (c) of Theorem 1, the upper bound on the echelon surplus and the stock level $I_1$ is $10 \times 5/1 = 50$. This is the maximum dimension of the probability vectors and the transition matrices in equations (60–62).

## 6. Conclusion

It is known that decentralized planning results in loss of efficiency with respect to centralized planning. It is, however, difficult to quantify the difference between the two approaches within the context of production planning, production scheduling and control policies. In this chapter this issue was investigated in the setting of a two plant series production system of aluminum doors and a petrochemical multi-stage system.

We have explored a "locally optimized" production planning procedure of ANALKO company where the downstream plant optimizes its production plan and the upstream plant follows his requests. Then we compared this decentralized optimized approach with centralized optimization where a single decision maker plans the production quantities of the supply chain in order to minimize total costs. Using our qualitative results, we have proved under which condition the two approaches give the same optimal solution. Future research could focus on development of efficient profit distribution strategies in case of centralized optimization.

A structure decomposition strategy and formulation is also presented for short-term scheduling of refinery operations. An analytical mathematical proof is given in order to demonstrate that both optimization strategies result in the same optimal solution when the developed structural decomposition technique is applied. An interesting direction for the future is to examine the solutions given from centralized and decentralized strategy under different objective functions, such as maximization of profit, minimization of the inventory in the tanks.

Finally, we have presented some Markovian queueing models to support the task of coordinated decision making between two factories in a supply chain, which produces items to stock to meet random demand. During stockout periods, each factory can purchase end items from subcontractors. Production and subcontracting decisions in each factory are made according to pull control policies. From theoretical results, it appears that managing inventory levels and backorders jointly achieves higher profit than independently determined control policies. Upper bounds for the control parameters are given follow by analytical mathematical proofs. The study of multi-item, stochastic supply chains could be another research direction. Since an exact analysis of multistage and/or multi-item supply chains is usually hopeless, the development of efficient simulation algorithms and the improvement of the accuracy of existing approximate analytical methods are the subjects of ongoing research.

## 7. Appendixes

**Appendix A**:

**Variables:** T: Time Horizon (12 months), $P_{i,t}$ : Production in factory $F_i$ during period *t*, $I_{i,t}$ : Inventory of factory $F_i$ during period *t*, $SC_{i,t}$ : Subcontracting of factory $F_i$ during period *t*,
**Parameters:** $cp_i$ : production cost of factory $F_i$ , $h_i$ : inventory cost of factory $F_i$ , $csc_i$ : cost of subcontracted products for factory $F_i$ , $d_t$ : the demand of the final product during period *t*.

**Appendix B**

**Sets:** $I$ : Tasks. $J$ :Reactors, $JST$ :Tanks, $S$ :Materials, $N$ : Event points, $I_j$ :Tasks that can happen in unit *j*, $Iseq_{i'}$ : Tasks that follow task $i'$ ($i'$ produces *s* product that will be consumed by *i*), $Jstprod_{jst}$ :Units that follow tank *jst*, $Jprodst_{jst}$ : Units that are followed by tanks *jst*, $Junitp_s$ : Units that can produce material *s*, $Junitc_s$ :Units that consume material *s*, $Jseq_{j'}$ : Units that follow unit $j'$ (no storage in between), $JST_s$ : Tanks that can store material *s*, $JSTprodst_j$ :Tanks that follow unit *j*, $JSTstprodt_j$ : Tanks that are followed by unit *j*.
**Parameters:** $R_{i,j}^{min}$ , $R_{i,j}^{max}$ :Min and Max production rate for unit *j* for task *i*, $V_{jst}^{max}$ :Maximum capacity of tank *jst*, $\rho_{s,j}^{p}$ , $\rho_{s,j}^{c}$ : Proportion of material *s* produced, and consumed from task *i*, $r_s$ : Demand for material *s* at the end of the time horizon.
**Decision Variables:** $wv_{i,j,n}$ : Binary variables for task *i* at time point *n*, $b_{i,j,n}$ : Amount of material in task *i* at unit *j* at time *n*, $Ts_{i,j,n}$ : Time that task *i* starts in unit *j* at event point *n*, $Tf_{i,j,n}$ Time that task in finishes in unit *j* at event point *n*, $in_{j,jst,n}$ : Binary variable for flow from unit *j* to tank *jst*, $inflow_{j,jst,n}$ : Amount of material flow from unit *j* to storage tank *jst*, $Tss_{j,jst,n}$ : Time that material starts to flow from unit *j* to tank *jst* at event point *n*, $Tsf_{j,jst,n}$ : Time that material finishes to flow from unit *j* to tank *jst* at event point *n*, $out_{jst,j,n}$ : Binary variable for flow from tank *jst* to unit *j*, $outflow_{jst,j,n}$ : Amount of material flow from storage tank *jst* to unit *j*, $Tss_{jst,j,n}$ : Time that material starts to flow from tank *jst* to unit *j* at event point *n*, $Tsf_{jst,j,n}$ : Time that material finishes to flow from tank *jst* to unit *j* at event point *n*, $inflow1_{jst,n}$ : Inflow of raw material to storage tank *jst* at event point *n*, $outflow1_{jst,n}$ : Outflow of final product from storage tank *jst* at event point *n*, $inflow2_{s,j,n}$ : Inflow of raw material s to unit *j* at event point *n*, $outflow2_{s,j,n}$ : Outflow of final product *s* from unit *j* at event point *n*, $unitflow_{s,j,jj,n}$ : Flow of material from unit *j* to unit *jj* for consumption, $st_{jst,n}$ : Amount of material in tank *jst* at event point *n*.

## 8. References

Bassett, M.H., Pekny, J., & Reklaitis, G. (1996). Decomposition Techniques for the Solution of Large-Scale Scheduling Problems. American Institute of Chemical Engineers Journal 42(12),3373-3387.

Chen, J.M., & Chen, T.H. (2005). The Multi-item Replenishment Problem in a Two-Echelon Supply Chain: The Effect of Centralization versus Decentralization. Computers & Operations Research 32,3191-3207.

Gnoni, M., Iavagnilio, R., Mossa, G., Mummolo, G., & Leva, A.D. (2003). Prodcution Planning of a Multi-site Manufacturing System by Hybrid Modeling: A Case Study From the Automotive Industry. International Journal of Production Economics 85,251-262.

Hadley, G., Whitin, T.M., (1963). Analysis of Inventory Systems. Prentice Hall, Englewood Cliffs, NJ.

Harjunkoski, I., & Grossmann, I.E. (2001). A Decomposition Approach For the Scheduling of a Steel Plant Production. Computers and Chemical Engineering 25,1647-1660.

Ioannidis, S., Kouikoglou, V.S., Phillis, Y.A., (2008). Analysis of admission and inventory control policies for production networks. IEEE Transactions on Automation Science and Engineering, 5(2), 275–288.

Kelly, J.D., & Zyngier, D., (2008). Hierarchical Decomposition Heuristic for Scheduling: Coordinated Reasoning for Decentralized And Distributed Decision-Making Problems. Computers and Chemical Engineering 32: 2684-2705.

Kouikoglou, V.S., Phillis, Y.A., (2002). Design of product specifications and control policies in a single-stage production system. IIE Transactions, 34, 590–600.

Liberopoulos, G., Dallery, Y., (2000). A unified framework for pull control mechanisms in multi-stage manufacturing systems. Annals of Operations Research, 93, 325–355.

Liberopoulos, G., Dallery, Y., (2003). Comparative modelling of mutli-stage production-inventory control policies with lot sizing. International Journal of Production Research, 41, 1273–1298.

Rupp, M., Ristic, T.M., (2000) Fine planning for supply chains in semiconductor manufacture. J. Materials Processing Technology 107: 390–397.

Zipkin, P.H., (2000). Foundations of Inventory Management. McGraw-Hill, New York.

# 2

# Integrating Lean, Agile, Resilience and Green Paradigms in Supply Chain Management (LARG_SCM)

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## 1. Introduction

### 1.1 What is the problem?

Different management paradigms, such as the lean, agile, resilience and green have been adopted for the management of supply chains. The lean supply chain is a paradigm based on cost reduction and flexibility, focused on processes improvements, through the reduction or elimination of the all "wastes", i.e., non-value adding operations (Womack et al., 1991). It embraces all the processes through the product life cycle, starting with the product design to the product selling, from the customer order to the delivery (Anand & Kodali, 2008). The agile supply chain paradigm intends to create the ability to respond rapidly and cost effectively to unpredictable changes in markets and increasing levels of environmental turbulence, both in terms of volume and variety (Agarwal et al., 2007). However, when organizations are subject to eventual disruptions, caused by sudden and unforeseen events (like economic and politic crisis or environmental catastrophes), the lean practices may have contributed to rupture conditions (Azevedo et al., 2008).

In a global economy, with supply chains crossing several countries and continents, from raw material to final product, those events (even if they happen in a remote place) can create large-scale disruptions (Craighead et al., 2007). These disruptions are propagated throughout the supply chain, causing severe negative effects in supply chains leading to unfulfilled orders. So, it seems that what can be good from the competitive point of view, can cause a disaster on crisis situations; it may be worst if the organizations can not be resilient and robust enough to recover the loosed competitiveness. In actual competitive market, it is necessary that supply chains become more resilient to disruption events (Sheffi & Rice, 2005; Tang, 2006).

Other pertinent issue in supply chain management is the environmental sustainability. The green supply chain management is as an important organizational philosophy to achieve corporate profit and market share objectives by reducing environmental risks and impacts while improving ecological efficiency of these organizations and their partners (Rao & Holt, 2005; Zhu et al., 2008). As a synergistic joining of environmental and supply chain management, the competitive and global dimensions of these two topics cannot go unnoticed by organizations.

### 1.2 What has been done by other researchers?

The literature shows that almost researches have been focused on the study of individual paradigms in supply chain management (Anand & Kodali, 2008; Agarwal et al. 2007; Hong et al. 2009; Glickman & White, 2006); or on the integration of only a couple of paradigms in supply chain management, e.g., lean vs. agile (Naylor et al., 1999), lean vs. green (Kainuma & Tawara, 2006), resilience vs. agile (Christopher & Rutherford, 2004) or resilience vs. green (Rosič et al., 2009). However the simultaneous integration of lean, agile, resilient, and green paradigms in supply chain management may help supply chains to become more efficient, streamlined, and sustainable.

### 1.3 What have we done?

In this chapter we use the acronym LARG_SCM to refer the integration of lean, agile, resilient, and green paradigms in supply chain management. The leanness in a supply chain maximizes profits through cost reduction, while agility maximizes profit through providing exactly what the customer requires. Resilient supply chains may not be the lowest-cost but they are more capable of coping with the uncertain business environment. Also, environmental policies must be addressed to assure that the system sustainable. The tradeoffs between lean, agile, resilient, and green management paradigms are actual issues and may help supply chains to become more efficient, streamlined, and sustainable.

This chapter intends to explore the integration of these paradigms and present a conceptual model to provide a deep understanding of synergies and divergences between all of them; this idea is expected to contribute for a more sustainable and competitive supply chain. The main objective is to identify the supply chain attributes that should be managed to obtain the necessary organizational agility; to speed-up the bridging between states that require more or less degree of resilience; to preserve the dynamic aspects of the lean paradigm and; to assure its harmonization with the ecologic and environmental aspects that production processes may attend. To this end, a conceptual model with the relationships between lean, agile, resilient and green practices and supply chain performance was developed. A deductive research approach was used to develop a conceptual model from the literature review; the model was developed using a causal diagram to capture the supply chain dynamics (Sterman, 2000). To construct the cause-effect diagram it was supposed that the supply chain attributes values, are consequence of different supply chain practices implementation and they will affect directly the supply chain key performance indicators values.

This chapter is organized as follows. First, a literature review related to lean, agile, resilient and green supply chain management paradigms is presented. Next, the deployment of the different paradigms in supply chain management is explored; being identified the main supply chain attributes and their relationships with supply chain key performance indicators. In the next section is developed a conceptual model exploring the relationship between the different supply chain paradigms practices and the supply chain key performance indicators. Finally, the main conclusions are drawn.

## 2. Supply chain management paradigms review

### 2.1 Lean

The Lean management approach, developed by Taiichi Ohno (1998) at Toyota Motor Corporation in Japan, forms the basis for the Toyota Production System (TPS) with two

main pillars: 'autonomation' and 'just-in-time' (JIT) production. The focus of the lean approach has essentially been on the waste reduction for increasing actual value-added, to fulfil customers needs and maintaining profits. This new structural approach and the way Toyota used lean production to change the nature of automobile manufacturing, has been better described in the book "The Machine that Changed the World" (Womack, 1991).
The lean supply chain is a strategy based on cost reduction and flexibility, focused on processes improvements, through the reduction or elimination of the all "wastes" (non-value adding operations). It embraces all the processes through the product life cycle, starting with the product design to the product selling, from the customer order to the delivery. Reichhart and Holweg (2007) had extended the concept of lean production to the downstream or distribution level: "we define lean distribution as minimizing waste in the downstream supply chain, while making the right product available to the end customer at the right time and location". To Vonderembse et al. (2006) a lean supply chain is the one that employs continuous improvement efforts that focus on eliminating waste or non-value steps along the chain. The internal manufacturing efficiency and setup time reduction are the enablers of the economic production of small quantities, cost reduction, profitability, and manufacturing flexibility (Vonderembse et al., 2006).
At operational level, the lean paradigm is implemented by using a number of techniques such as Kanban (visual signal to support flow by 'pulling' product through the manufacturing process as required by the customer), 5S (a visual housekeeping technique which devolved control to the shop floor), visual control (method of measuring performance), takt time (i.e. the production rate that equals the rate of sales), Poke yoke (an 'error-proofing' technique), SMED (a changeover reduction technique) (Melton, 2005). The application of these techniques throughout the network has a consequence in decreasing of redundancy in materials, processing and transportation activities, as well as in information and knowledge supply (Adamides et al., 2008).
However, there are some drawbacks of lean paradigm when applied to the supply chain: the short setup times provide internal flexibility, but a lean supply chain may lack external responsiveness to customer demands, which can require flexibility in product design, planning and scheduling, and distribution (Vonderembse et al., 2006). Extending lean beyond the factory and component supply system into distribution operations results in a potential conflict: the need of production smoothing and kanban systems (that cannot cope with high levels of variability) and the need to link the production pull signal to variable demand in the marketplace (Reichhart & Holweg, 2007).
The lean approach has been considered to perform better when there is high volume, low variety and predictable demand with supply certainty, so that functional products can be created. Conversely, in high variety and volatile supply chains, where customer requirements are often unpredictable, a much higher level of agility is required (Cox & Chicksand, 2005; Naylor et al., 1999; Agarwal et al., 2007). To add value to the customer, the lean approach seeks to find ways to manage variability and to create capability by utilising assets more effectively than in traditional systems (Hines et al., 2004). Leanness may be an element of agility in certain circumstances, but it is not a sufficient condition to the organization to meet the precise needs of the customers more rapidly (Agarwal et al., 2007; Christopher & Towill, 2000).

### 2.2 Agile

The supply chain objective is to delivering the right product, in the right quantity, in the right condition, to the right place, at the right time, for the right cost. Since customer requirements are continuously changing, supply chains must be adaptable to future changes to respond appropriately to market requirements (and changes).

In lean supply chains the focus is on "waste" elimination, but in agile supply chains the focus is on the ability of comprehension and rapid responding to market changes. An important difference is that lean supply is associated with level scheduling, whereas agile supply means reserving capacity to cope with volatile demand (Christopher & Towill, 2000). The agile supply chain intends to have the ability to respond rapidly and cost effectively to unpredictable changes in markets and increasing levels of environmental turbulence, both in terms of volume and variety (Agarwal et al., 2007; Christopher, 2000). Baramichai et al. (2007) used the following definition: "An agile supply chain is an integration of business partners to enable new competencies in order to respond to rapidly changing, continually fragmenting markets. The key enablers of the agile supply chain are the dynamics of structures and relationship configuration, the end-to-end visibility of information, and the event-driven and event-based management".

Naylor et al. (1999) used the decoupling point concept to divide the part of the supply chain that responds directly to the customer (demand is variable and high product variety) from the part of the supply chain that uses forward planning and a strategic stock to buffer against the demand variability (demand is smooth and products are standard). He proposed the designation "leagile" supply chain where the lean principles are followed up to the decoupling point and agile practices are followed after that point.

Agarwal et al. (2007) have shown that supply chain agility depends on the following: customer satisfaction, quality improvement, cost minimization, delivery speed, new product introduction, service level improvement, and lead-time reduction. Literature on supply chain agility describes the agility dependence on some performance variables; however, the influence of interrelationships among the variables on the supply chain agility has been hardly taken into account (Agarwal et al., 2007).

### 2.3 Resilience

There is evidence that the tendencies of many companies to seek out low-cost solutions, because of pressure on margins, may have led to leaner but more vulnerable supply chains (Azevedo et al., 2008; Peck, 2005). Today's marketplace is characterized by higher levels of turbulence and volatility. As a result, supply chains are vulnerable to disruption and, in consequence, the risk to business continuity has increased (Azevedo et al., 2008). Whereas in the past the principal objective in supply chain design was cost minimization or service optimization, the emphasis today has to be upon resilience (Tang, 2006). Resilient supply chains may not be the lowest-cost but they are more capable of coping with the uncertain business environment.

Resilience refers to the ability of the supply chain to cope with unexpected disturbances. It is concerned with the system ability to return to its original state or to a new one, more desirable, after experiencing a disturbance, and avoiding the occurrence of failure modes. The goal of supply chain resilience analysis and management is to prevent the shifting to undesirable states, i.e., the ones where failure modes could occur. In supply chain systems, the objective is to react efficiently to the negative effects of disturbances (which could be more or less severe). The aim of the resilience strategies has two manifolds (Haimes, 2006): i) to recover the desired values of the states of a system that has been disturbed, within an acceptable time period and at an acceptable cost; and ii) to reduce the effectiveness of the disturbance by changing the level of the effectiveness of a potential threat.

The ability to recover from the disturbance occurrence is related to development of responsiveness capabilities through flexibility and redundancy (Rice & Caniato, 2003). Flexibility is related to the investments in infrastructure and resources before they actually are needed, e.g., multi-skilled workforce, designing production systems that can accommodate multiple products, or adopting sourcing strategies to allow transparent switching of suppliers. Redundancy is concerned to maintaining capacity to respond to disruptions in the supply network, largely through investments in capital and capacity prior to the point of need, e.g., excess of capacity requirements, committing to contracts for material supply (buying capacity whether it is used or not), or maintaining a dedicated transportation fleet. Rice and Cianato (2003) differentiated flexibility from redundancy in the following way: redundancy capacity may or may not be used; it is this additional capacity that would be used to replace the capacity loss caused by a disruption; flexibility, on the other hand, entails restructure previously existing capacity.

Tang (2006) propose the use of robust supply chain strategies to enable a firm to deploy the associated contingency plans efficiently and effectively when facing a disruption, making the supply chain firm become more resilient. This author proposes strategies based on: i) postponement; ii) strategic stock; iii) flexible supply base; iv) make-and-buy trade-off; v) economic supply incentives; vi) flexible transportation; vii) revenue management; viii) dynamic assortment planning; ix) silent product rollover. Christopher and Peck (2004) proposes the following principles to design resilient supply chains: i) selecting supply chain strategies that keep several options open; ii) re-examining the 'efficiency vs. redundancy' trade off; iii) developing collaborative working; iv) developing visibility; v) improving supply chain velocity and acceleration. Iakovou et al. (2007) refer the following resilience interventions: i) flexible sourcing; ii) demand-based management; iii) strategic emergency stock (dual inventory management policy that differentiates regular business uncertainties from the disturbances, using on the one hand safety stocks to absorb normal business fluctuations, and on the other hand, keeping a strategic emergency stock); iv) total supply chain visibility; and v) process and knowledge back-up.

### 2.4 Green

Environmentally sustainable green supply chain management has emerged as organizational philosophy to achieve corporate profit and market share objectives by reducing environmental risks and impacts while improving ecological efficiency of these organizations and their partners (Zhu et al., 2008; Rao, 2005 ). Changes in government policies, such as the Waste Electrical and Electronic Equipment directive in European Union (Barroso & Machado, 2005; Gottberg, 2006), had make the industry responsible for post-consumer disposal of products, forcing the implementation of sustainable operations across the supply chain. At the same time, the increased pressure from community and environmentally-conscious consumers forces the manufacturers to effectively integrate environmental concerns into their management practices (Zhu et al., 2008).

It is necessary to integrate the organizational environmental management practices into the entire supply chain to achieve a sustainable supply chain and maintain competitive advantage (Zhu et al., 2008; Linton et al., 2007). The green supply chain management practices should cover all the supply chain activities, from green purchasing to integrate life-cycle management, through to manufacturer, customer, and closing the loop with reverse logistics (Zhu et al., 2008).

According to Bowen et al. (2001) green supply practices include: i) greening the supply process - representing adaptations to supplier management activities, including collaboration with suppliers to eliminate packaging and implementing recycling initiatives; ii) product-based green supply - managing the by-products of supplied inputs such as packing; iii) advanced green supply - proactive approaches such as the use of environmental criteria in risk-sharing, evaluation of buyer performance and joint clean technology programs with suppliers.

The greening of supply chain is also influenced by the following production processes characteristics (Sarkis, 2003): i) process' capability to use certain materials; ii) possibility to integrate reusable or remanufactured components into the system (which would require disassembly capacities); and iii) design for waste minimization (energy, water, raw materials, and non-product output).

Eco-design is defined as the development of products more durable and energy efficient, avoiding the use of toxic materials and easily disassembled for recycling (Gottberg et al., 2006). It provides opportunities to minimize waste and improve the resource consumption efficiency through modifications in product size, serviceable life, recyclability and utilization characteristics.However, the eco-design strategy presents some potential disadvantages including: high level of obsolete products in fashion driven markets, increased complexity and increased risk of failure, among others (Gottberg et al., 2006).

The reverse logistics focuses primarily on the return of recyclable or reusable products and materials into the forward supply chain (Sarkis, 2003). To reintroduced recycled materials, components and products into the downstream production and distribution systems, it is necessary to integrate reverse material and information flows in the supply chain. Due to the reverse material flow, traditional production planning and inventory management methods have limited applicability in remanufacturing systems (Srivastava, 2007). Therefore, it is necessary to consider the existence of the returned items that are not yet remanufactured, remanufactured items and manufactured items.

Distribution and transportation operations networks are also important operational characteristics that will affect the green supply chain (Sarkis, 2003). With the rapid increase of long-distance trade, supply chains are increasingly covering larger distances, consuming significantly more fossil-fuel energy for transportation and emitting much more carbon dioxide than a few decades ago (Venkat & Wakeland, 2006) . Lean supply chains typically have lower emissions due to reduced inventory being held internally at each company, but the frequent replenishment generally tends to increase emissions. As distances increase, it is quite possible for lean and green to be in conflict, which may require additional modifications to the supply chain (perhaps moving it away from the ideal lean configuration) if emissions are to be minimized (Venkat & Wakeland, 2006). Therefore, lean may be green in some cases, but not in others.

According to Srivastava (2007) green supply chain management can reduce the ecological impact of industrial activity without sacrificing quality, cost, reliability, performance or energy utilization efficiency; meeting environmental regulations to not only minimizing ecological damage, but also leading to overall economic profit.

## 2.5 Paradigms characterization

Although some authors (Vonderembse et al., 2006; Naylor et al., 1999; Christopher & Towill, 2000; Agarwal et al., 2006) provide an overview and comparison between lean and agile supply paradigms they don't consider the resilient and green paradigms. To fulfil this situation, the characterization of resilient and green supply chains was added to the framework proposed by Vonderembse et al. (2006). Table 1 presents the characterization of lean, agile, resilient and green supply chains in what is concerned to purpose, manufacturing focus, alliance type, organizational structure, supplier involvement, inventory strategy, lead time, and product design.

From Table 1, it is possible to identify differences between lean, agile, resilient and green paradigms; for example, lean, agile and green practices promote inventory minimization, but resilience demands the existence of strategic inventory buffers. Although, there are some "overlapping" characteristics that suggest that these paradigms should be developed simultaneously for supply chain performance improvement. According to Naylor et al. (1999) leanness and agility should not be considered in isolation; instead they should be integrated. The lean paradigm deployment in supply chain management produce significant improvements in resource productivity, reducing the amount of energy, water, raw materials, and non-product output associated with production processes; minimizing the ecological impact of industrial activity (Larson & Greenwood, 2004). According to Christopher and Peck (2004) resilience implies flexibility and agility; therefore, for the development of a resilient supply chain, it is necessary to develop agility attributes.

| | **Lean** | **Agile** | **Resilient** | **Green** |
|---|---|---|---|---|
| *Purpose* | Focus on cost reduction and flexibility, for already available products, through continuous elimination of waste or non-value added activities across the chain[(a)] | Understands customer requirements by interfacing with customers and market and being adaptable to future changes[(a)] | Ability to return to its original state or to a new one, more desirable, after experiencing a disturbance, avoiding the occurrence of failures modes | Focus on sustainable development and on reduction of ecological impact of industrial activity |
| *Manufacturing focus* | Maintain high average utilization rate [(a)]. It uses just in time practices, "pulling" the goods through the system based on demand[(b)] | Has the ability to respond quickly to varying customer needs (mass customization), it deploys excess buffer capacity to respond to market requirements[(a)] | The emphasis is on flexibility (minimal batch sizes and capacity redundancies) improving supply chain responsiveness. The schedule planning is based on shared information[(d)] | Focus on efficiency and waste reduction for environmental benefit and developing of re-manufacturing capabilities to integrate reusable/remanufactured components [(i)] |
| *Alliances (with suppliers* | May participate in traditional alliances such as | Exploits a dynamic type of alliance known | Supply chain partners join an alliance network | Inter-organizational collaboration involving |

| | | | | |
|---|---|---|---|---|
| *and customers)* | partnerships and joint ventures at the operating level [(a)]. The demand information is spread along the supply chain[(b)] | as a "virtual organization" for product design [(a)]. It promotes the market place visibility | to develop security practices, share knowledge[(e)] and increasing demand visibility[(d)] | transferring or/and disseminating green knowledge to partners[(l)] and customer cooperation[(f)] |
| *Organizational structure* | Uses a static organizational structure with few levels in the hierarchy[(a)] | Create virtual organizations with partners that vary with different product offerings that change frequently[(a)] | Create a supply chain risk management culture[(d)] | Create an internal environmental management system and develop environmental criteria for risk-sharing[(h)] |
| *Approach to choosing suppliers* | Supplier attributes involve low cost and high quality[(a)] | Supplier attributes involve speed, flexibility, and quality[(a)] | Flexible sourcing [(c; e)] | Green purchasing [(f; h)] |
| *Inventory strategy* | Generates high turns and minimizes inventory throughout the chain[(a)] | Make in response to customer demand[(a)] | Strategic emergency stock in potential critical points[(c; d; e)] | Introduce reusable/ remanufactured parts in material inventory[(j)]. Reduce replenishment frequencies to decrease carbon dioxide emissions[(k)]. Reduce redundant materials[(m)] |
| *Lead time focus* | Shorten lead-time as long as it does not increase cost[(a)] | Invest aggressively in ways to reduce lead times[(a)] | Reduce lead-time[(c; d)] and use flexible transportation systems [(c; e)] | Reduce transportation lead time as long as it does not increase carbon dioxide emissions[(k)] |
| *Product design strategy* | Maximize performance and minimize cost [(a)] | Design products to meet individual customer needs[(a)] | Postponement[(c)] | Eco-design and life cycle for evaluating ecological risks and impact[(f; g)] |
| *Legend*: (a) Vonderembse et al. (2006); (b) Melton (2005); (c) Tang (2006); (d) Christopher & Peck (2004); (e) Iakovou et al. (2007); (f) Zhu et al. (2008); (g) Gottberg et al. (2006); (h) Bowen et al. (2001); (i) Sarkis (2003); (j) Srivastava (2007; (k) Venkat & Wakeland (2006); (l) Cheng et al. (2008); (m) Darnall et al. (2008) | | | | |

Table 1. Lean, agile, resilient and green characterization.

## 3. Deployment of LARG_SCM

### 3.1 Supply chain management practices and attributes

According to Morash (2001) supply chain management paradigms or strategies should be supported on suitable supply chain management practices. Li et al. (2005) defined supply chain management practices as the set of activities undertaken by an organization to promote effective management of its supply chain. Some authors also deploy supply chain management practices in a set of sub-practices, or activities or even in tools. From table 1 is possible to infer the following practices for each one of the paradigms:

- Lean practices: inventory minimization, higher resources utilization rate, information spreading trought the network, just-in-time practices, and shorter lead times;
- Agile practices: inventory in response to demand, excess buffer capacity, quick response to consumer needs, total market place visibility, dynamic alliances, supplier speed, flexibility and quality, and shorter lead times;
- Resilient practices: strategic inventory, capacity buffers, demand visibility, small batches sizes, responsiveness, risk sharing, and flexible transportation;
- Green practices: reduction of redundant and unnecessary materials, reduction of replenishment frequency, integration of the reverse material and information flow in the supply chain, environmental risk sharing, waste minimization, reduction of transportation lead time, efficiency of resource consumption;

Supply chain management practices are enablers to achieve supply chain capabilities or core competences. Morash et al. (1996) defined supply chain capabilities or distinctive competencies as those attributes, abilities, organizational processes, knowledge, and skills that allow a firm to achieve superior performance and sustained competitive advantage over competitors. Therefore the supply chain practices, through the constitution of capabilities, have a direct effect on supply chain performance. In this chapter the word "supply chain attribute" is used to describe a distinctive characteristics or capabilities associated to the management of supply chains. These characteristics are related to the supply chain features that can be managed through the implementation of supply chain management practices. The attributes values may have a nominal properties (e.g. a product is reusable or not), ordinary properties (e.g. the integration level between two supply chain entities is higher or lower than the average) or cardinal properties (i.e. the attribute can be compute, like the production lead time).

In this chapter the following supply chain attributes were considered: "capacity surplus", "replenishment frequency", "information frequency", "integration level", "inventory level", "production lead time", and "transportation lead time". The attributes value can be altered by the deployment of the different supply chain paradigms. Supply chain attributes are key aspects of the supply chain strategies and determine the entire supply chain behaviour, so the supply chain attributes will enable the measuring of supply chain performance.

### 3.2 Supply chain performance

To develop an efficient and effective supply chain, it is necessary to assess its performance. Performance measures should provide the organization an overview of how they and their supply chain are sustainable and competitive (Gunasekaran, 2001). Several authors discuss which performance indicators are the key metrics for lean and agile supply chains (Nailor et al., 1999; Argwal et al., 2006; Christopher & Towill, 2000; Mason-Jones at al., 2000). Kainuma & Tawara (2006) refer that "there are a lot of metrics for evaluating the performance of supply chains. However, they may be aggregated as lead time, customer service, cost, and quality".

Christopher & Towill, (2000) discuss the differences in market focus between the lean and agile paradigms using market winners (essential requisites for winning) and market qualifiers (essential requisites to sustain competitiveness). These authors consider that when cost is a market winner and quality, lead time and service level are market qualifiers, the lean paradigm is more powerful to sustain supply chain performance. When service level (availability in the right place at the right time) is a prime requirement for winning and cost, quality and lead time are market qualifiers, agility is a critical dimension. In the resilient paradigm, the focus is on recovery the desired values of the states of a system (characterized by a service level and a certain quality) within an acceptable time period and cost. Hence, for resilient supply chains, the cost and time are critical performance indicators. The green paradigm is concerned with the minimization of the negative environmental impacts in the supply chain; however this minimization cannot be done to the detriment of supply chain performance in quality, cost, service level and time.

In this perspective, it is possible to state that the critical dimensions for each paradigm are: cost for lean; service level for agile; time and cost for resilient. Therefore in this chapter, "cost", "service level" and "lead time" were selected as key performance indicators to evaluate the effect of each paradigm in the supply chain performance. Quality was not considered in this analysis since is a prerequisite for lean, agile, resilient and green paradigms to sustain the supply chain performance.

To evaluate the effect of the paradigms deployment in supply chain management, it necessary to establish the relationship between the supply chain attributes (derived from the paradigms deployment) with the selected key performance indicators. Figure 1 contains a diagram with the relationships between supply chain performance indicators and attributes.

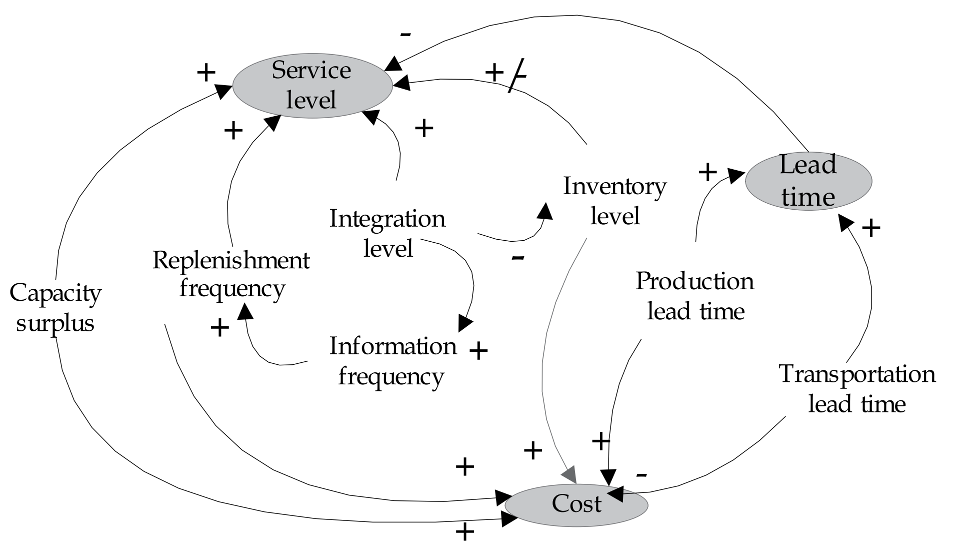


Fig. 1. Performance indicator and supply chain attributes relationships.

A causal diagram was selected to capture the supply chain dynamics. With this diagram, it is possible to visualize how the supply chain attributes affect the performance indicators. A positive link means that the two nodes move in the same direction, i.e., if the node in which the link start decreases, the other node also decreases (if all else remains equal). In the negative link, the nodes changes in opposite directions, i.e., an increase will cause a decrease in another node (if all else remains equal) (Sterman, 2000).

To construct the cause-effect diagram it was supposed that the supply chain attributes, which are the consequence of the policies implementation, are directly responsible for the supply chain performance measures value. For example, the "replenishment frequency" (a supply chain attribute) will establish the value of the performance measures "service level" and "cost", since more frequent deliveries imply a higher distribution cost, leading to higher supply chain costs

The key performance indicator "service level" is affected positively by the "replenishment frequency" (it increases the capacity to fulfil rapidly the material needs in supply chain) (Holweg, 2005), "capacity surplus" (a slack in resources will increases the capacity for extra orders production) (Holweg, 2005) and "integration level" (the ability to co-ordinate operations and workflow at different tiers of the supply chain allow to respond to changes in customers requirements) ( Gunasekaran, 2008). An increasing of "integration level" will lead to a high frequency of information sharing between supply chain entities; it will make possible a high "replenishment frequency". The lead-time reduction improves the "service level" (Agarwal et al., 2007).

The "inventory level" has two opposite effects in the "service level" (the mark +/- is used to represent this causal relation in Figure 1). Since it increases materials availability, reducing the stock-out ratio, a higher "service level" is expected (Jeffery et al., 2008). However, high inventory levels also generate uncertainties (Van der Vorst & Beulens, 2002) leaving the supply chain more vulnerable to sudden changes (Marley, 2006) and therefore reducing the service level in volatile conditions. This apparent contradict behavior is also present when an increasing in the "integration level" occurs, which may lead to an improvement in the "service level". However, the "inventory level" is affected negatively by the "integration level" (since it increases the supply chain visibility, minimizing the need of material buffers), improving the "service level".

The key performance indicator "cost" is affected positively by the "capacity surplus" and "inventory level", since they involve the maintenance of resources that have not being used. An increase in the "replenishment frequency" also increases the "cost", due to the frequent transport of small quantities. To reduce "transportation time" premium services may be used; usually these services are more expensive. The "production lead time" affects "positively" the cost (Towill, 1996).

Finally, the key performance indicator "lead time" is positively affected by the "production lead time" and "transportation time".

## 4. LARG_SCM practices and supply chain attributes inter-relationship Conceptual model

The tradeoffs between lean, agile, resilient, and green supply chain management paradigms (LARG_SCM) must be understood to help companies and supply chains to become more efficient, streamlined, and sustainable. To this end, it is necessary to develop a deep understanding of the relationships (conflicts and commitments) between the lean, agile, resilient and green paradigms, exploring and researching they contribute for the sustainable competitiveness of the overall production systems in the supply chain. Causal diagrams may be used to represent the relationships between each paradigm practices and supply chain attributes.

### 4.1 Lean practices vs. supply chain attributes

Lean practices are characterized by (see Table 1): inventory minimization, higher resources utilization rate, information spreading throught the network, just-in-time practices, traditional alliances and shorter lead times. Figure 2 was drawn to infer the lean practices impact in the supply chain performance - the diagram shows the relationships between the lean practices and the supply chain chain performance.

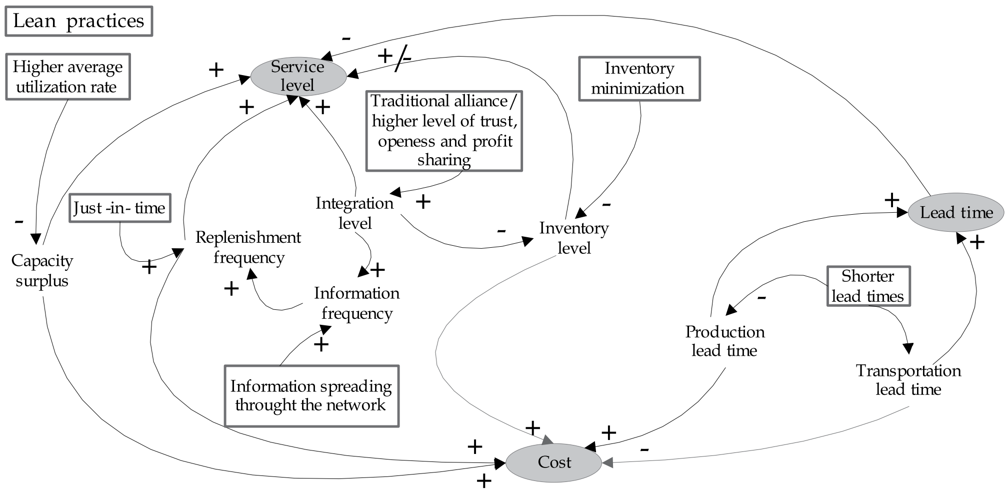


Fig. 2. Lean practices and supply chain performance relationships.

This figure may be better understood having in mind the following interpretation:

- The “inventory level” is affected negatively by the inventory minimization (a higher level of inventory minimization provokes a lower level of inventory).
- The “integration level” is positively related to the level of trust, openness and profit sharing of the traditional alliances in lean supply chains.
- The “information frequency” is improved by information spreading throught the network.
- The implementation of just in time practices increases the “replenishment frequency”.
- The lean paradigm is characterized by a higher utilization rate of the supply chain resources causing a decrease in the supply chain “capacity surplus”.
- The reduction of lead time affects negatively the “production and transportation lead times” (an increment level of lead time reduction provokes a reduction production and transportation lead times).

### 4.2 Agile practices vs. supply chain attributes

It is possible to conclude that the main agile supply chain practices are (see Table 1): inventory in response to demand, excess buffer capacity, quick response to consumer needs, total market place visibility, dynamic alliances, supplier speed, flexibility and quality, and shorter lead times. Figure 3 shows the relationships between the supply chain agile attributes and the supply chain performance:

- The “inventory level” is affected negatively by the inventory in response to customer demand (if the inventory is designed to respond to costumer needs, then lower levels of inventory in supply chain are expected) and by the supplier flexibility, speed and quality (if the supplier have higher levels of flexibility, speed and quality the need of inventory buffers is low, which may lead to lower inventory levels).

- The "information frequency" is improved by eventual increasing in the supply chain visibility.
- The "integration level" is positively related to the existence of dynamic alliances in the agile supply chains.
- The quick response to customer needs increases the "replenishment frequency".
- The agile paradigm prescribes the existence of a capacity excess in the supply chain resources provoking an increasing in "capacity surplus".
- The reduction of lead time affects negatively the "production and transportation lead times" (an increment level of lead time reduction provokes a reduction in production and transportation lead times).

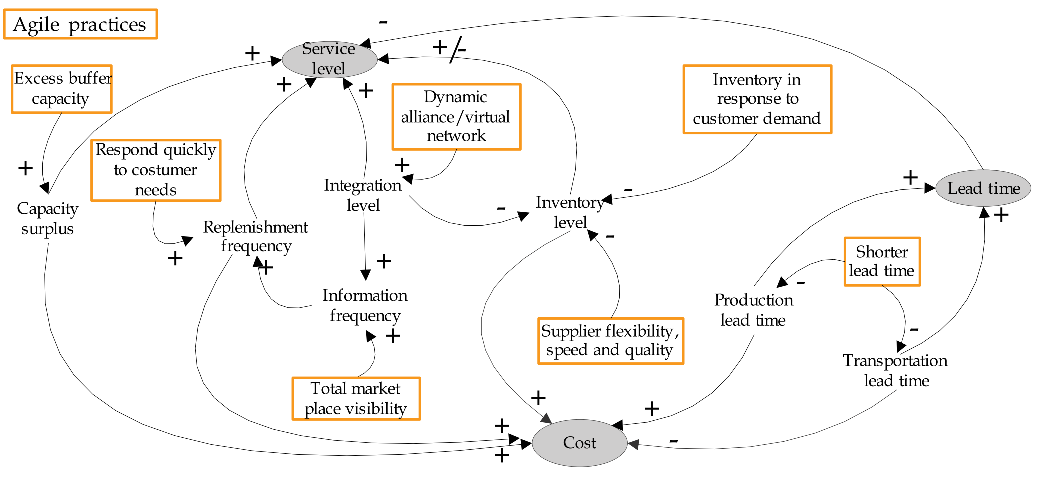


Fig. 3. Agile attributes and supply chain performance relationships.

### 4.3 Resilient practices vs. supply chain attributes

From Table 1, it is possible to verify that the main resilient supply chain practices are: strategic inventory, capacity buffers, demand visibility, small batches sizes, responsiveness, risk sharing, and flexible transportation. Figure 4 contains a diagram with the relationships between the supply chain resilient attributes and the supply chain performance:

- The "inventory level" is affected positively by the strategic stock policies (the constitution of strategic inventory buffers in supply chain increases the inventory levels).
- The "information frequency" is improved by the increasing in the demand visibility.
- The "integration level" is positively related to the risk sharing strategies in the resilient supply chains. A higher level of responsiveness increases the "replenishment frequency".

- The resilience practices prescribe the existence of supply chain capacity buffers provoking an increasing in "capacity surplus".
- The utilization of small batch sizes allows the reduction of the "production lead time". The flexible transport strategy contributes to a reduction in the "transportation lead time".

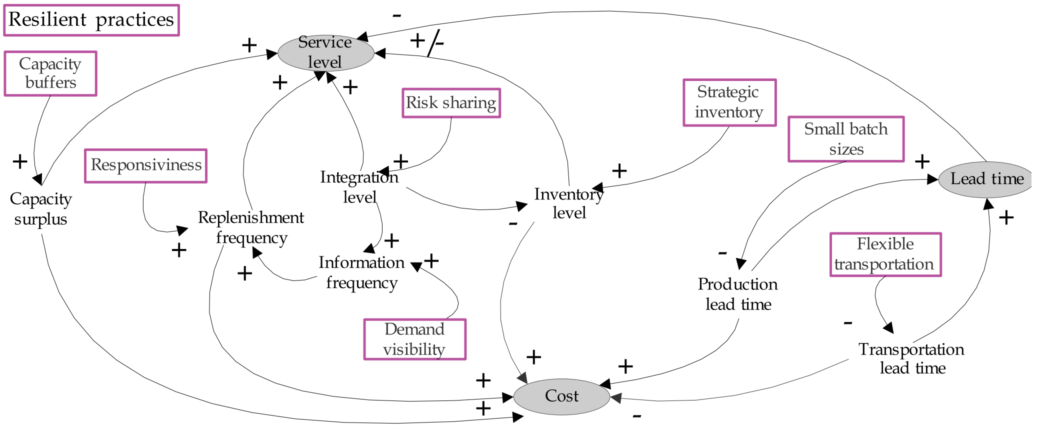


Fig. 4. Resilient practices and supply chain performance relationships.

### 4.4 Green practices vs. supply chain attributes

From Table 1, the main green supply chain practices were identified as: reduction of redundant and unnecessary materials, reduction of replenishment frequency, integration of the reverse material and information flow in the supply chain, environmental risk sharing, waste minimization, reduction of transportation lead time, efficiency of resource consumption. Figure 5 contains a diagram with the relationships between the supply chain green attributes and the supply chain performance:

- The "inventory level" is affected negatively by the reduction of redundant and unnecessary materials in the supply chain.
- The "integration level" is positively related to the development of environmental risk sharing strategies and to the level of reverse material and information flow integration in the supply chain.
- It was not found evidences in literature that supports the influence of green supply chain practices on "information frequency".
- The higher level of replenishment frequencies reduction decreases the "replenishment frequency".
- The green practices prescribe the efficiency of resources consumption contributing to supply chain "capacity surplus" reduction.
- The waste minimizations contribute negatively the "production lead time" (an increment in waste minimizations provokes a reduction in the production lead times). The reduction of transport lead time, without an increment in dioxide carbon emissions, contributes to a reduction in the "transportation time".

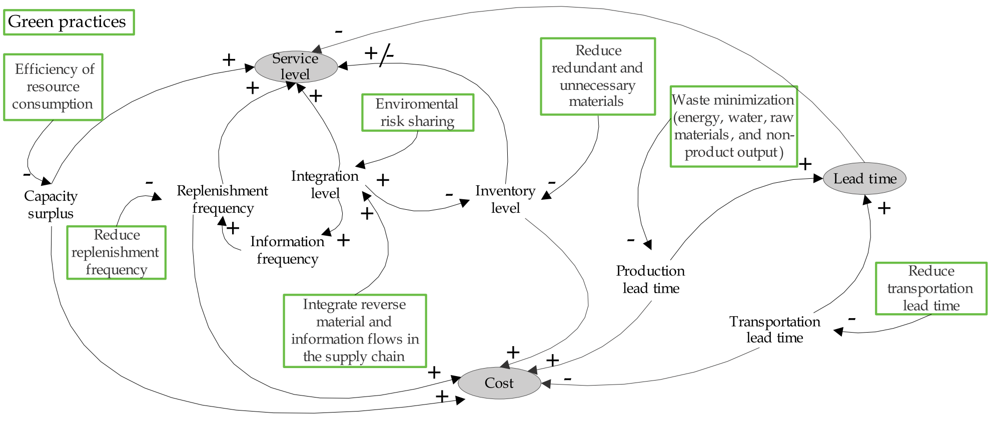


Fig. 5. Green practices and supply chain performance relationships.

### 4.5 LARG_SCM practices vs. supply chain attributes

To provide the necessary understanding of lean, agile, resilient and green paradigms divergences and commitments an overlap of the diagrams with the relationships between the different supply chain practices and the supply chain paradigms was developed. Figure 6 integrates the paradigms practices and supply chain performance relationships. From the causal diagram, it is possible to verify that some supply chain attributes are positively affected by all paradigms. All paradigms practices contribute to:

- "Information frequency" increasing.
- "Integration level" increasing.
- "Production lead time" reduction.
- "Transportation lead time" reduction.

For the others supply chain attributes, the paradigms implementation result in different directions. The divergences related to the "capacity surplus" are the following:

- The lean and green paradigms prescribe a reduction in the supply chain capacity buffers, in order to reduce the unnecessary wastes and promoting the efficiency of resource consumption.
- The agile and resilient paradigms prescribe an increase in the capacity surplus to increase the supply chain ability to respond to changes in customer's needs and to possible disturbances.

Another divergence is related to the "replenishment frequency":

- The lean, agile and resilient paradigms prescribe an increase in the replenishment frequency in order to respond quickly to costumer's needs and increase the supply chain responsiveness.
- The green paradigm prescribes a reduction in replenishment frequency to reduce transportation emissions, promoting the transport consolidation.

The third divergence between paradigms is related to the "inventory level":

- The lean, agile and green strategies prescribe a reduction in the inventory level.
- The resilient strategy promotes the constitution of strategic inventory buffers.

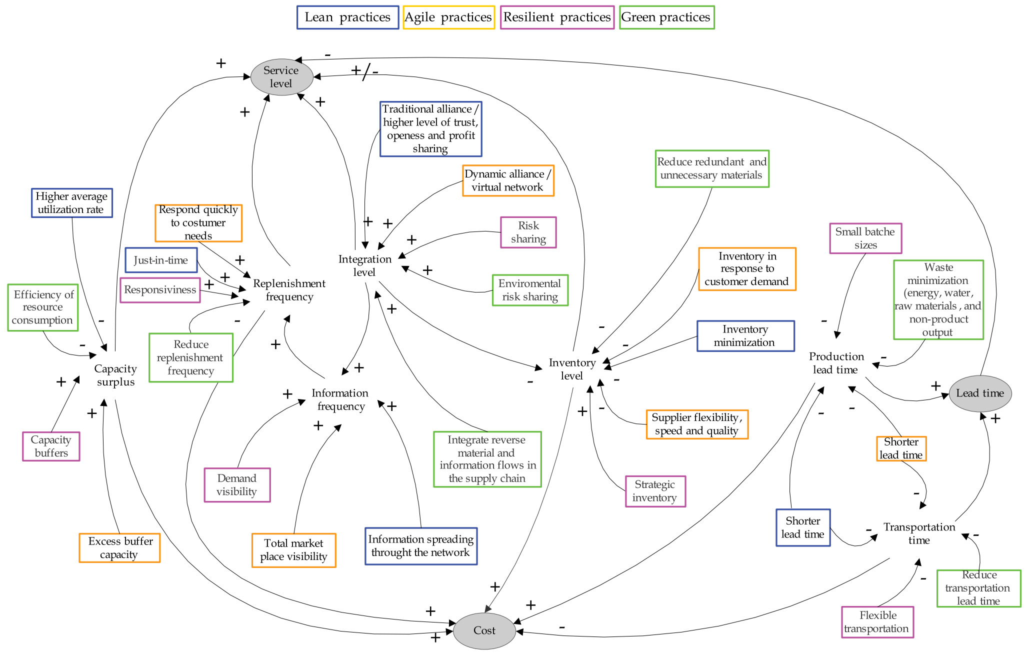


Fig. 6. Conceptual model with lean, agile, resilient and green practices and supply chain performance.

Table 2 shows an overview of main synergies and divergences between the paradigms under study. There are evidences that the lean, agile, resilient and green paradigms are complemented by each others. The implementation of these paradigms in the supply chain creates synergies in the way that some supply chain attributes should be managed, namely, "information frequency", "integration level", "production lead time" and "transportation lead time". However, the impact of each paradigm implementation in the characteristics

| Paradigms / Supply chain attributes | Lean | Agile | Resilient | Green | |
|---|---|---|---|---|---|
| Information frequency | ↑ | ↑ | ↑ | – | *Synergies* |
| Integration level | ↑ | ↑ | ↑ | ↑ | |
| Production lead time | ↓ | ↓ | ↓ | ↓ | |
| Transportation lead time | ↓ | ↓ | ↓ | ↓ | |
| Capacity surplus | ↓ | ↑ | ↑ | ↓ | *Divergences* |
| Inventory level | ↓ | ↓ | ↑ | ↓ | |
| Replenishment frequency | ↑ | ↑ | ↑ | ↓ | |
| Legend: ↑ increase; ↓ decrease; – without consequence; | | | | | |

Table 2. LARG_SCM synergies and divergences overview.

magnitude may be different. For example, the lean paradigm seeks compulsively the reduction of production and transportation lead times to promote the total lead time reduction and minimizing the total waste. However, the resilient paradigm, although it prescribes this reduction in lead times, it is not so compulsive, since the objective is to increase the supply chain visibility and capability to respond to unexpected events.

There are some apparent divergences in the application of the paradigms; namely, in what is concerned to the "capacity surplus", "replenishment frequency" and "inventory level". The capacity surplus is an attribute of agile and resilient supply chains, since this buffer in capacity allow to respond to changes in customers needs or to unexpected events. This does not mean that supply chain should have an enormous capacity surplus; that would be unacceptable in terms of cost and efficiency. However, existence of redundancies in critical processes should be considered in conjugation with lean and green paradigm implementation. The same question arises with the inventory level (which is another type of redundancy). The presence of high inventory levels may hide the causes of a poor supply chain performance and generate materials obsolescence; for that reason, the lean, agile and green paradigms prescribe the minimization of inventory levels. Even so, if the inventory of critical materials is maintained in low levels, the supply chain will be more vulnerable to unexpected events that affect these materials supply. Other conflict is related to the replenishment frequency, which should be improved to minimize wastes and increase supply chain responsiveness and adaptation. However, an increase in the replenishment frequency may be obtained trough the numerous deliveries of small quantities to supply chain entities, increasing the number of expeditions and consequently increasing the dioxide carbon emissions due to transportation. The green supply chain prescribes a reduction in the delivery frequency in order to reduce dioxide carbon emissions. However, this could be achieved, through not only the delivery frequency, but using other strategies as the selection of transport modes with low dioxide carbon emission, reducing geographic distances between entities, and transport consolidation, among others.

## 5. Conclusion

This paper investigated the possibility to merge lean, agile, resilient and green paradigms in the supply chain management (LARG_SCM). These four paradigms have the same global purpose: to satisfy the customer needs, at the lowest possible cost to all members in the supply chain. The principal difference between paradigms is the purpose: the lean supply chain seeks waste minimization; the agile supply chain is focused on rapid responding to market changes; the resilient supply chain as the ability to respond efficiently to disturbances; and the green supply chain pretends to minimize environmental impacts.

A state-of-the-art literature review was performed to: i) characterize and identifing the main supply chain practices of each paradigm; ii) to support the development of a conceptual model focused on the integration of lean, agile, resilient and green practices and supply chain attributes. The main objective was to identify supply chain attributes that should be managed to obtain: the necessary organizational agility; to speed-up the bridging between states that require more or less degree of resilience; to preserve the dynamic aspects of the lean paradigm and; to assure its harmonization with the ecologic and environmental aspects that production processes may attend.

### 5.1 Our results

The conceptual model development and analysis showed that some supply chain attributes are positively related to all paradigms creating synergies among them. All paradigms practices were found to contribute to: "information frequency" increasing, "integration level" increasing, "production lead time" reduction, and "transportation lead time" reduction. However, there are some apparent divergences in the application of the paradigms; namely, in what is concerned to the "capacity surplus", "inventory level" and "replenishment frequency". However, "capacity surplus" and "inventory level" increases may provide the supply chain with added agility and resilience characteristics, needed to respond to changes in costumer needs and unexpected events. The reduction of the "replenishment frequency" appears to be related to the concerns of reduction dioxide carbon emissions in the supply chain.

### 5.2 What is new and future research?

The identification of the conceptual relations among LARG_SCM paradigms is a contribution that we hope to become a step forward in the development of a new theoretical approaches and empirical research in supply chain management field. The conceptual model presented in this chapter provides a holistic perspective towards the investigation of the integration of lean, agile, resilience and green paradigms in supply chain management. It represent the first effort to "drill down" the key attributes related to lean, agile, resilience and green paradigms deployment in a supply chain context, providing links between supply chain attributes, paradigms and supply chain performance.

Therefore this chapter scientific contribution is twofold: first, it contributes for research on supply chain management by providing links between the deployment of LARG_SCM paradigms and supply chain performance; and second, it identifies synergies and divergences between the paradigms. From the managerial point of view, since it provides the links between supply chain paradigms with supply chain performance, it gives to supply chain manager's insights on how the adoption of paradigms will affect their network, and how it can increase the supply chain performance.

Despite the important contribution of this chapter, limitations of the study should be noted. The conceptual model was developed using anecdotal and empirical evidences present in the literature and no validation where performed. It is necessary to conduct further empirical research concerning to the deployment of lean, agile, resilience and green paradigms in supply chain management, both in terms of testing the model herein proposed and to the greater understanding of this discipline.

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## 7. References

Adamides, E. D.; Karacapilidis, N.; Pylarinou, H. & Koumanakos, D. (2008). Supporting collaboration in the development and management of lean supply networks. *Production Planning & Control*, Vol. 19, No. 1, pp. 35-52

Agarwal, A.; Shankar, R. & Tiwari, M. K. (2006). Modeling the metrics of lean, agile and leagile supply chain: An ANP-based approach. *European Journal of Operational Research* , Vol. 173, pp. 211-225

Agarwal, A.; Shankar, R. & Tiwari, M. (2007). Modeling agility of supply chain. *Industrial Marketing Management*, Vol. 36, No. 4, pp. 443-457

Anand, G. & Kodali, R. (2008). A conceptual framework for lean supply chain and its implementation. *International Journal of Value Chain Management*, Vol. 2, No. 3, pp. 313-357

Azevedo, S.G. ; Machado, V. H., Barroso A. P. & V. Cruz-Machado 2008. Supply Chain Vulnerability: Environment Changes and Dependencies. *International Journal of Logistics and Transport*, Vol. 1, No.1, pp. 41-55

Baramichai, M.; Zimmers Jr., E. W. & Marangos, C. A. (2007). Agile supply chain transformation matrix: an integrated tool for creating an agile enterprise. *Supply Chain Management: An International Journal*, Vol. 12, No. 5, pp. 334-348

Barroso, A. P. & Machado, V. H. (2005). Sistemas de Gestão Logística de Resíduos em Portugal. *Investigação Operacional*, Vol. 25, pp. 179-94

Bowen, F. E.; Cousine, P. D.; Lamming, R. C. & Faruk, A. C. (2001). Horse for courses: Explaining the gap between the theory and practice of green supply. *Greener Management International,* (Autumn), pp. 41-59.

Cheng, J.-H, Yeh, C.-H & Tu, C.-W. (2008) .Trust and knowledge sharing in green supply chains. *Supply Chain Management*, Vol. 13, No.4, pp. 283-295

Christopher, M. & Peck, M. (2004). Building the Resilient Supply Chain. *International Journal of Logistics Management*, Vol. 15, No. 2, pp. 1-14

Christopher, M. & Rutherford, C. (2004). Creating Supply Chain Resilience Through Agile Six Sigma. *Critical Eye*, (June-August), pp. 24-28

Christopher, M. & Towill, D. R. (2000). Supply chain migration from lean and functional to agile and customized. *Supply Chain Management: An International Journal*, Vol. 5, No. 4, pp. 206-213

Christopher, M. (2000). The agile supply chain, competing in volatile markets. *Industrial Marketing Management*, Vol. 29, No. 1, pp. 37-44

Cox, A. & Chicksand, D. (2005). The Limits of Lean Management Thinking: Multiple Retailers and Food and Farming Supply Chains. *European Management Journal*, Vol. 23, No. 6, pp. 648-662

Craighead, C.W. ; Blackhurst, J. ; Rungtusanatham, M.J. & Handfield, R. B. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, Vol. 38, No. 1, pp. 131-156

Darnall, N., Jolley, G. J. & Handfield, R. (2008). Environmental Management Systems and Green Supply Chain Management: Complements for Sustainability. *Business Strategy and the Environment*, Vol. 18, No. 1, pp. 30-45

Glickman, T. S. & White, S.C. (2006). Security, visibility and resilience: the keys to mitigating supply chain vulnerabilities. International Journal of Logistics Systems and Management, Vol. 2, No. 2, pp. 107-119

Gottberg, A., Morris, J.; Pollard, S.; Mark-Herbert, C. & Cook, M. (2006). Producer responsibility, waste minimisation and the WEEE Directive: Case studies in eco-design from the European lighting sector. *Science of the Total Environment*, Vol. 359, No. 1/3, pp. 38-56

Gunasekaran, A.; Patel, C. & Tirtiroglu, E. (2001). Performance measures and metrics in a supply chain environment. *International Journal of Operations & Production Management*, Vol. 21, No. 1/2, pp. 71-87

Gunasekaran, A.; Laib, K. & Cheng, T. C. E. (2008). Responsive supply chain: A competitive strategy in a networked economy. *Omega*, Vol. 36, No. 4, pp. 549-564

Haimes, Y. Y. (2006). On the Definition of Vulnerabilities in Measuring Risks to Infrastructures. *Risk Analysis*, Vol. 26, No. 2, pp. 293 -296

Hines, P.; Holweg M. & Rich, N. (2004). Learning to evolve A review of contemporary lean thinking. *International Journal of Operations & Production Management*, Vol. 24, No. 10, pp. 994-1011

Holweg, M. (2005). An investigation into supplier responsiveness: empirical evidence from the automotive industry. *International Journal of Logistics Management*, Vol. 16, No. 1, pp. 96-11

Hong, P.; Kwon, H. & Roh, J. J. (2009). Implementation of strategic green orientation in supply chain: An empirical study of manufacturing firms. *European Journal of Innovation Management,* Vol. 12, No. 4, pp. 512-532

Iakovou, E.; Vlachos, D. & Xanthopoulos, A. (2007). An analytical methodological framework for the optimal design of resilient supply chains. *International Journal of Logistics Economics and Globalisation*, Vol. 1, No. 1, pp. 1-20

Jeffery, M. M.; Butler, R.J. & Malone, L. C. (2008). Determining a cost-effective customer service level. *Supply Chain Management: An International Journal*, Vol. 13, No. 3, pp. 225-232

Kainuma, Y. & Tawara, N. (2006). A multiple attribute utility theory approach to lean and green supply chain management. International Journal of Production Economics, Vol. 101, No. 1, pp. 99-108

Larson T. & Greenwood, R. (2004). Perfect Complements: Synergies between Lean Production and Eco-Sustainability Initiatives. *Environmental Quality Management*, Vol. 13, No. 4, pp. 27-36

Li, S. ; Rao, S. ; Ragu-Nathan, T. S. & Ragu-Nathan, B. (2005). Development and validation of a measurement instrument for studying supply chain management practices. Journal of Operations Management, Vol. 23, No. 6, 618-641

Linton, J. D.; Klassen R. & Jayaraman, V. (2007). Sustainable supply chains: An introduction. *Journal of Operations Management*, Vol. 25, No. 6, pp. 1075-1082

Marley, K. A. (2006). Mitigating supply chain disruptions: essays on lean management, interactive complexity and tight coupling. Doctoral Dissertation, Ohio State University, Business Administration, 2006

Mason-Jones, R., Naylor J. B. & Towill, D. (2000). Engineering the Leagile Supply Chain, *International Journal of Agile Management Systems*, Vol. 2, No. 1, pp. 54-61

Melton, T. (2005). The benefits of lean manufacturing what lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, Vol. 83, No. 6, pp. 662-673

Morash, E.A., (2001). Supply chain strategies, capabilities, and performance. *Transportation Journal*, Vol. 41, No. 1, pp. 37-54

Morash, E.A., Droge, C. & Vickery, S. (1996). Strategic logistics capabilities for competitive advantage and firm success. *Journal of Business Logistics*, Vol. 17, No. 1, pp.1-22

Naylor, B.J.; Naim, M. M. & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. International Journal of Production Economics, Vol. 62, No. 1/2, pp. 107-118

Naylor, J. B.; Naim, M. M. & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain. *International Journal of Production Economics*, Vol. 62, No. 10, pp. 107-118

Ohno, T. (1998). *The Toyota Production System.* Productivity Press, Portland, 1998

Peck, H. (2005). Drivers of supply chain vulnerability: an integrated framework. *International Journal of Physical Distribution & Logistics Management*, Vol. 35, No. 4, pp. 210-232

Rao, P. & Holt, D. (2005). Do green supply chains lead to competitiveness and economic performance? *International Journal of Operations & Production Management*, Vol. 25, No. 9, pp. 898-916

Reichhart, A. & Holweg, M. (2007). Lean distribution: concepts, contributions, conflicts. *International Journal of Production Research*, Vol. 45, No. 16, pp. 3699-3722

Rice, B. F. & Caniato (2003). Building a secure and resilient supply network. *Supply Chain Management Review*, Vol. 7, No. 5, pp 22-30

Rosič, H.; Bauer, G. & Jammernegg, W. (2009). A Framework for Economic and Environmental Sustainability and Resilience of Supply Chains. In *Rapid Modelling for Increasing Competitiveness*, Reiner, G., pp. 91-104, Springer, New York

Sarkis, J. (2003). A strategic decision framework for green supply chain management. *Journal of Cleaner Production*, Vol. 11, No. 4, pp. 397-409

Sheffi, Y. & Rice, J. B. (2005). A supply chain view of the resilient enterprise. Sloan Management Review, Vol. 47, No. 1, pp. 41-48

Srivastava, S. K. (2007). Green supply-chain management: A state-of the- art literature review. I*nternational Journal of Management Reviews*, Vol. 9, No. 1, pp. 53-80

Sterman, J. (2000). Business Dynamics: Systems Thinking and Modeling for a Complex World, New York: McGraw-Hill

Tang, C. S. (2006). Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics Research and Applications: A Leading Journal of Supply Chain Management,* Vol. 9, No. 1, pp. 33

Towill, D. R. (1996). Time compression and supply chain management – a guided tour. *Supply Chain Management: An International Journal*, Vol. 1, No. 1, pp. 15–27

Van der Vorst J.G.A.J. & Beulens, A.J.M. (2002). Identifying sources of uncertainty to generate supply chain redesign strategies. *International Journal of Physical Distribution & Logistics Management*, Vol. 32, No. 6, pp. 409- 430

Venkat, K. & Wakeland, W. (2006). Is Lean Necessarily Green? *Proceedings of the 50th Annual Meeting of the ISSS* (International Society for the Systems Sciences)

Vonderembse, M. A.; Uppal, M.; Huang, S. H. & Dismukes, J. P. (2006). Designing supply chains: Towards theory development. *International Journal of Production Economics*, Vol. 100, No. 2, pp. 223-238

Womack, J. P.; Jones, D. T. & Roos, D. (1991). The Machine That Changed the World : The Story of Lean Production, Harper Perennial

Zhu, Q.; Sarkis, J. & Lai, K. (2008). Confirmation of a measurement model for green supply chain management practices implementation. International Journal of Production Economics, Vol. 111, No. 2, pp. 261-273

3

# A Hybrid Fuzzy Approach to Bullwhip Effect in Supply Chain Networks

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## 1. Introduction

Today all small and medium size enterprises, companies and even countries (either in private, public or military domain) in the national and international business area are continuously performing activities to provide capabilities for satisfying customer needs (i.e., demand) those indeed include many sophisticated interrelated functions and processes such as decision making, management, new product development, production, marketing, logistics, finance, quality control and etc. which, all together compose dynamic, complex and chaotic structures called supply chain networks (SCNs). These complex structures with all interrelated functions have to be designed and managed perfectly pointing us to the well-known term SCN management (SCNM). Due to the complex information flow in these systems; which consists of cumulative data about costs parameters, production activities, inventory systems and levels, logistic activities and many other related processes, we may unwaveringly express that the performance of a successful SCN directly related to the constant, accurate and appropriate demand information flow as this vital flow of information inarguably influences all decision making processes in all stages of SCNs.

A well-known phenomenon of SCNs called the "Bullwhip or Whiplash Effect" (BWE) is the variability of the demand information between the stages of the SCN and the increase in this variability as the demand data moves upstream from the customer to the following stages of the SCN engendering undesirable excess inventory levels, defective labor force, cost increases, overload errors in production activities and etc. From 1952 till now many studies have been done about BWE. However very few of them interested in fuzzy and neuro-fuzzy system (NFS) approaches to BWE such as Carlssson and Fuller (1999, 2001, 2002, 2004) and Efendigil et al. (2008).

Making accurate and appropriate estimation about future in decision making process is the leading activity providing bases for almost every managerial applications including SCNs. Demand forecasting and decision making are among the key activities that directly affect the SCN performance. To smoothen the undesirable variability of demand through the stages of SCN due to the chaotic nature of SCN system, appropriate demand forecasting is vital. As demand pattern varies due to the field of activity and architecture of SCNs, determining the appropriate forecasting model and adequate order/demand decision process for system interested in is snarl. As the nature of forecasting and decision making contains uncertainty or vagueness of the human judgment, they perfectly fit for the applications of fuzzy logic (FL) (Kahraman, 2006), artificial neural networks (ANNs) and; more specifically, the combination of these two complementary technologies (i.e.; NFS). The FL; which was introduced by Zadeh in 1965 with his pioneer work "Fuzzy Sets", can simply be defined as "a form of mathematical logic in which truth can assume a continuum of values between 0 and 1" (http://wordnetweb.princeton.edu/, 2009). On the contrary to crisp (discrete) sets which divide the given universe of discourse in to basic two groups as members and nonmembers, FL has the capability of processing data using partial set membership functions which makes FL a strong device for impersonating the ambiguous and uncertain linguistic knowledge (Kahraman, 2006). The advantage of approximating system behavior where analytic functions or numerical relations do not exist provide opportunity to fuzzy set theory for becoming an important problem modeling and solution technique which also bring along the usage of FL successfully in many fields of scientific researches, industrial and military applications such as control systems, decision making, pattern recognition, system modeling and etc. (Ross, 2004). Due to the perfect harmony of forecasting nature and fuzzy set theory, studies related to fuzzy forecasting is pretty much in the literature (see Kahraman, 2006). Fuzzy regression (FR) forecasting models are also among the successful applications fuzzy forecasting models. Contrary to the enormous literature about determining the appropriate forecasting and order/production decision models in SCNs, relatively few of them interested in fuzzy or neuro-fuzzy approaches.

The aim of this chapter is to carry out a literature review about the BWE, to provide a brief overview about FL, NFS, FR forecasting model and to introduce the proposed conjoint hybrid approach made up of an ANFIS based demand decision process together and FR forecasting model.

## 2. Basic literature

In this section at first, a basic review of literature about BWE is given and the fuzzy approach related studies about BWE is overviewed after that.

### 2.1 Bullwhip literature

The first academic research on BWE grounds on Jay W. Forrester (1958, 1961). In his pioneer work Forrester, using a simple four echelon SCN simulation (retailer, wholesaler, distributor and factory) discovered the existence of the 'demand amplification' which later denominated as BWE (Lee et al., 1997a, 1997b). He argued about the causes and suggested same ideas to control the BWE. He concluded that the decision making process and time delays in each phase of SCN and the factory capabilities could be the main reasons of the demand amplification through the chain from the retailer to the factory (upstream through the chain) as; any increase in customer demand at any point of time causes increases in retailers demand from the wholesaler, the wholesalers demand from distributor and in the same manner, the distributors demand from the factory. But in each, the amount of the demand accrual rate amplifies not only by taking account the real demand increases but also possible future increases causing inessential excessive inventory levels. Forrester also analyze the effect of advertising factor and saw that it also influences the system by engendering the BWE. He, as a solution, emphasized on the importance of knowledge about the system and suggested that the key fact for handling the BWE is to understand the whole SCN system.

Burbidge (1961); thought his study was about production and inventory control, also interested in demand amplification. In 1984, he concluded that an increase in demand variability would occur in every transfer of demand information if demands are carried over a series of inventories using “stock control ordering”. This definition is accepted to be the “first thorough definition” of BWE (Miragliotta, 2005).

Like Forrester, Sterman (1984, 1989a, 1989b) also focused on the existence and causes of BWE. He used an experimental four-stage SCN role-playing simulation that simulates the beer distribution in a simple SCN which is then became a well-known SCN simulation game that successfully depicts the notion of system dynamics; “The Beer Distribution Game”, widely used for teaching the behavior, concept and structure of SCN. The model was so simple but despite to its simplicity, it successfully showed the impact of the decision process in each echelon on the demand variability. Main objective is to govern echelons by achieving desired inventory and pipeline levels minimizing the total cost.

Participants of the game try to govern each echelon based on the information available for making ordering decision in each echelon. In other words, the real demand of customer only known by retailer who directly gets the customer orders and other echelons only have the demand information of the predecessor echelons those placed their demand directly to them. Game begins with the customer demand from the retailer, who tries to fill customer order from his/her own inventory if available. If demand exceeds the inventory, retailer placed his/her order to wholesaler. And in the same manner the demand and distribution processes go on through the SCN system of the game till the factory level where beers produced to meet the demand of distributor. The decision process in each echelon is based on the actual and desired inventory levels, current and expected demand; and finally, the desired and real level of items in pipeline.

Sterman; by analyzing the decision methodology of the participants, found out that, participants; instead of focusing on system delays and nonlinearities, focus on their current and target inventory levels ignoring the amount of orders placed but not received which then cause the demand and inventory enlargements that raises upstream from customer to factory. He also concluded that “anchoring and adjustment” heuristic (which is used for simulating the demand decision process of each echelon) is inconsequent as this heuristic is lack of sensibility to delays and repercussions of SCN system or; as to generalize, lack of “System Thinking” (Sterman 2000). With his simple beer SCN simulation game, he exposed general characteristics of SCN dynamics and; as Forrester, emphasized on irrational decision making process (via “misperception of feedback”) which is one of the main causes of and reason for the rise of BWE.

Forrester’s model also used by Towill (1991, 1992) and Wikner et al.(1991). Using the Forrester’s model with additional quantitative measures, Towill analyzed the S.C. systems by applying system dynamics models. System dynamics defined by Towill (1993a, 1993b) as “*A methodology for modeling an redesign of manufacturing, business and similar systems which are part man, part machine*”. He concluded that one of the reasons of demand amplification is time delays relevant to ‘value added’ or ‘idle’ operations. With an industrial example, he showed that via integration of decision mechanisms in SCN systems improvement could be achieved (both for demand amplifications and stock levels through the system). He also mentioned that this is still the case when MRP II capacity planning is conjoined to JIT flow shop control.

Wikner, Towill and Naim (1991); taking Forrester three echelon model as base, compared several methods of resolving dynamic performance of distribution systems. Though they suggested that Forrester's model is "far from optimal", they use it to evaluate their proposed systems. In the study authors tried to gain improvement by;

- eliminating echelons,
- altering decision rules for providing improvement,
- abating delays,
- arranging system ordering parameters and,
- constructing a smooth information flow.

In conclusion, they emphasized on the importance of smooth, better information flow through the whole chain and reducing delays, as these solutions have dominant impact for BWE reduction rather than improvement of ordering system.

Later Towill (1993a, 1993b) showed the influence of servo theory and cybernetics on the system dynamics and via examination he suggested that the input-output analysis is important for model building in system dynamics.

An important analysis in BWE history is made by Lee et al. in 1997 which than would light the way to many other studies (including their following studies) specially related to causes, quantification and also handling tools of the phenomenon (1997a, 1997b, 2002, 2004). Focusing on the operational causes of the problem and proving the existence by documentary evidences provided from several companies from different sectors (such as their well-known cases P&G and Hewlett-Packard), they declared four major causes and triggers of BWE as i.) demand signal processing (forecast updating), ii.) rationing game, iii.) order batching, iv.) price fluctuation.

Lee et al. (1997a) after proposing sources of BWE also proposed activities that can be used to mitigate the impact of these sources as summarized in the following table. Differently from Sterman and Forrester who generally declared that irrational behaviors of decision makers in SC is the main reason of BWE; the study of Lee; demonstrated that BWE is an outcome of the strategic interactions among rational SCN members; i.e., their attitudes inside the SCN constitution (see Table 1).

Though they are outnumbered relatively to others, researches about quantification of BWE can be considered as another category in the research area of this phenomenon. In general, most preferred system for quantifying BWE is computing demand variance or standard deviation ratios of two subsequent stages of SCN for their ability of easily capturing and displaying the scale of BWE. But studies that used cost parameters are also attract attention. Among the studies which tried to quantify BWE Metters' (1997) and Chen's (1998, 1999, 2000a, 2000b) studies are the remarkable ones. From the cost-profit perspective of quality management, Metters quantified BWE using costs arisen from BWE through the chain. Simulating a two-staged SCN model, he focused on demand variance, forecast errors and demand seasonality. Analyzing the model under several circumstances, he showed the effect of BWE on profitability and demonstrated that profit improvement can be achieved via BWE reduction. As this study directly shows the monetary impact of BWE on company profitability, it deservedly captured considerable attention from the managerial point of view.

Chen et al.(1998, 1999, 2000a, 2000b) studied the effects of forecasting, lead times and information sharing on BWE quantified as a ratio of demand variances of two consequent stages of simple SCN system. They showed order variances in the upstream echelon will be amplified if upstream echelons demand decisions are renewed systematically using the monitored values of predecessor downstream echelons orders periodically and even

| *Causes of Bullwhip* | *Information Sharing* | *Channel Alignment* | *Operational Efficiency* |
|---|---|---|---|
| Demand Forecast Update | -Understanding system dynamics<br>-Use of point-of-sale data (POS)<br>-Electronic data interchange (EDI)<br>-Computer-assisted Ordering (CAO) | -Vendor-managed inventory (VMI)<br>-Discount for information sharing<br>-Consumer direct | -Lead time reduction<br>-Echelon-based inventory control |
| Order Batching | -EDI<br>-Internet Ordering | -Discount for truck-load assortment<br>-Delivery appointments<br>-Consolidating<br>-Logistic outsourcing | -Reduction in fixed cost of ordering by EDI or electronic commerce<br>-CAO |
| Price Fluctuation | | -Continuous replenishment program<br>-Everyday low cost | -Everyday low price<br>-Activity-based costing |
| Shortage Gaming | -Sharing sales, capacity and inventory data | -Allocation based on past sales | |

Table 1. A Framework for Supply Chain Coordination Initiatives (**Lee, 1997a**)

thought the customer demand data is available for all echelons (i.e. centralized demand information), the forecasting technique and inventory system used is unique in each echelon through whole chain, the BWE will exist (1998, 2000a). In brief, Chen et al. constructed a two stage SCN model in which moving average technique is used for analyzing the unknown demand pattern essential for the inventory system that is operated (i.e. order-up-to policy) and developed a lower bound (a function of demand correlation, lead time and number of observations) on order variances placed by retailer concerning customer demand and developed their findings to multistage models. Despite the drawbacks described above and model simplicity, the study of Chen et al. introduced same executive overlook to quantified BWE adducing the effects of forecasting.

Later authors analyzed the effects of exponential smoothing forecasting technique on BWE for i.d.d. and linear trend demand cases (2000b). The study was very similar to their previous one. This time, the forecasting method used to predict the future demand of customer by the retailer was exponential smoothing. As a result of their study, they conclude following managerial insights:

- the size of demand variability directly influenced from the forecasting technique used to predict future demand variances and from the form of the demand pattern,
- BWE occurs when retailer updates the order-up-to point according to the periodically computed forecast values,
- The longer the lead time greater the demand variability,
- Smothering the demand forecast with more demand information will decrease BWE.

Gavirneni et al. (1999), Cachon et al. (2000), Kefeng et al.(2001) are the others who looked at the problem from the point of information sharing and its value. Gavirneni et al. betrayed the importance of information sharing in inventory control using, uniform and exponential demand patterns. Cachon and Fisher examining a simple SCN with two stages and stochastic stationary demand, compared the value of information sharing between the case in which only demand information available and the case in which both demand and inventory information are available. Their research results from their model showed that there is no remarkable difference between the analyzed cases. Later in his study of US industrial level data in 2005, Cachon et al. absorbed that; contrary to general understanding of BWE, demand variability does not always increase as one move up though the stages of SCN because of production smoothing attitude of manufacturers arisen from marginal costs and seasonality. Kefeng et al. analytically examined the improvement of coordination and appropriate forecasting in SCN. They presented their results for non-stationary, serially correlated demand and stationary one-lag demand before and after collaboration. The outcomes of the study showed that even under non-trendy and non-seasonal demand BWE exists and also the adaptation of forecasting method to the demand pattern and information sharing notably reduces BWE. So, they keynoted the importance of effective communication between the stages of SCN and consistent forecasting.

Kimbrough et al. (2002) looked thorough to SCN and BWE from a different perspective. They analyzed effectiveness of artificial agents in a beer game simulation model and investigated their ability of mitigating BWE through the system. They found out that agents have the effective ability of playing beer game. The study exposed that agents are capable of finding optimal policies (if there exists) or good policies (where analytical solutions are not available) that eliminates BWE tracking demand pattern under the assumptions of the model. Kimbrought and his coauthors study was important as it brought a different perfective to the solution of the problem from the point of computer aided decision models such as artificial intelligence and NF systems.

Towill, with other researchers such as Disney, Dejonckheere and Geary, have made several more important studies from the control theory approach (CTA) related to BWE which also are served as basis to many other researches (Towill et al. 2003; Dejonkheere et al. 2002, 2003, 2004; Disney et al. 2003a, 2003b, 2004, 2006).

From 2003 up till recent years other than Towill's, Dejonkheere's, Disney's and Geary's studies there is a remarkable increase in the research of BWE. Among these most considerable ones can be summarized as follow.

Aviv (2003), Alwan et al. (2003), So et al. (2003), Zhang (2004), and Liu et al. (2007) analyzed the phenomenon using stationary demand modeling the process as an ARMA type. Modeling demand as first order ARMA process, Aviv performed an adaptive replenishment policy, Alwan et al., Zhang and Liu et al. analyzed the forecasting procedures displaying the effects of moving average (MA), exponentially weighted moving average (EWMA) and minimum mean squared error (MMSE) forecasting models and, So et al. focused on lead times in a simple two phased model. Later Zhang (2005); again modeling customer demand as first order AR (i.e., AR(1)) process and using MMSE forecasting model, showed that delayed demand information reduces BWE.

Machuca et al. (2004) and Wu et al. (2005) studied on the effects of information sharing to BWE. Machuca et al. focused on the usage of EDI in SCN systems. A simple definition of EDI is given by The American Standards Institute as "the transmission, in a standard syntax, of unambiguous information of business or strategic significance between computers of independent organizations". As the smooth, correct and on-time information sharing is essential for SCN systems, usage of EDI provides rapid inter-organization coordination standardizing electronic communication (i.e., exchange of routine business data computer to computer), lead time reduction reducing the clerical process and reduction in the inventory costs due to the improvement of trading partner relationship, expedited supply cycle and enhanced inter-organizational relationship. Based on the idea that usage of EDI reduces the information delays, Machuca et al. analyzed the SCN system both as a whole and for individual echelons and showed that a reduction in BWE and related cost (especially costs driven by inventory) can be achieved with the usage of EDI, thought it did not completely eliminate the BWE in SCN systems.

Wu et al. (2005) used the beer game and analyzed the phenomenon from information sharing together with organizational learning perspective. Thought the study looked at the problem only in managerial view, the outcomes displayed that when organizational training and learning combined and coordinated thought data sharing and communication reduction in order oscillation could be achieved.

Makui et al. (2007) used a well known mathematical term; the Lyapunov exponent in their study and quantified BWE in terms of this exponent and; differently from the study of Boute et al. (2007) that importance of lead times in order smoothing, expressed the negative effect of lead times in terms of LPE. Based on the Chen et al.'s (1998) work, Makui et al. quantified and measured BWE for centralized and decentralized information cases in a two echelon SCN model and exposed the results with a simple numerical example. Authors' stated that the Lyapunov exponent; which may use for quantification of the irregularities of non-linear system dynamics, may also be use for quantifying BWE if LPE is sensed as a factor for expanding an error term of a system.

Like Makui et al. (2007) Hwarng et.al (2008) also used Lyapunov exponents in his work for quantify system chaos in SCNs and similar to BWE discovered the "chaos-amplification". The study; different from the previous recognized acknowledgment that points the main cause of system variability as the external unpredictable conditions, showed that exogenous factors such as demand together with related endogenous factors such as lead times and information flow may also generate chaotic behavior in SCN system. Based on this findings, Hwarng concluded that for effective management in chaotic SCN systems, the interactions between exogenous and endogenous factors have to be understood as well as the effects of various SCN factors on the system behavior for reducing system chaos and inventory variability.

Sohn et al. (2008), Wright et al. (2008), Saeed (2008), Sucky (2009) and Reiner et al. (2009) are the other researches who investigated mainly the effects of forecasting on BWE in their researches. Sohn et al.; using Monte Carlo simulation that simulates various conditions of market environment in SCN, aimed to suggest the appropriate information sharing policy together with appropriate forecasting method for multi-generation products of high-tech industry via which, customer satisfaction and net profit would be maximized considering the factors such as seasonality, supplier's capacity and price sensitivity of multi-generation products. Thought the study does not directly related to BWE, the research area and finding set a light to forecasting methods appropriate for specific information policies in SCNs for the cases such as the environmental factors like seasonality and price sensitivity exists.

Wright et al. (2008) expanded Stermans model and investigated BWE under different ordering policies and forecasting methods (Hold's and Brown's Method) separately and in combination. Based on the results Wright concluded that, forecasts which are made in conjunction with appropriate ordering policy decreases BWE and showed that Holt's or Brown's forecasting method might provide more stability in SCN when they are combined with slow adjustment of stock levels and rapid adjustment of supply line levels.

Saeed (2008) also worked on SCN stability in terms of forecasting. He suggested that if trend forecasting is applied to SCN systems as in derivative control, remarkable performance improvements in stability could be achieved. To support this idea, he constructed a SCN model in which, a classical control mechanism is implemented and used the forecasts of stock of inventory to demonstrate the use of trend forecasting as a policy tool in SCN.

Sucky (2008) differently from previous studies, analyzed BWE taking in to account the network structure of SCNs and the risk of pooling effect (which can be sensed as a special case of portfolio effect; see Ronnen, 1990). Using a simple three staged SCN, he revealed that BWE may be overestimated by assuming a reasonable SCN and risk of pooling effect could be utilized and also; like Dejonckheere et al. (2003), concluded that order-up-to systems generally generate BWE, depending on the statistical correlation of the demand data.

### 2.2 Fuzzy approaches to bullwhip effect

Since pioneer work of Zadeh (1965) "Fuzzy Sets" in which FL was introduced many studies have been done related to this brilliant subject. Though studies about FL are extremely high, its application to SC N and especially to BWE is narrow. The first application of FL approach to BWE topic; due to our knowledge, appears with the works of Carlsson & Fuller (1999, 2001, 2002, 2004). Authors built a decision support system describing four BWE driving factors of Lee et al. (1997a, 1997b); i.) demand signal processing, ii.) rationing game, iii.) order batching, iv.) price variations. Using an ordering policy with imprecise orders, they showed that BWE can significantly be reduced with centralized demand information and fuzzy estimates on future sales. But the study successfully sorted out the complexity of the phenomenon using fuzzy numbers.

Wang et al. (2005, 2007) developed a fuzzy decision methodology for handling SC uncertainties and determining appropriate strategies for SC inventories. In the study, fuzzy set theory is used to model SC uncertainties and a fuzzy SC model is proposed to evaluate SC performance. Though the study does not directly related to BWE; by improving SC performance against SC uncertainties, due to the proposed inventory policy and cost reductions demand variability indirectly reduced.

Zarandi et al. (2008) proposed a fuzzy agent-based model for reduction of BWE. In the study demand data, lead times and ordering quantities are considered as fuzzy and BWE is simulated and analyzed in fuzzy environment. A genetic algorithm module added added fuzzy time series forecasting model is used to estimate the future demand and a back-propagation neural network is used for defuzzification of the output. The simulation of BWE in fuzzy environment showed that the phenomenon still exists in fuzzy domain and genetic algorithm module added time series model perform successfully.

Another important study in recent literature about BWE is made by Efendigil, Önüt and Kahraman (2008). The study provides a comprehensive analysis for the first level of SC modeled by artificial intelligence approach. In the study both neural networks and ANFIS is used for demand forecasting only in retailer level with a real-world case study. The inputs for the demand forecast are unit sales price, product quality and effect of promotions, holidays and special cases. The study showed that hybrid forecasting models perform successfully for demand forecasting in SCNs.

Balan et al. (2009) again used soft computing approach to handle BWE. With a discrete time series single input single output model (SISO) model BWE is measured and via application of soft computing BWE is reduced. This study also showed that the application of FL and ANNs in SCN provides successful result in reduction of BWE.

## 3. Fuzzy, neuro-fuzzy systems and fuzzy regression forecasting model

As pointed out before, since pioneer work of Zadeh (1965), FL) has been successfully applied to many fields of science and engineering including SCNs. In dynamic complex nature of SCNs, demand forecasting; which sound basis for decision making process as mentioned before, is among the key activities that directly affect the performance of the system. As the demand pattern varies from system to system, determination of the appropriate forecasting model that best fits the demand pattern is a hard decision in management of SCNs. Most importantly, the usage of proper demand forecasting model that is adequate for the demand pattern is an important step for smoothing BWE in SCN systems. In this section, a brief overview about FL, NFS, FR forecasting model are encapsuled.

### 3.1 Fuzzy logic

On the contrary to many cases that involves human judgment, crisp (discrete) sets divide the given universe of discourse in to basic two groups; members, which are certainly belonging the set and nonmembers, which certainly are not. This delimitation which arises from their mutually exclusive structure enforces the decision maker to set a clear-cut boundary between the decision variables and alternatives. The basic difference of FL; which was introduced with the pioneer work of Zadeh; "Fuzzy Sets", in 1965, is its capability of data processing using partial set membership functions. This characteristic; including the ability of donating intermediate values between the expressions mathematically, turn FL into a strong device for impersonating the ambiguous and uncertain linguistic knowledge. But the main advantage of fuzzy system theory is its ability "*to approximate system behavior where analytic functions or numerical relations do not exist*" (Ross, 2004, pg.7). Palit et al.(2005) give a basic definition of FL from mathematical perspective as a nonlinear mapping of an input feature vector into a scalar output. As fuzzy set theory became an important problem modeling and solution technique due to its ability of modeling problems quantitatively and qualitatively those involve vagueness and imprecision (Kahraman, 2006, pg.2), it has been successfully applied many disciplines such as control systems, decision making, pattern recognition, system modeling and etc. in fields of scientific researches as well as industrial and military applications.

Differently from the classical sets that can be defined by characteristic functions with crisp boundaries, fuzzy sets can be characterized by membership functions providing to express belongings with gradually smoothed boundaries (Tanaka, 1997). Let $A$ be a set on the on universe $X$ with the objects donated by $x$ in the classical set theory. Then the binary characteristic function of subset $A$ of $X$ is defined as follow;

$$\mu_A(x) : X \to \{0,1\} \tag{1}$$

such that

$$\mu_A(x) = \begin{cases} 1 & x \in X \\ 0 & x \notin X \end{cases} \tag{2}$$

But fuzzy sets the characteristic functions; differently from the crisp sets whose characteristic function is defined binary (i.e., 0 or 1), are defined in the interval of $[0,1]$ (Zadeh, 1965). From this point, fuzzy set $\tilde{A}$ in the universe set $X$ with the objects $x$ and membership function $\mu_{\tilde{A}}$ is defined as follow;

$$\tilde{A} = \left\{ \left( x,\ \mu_{\tilde{A}}(x) \right) \quad \forall\ x \in X \ \right\} \tag{3}$$

where $\mu_{\tilde{A}}(x) : X \to [0,1]$.
If the fuzzy set is discrete then it can be represented as;

$$\tilde{A} = \sum_{k}^{n} \frac{\mu_{\tilde{A}}(x_k)}{x_k} \ , \ \ \forall x_k \in X \ , \ k = 1,2,.....,n \tag{4}$$

And if the fuzzy set is continuous then it can be denoted as;

$$\tilde{A} = \int_X \mu_{\tilde{A}}(x_k) \big/ x_k \ , \ \ \forall x_k \in X \tag{5}$$

The two vital factors for building an appropriate fuzzy set gets through the determination of appropriate universe and membership function that fits the system to be defined. The membership functions are the main fact for fuzzy classification. The highest membership grade value 1 represents full membership while the lowest membership value 0 have the meaning that the defined object have no membership to the defined set. Frequently used membership functions in practice are triangular, trapezoidial, Gaussian, sigmoidal and bell curve (the names are given according to the shapes of the functions). To give an example, trapezoidal membership function is specified by parameters $\{a,b,c,c\}$ as:

$$trapezoid(x;a,b,c,d) = \begin{cases} x-a \big/ b-a & ; \quad a \le x \le b \\ d-x \big/ d-c & ; \quad b \le x \le c \\ 0 & ; \quad x \ge d \ \text{ or } \ x \le a \end{cases} \tag{6}$$

where $a < b \le c < d$ denoting the $x$ coordinates of the trapezoidal membership function. The function reduces to triangular membership function when parameter $b$ and $c$ are equal. Similar to triangular function, control of the function can be maintained by adjusting parameters.
As fuzzy set theory provides a way to represent vagueness in linguistics in a mathematical manner, fuzzy if-then rules or the if-then rule-based form can simply be defined as schemes for capturing relative and imprecise natured knowledge; just like human knowledge. These provide a way of expressing knowledge in way of elastic nature language expressions in the general form of "IF X THEN Y". Here X is the antecedent (premise) and Y is the consequent (conclusion) (Ross, 2004, pg.148) with the linguistic values defined by fuzzy sets. The

conclusion described by consequent is come into being when premise described by the antecedent is true (i.e. when input fulfills the rule). The consequent of fuzzy rule are generally classified into three categories as crisp, fuzzy and functional consequent (Yen et al., 1999).

- Crisp consequent: Let z be a non-fuzzy numeric value or symbolic value then the crisp consequent can be expressed in the form: "IF…THEN y=z";
- Fuzzy consequent: Let $\tilde{A}$ be a fuzzy set then fuzzy consequent can be expressed in the form: "IF…THEN y= $\tilde{A}$ ";
- Functional consequent: Let $z_i$ be a constant for $i = 0,1,2,....,n$ then functional consequent can be expressed in the form: "IF $x_1$ is $A_1$ AND $x_2$ is $A_2$ AND… $x_n$ is $A_n$ THEN $y = z_0 + \sum_{i=1}^{n} z_i x_i$ ".

The antecedent of the rule may use three logical connectives which are "AND" the conjunction, "O" the disjunction and "NOT" the negation.

Zadeh (1965) adduced that fuzzy systems can be used to illustrate the human reasoning process as human understanding and reasoning take place in the fuzzy environment in general. Taking this prevision in to account, fuzzy (or approximate) reasoning can simply be defined as a path for deducting conclusions from incontestable knowledge and fuzzy rules. Defining input variables and required output together with the function that will be used for transferring crisp domain to fuzzy domain; the required fuzzy reasoning procedure can be achieved.

Fuzzy if-then rules and fuzzy reasoning compose bases for the most popular and cardinal computing tool called fuzzy inference systems (FIS) which, as general, perform mapping from a given input knowledge to desired output using fuzzy theory. This popular fuzzy set theory based tool have been successfully applied to many military and civilian areas of including decision analysis, forecasting, pattern recognition, system control, inventory management, logistic systems, operations management and so on. FIS basically consist of five subcomponents (Jang, 1993); a rule base (covers fuzzy rules), a database (portrays the membership functions of the selected fuzzy rules in the rule base), a decision making unit (performs inference on selected fuzzy rules), fuzzification inference and defuzzification inference. The first two subcomponents generally referred knowledge base and the last three are referred to as reasoning mechanism (which derives the output or conclusion).

The input (corresponding to system state variables) of FIS; either fuzzy or crisp, generates generally fuzzy output (corresponding to signal). Fuzzification is the comparison of the crisp input with the membership functions of the premise part to derive the membership values. If the required output value is crisp, then the fuzzy output is to be defuzzified. Ross (2004, pg.99) define this process as *"the conversion of a fuzzy quantity to a precise quantity"*. For basic concepts of fuzzy sets and related basic definitions see Bellman et al. (1970), Tanaka (1997 pg.5-44), Klir et al. (1995) and Ross ( 2004, pg.34-44).

### 3.2 Neuro-fuzzy systems

NFS; which also known as hybrid intelligent systems, can simply be defined as the combination of two complementary technologies: Artificial neural networks (ANNs) and FL. This combined system has the abilities of deducing knowledge from given rules (which come from the ability of FIS), learning, generalization, adaptation and parallelism (which come from the abilities of ANN). So these hybrid systems cover the frailty of both FL (i.e., no ability of learning, difficulties in parameter selection and building appropriate membership function, etc.) and ANN (i.e., black box, difficulties in extracting knowledge, etc.) and became a robust technology using both systems powerful abilities.

Simply, ANNs are mathematical information processing systems which are constituted based on the functioning principles human brains in which neurons in biological neural systems correspond to nodes and synapses correspond to weighted links in ANN (Maduko, 2007). Hecht-Nielsen (1990) described a neural network as; "*a parallel, distributed information processing structure consisting of processing elements (-which can possess a local memory and can carry out localized information processing operations) interconnected via unidirectional signal channels called connections*". As ANNs are computational models constituted of many interconnected neurons, the basic processing element of the ANNs are neurons and their way of interconnection also effect the ANN structure in addition to learning algorithm type, activation functions and number of layers. Using logical connections (weighted links) neurons in ANNs get the input from adjacent neurons with the input strength effected by the weight and; using the weighted input broadcasted from the adjacent neurons produce an output with the help of an activation function and broadcast the activation as an input; only one at a time, to other neurons (Fausset, 1994 pg. 3-25). In the input layer neurons receive input that is given to the system, contrarily the output layer neurons broadcast the ANN output to external environment while neurons in the hidden layers act as a black box providing links for the relation between the input and output (Choy et al., 2003a, 2003b).
The usage of hybrid NFS is rapidly increasing in many areas both civilian and military domain such as process controls, design, engineering applications, forecasting, modular integrated combat control systems, medical diagnosis, production planning and etc. This multilayer fuzzy inference integrated networks use neural networks to adjust membership functions of the fuzzy systems. This structure provides automation for designing and adjustment of membership functions improving desired output by extracting fuzzy rules from the input data with the trainable learning ability of ANNs and also overcomes the black box structure (i.e., difficulties of in understanding and explaining the way it deducts) of learning process of ANNs. Many studies have been made using different architectures of these hybrid systems, but among those architectures FL based neurons (Pedrycz, 1995); neuro-fuzzy adaptive models (Brown et al., 1994) and ANNs with fuzzy weights (Buckley et al., 1994) can be considered as noteworthy ones. A general NFS is constituted of three to five layers. The first layer represents the input variable, second layer are consists of input membership functions, the third layer or the hidden layers represents the fuzzy rules, the fourth and fifth layers represent the output membership function and output respectively (Jang, 1993; Wang, 1994).

### 3.2.1 Adaptive neuro-fuzzy inference systems

This system is the implementation of FIS to adaptive networks for developing fuzzy rules with suitable membership functions to have required inputs and outputs (Jang, 1993). In previous sections basic information about fuzzy reasoning and FIS was given. An adaptive network is a feed-forward multi-layer ANN with; partially or completely, adaptive nodes in which the outputs are predicated on the parameters of the adaptive nodes and the adjustment of parameters due to error term is specified by the learning rules (the other node type is named as fix node) (Jang, 1993). Generally learning type in adaptive ANFIS is hybrid learning. This learning model is appropriate for the systems having unsteady nature like SCNs. Jang defined this learning type as the learning that involves parameter updating after each data is given to the system. Due to its flexibility coming from the adaptive networks, ANFIS can design according to the system that it will be used. Using different fuzzy inference system with different IF-THEN rules and different membership functions and also with different network structures distinct types of ANFIS can be derived and extended (Jang et al., 1997). That is way this powerful system has many field of application. Here, ANFIS is used for demand decision process in a SCN simulation.

### 3.3 Fuzzy regression forecasting model

Linear regression model that explores the relation between response or dependent variable $y$ and independent or explanatory variable $x$, is a successful and commonly used statistical technique use in many fields of science and engineering problems. In linear regression model $y$ is a function of independent variables and can be written as;

$$Y = f(x,a) = \theta X = a_0 + a_1 x_1 + a_2 x_2 + \ldots + a_n x_n \tag{7}$$

where $\theta$ is the vector of coefficients which presents the degree of contribution of each variable to output and $X$ is the matrix of independent. The model is probabilistic as the differences between the observed and estimated values (i.e., output) is assumed to be due to observation errors considering the differences a random variable, and the confidence of estimate is represented by the probability that the estimated values are established between the upper and lower bounds. For the input data in linear regression model, unobserved error term is mutually independent and identically distributed; that is, the application of linear regression model is suitable for the systems in which the data sets observed are distributed according to a statistical model (Wang, 2000; Ross, 2004). But generally, fitting the demand pattern of systems like real SCNs to a specific statistical distribution hard to achieve. The FR model introduced by Tanaka et al. (1982, 1988); in which "deviations reflect the vagueness of the system structure expressed by the fuzzy parameters of the regression model" (i.e. possibilistic), relax and made the model suitable for the declared demand patterns. The model is explained as follow (Ross, 2004).
The fuzzy linear function in the model basically can be formulated as;

$$\tilde{Y} = (c_0, s_0) + (c_1, s_1)x_1 + (c_2, s_2)x_2 + \ldots + (c_n, s_n)x_n \tag{8}$$

where $c_t$ is the central value and $s_t$ is the spread value, of the $t$ th fuzzy coefficient; $\tilde{A}_t = (c_t, s_t)$, usually presented as a symmetrical triangular fuzzy number (STFN) with the membership function:

$$\mu_{\tilde{A}}(a_t) = \begin{cases} 1 - \dfrac{|c_t - a_t|}{s_t} & ; \quad c_t - s_t \le a_t \le c_t + s_t \\ 0 & ; \quad otherwise \end{cases} \qquad \forall t = 1,\ 2,\ \ldots,\ n \tag{9}$$

As can be seen from equations the coefficients of the FR model are represented by fuzzy functions. And this representation is fact that relaxes the crisp linear regression model. The usage of triangular membership function for the fuzzy coefficients allows the usage of linear programming for obtaining minimum fuzziness for the output values of the FR model (different membership function require alternative approaches, see Ross, 2004 pg.556). The membership function of output parameter is expressed as follow.

$$\mu_{\tilde{Y}}(y) = \begin{cases} \max(\min\left[\mu_{\tilde{A}_t}(a_t)\right] & ; \quad \{a \mid y = f(x,a)\} \ne 0 \\ 0 & ; \quad otherwise \end{cases} \tag{10}$$

And using the membership function expressed we can rewrite $\mu_{\tilde{Y}}(y)$ as;

$$\mu_{\tilde{Y}}(y) = \begin{cases} 1 - \dfrac{\left| y - \sum_{i=1}^{n} c_t x_t \right|}{\sum_{t=1}^{n} c_t |x_t|} & ; \quad x_t \neq 0 \\ 1 & ; \quad x_t = 0, \; y = 0 \\ 0 & ; \quad x_t = 0, \; y \neq 0 \end{cases} \tag{11}$$

The data for the model can be either fuzzy or crisp. In this study input data used to obtain future demand forecast is crisp. So, the following parts of the model express the computation of output for non-fuzzy data. As the aim is to obtain minimum fuzziness for the output parameter, the following linear programming formulation which minimizes the spread of the output parameter, minimum fuzziness for the output can be achieved.

$$\begin{aligned} & Z = Min\left\{ ms_0 - (1-h)\sum_{i=1}^{m}\sum_{t=0}^{n} s_t x_{ti} \right\} \\ & St \\ & \sum_{t=1}^{n} c_t x_{ti} - (1-h)\sum_{t=1}^{n} s_t x_{ti} \leq y_i \\ & \sum_{t=1}^{n} c_t x_{ti} + (1-h)\sum_{t=1}^{n} s_t x_{ti} \geq y_i \end{aligned} \tag{12}$$

where $x_{0i} = 1$, $\forall t = 1, 2, ..., n$, $\forall i = 1, 2, ..., m$ and $h \in [0, 1]$ which is specified by the designer of the model, defines the degree of belongings as;

$$\mu_{\tilde{Y}}(y_i) \geq h \quad , \quad i = 1, 2, ..., m \tag{13}$$

The value $h$ conditions the wide fuzzy output interval. The fuzzy forecast value for period $t$ expressed will than be computed as:

$$\tilde{F}_t = (c_0, s_0) + (c_1, s_1)x_1 + (c_2, s_2)x_2 + .... + (c_n, s_n)x_n \tag{14}$$

Notice that, If the forecast value is need to be crisp then a defuzzification method must be used.

## 4. Application of fuzzy hybrid model on supply chain networks

In this chapter, a near beer distribution game extended with ANFIS decision making process and FR forecasting model; which is improved from the base beer game of Sterman (1984, 1989) and its revised version of Paik's (2003), is used to simulate a two stage SCN for evaluating the impacts of proposed system under relatively medium demand variation which is determined with the demand standard deviation. For each comparison between the base and proposed models, BWE is quantified for each stage as a ratio of standard deviations of subsequent stages to reflect the amount of variability.

The most important issue for a realistic SCN model is modeling the decision making process as the whole system mainly depends on the demand decision of the phases. Parameters and decision variables have to be chosen carefully considering all complex activities included in SCN. In addition, the information that will be used in the decision process has to be appropriate for providing decision accuracy which makes model construction even more difficult. So, for modeling these complex systems same assumptions have to be made for providing simplification which, unfortunately may cause falling short of the reality if those assumptions suggested by not taking consideration of real SCN nature.

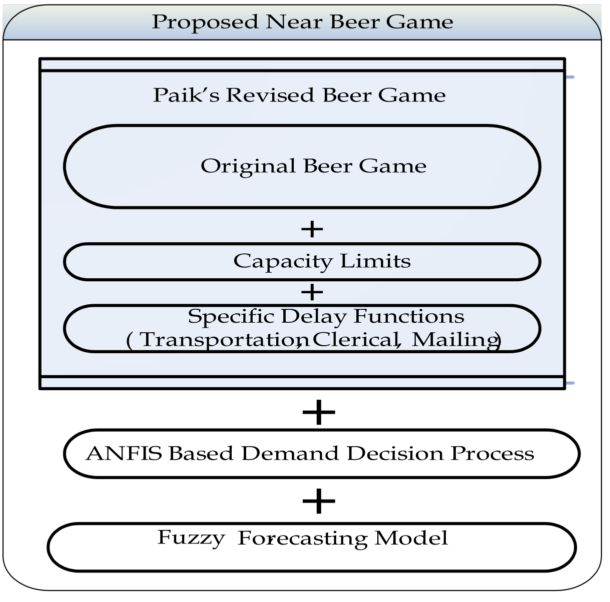



Fig. 1. Proposed simulation model structure

For analyzing the system like SCN (due to the purpose of the analysis), simulation approach is the most common choice. Among the simulation models, the most preferred one is the "Beer Game" (or "MIT Beer Game") model which was founded in 1960s at the Sloan School of Management (Strozzi et al., 2007) and then became well known after Sterman in 1989 (1989a, 1989c). Here, a near beer game simulation model improved from the base beer game model of Sterman and its revised version of Paik's is used to simulate SCN.

### 4.1 Supply chain network simulation

The beer distribution or MIT beer game is a role-playing simulation model that represents the beer production and distribution system in a simple SCN which is widely used as a teaching tool for pointing out SCN structure, concept and dynamics. The goal of the game is to govern each stage of the chain (generally consists of two or four stages in which stages simulates the retailer, the wholesaler, the distributor and factor (or producer) respectively) maintaining appropriate inventory levels to meet the desired demand of the predecessor stage and to minimize the total cost avoiding stock-outs taking by supply line into consideration under limited information flow. Due to the rich simulation environment including time delays, cost items, feedbacks and decision rules that successfully represents

the actual decision making process in stock management problems of the real business environment; general characteristic of the beer game fairly illustrates the nature of real world SCNs (Paik, 2003).
The game begins with the demand orders placed from the customer to retailer. Retailer tries to meet the demand from its own inventory upon the availability of the stocks. If demand exceeds the inventory level, retailer place order to wholesaler. Also for maintaining appropriate inventory level for the future customer demand, the ordering decision of the retailer must also comprehend customer demand rate for the upcoming periods. And in the same manner the demand and distribution processes go on through the SCN system of the game till the factory stage where beers produced to meet the demand of distributor. So, in each stage except factory, the participants of the game receives demand orders from downstream stage, tries to meet the demand from its own inventory (actual inventory), ships orders to downstream stage, receives shipments from upstream stage and places orders to upstream stage by taking, future demand from downstream stage, desired inventory level together with shipment and orders that have been placed that have been placed but not received yet into consideration. The only difference in factory (which is the final stage of the game) is that the orders placed from the wholesaler are attempt to be met from either factory inventory or by production made in factory.
Limited information availability, time delays in the information flow and shipments are other important characteristics of the game which increase the complexity of the game and make the game more realistic for reflecting real world applications.
The ordering/production decision process rule in each phase of the model is simple but effective as it takes almost all factors reflecting behaviors of SCN. These factors are (Sterman, 1989; Paik, 2003):

- Current demand: current received orders
- Actual inventory level: current inventory;
- Desired inventory level: adjustment of inventory to expected forthcoming demand for a specified time period which is usually constant and determined by the designer (the adjustment parameter can also be referred to as safety stock constant or safety constant only),
- Actual pipeline orders (actual supply line): total sum of outstanding orders plus shipments in transit,
- Desired pipeline orders (desired supply line): desired rate of outstanding orders and shipments in transit,
- Demand forecast: the expected demand for the forthcoming period; i.e., expected losses.

The decision rule in period $t$ can be formulated as follow (Sterman, 1989; Paik, 2003);

$$O_t = Max\left(0,\left[F_t + IC_t + SlC_t\right]\right) \tag{15}$$

where $O_t$ is the order quantity, $F_t$ is the forecast value, $IC_t$ is the correction of inventory and $SlC_t$ is the correction of supply line formulated as follow:

$$IC_t = \theta_I(DInv_t - Inv_t) \tag{16}$$

$$SlC_t = \theta_{Sl}(SD_t - SA_t) \tag{17}$$

where $DInv_t$ is the desired inventory level, $Inv_t$ is the current (actual) inventory level, $SD_t$ is the desired supply line, $SA_t$ is the current (actual) supply line and $\theta_I$, $\theta_{SI}$ are the adjustment parameters of inventory and supply line respectively. Both $\theta_I$ and $\theta_{SI}$ determines "how much emphasis is placed on the discrepancy" between the desired and actual values inventory and supply line (Paik, 2003).

The forecast value used in the decision rule of the game is computed using simple exponential smoothing forecasting model as;

$$F_t = \alpha \; OI_{t-1} + (1-\alpha)F_{t-1} \quad 0 \le \alpha \le 1 \tag{18}$$

where $OI_{t-1}$ is the actual value of the orders received (incoming orders) in period $t-1$ and $\alpha$ represents the smoothing constant.

The overall decision rule of the model can be rewritten by defining a disturbance term $\varepsilon$ to each period and new parameter $\beta$ as follow;

$$O_t = Max\left(0, \left[F_{\mathrm{t}} + \; \theta_{\mathrm{I}}(AI' - Inv_t - \beta \; SA_t\right] \; + \varepsilon_{\mathrm{t}}\right) \tag{19}$$

where $\beta = {\theta_{SI}}/{\theta_I}$ and $AI' = DInv_t + \beta \; SD_t$. For more detail see Sterman (1989), Paik (2003) and Strozzi et al. (2007).

#### 4.1.1 Proposed model

As stated before, the main objective here is to analyze the response of BWE to the proposed ANFIS based demand decision process in which the appropriate forecast values that are computed with FR forecasting model in addition to the identical decision variables and parameters used in the base SCN simulation model. The general ANFIS and the used forecasting models architectures and structures have been discussed in previous sections.

The possibilistic FR model is used to predict the appropriate upcoming demand value that will be used in the ANFIS based demand decision process. The demand data structure used in the model (input values) is crisp and the output forecast value is also defuzzified. The fuzzy coefficients of FR model ( $\tilde{A}$ ) chosen for the forecasting model are STFN; hereby, the linear programming is used for obtaining minimum fuzziness for the output values of the FR model via minimizing the spread of the output parameter (i.e., the forecast value)(Ross, 2004). As the value $h \in [0, 1]$ (which defines the degree of belongings) conditions the wide fuzzy output interval, similar to the most of previous studies the value of $h$ is taken as 0.5 (Tanaka et.al, 1982, 1988; Wang et.al, 1997; Ross, 2004) As the linear programming formulation states two constraints for each data set, there are $2m$ constraints for each data set. For example if $m = 200$ for the time period $t$, then the simulation model have to solve a 400 constrained linear programming model in each stage to determine the forecast value of the upcoming demand.

Differently from the previous SCN simulations which use beer game to simulate a realistic SCN (with "anchoring and adjustment" heuristic), the proposed model contains an ANFIS based decision process in each phase of SCN to determine order quantities (or, the quantity of production in factory stage) using the forecast values gathered from the selected forecasting model (i.e., FR) together with inventory and pipeline information which also are the same input used in the base model. Matlab "Fuzzy Logic Tool Box" is used for building the ANFIS structures and via determined input values the same tool box is also used for the solutions. (see Fuzzy Logic Toolbox Users Guide; The Math Works Inc.; 2001). After the performed trials of the simulation, the hybrid method; which is a combination of back propagation and least square estimation (the sum of the squared errors between the input and output), is selected and used for membership function parameter estimation of FIS (Matlab, 2001). The error tolerance is set to zero and ANFIS is trained for each selected forecasting model (fuzzy and crisp) in stage. Data characteristic are chosen as to illustrate a relatively medium variation in demand with demand mean $\mu_d = 50$ and demand standard deviations $10 \leq \sigma_d < 15$ .

Among the defuzzification methods, the centroid method is used to defuzzify the output forecast value of the FR model as to obtain crisp demand forecast information for the ANFIS based decision making procedure.

Results gathered from the all simulation runs of the base model (crisp) (which are used for making comparison with the results of the proposed model); for the demand pattern concerned (relatively medium) considering all parameter combinations with and without predefined capacity limit for factory, shows that parameter combination $\alpha = 0.36$, $\beta = 0.34$, $\theta = 0.26$ exposes the minimum $BWE_{TOTAL}$ values where;

$$BWE_{TOTAL} = \frac{BWE_{Cap} + BWE_{Uncap}}{2} \tag{20}$$

In the light of these results, proposed model is evaluated and compared with the base model for the mentioned best parameter combination with and without predefined capacity limit.

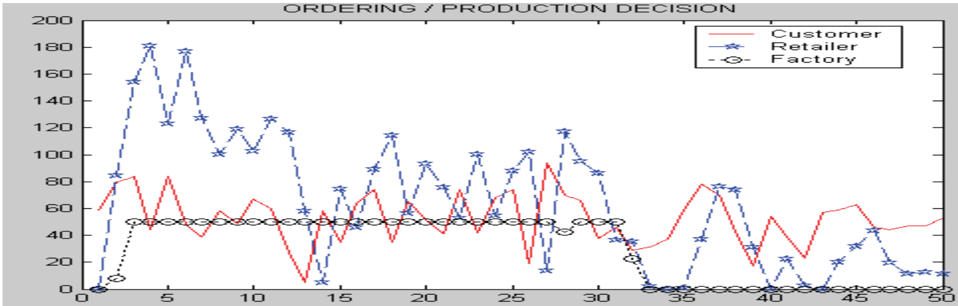
### 4.2 Simulation results

Results gathered from the simulation runs of proposed and base model with the best parameter combination with and without capacity limits for factory stage are illustrated in table 2.

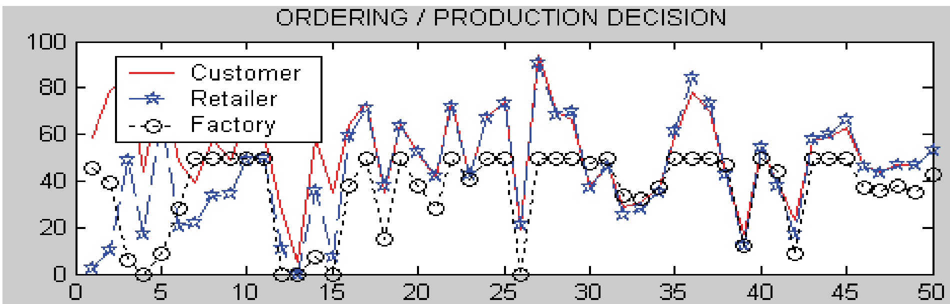
| **Parameter Combination** $\alpha = 0.36,\ \beta = 0.24,\ \theta = 0.26$ | **Medium Variation** | |
|---|---|---|
| | Base | Proposed Model |
| $BWE_{TOTAL}$ | 2.415 | 1.305 |
| **Percentage of Reduction (%)** | **45.962** | |

Table 2. Results of the base and proposed model

Results show that BWE is reduced approximately **46.%** using proposed FR and ANFIS based decision approach for demand pattern concerned. The following figures illustrates that proposed model captures rapidly the pattern of the customer orders.

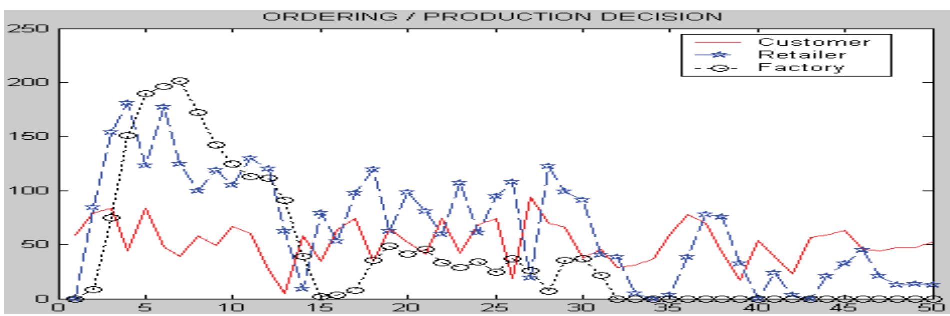



(a) Base (crisp) model with factory capacity for relatively medium demand variation

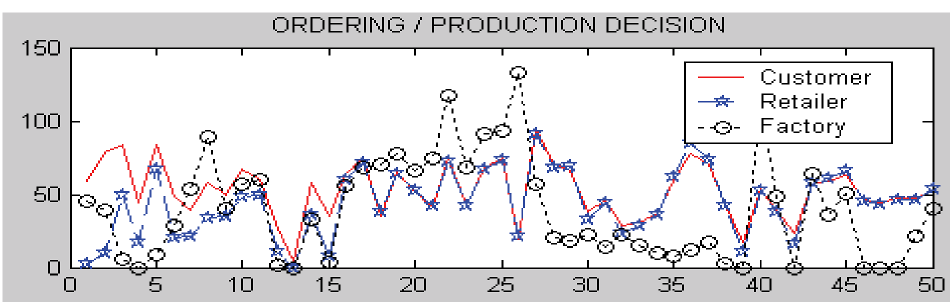



(b) Proposed model with factory capacity for relatively medium demand variation

Fig. 2. Order/production decisions with factory capacity of the base and proposed model




(a) Base (crisp) model without factory capacity for relatively medium demand variation




(b) Proposed model without factory capacity for relatively medium demand variation

Fig. 3. Order/production decisions without factory capacity of the base and proposed model

## 5. Conclusions and recommendations

SCNs are multi stage complex dynamical systems consist of various involved organizations performing different processes and activities in each and consequent stages which are connected through upstream and downstream linkages to produce value in the form of products and services (Christopher, 1994). Demand forecasting and decision making processes are among the key activities which directly affect the performance of this complex systems. As demand pattern varies due to the field of activity and architecture of system, appropriate forecasting and order decision model determination is a complicated work in SCNs. The variability of the demand information between the stages of SCN and the increase in this variability as the demand data moves upstream from the customer to the consequent stages (i.e., BWE) is a major problem that negatively influencing the stability of SCNs triggering several system defects which directly affects the total performance of SCN.

In this chapter a basic literature review is carried out a about the BWE and fuzzy related studies on BWE. A hybrid fuzzy approach made up of an ANFIS based demand decision process together with FR forecasting model is introduced and analyzes are made to expose the response of this phenomenon to the proposed approach under demand with relatively medium variation in a two stage SCN simulation. A brief overview about the FL, NFS and FR forecasting models is also given.

Results gathered from the simulation runs of the base and proposed models showed that the proposed model easily monitored the demand pattern and provided remarkable decreases in demand variability through the SCN.

Each study with its own purpose contains certain limitations. As Paik pointed out “No research method can guarantee flawless study” (2003, pg.16). Due to the dynamic, chaotic and complex characteristics of SCNs, developing a simulation model that can successfully reflect these specialties is complicated. So future studies can be made by redesigning models using ANNs specially developed for the system using fuzzy cost and lead-time values.

## 6. References

Alwan L. C., Liu J., Yao D., (2003). Stochastic characterization of upstream demand process in supply chains, IIE Transactions, 35, pp.207-219.

Aviv Y., (2003). A time series framework for supply chain inventory management, Operations Research, 51, pp.201-227.

Balan S., Vrat P., Kumar P., (2009).Information distortion in a supply chain and its mitigation using soft computing approaches”, International Journal of Management Science (OMEGA), 37, pp.282-299.

Bellman R. E., Zadeh L.A., (1970). Decision- making in fuzzy environment”, Management Science, 17, pp.141-164.

Boute R. N., Disney S. M., Lambrecht M. R., Van Houdt B., (2007). An integrated production and inventory model to dampen upstream demand variability in the supply chain, European Journal of Operational Research, 178, pp.121-142.

Brown M., Harris C., (1194).Neuro-fuzzy adaptive modeling and control”, Prentice Hall, NY.

Buckley J. J., Hayashi Y., (1994). Fuzzy neural networks”, In: Fuzzy sets, neural networks and soft computing by Yager L., Zadeh L., V. Nostrand Rainhol , NY.

Burbidge J. L., (1961).The new approach to production, Production Engineering, 40, pp.769-784.

Burbidge J. L., (1984). Automated production control with a simulation capacity", Proceedings of IFIP Conference, pp.1-14.

Cachon G. P., Fisher M., (2000). Supply chain inventory management and the value of shared information, Management Science, 46, pp.843-1048.

Cachon G. P., Randall T., Schimidt G. M., (2005). In search of the bullwhip effect", Manufacturing and Service Operations Management, 9,pp. 239-261.

Carlsson C., Fullér R. (1999). Soft computing and the bullwhip effect", Economics and Complexity, 2, pp.1-26.

Carlsson, C., Fullér, R. (2001). Reducing the bullwhip effects by means of intelligent, soft computing methods", In Proceeding of the 34th Hawaii International Conference on System Science, pp.1-10.

Carlsson, C., Fullér, R. (2002). A position paper on the agenda for soft decision analysis", Fuzzy Sets and Systems, 131,pp.3-11.

Carlsson C., Fedrizzi M, Fullér R. (2004). Fuzzy logic in management", Kluwer Academic Publishers, Boston.

Chen F., Drezner Z., Ryan J., Simchi-Levi D., (1998). Quantifying the bullwhip effect: The impact of forecasting, lead time and information", Working paper, Department of IE/MS North Western University, Evanston, IL. And School of IE, Purdue University, Lafayette, IN.

Chen F., (1999). Decentralized supply chains subject to information delays, Management Science, 45, pp.1076-1090.

Chen F., Drezner Z., Ryan J., Simchi-Levi D. (2000a). Quantifying the bullwhip effect: The impact of forecasting, lead time and information, Management Science, 46, pp.436-443.

Chen F., Samroengraja R., (2000b). The impact of exponential smoothing forecasts on the bullwhip effect, Naval Research Logistics, 47, pp.269-286.

Chen F., Drezner Z., Ryan J., Simchi-Levi D., (2000c). The stationary beer game, Products and Operations Management, 9, pp.19-30.

Christopher M, (1994). Logistics and Supply Chain Management, Pitman Publishing, Londan, UK.

Choy K. L., Lee W. B., Lo V., (2003a). Design of an intelligent supplier relationship management system: a hybrid case based neural network approach, Expert Systems with Applications, 24, pp.225-237.

Choy K. L., Lee W. B., Lo V., (2003b). Design of a case based intelligent supplier relationship management system—the integration of supplier rating system and product coding system, Expert Systems with Applications, 25, pp.87-100.

Dejonckheere J., Disney S.M., Lambrecht M., Towill D. R., (2002).Transfer function analysis of forecasting included bullwhip in supply chains, Int. Journal of Production Economics, 78, pp.133-144.

Dejonckheere J., Disney S. M., Lambrecht M., Towill D. R., (2003). Measuring and avoiding the bullwhip effect: A control theoretic approach, European Journal of Operational Research, 147, pp.567-590.

Dejonckheere J., Disney S. M., Lambrecht M., Towill D. R., (2004). The impact of information enrichment on the bullwhip effect in supply chains: A control engineering perspective, European Journal of Operational Research, 153, pp.727-750.

Disney S. M., Towill D. R., (2003a).On the bullwhip and inventory variance produced by an ordering policy, International Journal of Management Science, 31, pp.157-167.

Disney S. M., Towill D. R., (2003b). The effect of vendor managed inventory (VMI) Dynamics on the bullwhip effect in supply chains, International Journal of Production Economics, 85, pp.199-215.
Disney S. M., Towill D. R., Velde W., (2004). Variance amplification and the golden ratio in production and inventory control, International Journal of Production Economics, 85, pp.295-309.
Disney S. M., Farasyn I., Lambrecht M, Towill D. R., Van de Velde W., (2006). Taming the bullwhip effect whilst watching customer service in a singular supply chain echelon, European Journal of Operational Research, 173, pp.151-172.
Efendigil T., Önüt S., Kahraman C., (2008). A decision support system for demand forecasting with artificial neural networks and neuro-fuzzy models: A comprehensive analysis, Expert Systems with Applications, 36, pp.6697-6707.
Fausset L., (1994). Fundamental of neural networks: Architectures, algorithms and applications, Prentice Hall, New Jersey.
Forrester J. W., (1958). Industrial dynamics: A major breakthrough for decision makers, Harvard Business Review, 36, pp.37-66.
Gaery S., Disney S. M., Towill D. R., (2006). On bullwhip in supply chains-historical review, present practice and expected future impact, International Journal of Production Economics, 101, pp.2-18.
Gavirneni S., Kapuscinski R., Tayur S., (1999). Value of information in capacitated supply chains, Management Science, 101, pp.16-24.
Hecht-Nielsen R., (1990). Neurocomputing, Addision-Wesley, 1990.
Heshmaty B., Kandel A., (1985).Fuzzy linear regression and its applications to forecasting in uncertain environment, Fuzzy Sets and Systems, 15, pp.159-191.
http://wordnetweb.princeton.edu/, 2009.
Hwarng H. B., Xie N., (2008). Understanding supply chain dynamics: A chaos perspective, European Journal of Operational Research, 184, pp.1163-1178.
Jang J-S. R., (1993). ANFIS: Adaptive network based fuzzy inference system, IEEE Transactions on Fuzzy Systems, Man and Cybernetics, 23, pp.665-685.
Jang J-S. R., Sun C. T., Mizutani E., (1997). Neuro-fuzzy and soft computing: A computational approach to learning and machine intelligence, Prentice Hall, Upper Saddle River, NJ, USA.
Kahraman C., (2006). Fuzzy Applications in Industrial Engineering, Studies in Fuzziness and Soft Computing, 201, Springer Verlag , NJ USA.
Kefeng X., Dong Y., Evers P. T., (2001). Towards better coordination of supply chain, Transportation Research Part E , 37, pp.35-54.
Kimbrough S. O., Wu D. J., Zhong F., (2002). Computers play beer game: Can artificial agents manage supply chains ?, Decision Support Systems, 33, pp.323-333.
Klir G. J., Yuan B., (1995). Fuzzy sets and fuzzy logic: Theory and applications, Prentice Hall.
Lee H. L., Padmanabhan V., Whang S., (1997a).The Bullwhip Effect in Supply Chains, MIT Sloan Management Rev., 38, pp.93-102.
Lee H. L., Padmanabhan V., Whang S., (1997b). Information Distortion in a Supply Chain: The bullwhip effect, Management Science, 43, pp.546-558.
Lee H. L., (2002). Aligning supply chain strategies with product uncertainties, California Management Review, 44 (2002) 105-119.
Lee H. L., Padmanabhan V., Whang S., (2004). Information Distortion in a Supply Chain: The bullwhip effect, Management Science, 50, pp.1875-1886.

Lee H. T., Chen S. H., (2001). Fuzzy regression model with fuzzy input and output data for manpower forecasting, Fuzzy Sets and Systems, 119, pp.205-213.

Liu H., Wang P., (2007). Bullwhip effect analysis in supply chain for demand forecasting technology, Systems Engineering-Theory and Practice, 27, pp.26-33.

Machuca J. A. D., Barajas R. P., (2004). The impact of electronic data interchange on reducing bullwhip effect and supply chain inventory, Transportation Research Part E, 40, pp.209-228.

Maduko, A., (2007). Developing and testing a neuro-fuzzy classification system for IOS data in asthmatic children", PhD. Thesis, Texas University.

Makui A., Madadi A., (2007). The bullwhip effect and Lyapunov exponent, Applied Mathematics and Computation, 189, pp.35-40.

Matlab, (2001). Fuzzy logic toolbox user's guide, The Matworks Inc.,.

Metters R., (1997). Quantifying the bullwhip effect in supply chains, Journal of Operation Management, 15, pp.89-100.

Miragliotta G., (2006). Layers and mechanisms: A new taxonomy for the bullwhip effect, International Journal of Production Economics, 104, pp.365-381.

Palit A. K., Popovic D., (2005). Computational intelligence in time series forecasting: Theory and engineering applications, Advances in Industrial Control, Springer Verlag, NJ USA.

Paik S.-K., (2003). Analysis of the causes of bullwhip effect in a supply chain: A simulation approach, PhD Thesis, George Washington University, Washington, USA.

Pedrycz W., (1995). Fuzzy sets engineering, CRC Press, Florida 1995.

Reiner G., Fichtinger J., (2009).Demand forecasting for supply process in consideration of pricing and market information, International Journal of Production Economics, 118, pp.55-62.

Ross T. J., (2004). Fuzzy Logic with Engineering Applications, 2th Edt., Wiley.

Saeed K., (2008). Trend forecasting for stability in supply chains, Journal of Business Research, 61, pp.113-1124.

So K. C., Zheng X., (2003). Impact of supplier's lead time and forecast demand updating on retailer's order quantity variability in a two echelon supply chain, International Journal of Production Economics, 86, pp.169-179.

Sohn S. Y., Lim M., (2008). The effect of forecasting and information sharing in SCM for multi-generation products, International Journal of Operational Research, 186, pp.276-287.

Sterman, J. D., (1984). Instructions for running the beer distribution game, System Dynamics Group Working Paper D- 3679, MIT, Sloan School of Management, Cambridge, MA.

Sterman J. D., (1989a). Modeling managerial behavior: Misperception of feedback in a dynamic decision making experiment, Management Science, 35, pp.321-339.

Sterman J. D., (1989b). Deterministic chaos in an experimental economic system, Journal of Economic Behavior and Organization, 12, pp.1-28.

Sterman J. D., (1989c). Misperceptions of feed back in dynamic decision making, Organizational Behavior and Human Decision Making Processes, 43, pp.301-335.

Sterman J. D., (200). Business Dynamics: System thinking and modeling for a complex world", McGraw-Hill, New York, USA.

Strozzi F., Bosch J., Zaldivar J. M., (2007).Beer game order policy optimization under changing customer demand, Decision Support Systems, 42, pp.2153-2163.

Sucky E., (2009). The bullwhip effect in supply chains-An overestimated problem?, International Journal of Production Economics, 118, pp.311-322.

Tanaka H., Watada J., (1988). Possibilistic linear systems and their application to the linear regression model, Fuzzy Sets and Systems, 27, pp.275–289.

Tanaka K., (1997). An introduction to fuzzy logic for practical application, Springer, (1997).

Towill D. R., (1991).Supply chain dynamics, International Journal of Computer Integrated Manufacturing, 4, pp.197-208.

Towill D. R., (1992).Supply chain dynamics - the change engineering of challenge of the 1990s, Proceedings Institute of Mechanical Engineering Conference on Engineering Manufacture, 206, pp.233-245.

Towill D. R., (1993a). (System dynamics background, methodology and applications-Part1: Background and methodology, IEE Computing & Control Engineering Journal, 4, pp.201-208.

Towill D. R., (1993b). System dynamics background, methodology and applications-Part 2: Applications, IEE Computing & Control Engineering Journal, 4, pp.261-268.

Towill D. R, Lambrecht M., Disney S. M, Dejonckheere J., (2003). Explicit filters and supply chain design, Journal of Purchasing and Supply Management, 9, pp.73-81.

Wang, H. F., Tsaur R. H., (2000). Insight of a fuzzy regression model, Fuzzy Sets and Systems, 112, pp.355-369.

Wang J, Shu Y-F., (2005). Fuzzy decision modeling for supply chain management", Fuzzy Sets and Systems, 150, pp.107-217.

Wang J, Shu Y-F., (2007).A possibilistic decision model for new product supply chain design, European Journal of Operational Research, 177, pp.1044-1061.

Wikner J., Towill D. R., Naim M., (1991). Smoothing supply chain dynamics, International Journal of Production Economics, 22, pp.231-248.

Wright D., Yuan X., (2008).Mitigating the bullwhip effect by ordering policies and forecasting methods, International Journal of Production Economics, 113, pp.587-597.

Wu D. Y., Katok E., (2005) Learning, communication, and the bullwhip, Journal of Operations Management, 24, pp.839-850.

Yen J., Langri R., (1999). Fuzzy logic: Intelligence, control and information, Prentice Hall.

Zadeh L. A.: "Fuzzy sets", Information and Control, 8 (1965) 338-353.

Zarandi F. M. H., Pourakbar M., Tursen I. B., (2005). A fuzzy agent-based model for reduction of bullwhip effect in supply chains", Expert Systems with Applications, 34, pp.1680-1691.

Zhang X., (2004). The impact of forecasting methods on the bullwhip effect, International Journal of Production Economics, 88, pp.5-27.

Zhang X., (2005).Delayed demand information and dampened bullwhip effect, Operations Research Letters, 33, pp.289-294.

4

# Managing and Controlling Public Sector Supply Chains

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## 1. Introduction

Supply chain management (SCM) represents a significant change in the way that organisations view themselves and has witnessed values created through the integration and coordination of supply, demand and relationships in order to satisfy customers in an effective and profitable manner both in the private and public sectors. The concept has seen interest among organisations (Burges & Singh, 2006) including the public sector (Hendricks & Singhal, 2003; Gansler et al., 2004; OCG, 2005; 2006; Ambe, 2006; Matthee, 2006; Essig & Dorobek, 2006; Migiro & Ambe, 2008; Ambe, 2009). As a result, a number of studies on SCM have been undertaken in many different industries and sectors. However, majority of these related studies recognize that an effective SCM is a powerful tool to achieve cost advantage and a more profitable outcome for all parties within and beyond any organization (Zsidisin et al., 2000; Davis, 2008). It is for this reason that the concept has gained interest in the public sector in recent years (South Africa, 2005; Blanchard et al., 2008; Kumar, S. et al., 2008; Pan & Pokharel, 2007; Migiro & Ambe, 2008; Ambe, 2009). For example, countries such as the UK, US and Canada have for long employed SCM in the management of their procurement and logistics (OCG, 2005) as well as South Africa (Ambe, 2009) among others.

Despite the interest and employment of SCM in public institutions, Humphries and Wilding (2004) assert that much has not been done compared to the private sector. According to Korosec (2003), majority of SCM literature that does exist focuses primarily on private sector transactions or on international governments owing to the fact that SCM has been used in both of these arenas for almost two decades. Notwithstanding this, many professional government organizations have indicated that SCM could hold great promise in enhancing public procurement systems. However, Essig & Dorobek (2006:1) argue that the management of public supply chain raises various research questions that need to be answered. The chapter explore the concept of supply chain management in the public sector. The chapter utilises a case study of the SCM in the South African public sector to differentiate between public versus private sectors supply chains. It presents the critical components, features and importance of public sector supply chains. Furthermore, the chapter portray the need for supply chain improvement and the employment of performance measures in the public sector. A balanced scorecard as a supply chain performance indicator is suggested for application to the public sector supply chain. The chapter contributes to literature on the application of public sector supply chains.

## 2. Supply chain management in the public sector

Supply chain management (SCM) is a term used in business literature to refer to the control of materials, information, and finances as they move in a process from supplier to manufacturer to wholesaler to retailer to consumer. The term supply chain is inspired by the product flow that should be delivered to citizens or businesses by passes through several organizations. According to the Council of Supply Chain Management Professionals (CSCMP, 2007), "Supply chain management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. It also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers." In a functional sense, this focus on activities and relationships implies logistics, marketing, purchasing/supply, and production/operations are involved in SCM.

In essence, SCM integrates supply and demand management within and across organizations. A supply chain consists of all parties involved directly or indirectly in fulfilling a customer request. It includes all functions involved in receiving and filling a customer request. These functions include but are not limited to new product selection, procurement, marketing, operations, distribution, finance, and customer service. A supply chain, as opposed to supply chain management, is a set of organizations directly linked by one or more of the upstream and downstream flows of products, services, finances, and information from a source to a customer. Managing a supply chain is 'supply chain management' (Mentzer et al., 2001). Each stage in a supply chain is connected through the flow of products, information, and funds.

In the public sector, SCM is concerned with the "co-ordination of all parties involved in delivering the combination of inputs, outputs or outcomes that will meet a specified public sector requirement." These parties include external suppliers, partner organisations, and internal corporate service units both inside and outside the organisation. The supply chain may be inbound into the public sector. That is an operational requirement for internal customers for example, or it may be outbound from the public sector. That is in place to deliver wider organisational objectives to provide services for delivery to citizens, or a combination of both. Supply chains in the public sector addresses different focus areas. The focus of SCM can differ from government sector-to-sector and SCM can differ from industry sector-to-sector. An example of a government sector to sector focus area could be in the health sector, where the focus may be more on logistics and the effective movement of goods and services in and out of hospitals whereas SCM in the education sector may focus on streamlining the chain through which teaching materials are delivered to students. The shape of the supply chain and the supply chain management processes employed will vary considerably depending on a range of different considerations (OGC, 2005).

Public sector SCM offers a reference framework for the composition of public sector supply chains and multilevel networks (Migiro & Ambe, 2008). Actors in public sector supply chain comprise (1) private firms which receive orders from public sector agents, (2) accounting officers and (3) policy-makers. The SCM in the public sector not only concentrates on the question, which institutions cooperate in goods and services, but also how these enterprises are involved with enterprises operating at other levels. Thus, analyses of intra-network-relationships as well as analyses of inter-network-relationship are essentially necessary elements of the concept.

### 2.1 Importance of supply chain management in the public sector

Supply chains and their associated management processes often remain invisible to the public sector client. Government has traditionally focused on the contracting process with first tier suppliers, the supply chain members with whom the procuring organisation directly contracts. According to OGC, UK (2005), the 2004 Public accounts committee Report on 'Improving departments' capability to procure cost-effectively' highlighted that only 17% of departments, agencies and non departmental public bodies analyse their suppliers' supply chains as part of their criteria for selecting suppliers and thus suffer from a lack of assurances about the reliability and resilience of their key suppliers' subcontractors. In 2004, OGC undertook a survey of central civil government (CCG) departments and key suppliers to the public sector looking at activities and attitudes in relation to SCM. The findings reveals that 68% of respondents did not know how their main suppliers advertised opportunities to potential new entrants to the SC, while 36% of respondents sought feedback from main suppliers' subcontractors during contract delivery. In a survey conducted in the local government sector by IdeA in 2004 to evaluate progress against milestones for the National Procurement Strategy for Local Government in the UK, denoted that 41% of councils report that they invite bidders for partnership contracts to demonstrate their track record in achieving value for money through their use of the supply chain, including use of small firms and only 39% track suppliers' use of the supply chain in contract management.

In the 'A New World of Risk' by Zurich Municipal (2009), a survey conducted by the House of Commons Public Accounts Committee's 2009 report, on Central Government's Management of Service Contracts, indicated that the extent to which central government tests the value for money of ongoing services and contract changes is variable. 41% of contract managers do not test the value for money of new services purchased under an existing contract. Planning and governance is one of the weaker areas of contract management, and 30% of contracts where suppliers were dealing with personal or security information did not have a risk register. In the Republic of South Africa (RSA), report on Opportunities for Reform of Government Procurement and Joint Country Assessment Review (CPAR) conducted by the World Bank during 2001/2002 indicated that there were divergent interpretations of government's objectives and strategies. The difficulties highlighted was that, there were inadequate provisions to capacity building for disadvantaged enterprises to successfully compete for government contracts. Also, the preferential procurement policies were not clearly formulated and targets were not met. The performance of these initiatives did not take place in a holistic evaluation environment. Furthermore, the report revealed that the effective and efficient financial management within government was questionable (National Treasury, RSA, 2005).

Whilst it is relatively common, especially in complex procurements, for the first tier supplier(s) to manage the supply chain on behalf of the contracting authority, relatively little effort has been made by the public sector to improve its visibility of SCs and its ability to exert influence over how the first tier supplier(s) manages this chain, except perhaps in the construction industry. The limited effort in other industries to improve supply chain performance could be for reasons of simplicity, resource constraints, a lack of understanding or perceived need for understanding, or perhaps even a perception on the client side that the policy and legal framework does not allow for such activities. Increasingly, the complexity of many contracts, a greater appreciation of the need to improve competition and innovation, and an increasing awareness of the impacts of terrorism or natural disasters on SCs and business continuity, means that wider supply chain issues increasingly need to be taken into account in seeking improved efficiency and value for money. The supply chain is an area of strategic importance to an organisation due to the significant percentage of overall cost it accounts for. But is it strategic? In the commercial world companies seek to create competitive advantage, lowering their cost base to contribute to their bottom line, that is profit. In the public sector the cost advantage gained through the procurement function contributes to lower costs for the organisation, enabling funds to be diverted to frontline services such as hospitals and schools. This means better value for money for public sector shareholders that are taxpayers.

As noted by Ambe (2009), countries such as the UK, US and Canada have long employed SCM in the management of their procurement and logistics. Gansler et al. (2004: 4) acknowledge that the Department of Defence (DOD) in the US have minimised cost through lead time in the management of its logistics by employing SCM best practices. Also, the Office of Government of Commerce (OGC) in the UK releases year to year updates about best practices of SCM in the public sector. Luby [Consultant for Department of Defense Supply Centres and Defense Supply Chain Leader with IBM Consulting Services (2004)] noted that" the key to modernizing SCM in the private sector has been internal and external digital integration, including new linkages, procurement and finance operations. He however, suggested that governments can and must do more to adopt available and proven tools for implementing a modern supply chain. These include: instant worldwide communications; interoperable, flexible and secure information technology; remote diagnostics and automated decision-making aids and employ modern, high-speed transportation (Essig & Dorobek, 2006). Streamlining and modernising government supply chain can result in substantial cost savings as well deliver-time improvement (Gansler et al., 2004).

According to Essig & Dorobek (2006), the integration of SCM in the public sector is playing a critical role in optimising logistics support and improving the management of secondary inventory. All governments attempt to promote efficiency in the public sector. People want to see efficient financial management. One of the ways governments in several jurisdictions are attempting to significantly improve efficiency in the delivery of public-sector services is through the introduction of supply chain management (SCM) best practices. Citizens expect their public services to operate as an efficient, seamless and effective system. Governments, along with its partners, through SCM are trying to ensure this is happening. If vital amounts are spent needlessly on back-office processes, fewer amounts are left to be spent on classrooms, hospital wards and lecture halls. It makes sense, therefore, that if there are better ways for the public sector to plan, source, move and pay for goods and services, these should be examined and implemented.

There are a number of clear benefits to the public sector for effective management and controlling SCM. Some of the clear benefits include:

- **Better risk allocation.** Effective risk allocation is a critical consideration in procurement. Risk should always be allocated according to the party best placed to manage it, and a better understanding of the way in which the requirement can be delivered.
- **Greater visibility.** Visibility creates subcontracting opportunities for a diverse range of organisations that can bring increased competition, dynamism and particular skills or strengths to the public sector. This can increase competition and allow organisations with particular skills or strengths to get involved in the public sector marketplace.

- **Greater opportunities for innovation.** Supplier innovation in the SC can contribute to better quality, faster delivery and reduced whole life costs. Effective SCM offers strong potential for innovation to be released through the supply chain.
- **Better-defined requirements.** Early supply chain involvement shapes business need through market sounding.
- **Improved ability to identify risks or bottlenecks.** In contract delivery, greater authority creates awareness of exactly how the contract is going to be implemented and the key SC dependencies.
- **Better quality.** Solutions offered by suppliers as opportunities can be more easily identified in their supply chains to improve quality, increase delivery times and reduce costs.

More effective use of the supply chains contributes to the wider agenda of improving efficiency and value for money in the public sector's commercial activities, by promoting competition, not just at first tier supplier level, but across the wider supply base and also encouraging more efficient management of suppliers.

### 2.2 Need for controlling in public sector supply chains

There are enormous challenges in the application of SCM both in the private and the public sector management. Some of the challenges that need to be addressed for successful management of the public sector supply chains include: tension between citizen and customer requirements, cost pressure in public supply chains, and complexity of multidimensional supply chains as reasons for a need of controlling in public supply chains.

#### 2.2.1 Tension between citizen and customer requirements

In the private sector, SCM as a concept, points to increasing demands for customer proximity as a key objective to be achieved through controlling (Jehle et al., 2002). In the public sector, the need for controlling is derived from the complex relation between citizens' general demand for public goods and the individual citizen's willingness to pay for provision of good. Citizens have multiple differing interests – some of which are trading off one another. Citizens as taxpayers demand economic utilization of public resources (Brösel & Keuper, 2004). These reveal a serious tension between citizen and established SCM's assumptions. Due to non-conclusive exchange relationships, citizens become most frequently 'forced' customers. The central benefit of rewarding the entire network with a customer's positive purchase decision provided by SCM thus loses its effect in public supply chains. Citizen/Customers' demands are understood in term of a society's interest in public goods. However, due to the peculiarities of public goods and the resulting problems of collective action, it is difficult to assess citizen/customers' demands by their willingness to pay.

#### 2.2.2 Cost pressure in the supply chain

A major reason for controlling given by (private) SCM apart from the demand for ever increasing performance is the mounting pressure towards cost reduction. Well-devised controlling for the supply chain can yield both cost reduction and economization effects (Jehle et al., 2002]. Cost pressure in the public sector results from legal regulations prescribing economic utilization of resources. The frequent failure of administrative agencies to integrate single policies into coherent strategies instead of resorting to an indiscriminate distribution of means results in inefficiency and waste of resources

(Bergmann, 2004; Scherer & Alt, 2002). Taking the public sector perspectives into consideration, cost pressure in public supply chains are derives from legally prescribed economic utilization of resources on both network levels of political governance and public administration as well as from the pressure to reach 'competitive advantages' on the network level of private enterprises within public supply chains.

### 2.2.3 Complexity of multidimensional supply chains

As denoted by Essig & Dorobek (2006), SCM asserts an increasing need for controlling in private sector to counteract the rising complexity of goods and services. It is also use to accelerate dynamics and ambiguities that go along with it by improving transparency and manageability. In the public sector, the need from a lack of strategic considerations: a deficit in public agencies' consciousness for strategic implications of single decisions leads to spontaneous and unintentional creation of programs that take long-term effects by setting paths for future decisions. Public supply chains compared to private ones in addition consider the level of political governance as well as the level of public administration. This multidimensionality adds a further level of complexity to the already existing problems of coordination on the network level of private enterprises that correspond to those established by the private sector. Deficits in strategic considerateness on the level of political governance may produce sub-optimal and/or unintended outcomes on the administrative level. The administrative level in turn is directly affected by the increased complexity in the fabrication of goods and services and the resulting effects on the level of private enterprises – requiring for instance a high degree of technical expertise (Essig & Dorobek, 2006).

## 2.3 Features of public sector supply chains

Public sector SCM focuses on **network** of institutions, which are interlinked vertically, and horizontally to add value (Essig & Dorbek, 2006). Characteristically, SCM takes place in a multi-level-network context. Departing from established Private-SCM, this approach includes to its focus both the (network-) level of political governance and the (network-) level of public administration. Public sector SCM takes the distinction between supply chain efficiency and supply chain effectiveness. This distinction results from the assumption that public spending is subjected to criteria of efficiency. The concept of efficiency is a characteristic trait of public management. Public SCM supports this **target** by adding to reorganization and optimisation of entire public supply chains. Efficiency in the terms of public sector supply chains is targeted towards the demands of the end customer, the citizen.

Public sector SCM is considerably more complex. The public in accordance with methodological individualism citizens, to be 'customers' of the public supply chain network, a supply-chain-oriented approach to analysing **flows** of services, information and finance becomes possible. Customer demands are conceptualised as the publics, citizens', interest in public goods, for instance domestic order or national security (Budäus & Grüning, 1997). Essig & Dorobek (2006) noted that it is, however, difficult to calculate customers' demands through payment reserves due to the characteristic peculiarities of public goods. The demands, instead, are articulated according to the democratic principle through elected representatives (level of analysis: political network). Payment **flows** occur by way of taxes and duties. Thus delivered goods and services affect citizens' individual utility ratio, for instance by meeting their demand for peace. Which public goods and services a public supply chain delivers well depends on the citizens' aggregate payment reserves.

Furthermore, public sector supply chains' network-centered perspective requires an account of the **management** level that accomplishes inclusive coordination of public SCM. The government as head of the executive branch represents the political network level in an organizational sense on even same level; parliaments (legislative branch) provide checks and balances in terms of control and criticism of governmental activities. SCM takes the role of a strategic planner. This includes for instance the consideration of long-term effects (outcome of the multi-level network) and strategic objectives of public action and legislature (Thom & Ritz, 2000). Administrative agencies, representing the subordinate levels of the executive branch, are commissioned to implement the actions and legislature passed by the political network level. This administrative network level is responsible for outcomes that are within the limits of both the output demands and the budgetary restrictions imposed by the political network level (Thom & Ritz, 2000). Thus, the administrative level serves as intersection between the public sector and the network level of private enterprises. Due to social responsibility it is irrelevant whether implementation is reached through administrative action or commercial (private) suppliers' service. Table 1 summarises the features of public sector supply chains.

| Feature | Description of feature |
|---|---|
| Network | Network composes of institution (Both vertically and horizontally) |
| Target | Key target is to achieve efficiency and effectiveness in public management |
| Flows | Have complex flow of information, service and finance. |
| Management | Headed by government and guided by legislations, laws and regulations. |

Table 1. Important features of public sector supply chains

## 3. Case study: An examination of SCM in the South African public sector

### 3.1 Background

The South African public sector supply chain has undergone transformation through the introduction of procurement reforms. The procurement reforms started in 1995 and were directed at two broad focus areas, namely the promotion of principles of good governance and the introduction of a preference system to address socio-economic objectives. SCM is an integral part of prudent financial management in the South African public sector management. It introduces internationally accepted best practice principles, while at the same time addressing Government's preferential procurement policy objectives (OGC, 2005). SCM aims to add value at each stage of the process – from demand of goods or services to their acquisition, managing the logistics process and finally, after use, to their disposal. In doing so, it addresses deficiencies in current practice related to procurement, contract management, inventory and asset control and obsolescence planning. Therefore, the adopting SCM policy ensures uniformity in bid and contract documentation; and options as well as bid and procedure standards, among others, will promote standardisation of supply-chain management practices (National Treasury RSA, 2003; Mkhize, 2004).

### 3.2 Legislative framework governing SCM

The SCM process is guided by policies and legislations. Without a legislative framework, political representatives will not be able to make informed and intelligent decisions. The legislative requirement of the SCM warrants each department or entity to create a SCM unit and to implement supply chain management policy (SCMP) as stipulated by the SCM policy. Some of the legislative framework that guides the SCM policy includes: the Constitution; Public Finance Management Act (PFMA) (Act No. 1 of 1999); Local Government: Municipal Finance Management Act (MFMA); (Act No 56 of 2003); Preferential Procurement Policy Framework Act (PPPFA) (No. 5 of 2000); Policy to Guide Uniformity in Procurement Reform Processes In Government; Broad-Based Black Economic Empowerment Act (BBBEE) (Act 53 of 2003); Municipal Systems Act (MSA) (Act No32 of 2000); South Africa: Competition Law (Act No 89 of 1998); South Africa: National Small Business Act (Ac No 102 of 1996); Anti-Corruption Measures and Practices; South African Local Government Association (SALGA) etc (National Treasury RSA, 2005).

### 3.3 Key elements of SCM

The South African National Treasury provides guidelines for implementation of the SCM policy. The framework for the SCM system constitutes demand management, acquisition management, logistics management, disposal management, risk and performance management. The framework is guided by the preference point system to achieve re-distribution of wealth (ensuring equal opportunities). The components of the supply chain constitute the elements of the supply chain management systems. The supply chain is build upon ensuring value for money, open and effective competition, ethics and fair dealings; accountability and reporting; and equity. Ensuring these will achieve the ultimate goal of uniformity in procurement processes, good governance and economic development (NT, 2005). Elements of the SA government SCM and their activities are stated below:

- **Demand management:** The first element of SCM. Fulfil the needs identified during the strategic planning process; total needs assessment should be undertaken; Resources required must be analysed and assessed; Key elements in the demand management process should be considered; Brings the SCM practitioner closer to the end users; Bid specification committee; Procurement methods etc.
- **Acquisition management:** The management of procurement; Evaluate bids (comprise of bid committees; Consult register for defaulters; Range of procurement systems; Establishment of total cost of ownership of assets; Bid adjudication; Appointment of consultants etc.
- **Logistics management:** Strategically manage acquisition, movement and storage of materials; Cost fulfilment of orders; Ensure effective flow of goods, services and related information from the point of origin to the point of consumption etc.
- **Disposal management:** Management of assets that are no longer needed; Gives consideration to obsolescence planning; create a database of redundant materials; Inspect materials for re-use; Determine disposal strategy and methods of execution etc.
- **Risk management:** Management unintended or unexpected outcome of a decision; Make provision for identifying, consider and avoid risk as well as provision for adequate cover for residual risks etc.
- **Supply chain performance:** Monitor progress undertaken a retrospective analysis to determine whether the processes have been followed and if the desired objectives were achieved. Usage of the National Treasury template for measuring performance.

### 3.4 Role players

Based on the SCM policy, each government unit adopts the SCM policy to suit it needs. The structures for management of supply chain activities within the Country are unique. The document "SCM guide for Municipalities/Municipal Entities" prescribed the actors of SCM, their roles and duties (National Treasury RSA, 2005). The SCM policy requires the creation of bid committees. The various committees to be created include: the bid specification

| **Key role players** | **Functions** |
|---|---|
| National Treasury | Introduce and oversee the implementation of SCM; Develop treasury regulations; Issue guidelines, general conditions of contract and bid documents to Accounting Officer; Setting minimum reporting standards; Monitor policy outcomes. |
| Provincial Treasuries | Assist departments with the implementation of SCM; Support departments by providing advice and build capacity; Co-ordinate training in the province; Monitor policy outcomes. |
| Accounting Officer/Chief executive Officers | Establish a SCM unit under the direct supervision of the Chief Financial Officer; Compile and implement a SCM policy; Adhere to guidelines supporting documents for the implementation issued by the National Treasury; Develop internal procedures and processes; Ensure that officials are trained and adequately skilled; Report to National Treasury; Comply with ethical standards. |
| Chief Financial Officer/ SCM Units | Recruiting, selecting, developing and managing skills to build and maintain an effective SCMU; Training skills and resources to develop managers and supervisors to operate and manage varieties of SCM activities, facilities and networks. |

Table 2. Key role players of the SA government SCM and their functions

| **Bid committee** | **Constituent of the committee and functions** |
|---|---|
| Bid Specification Committee | May comprise one or more official, preferably manager responsible for function including external specialist advisors (cross functional principle); Accounting Officer or delegated official to appoint chair person<br>ROLES: Compile technical specifications; terms of reference; requirements; conditions of contract; evaluation criteria; determine goals; and indicate method of procurement. |
| Bid Evaluation Committee | Comprises of a SCM practitioner; technical expert from department requiring the good/service.<br>ROLES: Accounting officer must appoint the chair person and members; evaluate bids accordance with the criteria (PPPFA); Evaluate bidders tax matters; Submit a report for recommendation regarding the award; check list for restricted bidders; consult the register for tender defaulters. |
| Bid Adjudication Committee | Comprises of at least 4 senior managers which include: the CFO; at least one senior SCM practitioner to ensure compliance and a technical expert who is an official to ensure compliance to the specification.<br>ROLES: Accounting officer must appoint the chairperson and members; A member of the bid evaluation committee may presents its case to the bid adjudication committee; neither a member of or a person assisting the bid evaluation committee, nor any advisor may be a member of this committee |

Table 3. Bid committees, Constituent and roles.

committee, bid evaluation committee and the adjudication committee. The document "SCM guide for Municipalities/Municipal Entities" prescribed the actors of SCM, their roles and duties. Table 1 shows the actors of the government SCM, their roles and duties.

The SCM policy requires the creation of bid committees. The various committees to be created include: the bid specification committee, bid evaluation committee and the adjudication committee. Table 2 shows the bid committees, their constituent and roles

## 4. Differences between public and private sector supply chain

The literature suggests that public procurement professionals have different perspectives of SCM to their private sector counterparts (Larson, 2009). To be able to understand and make comparisons between public versus private sectors SCM, it is important to understand the concept of public procurement. Larson (2009) denoted that public procurement is very "big business." In public Works and government services, billions are spend on goods and services annually, to support the activities of agencies and departments. Public sector procurement forms the biggest national spend and in South Africa, it is decentralized within a strictly controlled legislative environment wherein processes are prescribed and the relevant norms and standards constantly monitored.

"In South Africa and the emerging world many practitioners still consider the terms to be interchangeable. However various academics and seasoned industry professionals have over the last twenty years succinctly distinguished between SCM and Procurement. Based on extensive consultation within Europe, America and Africa, the preferred view is one which provides a clear distinction between SCM and Procurement management. SCM involves the management of all the inter-linked activities within a value adding chain. These include, but are not limited to, Planning, Procurement, Manufacturing or Production Distribution and Customer Service. Also included are all the value adding linkages outside an organisation. "Procurement management, on the other hand, is one of the elements within a supply chain primarily focusing on the sourcing and purchasing of goods and services within the supply value chain" (Boateng, 2008). In line with the views of the Chartered Institute of Purchasing and Supply (CIPS) and Council of Supply Chain Management Professionals (CSCMP), procurement can be described as one of the macro processes within a supply chain. It is the activity to plan, implement and control the sourcing and purchasing of tangible or intangible goods.

McCue & Pitzer (2005) stated that, public and private procurement professions "are essentially different in their fundamental goals and practices." While public sector practitioners are governed by legislative bodies, laws, and regulations; private sector practitioners are guided by boards of directors and business plans. Public agencies draw revenues from taxes and fees, and use these funds to serve the public. On the other hand, private firms generate revenue through sales of goods and services. Unlike their public sector counterparts, these private firms have profit-making motives. McCue & Pitzer (2005) also suggest that private sector purchasing has been redefined in terms of strategic SCM. However, constrained by rules and regulations, the public sector remains unable to develop strategic supply chain partnerships. In South African public sector, the head of SCM unit is the National Treasury. The National Treasury (NT) develops laws, policies and regulations governing SCM implementation.

Leenders, Fearon, Flynn, & Johnson (2002) describe a number of unique characteristics of public sector purchasing, including the following: (1) perceived lack of interest expenses and other inventory carrying costs, (2) lack of traffic and transportation expertise, (3) lack of confidentiality about dealings with suppliers, and (4) emphasis on competitive bidding (vs. negotiation) in the procurement process. These characteristics have implications for public sector procurement and SCM and a lack of collaborative, long-term relationships with suppliers. SCM occupies a centre stage in the financial management reform process in the public sector in South Africa. SCM aims to add value at each stage of the process from demand of goods or services to their acquisition, managing the logistics process and finally, after use, to their disposal. However, studies reveals that the implementation of supply chain management practices is far from satisfactory (Mathee, 2005; Ambe, 2006; van Zyl, 2006; Migiro & Ambe, 2008). This is as result of lack of personnel with the necessary knowledge, skills and capacity to effectively implement supply chain management as required by the SCM policy in various departments and municipal entities.

In the public sector context, Korosec (2003) states "SCM is a procurement tool that, strategically integrates the whole procurement process." Thus, SCM is thought to be narrow in a functional sense, an element of procurement rather than spanning multiple functional areas. To the contrary, in the private sector context, Mason-Jones (2004) argues that "procurement is a crucial central element of SCM" and SCM covers "all functions throughout organisations, from marketing and production to procurement." Similarly, Lambert (2004) describes SCM as the integration of eight business processes: (1) customer relationship management, (2) customer service management, (3) demand management, (4) order fulfillment, (5) manufacturing flow management, (6) supplier relationship management, (7) product development and commercialization, and (8) returns management. These eight processes subsume much of logistics, purchasing, operations management and marketing. According to Mentzer et al. (2001), SCM consists of "all the traditional intra-business functions." These traditional business functions are marketing, sales, research and development, forecasting, production, purchasing, logistics, information systems, finance and customer service. South African public sector addresses six key elements constitutes demand management, acquisition management, logistics management, disposal management, risk and performance management. Proper implementation of these elements ensure value for money, open and effective competition, ethics and fair dealings; accountability and reporting; and equity, thus creating uniformity in procurement practices, good governance and to enhance economic development.

Newman (2003) noted that, while private sector procurement is more receptive to entrepreneurship and innovation; public procurement is based on legislation, policy and process. Public sector procurement serves a broader range of stakeholders, places greater emphasis on accountability and transparency, and allows little or no flexibility for negotiating with bidders/responders to a request for proposal (RFP). McGuinness and Bauld (2004) concur that "the skill set of the public sector purchasing manager is geared more toward supervising the procurement process and preparing reports than negotiating the best deal." However, they suggest flexibility rather than formality is the key to improving public procurement performance. The South African National Treasury provides guidelines for implementation of the SCM policy. Accounting Officers in municipal entities and departments have to ensure compliance of the SCM process and reports to the treasury.

According to Gragan (2005), the public procurement task is "to help user agencies obtain the goods and services needed to do their jobs, while controlling the process that spends large amounts of public funds." Although public sector procurement operates in a rulebound environment, many of its tasks can be automated. Gragan advises public procurement professionals to promote communication with vendors and users, and to explain the strategic role of purchasing in public sector operations to their requisitioners or users, in particular. He also argues that "training should be mandatory for anyone charged with spending public funds." Public procurement has a reputation of being tactical, even clerical; adhering to "stringent policies and guidelines;" not requiring highly educated professionals; and stifling innovation (Matthews, 2005). However, public sector procurement is shifting from tactical to more strategic-and a focus on alliances, global sourcing, life cycle costing, empowerment, and tools such as procurement cards. According to Baily, Farmer, Jessop, & Jones (2005), "professional training and education of those personnel responsible for the strategic direction and practical application of procurement action" is needed in the public sector. In South Africa, training has been ongoing from 2005 on the implementation of SCM involving actors such municipal entities, departments and stakeholders. Several initiatives are being considered by the government to dramatically increase efficiencies and service delivery country wide. Among these include rolling out strategic sourcing objectives and transversal contracts.

Based on the review indicated above, it is evident that there is a difference in the application of SCM in the public and private sectors. This is because the two sectors have diverse goals and objectives. While the key goal in the public sector is delivering value service to the public, the private sector goal is to maximize value and profitability in its supply chain. Table 2 shows the difference in practices between private and public sectors supply chain management.

| **Feature** | **Private sector SCM** | **Public sector SCM** |
|---|---|---|
| Goal | Profit making from customers | Quality service delivery to citizens |
| View of SCM | Procurement is viewed as an element of SCM | SCM is viewed as a procurement tool |
| Sources of revenue | Sales of goods and services | Taxes and fees |
| Governance | Guided by board of directors and business plans | Legislative bodies, laws and regulations |
| Skills | Have highly skilled actors | Have less skilled actors |
| Receptiveness | Emphasis on innovation and entrepreneurship | Emphasis on accountability and transparency |
| Organisational structures | Firms of many sizes with room for new entrants (less complex) | Highly complex system of organizations with various tasks |
| Competencies | Very high | Low |
| Confidentiality | Very high | Low |
| Degree of collaboration | Very high | Low |
| Degree of integration | Very high | Low |
| Strategic partnership | High level | Low |
| Degree of implementation | High | Low |
| Technological application | High application | Low application |

Table 4. Public versus private sector supply chains

The major difference between the public and private sector SCM is their main goals. The private sector is profit oriented while the public sector is oriented toward quality service delivery. Furthermore, the enablers of SCM (which include integration, collaboration, coordination and information systems) are applicable both to the private and public sectors. However, the rate of application in the public sector is limited due to complex rules and procedures. Despite the comprehensive legislation and measures implemented by the public sector, there are always challenges to manage the risks of fraud and corruption in the supply chain. Incidence of financial mismanagement which includes the SCM process remains prevalent in the public sector. Therefore, a system of continuously monitoring and improvement of the supply chain is critical for the success of the public sector.

## 5. Public sector supply chain performance

The public sector is under pressure from both internal and external sources to demonstrate improvements in their performance (McAdam et al. 2005). Local/municipal entities and other government departments are taking an interest in supply chain performance measures and reporting for improving performance and increasing accountability (Barry 2000; Berman & Wang 2000). Public sectors need to review the way they plan, prepare budgets, implement and manage programs and deliver services to meet the government's and citizens' demands for improved performance and accountability. Countries such as Australia, Britain, South Africa and New Zealand have instituted public sector reform to improve their performance and consequently many organisations are going through the process of change management (Boyne 2003).

As part of overall management strategy, the managers of public organisations need to measure performance to evaluate whether departments are performing as expected, to ensure that the employees are doing the right things, to motivate line staff / middle managers and the stakeholders to do the things necessary to improve performance, to determine the budgeting priorities such as on which programs the agency should be spending the public's money, to convince legislators / stakeholders that the agency is doing a good job, to learn whether the activities are working, and determine exactly who should do what to improve performance (Behn 2003). There is growing recognition that using performance measures to gauge success is vital to any organisation, in the private or public or non-profit sectors (Niven 2005). Measuring performance, however, has been a challenge for both managers and researchers (Maltz et al. 2003) as the process of 'designing and implementing an effective performance management system' involves 'addressing a number of methodological issues' and managing the change process (Poister 2003). In spite of having workable performance management systems in place in public organisations, 'many of those systems fall apart' before they are complete and also there are others who 'end up installing a system that is not helpful or is simply not used effectively' (Poister 2003).

There are different types of performance measurement systems that can be applicable to public sector supply chains. Some of the common performance measurements methods include the balanced scorecard, SCOR model and benchmarking (Handfield et al., 2009). The Balanced Scorecard (BSC) approach to performance measurement was developed by Kaplan and Norton (1992-1996) as a way to align organisational performance measures with its strategic plans and goals (Fawcett et al., 2007; 2007; Wisner et al., 2008). The SCOR model is used as a SCM diagnostic, benchmarking and process improvement tool by manufacturing and service firms in a variety of industries around the globe (Wisner et al., 2008).

Benchmarking is a popular tool which is used universally to improve organisational performance and competitiveness (Wong & Wong, 2008).

### 5.1 Development of a balanced scorecard for the public sector

The balanced scorecard (BSC) was originally developed for the private sector as a means of clarifying and updating strategy, communicating strategy in the company, aligning unit and individual goals to strategy, linking objectives to long term targets and budgets, and conducting performance reviews to improve strategy (Kaplan & Norton 2001a); and it is now also being used as 'a powerful tool for rapid and effective strategy implementation' (Kaplan & Norton 2005). However, in the last decade, the balanced scorecard's multidimensional focus has also been viewed as a way of addressing the need for a strategic performance measurement system within public sector organisations (Umashev & Willett 2008). Performance measurement in the public sector has traditionally focused on financial measures such as revenues and cash flows. However, the accounting or financial indicators which are readily available in most public sector organisations reflect what has happened in the organisation but do not indicate the underlying drivers of either satisfactory or unsatisfactory performance (Niven 2005; Davig et al. 2004).

Unlike the private sector, where financial measures are used such as return on assets (profitability), return on shareholder's equity, and growth, in the public sector, it is more relevant to focus on efficiency of launching the programs and making best use of resources. However, the task of determining the measures, targets and collecting the relevant information for non-financial measures is not easy. Balanced scorecard research in the public sector has been conducted within the context of the healthcare industry (Coop 2006, Yang et al. 2005), public service organisations (including local government institutions and 'municipalities') (Umashev & Willett 2008; Farneti & Guthrie 2008), and not-for profit SMEs (Manville 2007). Gumbus et al. (2003) reported a successful story of BSC application in a hospital. Likewise, the study of Askim (2004) reported how local government institutions can become active learners by adopting a performance management reform system like the BSC.

### 5.2 Components of balanced scorecard in the public sector

The components of the BSC in the public sector may include the citizen who acts as the customer, finance or resources, internal processes and learning and innovative perspectives as explain below.

#### 5.2.1 The citizen's perspective

In this perspective, public supply chain serves to the public with the ultimate goal to satisfy citizen demand. Delivering services to citizens are primarily the responsibility of State and Local Governments. For example the South African public sector provides a range of services to the citizens through the Minister responsible for the function. Departments also have a legal requirements which set up 'citizen's relationships', especially with authorities such as the Auditor General and to the Parliament in respect of 'governance'. Therefore, the public sector provides services direct to the public, they are required to prepare and implement a service charter, providing a clear 'citizen relationship'. Thus three types of 'citizens' may arise when addressing the need of the public sector. This include: for most departmental activities, the Minister, and through him/her, the Government; in respect of governance, the Auditor General and Parliament, as well as the Minister; and for service delivery activities, the corporate or individual service recipients.

#### 5.2.2 Finance/resources perspective

Financial results are among the top three indicators to achieve organisation's success. Financial management in the public sector differs dramatically from the private sector context in that the revenue side of the budget is a given, and the focus is simply on effective and efficient management of expenditure. The quantum of funds made available to a Minister to implement Government programs is the end result of a complex interplay of macro-economic deliberations, ministerial bargaining and political judgement. Issues regarding what can be delivered (in terms of quality and quantity) for the proposed funds are significant inputs. But such relationships are largely approximations. Lack of skilled management (for example as a result of high turnover or overwork) can result in errors in estimating required workload. For example, when a Government has determined its policy, the bureaucracy has only minor leeway in changing the quantum or time schedule of the service. In addition, a variety of unplanned business pressures inevitably impact on planned business. Unforeseen events such as fraud within the Department, a by-election in a sensitive electorate, or a major controversy relating to the Minister's policy responsibility inevitably generate workload which is expected to be 'absorbed'. The resource management task is to deliver the planned outputs within budget.

#### 5.2.3 Internal processes perspective

The core processes in the public sector are essentially the same as for the private sector. These are to: establish direction; acquire resources; provide capability; and execute the mission. Whilst Governments establishes the policy and program outcomes that are to be achieved in exchange for the financial resources, management translates the vision and allocates the capabilities to achieve the delivery of agreed outputs. The resource management framework provides a backdrop for an integrated planning process that links corporate plans, business plans and individual plans. This planning process focuses on achieving results through the delivery of outputs as the agency, the business unit and the individual's performance is linked to the outputs which in turn are linked to the outcomes that the public sector desires for the community.

#### 5.2.4 Innovation and learning perspective

In an increasingly competitive global environment, the public sector's vision for the public service should have good leadership capabilities at all levels. In order to maintain performance in the public supply chain management, it is necessary to have access to a sufficient stock of well-trained personnel. Recruitment standards should be set high. Furthermore, staff should receive support to upgrade qualifications. Middle and senior management training should be of a high priority. At the same time, work pressure on all staff, and unpaid overtime should be minimised. Figure 1 shows an illustration of a balanced scorecard in the public sector.

## 6. Conclusion

The chapter examined the concept of SCM in the public sector. In the course of the chapter, the features, practices as well as the measures to improve the management of public sector supply chains were explored. SCM allows organisations to reduce costs, improve quality,

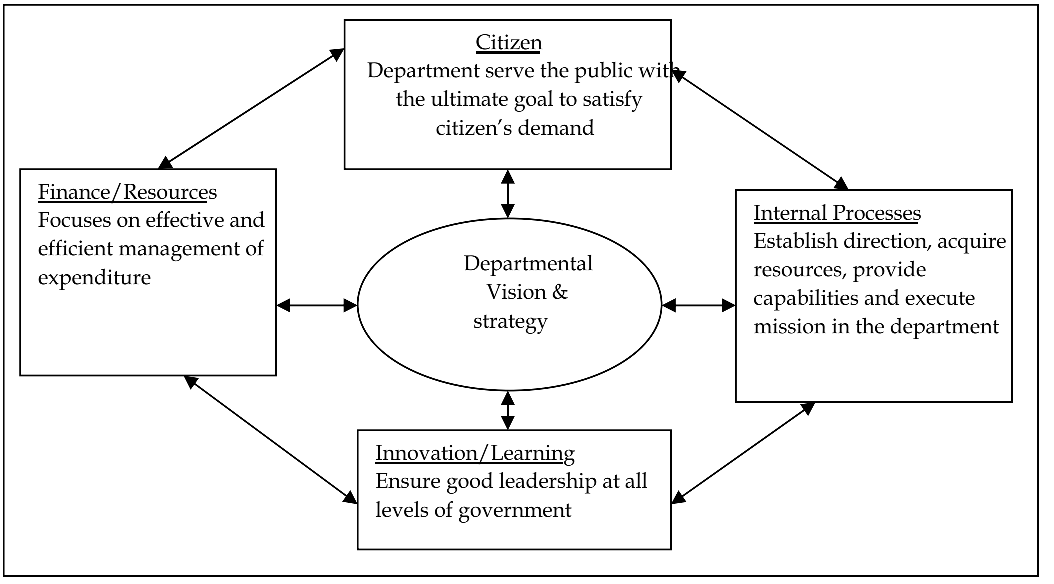


Fig. 1. Public sector supply chain scorecard

reduce lead-times, and improve organisational effectiveness. The chapter reveals that, there are major differences about supply chain practices in the private and public sectors. In the private sector, the focus of SCM is profit oriented whilst minimising production costs. In the public sector, SCM is used as an instrument to enhance quality service delivery to citizens. However, both sectors can utilise SCM enablers such as integration, collaboration, coordination and information systems to drive and enhance the practice in their respective sectors. But, the level of application of these enablers in the public sector is inhibited compared to the private sector because the sector is governed by legislative bodies, laws and regulations as well as lack of personnel with appropriate knowledge and skills.

That notwithstanding, supply chain managers in the public sector need to measure their performance to evaluate if they are performing as expected. The balanced scorecard is one of the measures that could improve the performance of public sector supply chains. SCM processes may fail if control is retained by one department in the supply chain, or if strategic fit is lacking, or if there is a lack of willingness to cooperate for the benefit of all. Therefore, understanding and managing supply chain issues such as risks, implementing longer-term commitments and developing a professionally trained procurement team, senior management can achieve commercial and operational success in the public sector.

## 7. References

Ambe, I.M. (2009). An exploration of supply chain management practices in the central district municipality; *Educational Research and Review,* (September, 2009), Vol. 4 (9), pp. 427-435, Ambe, I.M. (2006). 'Supply chain management implementation in the Central District Municipality and its affiliated municipalities', Master Thesis, Department of management, North West University.

Askim, J. (2004). Performance management and organisational intelligence: Adapting the balanced scorecard in Larvik Municipality, *International Public Management journal*, Vol. 7, No.3, pp.415-438.

Barry, M.A. (2000). How can performance standards enhance accountability for public health? *Journal of Public Health Management Practice*, Vol. 6, no. 5, pp. 78-84.

Bechtel, C. & Jajaram, J. (1997). Supply Chain Management: A Strategic Perspective. *International Journal of Logistics Management*, Vol 8, No 1, pp.15-34.

Behn, R.D. (2003). Why measure performance? Different purposes require different measures, *Public Administration Review*, Vol. 63, No.5, pp.586-606.

Berman, E. & Wang, X. (2000). Performance measurement in US counties: capacity for reform, *Public Administration Review*, Vol. 60, No. 5, (Sep/Oct, 2000), pp. 409-420.

Blanchard, C., Comm, C.L. & Mathaisel, D.F.X. (2008). "Adding value to service providers: benchmarking Wal-Mart", *Benchmarking: An International Journal*, Vol. 15 No. 2, pp.166-77.

Boateng, D. (2008). Government service delivery lies in supply chain management, not centralised procurement, *Smart Procurement,* 2008.

Boyne, G.A. (2003). What is public service improvement? *Public Administration*, Vol. 81, No. 2, pp. 211-228.

Brösel, G.& Keuper, F. (2004). Einsatz der Balanced Scorecard im öffentlich-rechtlichen Rundfunk, *Controlling & Management*, Vol 48, No 5, pp.326-334.

Budäus, D. & Grüning, G. (1997). Public Private Partnership - Konzeption und Probleme eines Instruments zur Verwaltungsreform aus Sicht der Public Choice Theorie. Public Private

Partnership: Neue Formen öffentlicher Aufgabenerfüllung. Budäus D.; Eichhorn, P. Baden Baden, 25-66.

Council of Supply Chain Management Professionals (2007). Supply Chain Management and Logistics Management Definitions. [Online]. Available at http://cscmp.org. [Retrieved August 16, 2007]

Davis, P.R. (2008). "A relationship approach to construction supply chains", *Industrial Management & Data Systems*, Vol. 108 No. 3, pp. 310-27.

Davis, S. & Albright, T. (2004). An investigation of the effect of balanced scorecard implementation of financial performance, *Management Accounting Research*, Vol. 15, No. 2, pp. 135-53.

Essig, M. & Dorobek, S. (2006). 'Adapting the Balanced Scorecard to Public Supply Chain Management'. *Working Paper for the 15th Annual IPSERA Conference*, San Diego, CA.

Farneti, F. & Guthrie, J. (2008). Italian and Australian local governments: balanced scorecard practices:. A research note, *Journal of HRCA: Human Resource Costing & Accounting,* Vol. 12, Iss.1; pp. 4-13.

Gansler, C. Luby, R.E.Jr.& Kornberg, B. (2004). 'Supply Chain Management in Government and Business', in Transforming Government in Gansler J, and Luby, JR. The IBM Centre for the Business for Government Series.

Gragan, D. P. (2005). "Harnessing Procurement Transformation in the Public Sector." *Government Procurement*, 13 (1): 18-19.

Grünenfelder, P. (1997). Die Rolle der politischen Führung im New Public Management, Bern.

Thom, N. & Ritz, A. (2000). Public Management: Innovative Konzepte zur Führung im öffentlichen Sektor, Wiesbaden 2000.

Gumbus, A., Bellhouse, D.E. & Lyons, B. (2003). A three journey to organisational and financial health using the balanced scorecard: a case study at a Yale New Haven Health System Hospital, *The Journal of Business and economic Studies*, Vol. 9, No. 2, pp.54-64.

Handfield, R.B., Monczka, R.M, Giuinipero, L.C. & Patterson, J.L. (2009). *Sourcing and Supply Chain management*, 4th edition. Ontario: Southern Western.

Hugo, W.M.J, Badenhorst-Weiss, J.A. & Van Rooyen, D.C. (2002). *Purchasing and supply management*, 3rd edition. Pretoria: Van Schaik.

Jehle, E.; Stüllenberg, F.; Schulze, A. (2002). Netzwerk-Balanced Scorecard als Instrument des Supply Chain Controlling, Supply Chain Management, IV, 19-25.

Kaplan, R.S. & Norton, D.P. (2001). *The Balanced Scorecard: Translating strategy into Action*, Harvard Business School Press, Boston, MA.

Kaplan, R.S.& Norton, D P. (2005). The office of strategy management, *Strategic Finance*, Vol. 87, No. 4, pp.8,10,59-60.

Korosec, R.L. (2003). "Assessing the Feasibility of Supply Chain Management within Purchasing and Procurement." Public Performance & Management Review, Vol 27, No 2, pp. 92-109.

Kumar, S., DeGroot, R.A. and Choe, D. (2008). "Rx for smart hospital purchasing decisions: the impact of package design within US hospital supply chain", International Journal of Physical Distribution & Logistics Management, Vol. 38 No. 8, pp.601-15.

Lambert, D. M. (2004). "The Eight Essential Supply Chain Management Processes." Supply Chain Management Review, Vol 8, No 6, pp.18-26.

Larson, P.D. (2009). Public vs. Private sector perspectives on supply chain management". Journal of Public Procurement. FindArticles.com. 30 Jul, 2010.
http://findarticles.com/p/articles/mi_7625/is_200905/ai_n54367357/.

Leenders, M. R., Fearon, H. E., Flynn, A. E., & Johnson, P. F. (2002). *Purchasing and Supply Management* (12th ed.). Boston, MA: McGraw-Hill Irwin.

Maltz, A.C., Shenhar, A.J. & Reilly, R.R. (2003). Beyond the balanced scorecard: Refining the search for organisational success measures, *Long Range Planning*, Vol. 36, No. 2, pp.187-204.

Manville, G. (2007). Implementing a balanced scorecard framework in a not for profit SME, *International Journal of Productivity and Performance Management. Bradford,*. Vol. 56, No. 2; pp. 162-169.

Mason-Jones, R. (2004). "Procurement's Place in the Chain." Supply Management, Vol 9, No 15, pp.30-31.

Matthews, D. (2005). "Strategic Procurement in the Public Sector: A Mask for Financial and Administrative Policy." Journal of Public Procurement, Vol 5, No 3, pp.388-399.

Matthee, C.A. (2005). 'The potential of internal audit to enhance supply chain management outcomes', Master's Thesis, University of Stellenbosch.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D., & Zacharia, Z. G. (2001). "Defining Supply Chain Management." *Journal of Business Logistics*, Vol 22, No 2, pp.1-25.

McAdam, R., Hazlett, S.A. & Casey, C. (2005). Performance management in the UK public sector: Addressing multiple stakeholder complexity, *The International Journal of Public Sector Management*, Vol. 18, No.3, pp. 256-273.

McGuinness, K. & Bauld, S. (2004). "Is Negotiation Underutilized in Public Procurement?" Summit: Canada's Magazine on Public Sector Purchasing, Vol 7, No 3,p. 28.

Migiro S .O. & Ambe I. M. (2008). Evaluation of the implementation of public sector supply chain management and challenges: A case study of the central district municipality, North west province, South Africa; *African Journal of Business Management*, (December 2008), Vol.2 (12), pp. 230-242.

Mkhize, Z. (2004). 'Supply Chain Management Conference: Transforming Government Procurement System', Durban, Republic of South Africa: 22 – 23 November.

McCue, C. & Pitzer, J. T. (2005). Fundamentals of Leadership and Management in Public Procurement. Herndon, VA: National Institute of Governmental Purchasing.

National Treasury. (2003). Policy Strategy to guide uniformity in Procurement reforms processes in government, Republic of South Africa.

National Treasury. (2005). Supply Chain Management: A guide for accounting officers and municipal entities, Republic of South Africa.

Newman, D. (2003). "Comparing Public- and Private-Sector Procurement." Summit: Canada's Magazine on Public Sector Purchasing, Vol 6, No 2, pp.10-11.

Niven, P.R. (2005), Driving focus and alignment with the balanced scorecard, *The Journal for Quality and Participation*, Vol. 28, No. 4, pp. 21-25.

Office of Government of Commerce. (OGC) (2005). 'Supply Chain Management in Public Sector Procurement': A Guide Version: Final Version 6th June, 2005.

Pan, T.Z.X. & Pokharel, S. (2007). "Logistics in hospitals: a case study of some Singapore hospitals", Leadership in Health Services, Vol. 20 No. 3, pp. 195-207.

Poister, T.H. (2003), *Measuring performance in public and nonprofit organisations*, Jossey-Bass: San Francisco, A Wiley Imprint.

Umashev, C. & Willett, R. (2008), Challenges to Implementing Strategic Performance Measurement Systems in Multi-Objective Organizations: The Case of a Large Local Government Authority, *Abacus,* Vol 44, No.4, pp.377-398.

Van Zyl D.C (2006). Strategic supply chain management by Matatiele Municipality, Master's Thesis, University of Stellenbosch.

Wisner, J.D; Tan, K-C. & Leong, G.K. (2008). *Principles of supply chain management: A balanced Approach*. Mason, Ohio: South-Western Cengage learning.

Wong, W.P. & Wong, K.Y. (2008). A review on benchmarking of supply chain performance measures. *Benchmarking: An international journal*, Vol.15 No.1, 2008 pp.25-51.

Zsidisin, G.A., Jun, M. & Adams, L.L. (2000). "The relationship between information technology and service quality in dual-direction supply chain", *International Journal of Service Industry Management*, Vol. 11 No. 4, pp. 312-28.

Zurich Municipal. (2009). Public sector supply chain: risks, myths and opportunities, A New World of Risk.

# 5

# Supply Chain Management Based on Modeling & Simulation: State of the Art and Application Examples in Inventory and Warehouse Management

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## 1. Introduction

The business globalization has transformed the modern companies from independent entities to extended enterprises that strongly cooperate with all supply chain actors. Nowadays supply chains involve multiple actors, multiple flows of items, information and finances. Each supply chain node has its own customers, suppliers and inventory management strategies, demand arrival process and demand forecast methods, items mixture and dedicated internal resources. In this context, each supply chain manager aims to reach the key objective of an efficient supply chain: 'the right quantity at the right time and in the right place'.

To this end, each supply chain node (suppliers, manufacturers, distribution centers, warehouses, stores, etc.) carries out various processes and activities for guarantying goods and services to final customers. The competitiveness of each supply chain actor depends by its capability to activate and manage change processes, in correspondence of optimistic and pessimistic scenarios, to quickly capitalize the chances given by market. Such capability is a critical issue for improving the performance of the 'extended enterprise' and it must take into account the complex interactions among the various supply chain nodes. The evaluation of correct trades-offs between conflicting factors, such as inventory reduction and fill rates, customers' satisfaction and transportation cost, sales loss and inventory costs, resources management and internal costs, are (among others) the most important tasks of a competent supply chain manager.

Therefore, supply chains have to be regarded as complex systems; a wide range of factors usually affects the behaviour of complex systems. The ways in which such factors interact and the stochastic nature of their evolution over the time increase the complexity of many real-world supply chains up to critical levels, where the use of ad-hoc methodologies, techniques, applications and tools is the only way to tackle problems and succeed in identifying proper and optimal solutions (Castilla and Longo, 2010).

To this end, Modelling & Simulation (M&S) has been widely recognised as the best and most suitable methodology for investigation and problem-solving in real-world complex systems in order to choose correctly, understand why, explore possibilities, diagnose problems, find optimal solutions, train personnel and managers, and transfer R&D results to real systems (Banks, 1998). In addition, M&S, regardless of the application domain, usually provides innovative solutions and new user-friendly tools, with special attention to integration into business processes and management. The identification of proper and optimal solutions in complex real-world systems often requires the solution of multi-objective problems involving multiple stochastic variables. As stated in Chen (2003), real world optimisation problems involve contrasting and competing objectives and require the definition of multiple performance measures. In such a context, where the whole is greater than the sum of parts, successful approaches require something more than simple mathematical or stochastic models. M&S capabilities to recreate (with high level of accuracy) the intrinsic complexity of real-world systems allows to find out and test alternative solutions under multiple constraints and to monitor, at the same time, multiple performance measures.
In this chapter the use of M&S as enabling technology is investigated, highlighting the contribution of this approach in supply chain management (with a specific focus on supply chain inventory and warehouse management). The objective of this chapter is twofold:

- provide the reader with a survey of most recent research works including theories and M&S based methodologies for supply chain inventory and warehouse management;
- propose two application examples (based on real case studies) that respectively consider the supply chain inventory management and the supply chain warehouse management. The application examples deal with advanced modeling approaches and simulation models for investigating the inventory management problem along the supply chain and warehouse management problem within a single supply chain node. In both the application examples, the simulators are decision-making tools capable of analyzing different scenarios by using approaches based on multiple performance measures and user-defined set of input parameters. The first application example considers the entire supply chain and it is mainly devoted to investigate the behaviour (in terms technical efficiency, i.e. fill rates, on hand inventory, etc.) of different inventory control policies. The second application example deals with a single supply chain node (a distribution center) and considers the effect of resources management on internal logistic costs.

Before getting in the details of the study, in the sequel a brief summary of the chapter is reported. Section 2 structures the state of the art on the most relevant articles in the field of supply chain inventory and warehouse management (also highlighting critical issues in supply chain Modeling & Simulation). The remainder of the chapter is structured in two different parts. Sections 3 and 4 propose the first application example: a supply chain conceptual and four different inventory control policies are presented and discussed; the supply chain conceptual model is then translated into a computerized simulation model (by using an advanced modelling approach) and the inventory management problem along the supply chain is investigated. Sections 5 deals with the second application example: a simulation model is presented and used for investigating interactions among operational strategies, available resources and internal logistics costs in a real warehouse. Finally section 6 summarizes conclusions and lessons learned.

## 2. Supply Chains: a state of the art overview on inventory and warehouse management

A Supply Chain is a network of different entities or nodes (suppliers, manufacturers, distribution centers, warehouses, stores, etc.) that provide materials, transform them in intermediate or finished products and deliver them to customers to satisfy market requests. Among others two main factors characterize a supply chain node: the demand and the productive capacity. The definition of these parameters usually requires a huge effort in terms of data collection. In effect, the information management related to demand and productive capacity is a very complex task characterised by a great number of critical issues: market needs (volumes and production ranges), industrial processes (machines downtimes, transportation modes) and supplies (parts quality, delivery schedules). The market demand and the productive capacity also generate a flow of items and finances towards and from the supply chain nodes. Needless to say, the supply chain management takes care of the above-mentioned issues, studying and optimising the flow of materials, information and finances along the entire supply chain. The main goal of a supply chain manager is to guarantee the correct flows of goods and information throughout the supply chain nodes for assuring the right goods in the right place and at the right time.

Among others, the inventory management problem along the supply chain plays a critical role because it strongly affects the supply chain performances. Lee and Billington (1993) consider the inventory control as the only tool to protect supply chain stability and robustness. Longo and Ören (2008) also assert that an efficient inventory management along the supply chain positively affects the supply chain resilience. In effect, the objective of the supply chain inventory management is to satisfy the ultimate customer's demand increasing the quality and service level and decreasing at the same time total costs. Inventories affect supply chain costs and performances in terms of:

- values tied up, e.g., raw materials have a lower value than finished products;
- degrees of flexibility, e.g., raw materials have higher flexibility than the finished products because they can be easily adopted for different production processes;
- levels of responsiveness, e.g., products delivery could be made without strict lead times whereas raw materials transformation usually requires stringent lead times.

However, the inventory problem is not the only critical issue affecting the supply chain performances. In effect, the internal logistics management within each supply chain node (i.e. warehouse management in a distribution center) similarly affects supply chain performances. The correct organisation of all the logistic processes and activities that take place within a supply chain node (i.e., capability of using material-handling systems efficiently, time windows planning for suppliers/retailers unloading/loading operations, etc.) could have a remarkable impact on both processes upstream and downstream the supply chain and on supply chain node internal costs.

This section surveys the most relevant articles both in the field of supply chain inventory management and in the field of internal logistics management (with a specific focus on warehouse management). Section 2.1 and section 2.2 are respectively dedicated to the inventory management problem along the supply chain and to the internal logistics management. In addition, section 2.3 discusses some critical issues in supply chain Modeling & Simulation.

### 2.1 The supply chain inventory management problem: a survey

The inventory management system at each supply chain node has to answer to three different questions: (i) how often to review the stock status; (ii) when to order new products; (iii) quantity of new products. In order to help supply chain managers and practitioners to approach and face the supply chain inventory management problem and answer to the previous questions, this section surveys the most relevant studies in the supply chain inventory management area. The survey also emphasizes the potentials of the M&S approach as enabling technology for supply chain inventory management.

A general survey on supply chain inventory simulation can be found in Cimino et al. (2010). Specific studies on the base stock policy are reported in Roundy and Muckstadt (2000), Graves (1999) and Parker and Kapuscinski (2004). In the first case the authors propose an heuristic computation of the base stock policy parameters obtaining a good approximation to the optimal policy. In the second case, the base stock policy is applied in correspondence of different operative scenarios (demand pattern variation). In the third case the authors demonstrate that the base stock policy, in a two echelon supply chain, obtains the best performance (respect to the other inventory policies) if downstream stages capacity is lower than upstream ones.

Similar studies have been carried out for other inventory control policies. The influence (on supply chain performances) of the most applied inventory policies (economic order quantity with stationary demand and dynamic economic lot-size with non stationary demand) is reported in Zipkin (2000). Interesting approaches to the supply chain inventory management problem can also be found in the following books: Simchi-Levi (2000), Stadtler and Kilger (2000) and Chopra and Meindl (2001).

As mentioned earlier, nowadays the supply chain manager has to take into account the concept of extended enterprise. Useful managerial insights must come from a research effort devoted to consider the inventory management problem along the entire supply chain. In effect, many authors provide an enlarged framework for inventory systems analysis. Wikner *et al*. (1991) face the inventory management problem along the supply chain considering as critical the tuning of order policy parameters, the reduction of delivery delays in each stage of the supply chain, the distribution echelon elimination and the enhancement of decisions rules and information flow (the latter by separating customers' real orders from the orders emitted for the safety stock). The authors propose a model composed by a single production plant, various distribution centres and retailers, each one operating under specific inventory control policies. Simulation is used for evaluating the best inventory policies that minimizes demand fluctuation along supply chain.

As matter of fact, enlarged inventory management scenarios (focused on entire supply chains instead of a single stage inventory problem) usually require the use of Modeling & Simulation. Lee et al. (2002) underline the need to use M&S not only for inventory management problems but as support tool for analyzing and designing the whole supply chain. Existing analytical methods are not able to handle all the dynamically changing supply chain variables; a M&S based approach is a powerful tool for managing the stochastic behavior of supply chains. A complete list of advantages and disadvantages in using simulation approach for supply chain modeling can be found in Ingalls (1998).

In effect different studies are reported in literature regarding the use of M&S not only for supporting supply chain inventory management. F.T.S. Chan and H.K. Chan (2005) use simulation for supply chain design by building and testing five different supply chain models. Supply chain performances are calculated following a multi measures based approach. Persson and Olhager (2002) propose a supply chain design problem based on a real case study; the authors evaluate alternative supply chain scenarios with the aim of improving quality and costs and understanding how these parameters affect each other (as in the previous case, a multi measures based approach to supply chain performance is propsoed). Zhang and Zhang (2007) deal with the information sharing implementation problem in a multi stage supply chain. They use simulation for analyzing the impact of information sharing on supply chain performances.

Many of the research studies based on Modeling & Simulation approaches (not only those studies focusing on supply chain inventory management) highlight that a multi measures based approach is required for obtaining successful results (Thor, 1994). Viswanadham (1999) states that supply chain performance measures can be divided in two categories: quantitative (such as fill rates, costs, inventory levels, resources utilization) and qualitative (such as customer satisfaction, products quality, supply chain vulnerability, supply chain resilience). A complete description of quantitative and qualitative measures is reported in F.T.S. Chan and H.K. Chan (2005), whilst a comprehensive analysis of the most recent qualitative performance measures, including supply chain resilience and vulnerability, can be found in Bruzzone et al. (2006), Longo and Oren (2008). Baganha and Cohen (1998) provide different criteria for choosing new supply chain performance measures. Moreover, an accurate overview of supply chain performance measures can be found in Beamon (1998, 1999).

The use of simulation tools supports the evaluation of multiple performance measures under the effects of different constraints and combinations of critical parameters such as inventory control policies, lead times, demand intensity, demand variability, etc. Specific examples regard supply chain inventory management problems. Axsater (2003) considers the problem of minimizing the holding cost under fill rate constraints; the approach proposed by the author allows the evaluation of the optimal inventory control policy. Moinzadeh (2002) studies the effects of information sharing on the inventory management problem within a two echelons supply chain; the author proposes an inventory control policy (for suppliers) that takes into consideration the stores inventory position and compares such policy to those policies not using this information. A simulation study for understanding the impact of inaccurate inventory information on supply chain performance is presented by Fleisch and Tellkamp (2005); once again, a multi measures approach, considering costs and stock outs, is proposed.

An interesting approach in studying the effects of inventory control policies on supply chain performance is proposed by Tagaros and Vlachos (2001). They consider a periodic-review inventory control policy working with two replenishment modes (regular and emergency). The paper demonstrates that such control policy works better (in terms of costs) than a traditional one. Cost minimization is obtained with heuristic algorithms able to find near optimal solutions if compared with optimal solutions derived by simulation. Graves and Willems (2005) propose a more centric approach on the entire supply chain. They deal with supply chain configurations in terms of suppliers, parts, processes and transportation modes to be selected at each stage trying to minimize the total supply chain cost. Another study on the whole supply chain using modeling and simulation is presented by Ganeshan et al. (2001). The authors study the impact of critical inventory parameters and management techniques on the performance of an expanded and comprehensive supply chain. Particular attention is also devoted to the inventory management problem along the supply chain in the case of reverse logistics. An updated survey of the state of the art on inventory with products returns can be found in Cimino et al. (2010).

The study of inventory systems in real stochastic supply chains is one of the major concerns in today's supply chain management. As soon as the number of parameters affecting supply chain performances becomes high and the objective becomes the whole supply chain analysis, simulation plays a more critical role in finding the optimal trade off among the involved variables, i.e. inventory policies, transportation cost, lead times, demand patterns, customers' satisfaction (Chang and Makatsoris, 2001). To this end Modelling & Simulation based approaches are jointly used with advanced statistics techniques such as Design of Experiment, DOE, and Analysis of Variance, ANOVA, (Suwanruji and Enns, 2006; Curcio and Longo, 2009).

The literature survey highlights that:

- simulation combined with statistic techniques is usually used for analyzing supply chain scenarios (different combinations of critical parameters);
- there is a lack in the research studies on inventory systems of real multi-echelon stochastic supply chain, considering a complete set of operative scenarios regarding customers' demand intensity, customers' demand variability, lead times and the impact of such scenarios on multiple performance measures. In such a context, research works based on analytical approaches are characterized by simplifying assumptions, studies based on Modelling & Simulation consider a limited number of operative scenarios, or a limited number of inventory policies, or they are based on theoretical case study or, at last, they consider only one performance measure.

Therefore the main contribution of the first application example proposed in this chapter is a focus on a real three-echelon stochastic supply chain; a supply chain simulation model is used for investigating a comprehensive set of operative scenarios including different inventory control policies under customers' demand intensity, customers' demand variability and lead times constraints.

As additional aspect (keeping in mind the literature overview proposed above), it is worth say that a supply chain manager needs of decision-making tools capable of investigating the effects of critical parameters on multiple performance measures. Note that different supply chains are characterized by different critical parameters, therefore a simulation based decision-making tool should provide to managers (i) high flexibility in terms of scenarios definition and (ii) critical parameters and performance measures selection.

### 2.2 Internal logistics: a survey on warehouse management

As for the inventory problems, Simulation can be also profitably used for supply chain node design and management, regardless of the node type (i.e. Bruzzone et al., 2007 and Longo, 2010 respectively propose the use of simulation for logistics node design and for integrating security activities in the normal operations of a container terminal part of an extended supply chain). It is worth saying that the internal logistics management of each supply chain node (above all from the warehouse management point of view) also provides to researchers and practitioners challenging problems.

Warehouses are usually large plain buildings used by exporters, importers, wholesalers, manufacturers for goods storage. Warehouses are equipped with loading docks, cranes, forklifts and material handling systems for moving goods. The main processes that take place within a warehouse are receiving items, storage, retrieval, picking, shipping. Warehousing costs can be distinguished in general overhead costs, delivery costs and labour costs.

This Section proposes a review of the state of art on warehouse management. According to Gu *et al.* (2007), the warehouse management problem can be re-conducted to five major decisions:

- defining the overall warehouse structure in terms of functional departments and their relationships (by analyzing warehouse materials flow);
- warehouse sizing and dimensioning that aim at defining warehouse size and dimensions and its departments;
- defining the detailed layout within each department (i.e. aisle design in the retrieval area, pallet block-stacking pattern in the reserve storage area, configuration of an Automated Storage/Retrieval System, etc.);
- material handling systems design and selection (determination of an appropriate automation level for the warehouse and identification of equipment types for storage, transportation, order picking, and sorting);
- selection of the operational strategies (i.e. the choice between randomized storage or dedicated storage, whether or not use zone picking, the choice between sort-while-pick or sort-after-pick, etc.).

General surveys on warehouse management can be found in Cormier and Gunn (1992), Van den Berg (1999), Rowenhorst et al. (2000), Cormier (2005).

The design of the departments and their functions is part of the definition of the overall warehouse structure (or conceptual design). Main tasks in this case are the number of storage departments (Park and Webster, 1989; Gray *et al.*, 1992; Yoon and Sharp, 1996), technologies to adopt (Meller and Gau, 1996), personnel to employ, in order to satisfy storage and throughput requirements and minimize costs.

Warehouse sizing and dimensioning has important implications on construction, inventory management and material handling costs. In particular, warehouse sizing establishes the warehouse storage capacity. Two alternatives can be considered in solving the warehouse sizing problem. In the first case the inventory level is defined externally and, consequently, there is no direct control on the incoming items (e.g. in a third-party warehouse or vendor managed inventory). The warehouse has to satisfy all the requirements for storage space. White and Francis (1971) study this problem for a single product over a finite planning horizon taking into consideration costs related to warehouse construction, storage of products and storage demand not satisfied. In the second case, there is a direct control (i.e. an independent wholesale distributor) therefore optimal inventory control policies and inventory costs should be evaluated, see Levy (1974), Rosenblatt and Roll (1988), Cormier and Gunn (1996) and Goh *et al.* (2001). The state of art also proposes research studies with either fixed and changeable storage size (i.e. the storage size changes over the planning horizon) as reported in Lowe *et al.* (1979), Hung and Fisk (1984) and Rao and Rao (1998).

From the other side, warehouse dimensioning deals with the required floor space in order to evaluate construction and operating costs. Francis (1967) faces this problem for the first time by using a continuous approximation of the storage area without considering aisle structure. Bassan *et al.* (1980) review Francis model by considering aisle configurations. Rosenblatt and Roll (1984) integrate the optimization model in Bassan *et al.* with a simulation model devoted to evaluate shortage costs as a function of storage capacity and number of zones. Other research studies on warehouse dimensioning can be found in Pliskin and Dori (1982), Azadivar (1989) and Heragu *et al.* (2005). A specific study (also focused on warehouse department dimensioning in a retail store) using advanced 3D simulation tools and artificial intelligence techniques is proposed by Bruzzone and Longo (2010).

Within each warehouse department, the department layout or storage problem can be classified in:

- pallet block-stacking pattern (storage lane depth, number of lanes for each depth, stack height, pallet placement angle with regards to the aisle, storage clearance between pallets and length and width of aisles);
- storage department layout (doors location, aisles orientation, length, width and number of aisles);
- Automated Storage/Retrieval System configuration, AS/RS (dimension of storage racks, number of cranes).

These layout problems affect warehouse performances in terms of:

- construction and maintenance costs;
- material handling costs;
- storage capacity;
- space utilization;
- equipment utilization.

The literature proposes several research works related to the warehouse layout problem. A number of papers discuss the pallet block-stacking problem. Moder and Thornton (1965) focus on different ways of stacking pallets within a warehouse. Berry (1968) discusses the tradeoffs between storage efficiency and material handling costs through analytic models. Marsh (1979) uses simulation to evaluate the effect on space utilization of alternate lane depths and the rules for assigning incoming shipments to lanes; Marsh (1983) compares alternative layout designs and extends the analytic models proposed by Berry (1968). Goetschalckx and Ratliff (1991) develop an efficient dynamic programming algorithm to maximize space utilization while Larson *et al.* (1997) propose an heuristic approach for the layout problem in order to maximize storage space utilization and minimize material handling costs. Additional research works on the storage department layout are reported in: Roberts and Reed (1972), Bassan *et al.* (1980), Roll and Rosenblatt (1983), Pandit and Palekar (1993) and Roodbergen and Vis (2006).

Concerning the AS/RS configuration interesting solutions based both on analytical and simulation approaches can be found in Karasawa *et al.* (1980), Ashayeri *et al.* (1985), Randhawa *et al.* (1991), Randhawa and Shroff (1995), Malmborg (2001).

Material handling systems design and selection is devoted to determine an appropriate warehouse automation level and select equipment for storage, transportation, order picking, and sorting (Cox, 1986; Sharp *et al.*, 1994).

Finally operation strategies have important effects on the overall warehouse performances and are mainly related to storage strategies and picking approaches. As explained in Gu *et al.* (2007), the basic storage strategies include random storage, dedicated storage, class based storage, and Duration-of-Stay (DOS) based storage. Hausman *et al.* (1976), Graves *et al.* (1977) and Schwarz *et al.* (1978) make a comparison of random storage, dedicated storage, and class-based storage in single-command and dual-command AS/RS using both analytical models and simulations. Goetschalckx and Ratliff (1990) and Thonemann and Brandeau (1998) demonstrate theoretically that the DOS-based storage policies perform better in terms of internal logistics costs. About zone picking approaches, some interesting research works are reported in Lin and Lu (1999), Bartholdi *et al.* (2000) and Petersen (2000).

It is worth saying that most of the approaches used for warehouse performances evaluation are based on benchmarking, analytical models and simulation and provide information about the quality of the proposed design and/or operational policy in order to improve/change it. Warehouse benchmarking is the process of systematically assessing the performance of a warehouse identifying inefficiencies and proposing improvements. A powerful methodology for solving this problem is the Data Envelopment Analysis (*DEA*), which has the capability to capture simultaneously all the relevant inputs (resources) and outputs (performances), identify the best performance domain and delete the warehouse inefficiencies. Schefczyk (1993), Hackman *et al.* (2001) and Ross and Droge (2002) propose approaches and case studies using DEA for warehouse benchmarking.

Analytical models can be divided into:

- aisle based models which focus on a single storage system and evaluate travel and service time; examples of aisle based models can be found in Hwang and Lee (1990), Chang *et al.* (1995), Chang and Wen (1997), Lee (1997), Hwang *et al.* (2004), Meller and Klote (2004), Roodbergen and Vis (2006);
- integrated models which address (in addition to travel/service times) either multiple storage systems and criteria; examples of integrated models can be found in Malmborg (1996), Malmborg and Al-Tassan (2000).

Finally a number of studies propose advanced tools (also based on simulation) to address warehouse performance evaluation and enhancement problem. Perlmann and Bailey (1988) present a computer-aided design software that allows to quickly generate and compare a set of conceptual design alternatives including building shape, equipment selection and operational policy selection. Linn and Wysk (1990), Wang and Yih (1997) develop expert systems for AS/ RS control also based on neural networks. Similarly Ito *et al.* (2002) propose an intelligent agent based simulation system to model a warehouse; the simulation system includes three subsystems: the agent-based communication system, the agent-based material handling system, and the agent-based inventory planning and control system. Additional research work that use simulation based tools are Macro and Salmi (2002) and Hsieh and Tsai (2006). Macro and Salmi present a ProModel-based simulation tool used for analyzing the warehouse storage capacity and rack efficiency. Hsieh and Tsai implement a simulation model for finding the optimum design parameters of a real warehouse system.

The literature survey highlights that, as for the supply chain inventory management, simulation is an enabling technology for investigating the warehouse management problem. The second application example (proposed in the final part of this chapter) investigates the effects of warehouse resources management on warehouse efficiency highlighting as the interactions among operational strategies and available resources strongly affect the internal logistic costs.

### 2.3 Critical issues in supply chain Modeling & Simulation

As final part of the state of the art overview, in this section some critical issues in supply chain Modeling & Simulation are presented and discussed. The Modeling & Simulation (M&S) based approach for studying supply chains has to be:

- flexible and parametric for creating and investigating different supply chain scenarios;
- efficient in terms of time required for simulation runs execution even in correspondence of complex supply chains (i.e. high number of supply chain stages, high numbers of items, etc.);
- repetitive in its architecture for easily changing the number of supply chain echelons and the supply chain configuration.

A supply chain simulator that aims at reaching such features should pay attention to the modeling approach. Let us consider the traditional modeling approach proposed by two of

the most used commercial discrete event simulation packages, Em-Plant (by Siemens-UGS) and Anylogic (by Xj-Technologies). Both of them propose a typical object oriented modeling approach. Each discrete event simulation model (developed by using these software) is made up by system state variables, entities and attributes, lists processing, activities and delays. Let us focus on entity, it can be dynamic (it moves through the system) or it can be static (it serves other entities, generally called resources) and it may have attributes for recording specific information (Banks, 1998). Typically, supply chain simulation models can involve a high number of dynamic entities (i.e. for modeling the flow of items and information) and, in comparison with the previous ones, a small number of resources (stores, plants, warehouses). Even if the simulation model is being used for analyzing a single supply chain node the number of dynamic entities is usually greater than the number of static entities. Consider a production plant, the number of work pieces is usually greater than the number of machines; similarly in a marine container terminal the number of containers is remarkable greater than the number of berth and yard resources.
Each single dynamic entity corresponds to an object flowing in the simulation model. As soon as the number of dynamic entities becomes high, the time required for executing a simulation run becomes unacceptable. In addition, library objects (used for modeling static entities) very often fall short of recreating the real system with satisfactory accuracy. In other words, it can happen that the traditional modeling approach (proposed by a number of discrete event simulation packages), in terms of library objects and dynamic entities, presents two main problems: (i) difficulties in modeling complex scenarios; (ii) too many entities cause computational heavy models. In the remainder of the chapter, as part of the description of the first application example (and as a part of a successful approach to develop supply chain simulation models), an advanced modeling approach for developing flexible, time-efficient and parametric supply chain simulators is proposed.

## 3. From the supply chain conceptual model and inventory models definition to the supply chain simulation

Sections 3 and 4 present the first application example in which a supply chain simulation model is used for investigating a comprehensive set of operative scenarios including different inventory control policies under customers' demand intensity, customers' demand variability and lead times constraints. The application example is mainly based on simulation studies already carried out, some years ago, by the author (Longo and Mirabelli, 2008; De Sensi et al., 2008).
In order to provide the reader with a logic and easy-to-read structure, in our treatment, the same set of steps of a simulation study described by Banks (1998) are adopted. The list is as follows:

- problem formulation;
- setting of objectives;
- model conceptualization;
- data collection;
- model translation;
- verification, simulation run length and validation;
- experimental design;
- simulation runs and analysis.

We have already introduced the problem formulation and the objectives of the study proposed in this chapter, highlighting (by means of the state of the art survey) the contribution to the literature.

Therefore, in the sequel, a supply chain conceptual model, that includes four different inventory models, is presented and discussed. In our supply chain conceptual model a single network node can be considered as store (ST), distribution center (DC) or plant (PL). A supply chain begins with one or more PLs and ends with one or more STs. Usually STs satisfy market demand or demand from other STs, DCs satisfy STs demand or demand from others DCs and PLs satisfy DCs demand and demand from other PLs. By using these three types of supply chain nodes we can model a whole supply chain. Let us briefly consider the conceptual model of each supply chain node.

### 3.1 Stores, distribution centers and plants conceptual models

Starting from the end of the supply chain, the arrival process of market demand at STs is Poisson and the quantity required for each item is triangular with different levels of intensity and variability. Once customers arrive at stores, the quantity required is compared with the on hand inventory and the order is eventually satisfied (lost quantity are recorded for fill rate calculation). Just before the ST business hour (8:30 AM) the inventory is updated with deliveries from DCs or other STs. Just after the ST business hour (4:30 PM) the inventory is checked using one of the available control policies. In case of purchase order emission, it is required to choose the distribution center or the store toward which the order will be emitted. Such decision is taken considering the lead time, the lead time demand and the quantity that DCs or stores can replenish. Note that the lead time demand can be evaluated by using different forecast methods (i.e. single exponential smoothing, double exponential smoothing, triple exponential smoothing, moving average, etc.). The quantity received can be different from the quantity ordered due to problems at PLs, DCs or STs. Figure 1 shows the operations flow chart including logics and rules governing ST behavior.

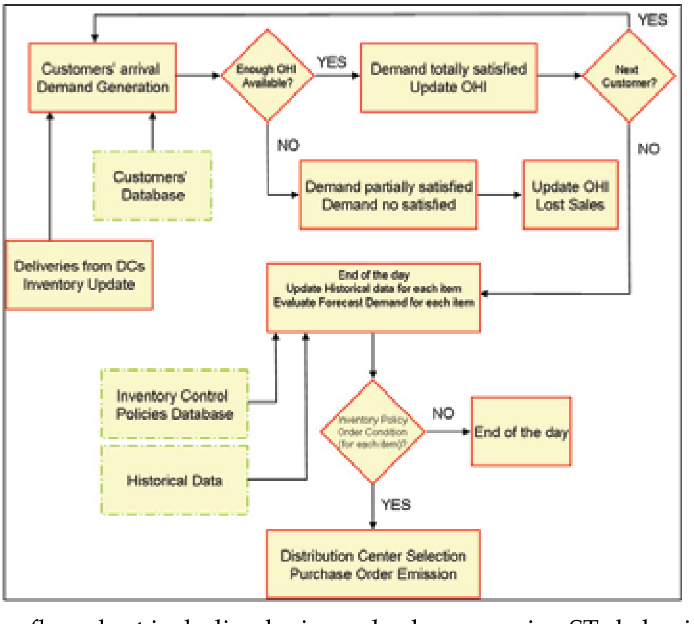



Fig. 1. Operations flow chart including logics and rules governing STs behavior

The DCs operate according to the following logic. Every day the supply chain DCs try to satisfy purchase orders. Items distribution is performed according to the same priority index for all the supply chain nodes. In other words, if the on hand inventory of item $j$ is not enough for satisfying nodes demand, the available quantity is divided proportionally to quantity required. Lost quantities are recorded, thus, the distribution center performance measures, such as fill rate, can be easily calculated. The inventory is checked using one of the available control policies. The purchase order emission requires a decision on which PL or DC to send the order and the evaluation of the lead time demand. PL selection is made according to PLs and machines performances and working queues. DC selection is made according to lead time and quantity that can be replenished. Once again, the order is sent toward the PL or DC that assures the highest quantity in the shortest time. Figure 2 shows the operations flow chart including logics and rules governing DC behavior.

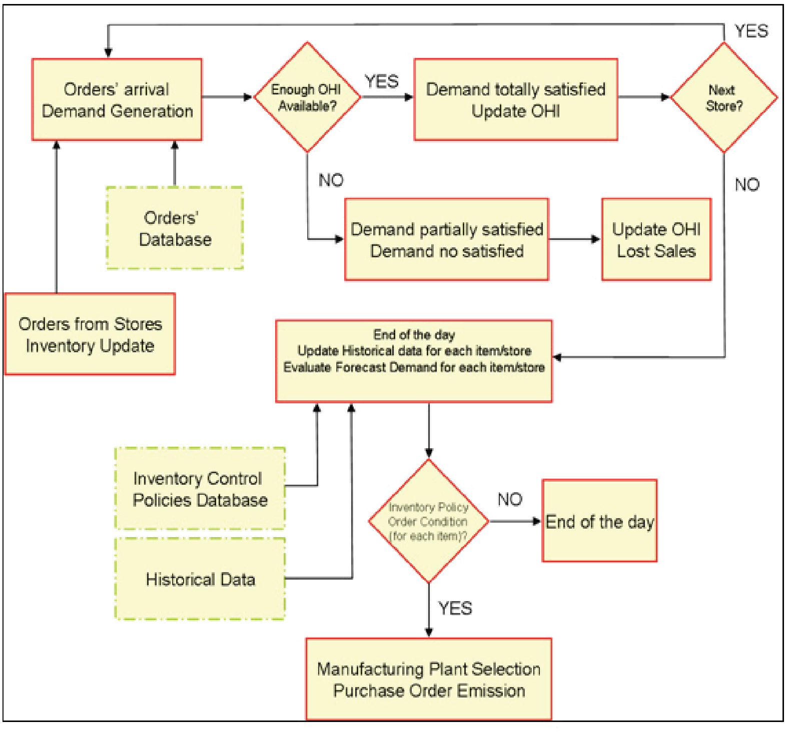



Fig. 2. Operations flow chart including logics and rules governing DCs behavior

Finally PLs behave as described below. Each production order waits in a queue and it is sent to a distribution center (or plant) just after the production. Each PL has a certain number of machines and each machine can manufacture all the types of items (with different efficiency, working times and setup times when switching from a product to another). The PLs inventory management is similar to DCs inventory management. Different inventory control policies, demand forecast methods and lead times are available. Figure 3 shows the operations flow chart including logics and rules governing PLs behavior.

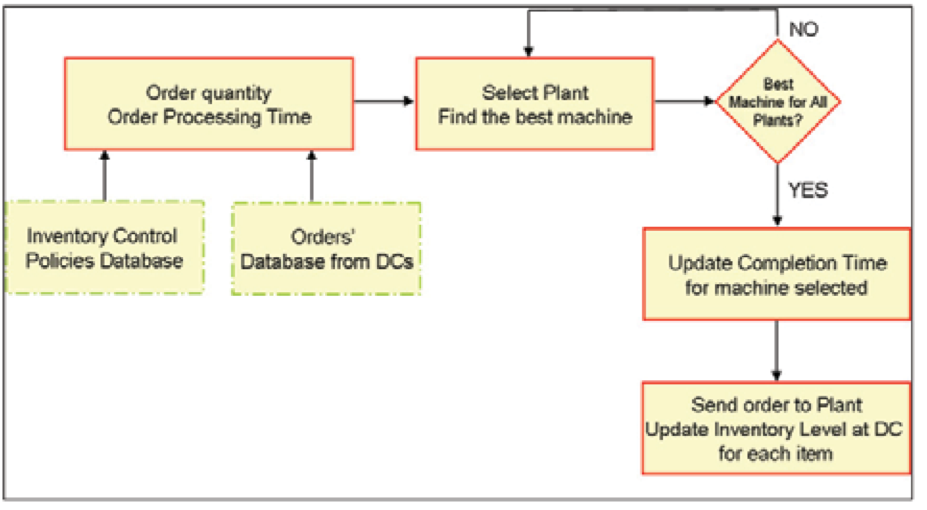



Fig. 3. Operations flow chart including logics and rules governing PLs behavior

### 3.2 Inventory control policies definition

Let us consider now the inventory control policies. Four different inventory control policies are considered and implemented within each supply chain node: (i) continuous review with re order point equals to the target level and constant safety stock, rR1; (ii) continuous review with re order point equals to the target level and variable safety stock, rR2; (iii) continuous review with fixed review period for policy parameters, rR3; and, (iv) continuous review with optimized review period for policy parameters, rR4.

The inventory management at each node of the supply chain has to answer to three different questions: (i) how often to review the stock status; (ii) when to order new products; (iii) quantity of new products. Before getting into inventory policies details let us define the following notations:

- $rl_{ij}(t)$, re-order level at time $t$ of the item $j$ at the network node $i$;
- $RL_{ij}(t)$, target level at time $t$ of the item $j$ at the network node $i$;
- $SS_{ij}(t)$, safety stock at time $t$ of the item $j$ at the network node $i$;
- $OHI_{ij}(t)$, on hand inventory at time $t$ of the item $j$ at the network node $i$;
- $QO_{ij}(t)$, quantity already on order at time $t$ of the item $j$ at the network node $i$;
- $QS_{ij}(t)$, quantity to be shipped at time $t$ of the item $j$ at the network node $i$;
- $Q_{ij}(t)$, quantity to be ordered at time $t$ of the item $j$ at the network node $i$;
- $D_{ij}(t)$, customers' demand at time $t$ of the item $j$ at the network node $i$;
- $DF_{ij}(t)$, demand forecast at time $t$ of the item $j$ at the network node $i$;
- $LT_{ij}$, lead time of the item $j$ at the network node $i$;

The evaluation of $Q_{ij}(t)$ has to take into consideration the quantity already on order and the quantity to be shipped, so the correct measure to be used is the Inventory Position defined in (1).

$$IP_{ij}(t) = OHI_{ij}(t) + QO_{ij}(t) - QS_{ij}(t) \tag{1}$$

The calculation of $Q_{ij}(t)$ requires the calculation of the demand forecast, $DF_{ij}(t)$, over the lead time. The Lead Time Demand of the item *j* at network node *i*, $LTD_{ij}(t)$, is evaluated by using the single exponential smoothing methodology. We can write:

$$LTD_{ij}(t) = \sum_{k=t+1}^{t+LT_{ij}} DF_{ij}(k) \tag{2}$$

As before mentioned, four different inventory control policies are investigated. Each policy is based on the continuous review approach (the inventory is reviewed continuously and the time axis is modeled continuously).

*Continuous review with re-order level equals to target level and constant safety stock (rR,1)*

An inventory control policy has to answer three different questions: how often to check the inventory status, instant of time for purchase order emission and quantity to be ordered. The first question is easily answered; in this case the inventory is checked continuously. The second question is answered by condition expressed in equation (3). The quantity to be ordered is evaluated in equation (4). The safety stock is calculated as standard deviation of the lead time demand. In this policy $SS_{ij}$ is constant.

$$IP_{ij}(t) < rl_{ij}(t) = RL_{ij}(t) = LTD_{ij}(t) + SS_{ij} \tag{3}$$

$$Q_{ij}(t) = RL_{ij}(t) - IP_{ij}(t) = LTD_{ij}(t) + SS_{ij} - IP_{ij}(t) \tag{4}$$

*Continuous review with re-order level equals to target level and variable safety stock (rR,2)*

The purchase order emission and the quantity to be ordered follow equations (3) and (4). The safety stock is calculated as the standard deviation of the daily demand times the safety time. The safety time is the Lead Time plus the standard deviation of the Lead Time multiplied by a factor expressing the service level that should be provided at the supply chain node.

*Continuous review with fixed review period (rR,3)*

The re-order level, the target level and the safety stock are supposed to be constant over the review period (RP). Let us indicate the demand forecast over *RP* with $RPD_{ij}(t)$. We can write:

$$rl_{ij}(t) = LT_{ij} * \frac{RPD_{ij}(t)}{RP} + SS_{ij}(t) \tag{5}$$

$$RL_{ij}(t) = \frac{RPD_{ij}(t)}{RP} + rl_{ij}(t) \tag{6}$$

The emission condition of the purchase order is reported in (7) and the quantity to be ordered in (8).

$$IP_{ij}(t) < rl_{ij}(t) \tag{7}$$

$$Q_{ij}(t) = RL_{ij}(t) - IP_{ij}(t) \tag{8}$$

*Continuous review with optimized review period (rR,4)*

In addition to the traditional continuous review control policies, we propose an optimized review period based approach. Let us consider the inventory costs described as follows.

- $C_{ij,o}$, order placing cost for item *j* at the network node *i*;
- $C_{ij,t}$, transportation cost for item *j* at the network node *i*;
- $C_{ij,r}$, order reception cost for item *j* at the network node *i*;
- $C_{ij,st}$, storage cost for item *j* at the network node *i*;
- $C_{ij,w}$, worsening cost for item *j* at the network node *i*;
- $C_{ij,ob}$, obsolescence cost for item *j* at the network node *i*;
- $C_{ij,i}$, interest cost for item *j* at the network node *i*;
- $P_{ij}$, price for the item *j* at the network node *i*;

Let us define the total cost for purchase order emission (9) and the total cost for storage (10). We can write:

$$TC_{POE,ij} = C_{ij,o} + C_{ij,t} + C_{ij,r} \tag{9}$$

$$TC_{ST,ij} = C_{ij,st} + C_{ij,w} + C_{ij,ob} + C_{ij,i} \tag{10}$$

The optimized review period, $ORP_{ij}(t)$, can be calculated trying to minimize, on the basis of demand forecast, the unitary inventory cost $UIC_{ij}(t)$, that is

$$UIC_{ij}(t) = \frac{TC_{POE,ij} + TC_{ST,ij} * \sum_{t}^{t+T-1}(t-1) * DF_{ij}(t)}{\sum_{t}^{t+T-1} DF_{ij}(t)} = MIN \tag{11}$$

The value of $T$ that minimizes $UIC_{ij}(t)$ is the $ORP_{ij}(t)$. Let us indicates with $ORPD_{ij}(t)$ the forecast demand over the optimized review period, the reorder level and the target level can be calculated using equations (12) and (13).

$$rl_{ij}(t) = LTD_{ij} + SS_{ij}(t) \tag{12}$$

$$RLij(t) = ORPD_{ij} + rl_{ij}(t) \tag{13}$$

In other words the $ORPD_{ij}(t)$ is the optimal lot size calculated by means of demand forecast. The first term of the sum in equation (13) is recalculated every $ORPD_{ij}(t)$ days whilst the second term is recalculated every day. The emission condition of the purchase order and the quantity to be ordered follow the equation (7) and (8).

### 3.3 Data collection and analysis

Data collection in a whole supply chain is one of the most critical issues. The random behaviour of some variables makes the supply chain a stochastic system. As reported by Banks (1998), for each element in a system being modelled, the simulation analyst must decide on a way to represent the associated variables. The Data Collection step takes care of collecting data in each supply chain node as well as finds the most suitable computer representation for such data.

Usually there are three different choices: (i) data are deterministic or data are considered as deterministic, (ii) a distribution probability is fitted to empirical data and (iii) the empirical distribution of the data is directly used in the simulation model.

In our treatment, the supply chain is characterized both by deterministic data and stochastic data (both numerical data and inputs that drive the logics of the supply chain). Therefore, the second and the third choices are adopted for representing, in the simulation model, supply chain stochastic variables.

In case of stochastic variables and distributions fitting, the procedure for input data analysis is the classical procedure proposed by many statistics references as well as implemented in all statistics software. Starting from the histogram of the data, one or more candidate distributions are hypothesized; for each distribution the characterizing parameters are estimated and a goodness of fit test is preformed. Finally, the best distribution is chosen. For any additional information on input data analysis for simulation studies please refer to Johnson et al. (1992, 1994, 1995) and D'Agostino and Stephens (1986).

Table 1 consists of a list of the most important variables and information collected for each plant, distribution center and store. Most of the data have been obtained using companies' informative systems. The data in *italicized style* are characterized by stochastic behaviour. As example of the input data analysis procedure, consider the market demand arrival process. Customers' inter-arrival times are collected and fitted using the above mentioned procedure for each store.

| Plants | Distribution centers | Stores |
|---|---|---|
| List of operations | List of operations | List of operations |
| *Process Time* | *Lead Time* | *Demand arrival process* |
| *Setup Time* | Inventory Control Policy | *Customer demand* |
| *Lead Time* | Forecast Method | *Lead Time* |
| Number and type of machines | Inventory Costs | Inventory Control Policy |
| Bill of materials | Items mixture | Forecast Method |
| Items mixture | | Inventory Costs |
| | | Items mixture |

Table 1. Data Collection in each supply chain echelon.

Let us focus on the store #1. Starting from the histogram of the data (based on 21 classes, see figure 4) four different distributions are hypothesized: Erlang, Weibull, Negative Exponential and Lognormal. The collected data allow the calculation of the distributions parameters, summarized in table 2. The successive step is the goodness of fit test. Note that we deal with a large sample so the Chi-Square test performs better than Ardenson-Darling and Kolmogorov-Sminorv tests. As well known from statistics theory if the *Chi Statistics* is lower than the *Chi Value*, the distribution accurately fit the real data. The Result column in table 2 shows that the Erlang and Negative Exponential distributions perform a good fit of the data. In presence of two or more available distributions, the choice falls on the distributions with lowest *Chi Statistics*. In our case, the Negative exponential distribution has been selected for representing customers' inter-arrival times for store #1.

As final result, we obtained that, for each store, the customers' inter-arrival process is well represented by a Poisson process (numerous scientific works confirm such results for inter-arrival times). Due to high number of items, the data regarding the quantity required by customers have been analyzed in terms of minimum, average and maximum values (triangular distributions). Each customer can require each type of item; items mixture is represented in the simulation model with empiricaldistributions. Lead times have been

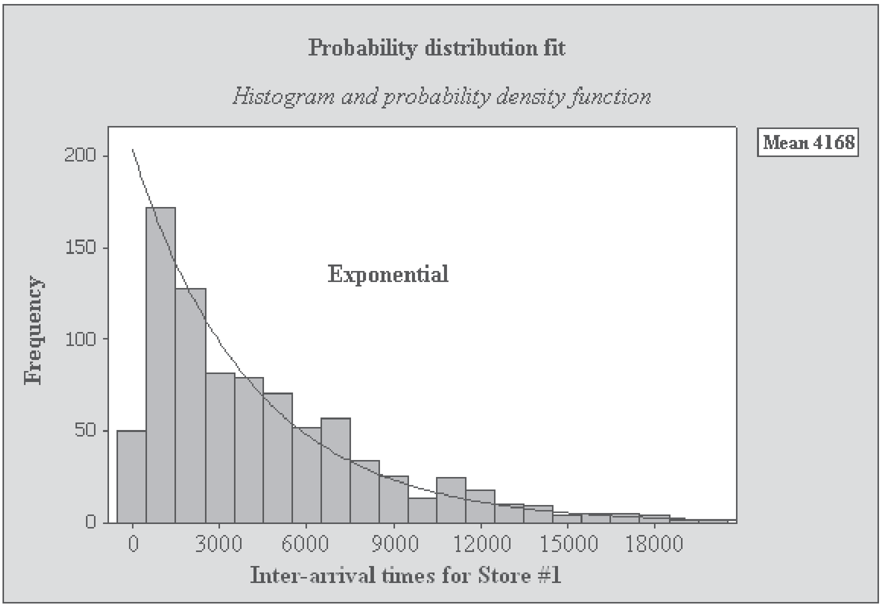



Fig. 4. Histogram and Distribution fitting for customers' inter-arrival times at Store #1

| Distributions | Chi Statistics | Chi Value | Results | Parameter 1 | Parameter 2 |
|---|---|---|---|---|---|
| Erlang | 18.419 | 24.997 | true | 4163.164 | 4163.164 |
| Weibull | 25.925 | 24.997 | false | 1.009 | 4184.344 |
| Negexp | 16.315 | 26.297 | true | 4168.058 | |
| Lognorm | 129.001 | 24.997 | false | 5383.540 | 11142.929 |

Table 2. Distribution fitting for store #1: Chi-square goodness of fitting test and distribution parameters

fitted with normal distributions. Plants process times and setup times use empirical distributions. Table 3 consists of statistic distributions and parameters related to collected data. Note that the triangular distribution is reported (as example) only for item #1. Analogous information are available for each item

| Variables | Distribution Type | Parameters estimation |
|---|---|---|
| Inter-arrival time | Neg. Expon. | m = 1.16 hours (mean inter arrival time) |
| Quantity (item#1) | Triangular | min = 21, mean = 30, max = 40 pallets |
| Item mixture | Empirical | |
| Lead Time (Plants) | Gaussian | m = 2 days (mean value); s = 0.4 days (stand. dev.) |
| Lead Time (DCs) | Gaussian | m = 3 days (mean value); s = 0.5 days (stand. dev.) |
| Process Time (Plants) | Empirical | |
| Setup Time (Plants) | Empirical | |

Table 3. Statistic distributions and parameters for collected data

### 3.4 Modeling the stores, the distribution centers and the plants

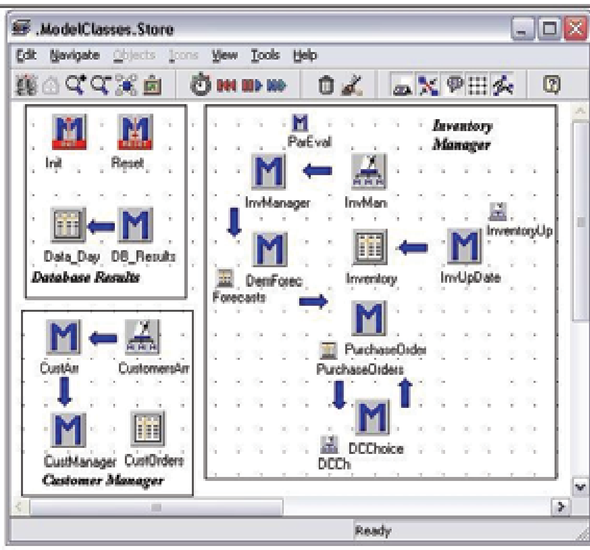
The following section deals with the supply chain conceptual model translation into a computerized simulation model. The commercial discrete event simulation software eM-Plant (by Siemens-UGS) is used and an advanced modeling approach is presented and discussed. Despite the specific simulation software used, the modeling approach proposed in the sequel can be easily adapted and used with all the discrete event simulation software that provide the user with a programming language (specific or general purpose).

The modeling approach proposed by eM-Plant is object oriented (as most of the modeling approach proposed by discrete event simulation software). The translation of the conceptual model in a computer simulation model could be performed using library objects. Specific classes could be implemented for STs, DCs and PLs; the supply chain flow of items and information could be modeled by means of dynamic entities. Using such approach we should pay attention to the number of dynamic entities flowing in the simulation model; the higher is the number of dynamic entities, the lower is the simulation model speed and the higher is the total time required for executing a simulation run.

In our treatment an advanced modeling approach based on programming code, tables and events generators is proposed. eM-Plant provides the user with the simulation languages Simple++ that can be used for writing specific routines, called methods. The methods, by means of programming efforts, allow to correctly translating the supply chain conceptual model. The supply chain flow of dynamic entities, representing items and information, is substituted by information recorded in tables. Without the flow of dynamic entities, simulation events are generated using event generator objects (provided by the library) and, in correspondence of such events, the methods elaborate and update the information stored in tables. Following this modeling approach we obtain a flexible, parametric (every class object can be easily accessed and modified for adding new features) and time efficient simulation model (some results in term of time for executing a simulation run, will be discussed later). To give the reader an idea of the modeling approach, let us now examine the simulation model architecture, made up of five different classes: *Store*, *Distribution Center*, *Plant*, *Simulation Model Interface* and *Simulation Model Main Frame*.

The upper part of figure 5 shows the store modeling frame. It has been subdivided in three main sections: *Customer Manager, Inventory Manager*, *Database Results* (the description proposed below will be useful for those readers interested in developing similar approaches, it can be neglected by the others interested only in dealing with supply chain inventory problems).

The object *CustomersArr* is an event generator. It generates the customers' arrival process (if the store is at the end of the supply chain). The methods *CustArr* and *CustManager* take care of customers' demand checking the on hand inventory and recording all the orders information in the table *CustOrders* (see figure 5). Every day, just after the store business hour, the object *InvMan* generates the event for starting the inventory control process. The method *InvManager* checks the inventory using the inventory control policy selected by the user. The method *InvManager* is supported by the method *ParEval* for evaluating the policy parameters, $rl_{ij}(t)$, $RL_{ij}(t)$, $SS_{ij}(t)$ and by the method *DemForec* for evaluating the lead time demand, $LTD_{ij}(t)$ (stored in the table *Forecasts*). In case of order emission, the method *PurchaseOrder* is called and the purchase order is recorded in the table *PurchaseOrders*. The method *DCChoice* chooses the best distribution center or store in terms of quantity and lead time and sends the purchase order to the distribution center or store chosen. Every morning, just before the store business hour, the object *InventoryUp* generates the event for starting the inventory update. The table *PurchaseOrders* is checked for deliveries and the inventory is eventually updated. The inventory information are stored in the table *Inventory* (see figure 5). At the end of the day, the store performance measures are collected in the table *Data_Day*.




*CustOrders table*

| CO_ID (Customer Order ID) | Date and Time | Item Ordered (ID) | Quantity | Order Condition | Lost Sales Quantity |
|---|---|---|---|---|---|
| 1 | 2005/05/02 09:43:19.4213 | 1 | 40 | Fully satisfied | |
| 2 | 2005/05/02 09:43:19.4213 | 2 | 32 | Fully satisfied | |
| 3 | 2005/05/02 09:43:19.4213 | 3 | 33 | Fully satisfied | |

*Inventory table*

| Items | On Hand Inv. (OHI) | Quantity on Order (QO) | Quantity to be shipped (QS) | Inventory Position (IP) | Safety Stock (SS) | Re Order Level (d) | Target Level (RL) |
|---|---|---|---|---|---|---|---|
| 1 | 99 | 891 | 35 | 955 | 153 | 891 | 1038 |
| 2 | 254 | 672 | 23 | 903 | 156 | 979 | 1143 |
| 3 | 217 | 701 | 41 | 877 | 165 | 956 | 1114 |

Fig. 5. Store Modeling frame and examples of information stored in tables.

The same architecture is implemented for the Distribution Center class, even if there are some variables and methods with different names. The Plant class proposes the same modeling approach; in addition, in this class we have implemented the *Manufacturing Manager* section for plant machines modeling and management. The same modeling approach for STs, DCs and PLs guarantees high flexibility if the supply chain echelons number has to be modified or different supply chain echelon has to be considered.

Note that the use of dynamic entities flowing in the simulation model dynamic entities is completely eliminated. Stores, Distribution Centers and Plants classes instantiated in the model have different identifying numbers that allow the information exchange protocol to work correctly.

As already mentioned, flexibility in terms of supply chain scenarios definition is a critical issue for simulation models that must be used as decision-making tool. Now, we examine how a supply chain manager can define alternative supply chain scenarios by using a *Simulation Model Interface* (see figure 6). Again, the description proposed below would be interesting for those readers interested in developing similar approaches. The main dialog of the *Simulation Model Interface* provides the user with many commands as, for instance, number of items, simulation run length, start, stop and reset buttons and a Boolean control for the random number generator (to reproduce the same experiment conditions in correspondence of different operative scenarios). The supply chain conceptual model considers a three -echelon supply chain made up by stores, distribution centers and plants. Three different dialogs can be activated respectively by clicking on the tree buttons *Stores data input, Distribution Centers data input* and *Plants data input* (see fig. 6). Thanks to these dialogs, the user or supply chain manager can set the number of supply chain echelons, nodes position in the supply chain, total number of network nodes and all numerical values, input parameters and information in specific tables.

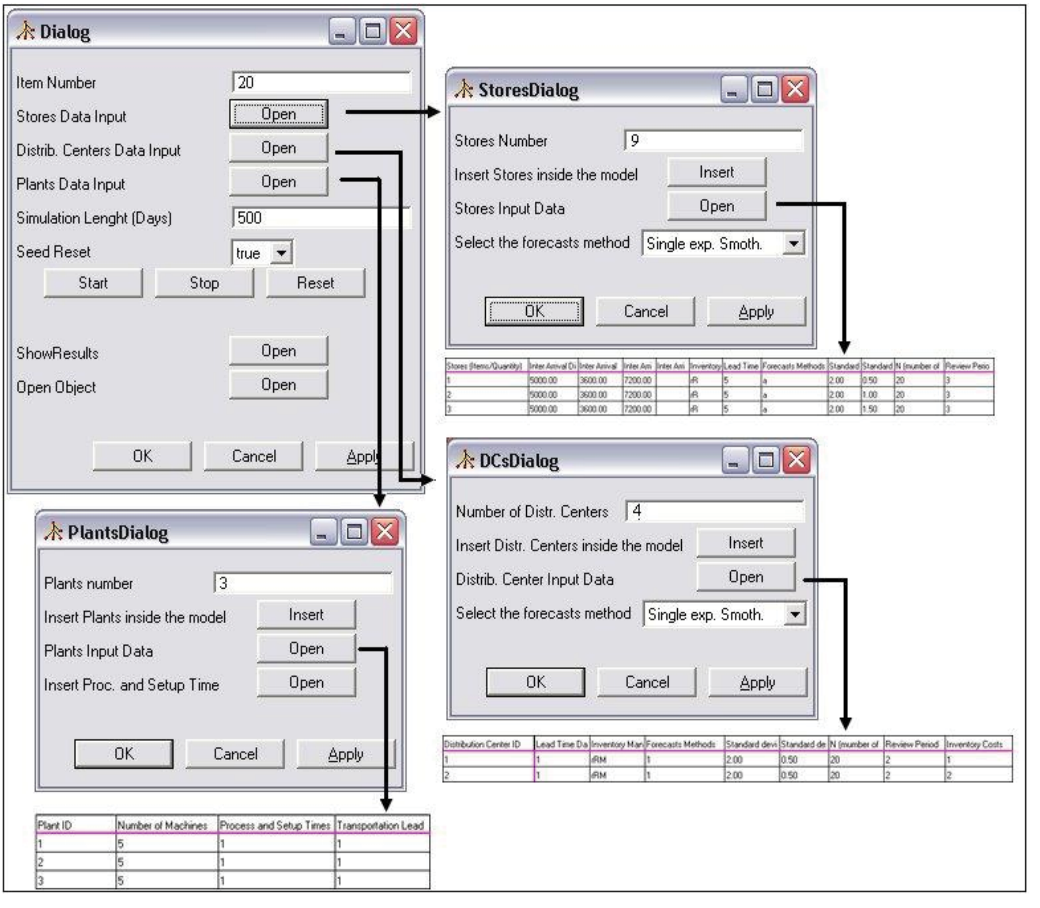



Fig. 6. Simulation Model Interface

After the definition of the supply chain scenario, the supply chain can be created simply by clicking (in each dialog) the insert button. The user-defined scenario is automatically recreated; instances of the classes *Store*, *DistributionCenters* and *Plants* are inserted within the *Simulation Model Main frame* (see figure 7). The Simulation Main Frame also shows an indicator of date, time and day of the week. The user can access the simulation interface object at every moment for changing the supply chain scenario; similarly each node of the supply chain can be accessed during the simulation for real-time monitoring all the supply chain information and performance measures stored in tables.

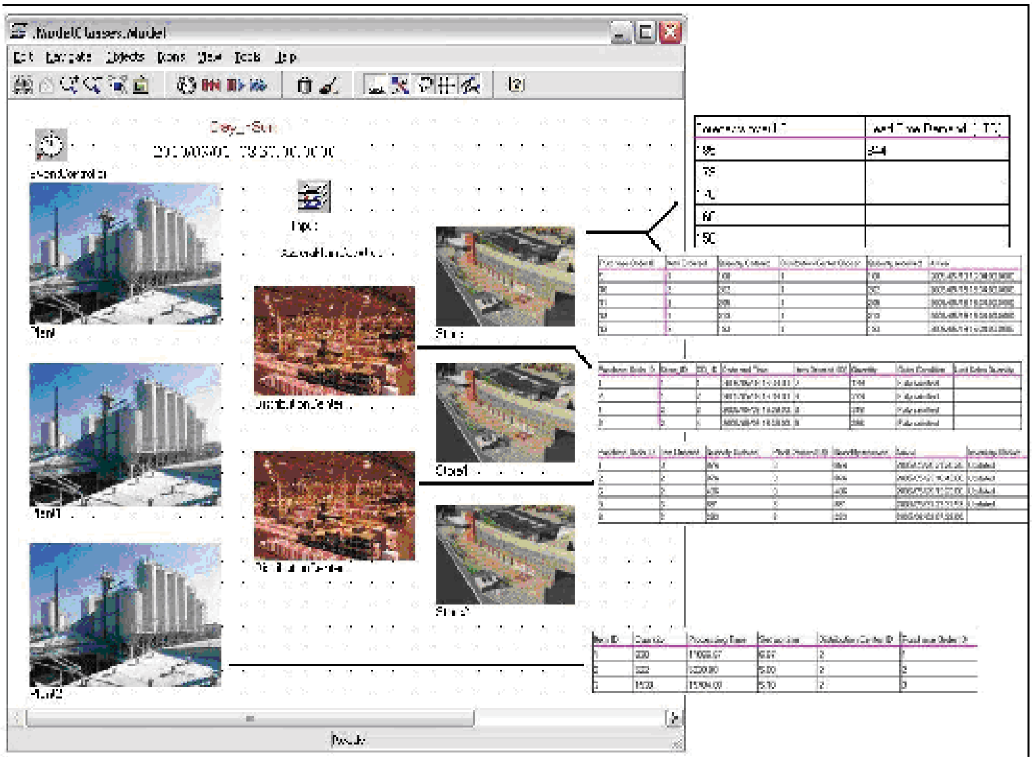


Fig. 7. Simulation Model Main frame and information stored in tables

Note that the high flexibility of the simulation model in terms of scenarios definition is one of the most important features for using it as a decision-making tool. The simulator interface object gives to the user the possibility to carry out a number of different what-if analysis by changing supply chain configuration and input parameters (i.e. inventory policies, demand forecast methods, demand intensity and variability, lead times, inter-arrival times, number of items, number of stores, distribution centers and plants, number of supply chain echelons, etc.).

Note that, in case of information sharing along the supply chain, the user can directly use the real supply chain node as empirical data source. When no data are available, one possibility is to obtain subjective estimates by means of interview to supply chain experts and data collection. Estimates made on the basis of assumptions are strictly tentative (Banks, 1998). In this case, the simulation model should be tuned for recreating as much as possible the real supply chain (this is a typical situation in the case of both theoretical research studies and real supply chain applications).

All the performance measures can be directly accessed inside the main frame of each supply chain node: the user can see what is going on inside each supply chain node in terms of fill rates, on hand inventory, inventory position and safety stocks for each items. In addition, all the results can be easily exported in Microsoft Excel and analyzed by using chart and histograms. Different Microsoft Excel spreadsheet has been programmed with *Visual Basic Macro* for simulation results collection and analysis in terms of performance measures average values and confidence intervals.

### 3.5 Simulation model verification, run length and validation

The accuracy and the quality throughout a simulation study are assessed by conducting verification and validation processes (Balci 1998). The American Department of Defence Directive 5000.59 defines verification and validation as follows. "Verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specifications". Obviously, this step is strictly related to model translation. "Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model". Problems during the validation phase can be attributed to model conceptualization or data collection. In our treatment, according to the published literature, the verification and validation has been conducted throughout the entire lifecycle of the simulation study and using both dynamic and informal verification and validation techniques.

The simulation model verification is made using a dynamic technique (debugging). As explained in Dunn (1987), debugging is an iterative process that aims to find model errors and improve the model correcting detected errors. The model is tested for revealing the presence of bugs. The causes of each bug must be correctly identified. The model is opportunely modified and tested (once again) for ensuring errors elimination as well as for detecting new errors. All the methods (Simple++ programming code) have been iteratively debugged line by line, detecting and correcting all the errors. Errors detected during the simulation study life cycle were mostly due to: misunderstanding or numerical error in input data, tables and spreadsheet indexes management, events list organization and management. In addition, before model translation, logics and rules governing supply chain behaviour have been discussed with supply chain' experts.

Before getting into details of simulation model validation, we need to introduce and discuss the simulation run length problem. The length of a simulation run is an information used for validation, for design of experiments and simulation results analysis. Such length is the correct trade-off between results accuracy and time required for executing the simulation runs. The run length has been correctly determined using the mean square pure error analysis ($MS_{PE}$). The mean square of the experimental error must have a knee curve trend. As soon as the simulation time goes by, the standard deviation of the experimental error (due to statistic and empirical distributions implemented in the simulation model) becomes smaller. The final value has to be small enough to guarantee high statistical result accuracy. In our case, the experimental error of the supply chain performance measures (i.e. fill rate and average on hand inventory), must be considered.

The simulation model calculates the performance measures for each supply chain node, thus, the $MS_{PE}$ analysis has to be repeated for each supply chain node and for each performance measure. The $MS_{PE}$ curve, that takes the greatest simulation time for obtaining negligible values of the mean squares pure error, defines the simulation run length. Figure 8 shows the $MS_{PE}$ curve of distribution centre #2 that takes the greatest simulation time. After 500 days the $MS_{PE}$ values are negligible and further prolongations of the simulation time do not give significant experimental error reductions.

Choosing for each simulation run the length evaluated by means of $MS_{PE}$ analysis (500 days), the validation phase is conducted using the *Face Validation* (informal technique). For each retailer and for each distribution centre the simulation results, in terms of fill rate, are compared with real results. For a better understanding of the validation procedure, let us consider the store #1. Figure 9 shows six different curves, each one reporting the store

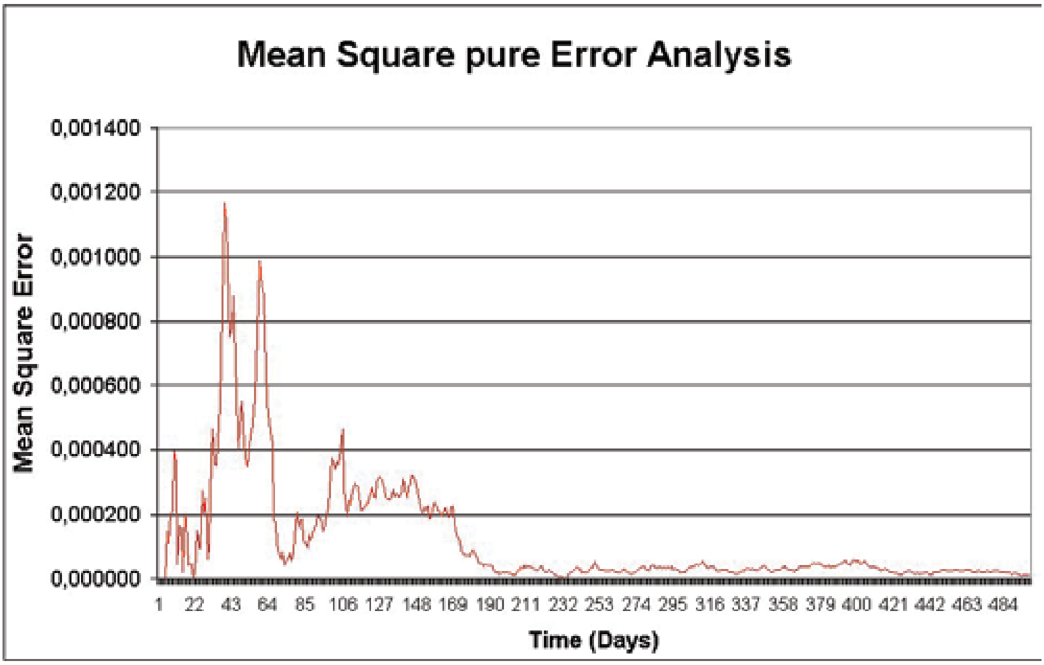



Fig. 8. Mean Square Pure Error Analysis and Simulation Run Length

#1 fill rate versus time (days). In the graphs there is one real curve and five simulated curves (note that during the validation process the simulation model works under identical input conditions of the real supply chain).

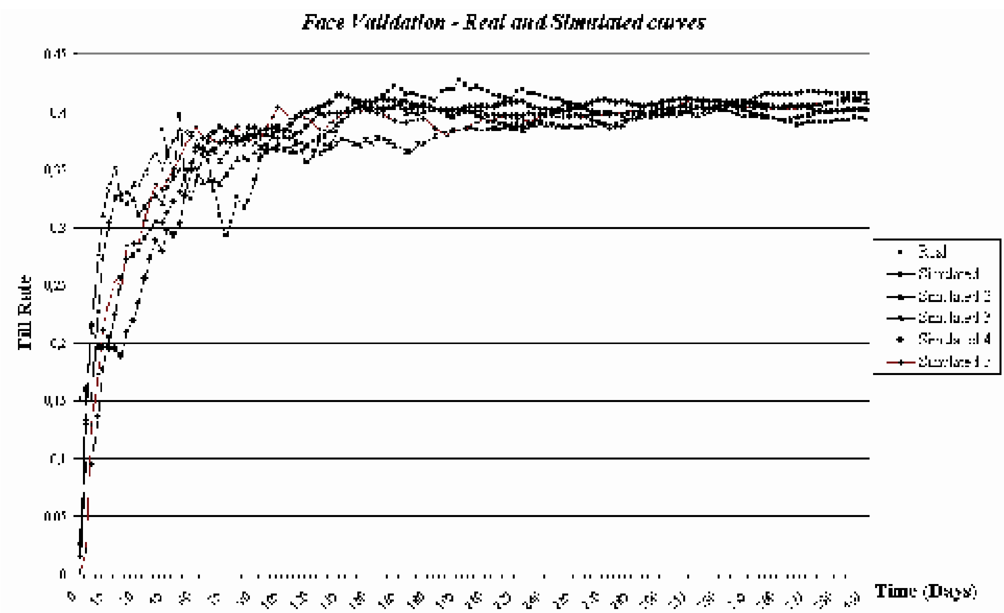



Fig. 9. Main effects plot: Store #1 fill rate versus inventory control policies, lead time, demand intensity and demand variability

The plot is then shown to the supply chain's experts asking them to make the difference between the real curve and the simulated curves on the basis of their estimates (obviously showing all the curves without identification marks). In our case the experts were not able to see any difference between real and simulated curves, assessing (as consequence) the validation of the simulation model. The Face Validation technique has been applied for the remaining stores as well as for each distribution centre. Further results in terms of fill rate confidence intervals have been analyzed. We concluded that, in its domain of application, the simulation model recreates with satisfactory accuracy the real supply chain.

## 4. Experimental design, simulation runs and analysis

The first application example (proposed in this section) is a focus on the inventory problem within the three-echelon stochastic supply chain presented above. The supply chain simulation model is used for investigating a comprehensive set of operative scenarios including the four different inventory control policies (discussed in section 3.2) under customers' demand intensity, customers' demand variability and lead times constraints. The application example also shows simulation capabilities as enabling technology for supporting decision-making in supply chain management especially when combined with Design of Experiment, DOE, and Analysis of Variance, ANOVA for simulation results analysis.

In this application example, nine stores, four distribution centers, three plants and twenty items form the supply chain scenario. Before getting into simulation results details, let us give some information about the simulation model efficiency in terms of time for executing a simulation run. Each 500 days replication takes about one minutes (running on a typical commercial desktop computer). If the number of replications is three, a simulation run is over in 3 minutes. Our experience with supply chain simulation models developed using eM-Plant (Longo, 2005a, 2005b), suggests simulation times higher then 10 minutes if the traditional modeling approach is selected. Having obtained such times is not difficult to carry out complete design of experiments using the full factorial experimental design.

Let us consider for each supply chain node four different parameters: the inventory control policy, the lead time, the market demand intensity and the market demand variability and let us call these parameters factors (in literature factors are also called treatments). In this study, we have chosen, for each factor, different number of levels as reported in table 4.

| Factors | Levels | | | |
|---|---|---|---|---|
| Inventory Control Policy ($x_1$) | rR,1 | rR,2 | rR,3 | rR,4 |
| Stores Lead Time ($x_2$) | 1 | 3 | 5 | |
| Customers' Demand Intensity ($x_3$) | Low | Medium | High | |
| Customers' Demand Variability ($x_4$) | Low | Medium | High | |

Table 4. Factors and Levels

Note that the simulation model user can easily define a different supply chain scenario by changing the number of echelons, the number of STs, DCs and PLs, the number of items or select different parameters (i.e. demand forecast methodologies, transportation modalities, priority rules for ordering and deliveries, etc.). Analogously new parameters or supply chain features can be easily implemented thanks to simulator architecture completely based on programming code. The objective of the application example is to understand the effects of factors levels on three performance measures: fill rate ($Y_1$), average on hand inventory

($Y_2$) and inventory costs ($Y_3$). The outcomes are input-output analytical relations (called the meta-models of the simulation model).

In our application example, checking all possible factors levels combinations (full factorial experimental design) requires 108 simulation runs; if each run is replicated three times we have 324 replications. Having set the simulation model for executing three replications for each simulation run and considering all the factors levels combinations, we have executed, on a single desktop computer, all the experiments taking less than 6 hours. Note that, very often, pre-screening analyses reduce the number of factors to be considered as well as fractional factorial designs reduce the total number of simulation runs. The efficiency of the simulation model in terms of time for executing simulation runs is largely due to the simulation model architecture and modeling approach.

Monitoring the performance of an entire supply chain requires the collection of a huge amount of simulation results. To give the reader an idea of the simulation results generated by the simulation model in our application example, let us consider the fill rate: the simulation model evaluates the fill rate at the end of each replication, as mean value over 500 days. For each supply chain node (both STs and DCs) and for each simulation run (a single combination of the factors levels) the model evaluates 3 fill rate values (9 stores x 4 DCs x 109 simulation runs x 3 replications = 11772 values). Consider the average on hand inventory: the simulation model evaluates, at the end of each replication, the mean value over 500 days. For each supply chain node, for each simulation run and for each item, 3 values of the performance measures are collected (9 stores x 4 DCs x 109 simulation runs x 3 replications x 20 items =235440 values). The same number of values are automatically collected for inventory costs. Obviously it is out of the scope of this chapter to report all simulation results; some simulation results are reported and discussed to provide the reader with a detailed overview of the proposed approach. Table 5 consists of some simulation results for store #1 in terms of fill rate, average on hand inventory and inventory costs (only for three of twenty items). The simulation results consider all factors levels combinations keeping fixed the inventory control policy (rR1). The complete analysis consider 108 simulation runs for checking all factors levels combinations both for stores and DCs. The huge number of simulation results has required the implementation of a specific tool for supporting output analysis. To this end eM-Plant is jointly used with Microsoft Excel and Minitab. As before mentioned, at the end of each replication, simulation results are automatically stored in Excel spreadsheets. Visual Basic Macros are implemented and used for performance measures calculation. Such values are then imported in Minitab projects (opportunely set with the same design of experiments) for statistic analysis. The Microsoft Excel interface works correctly in each supply chain scenario (not only in the application example proposed). The results in terms of mean values calculated by the Microsoft Excel interface can be analyzed by using plots and charts (i.e. fill rate versus inventory policies, on hand inventory versus lead time, etc.). The use of the simulation model does not necessarily require DOE , ANOVA or any kind of statistical methodologies or software.

### 4.1 Simulation results analysis and input output meta-models

Table 5 reports some simulation results for store #1. Let us give a look to the fill rate: the higher is the demand intensity and variability the lower is the fill rate. Such behavior could be explained by considering a greater error in lead time demand (demand forecast over the lead time) as well as a greater number of stock outs and unsatisfied orders. A three-day lead time performs better (in terms of fill rate) than one-day lead time. In addition the higher is

the demand intensity and demand variability the lower is the average on hand inventory (see items 1, 2, 3 in table 5, remaining items show a similar behavior). The higher is the lead time the higher is the average on hand inventory. In effect the higher demand intensity causes an inventory reduction (due to the higher number or orders) whilst a five-day lead time causes high values of the lead time demand. The qualitative explanation of inventory cost seems to be more difficult because of the interaction among the different factors levels.
It is worth say that a qualitative description or analysis of simulation results does not provide a deep understanding of the supply chain behavior and could lead to erroneous conclusions in the decision making process. We know that experiments are natural part of the engineering and scientific process because they help us in understanding how systems and processes work. The validity of decisions taken after an experiment strongly depends on how the experiment was conducted and how the results were analyzed. For these reasons, we suggest to use the simulation model jointly with the Design of Experiment (DOE) and the Analysis of Variance (ANOVA): DOE for experiments planning and ANOVA for understanding how factors (input parameters) affect the supply chain behavior. In effect, many definitive simulation references (i.e. Banks, 1998) say that if some of the processes driving a simulation are random, the output data are also random and simulation runs result in estimates of performance measures. In other words, specific statistical techniques (i.e. DOE and ANOVA) could provide a good support for simulation results analysis.
Our treatment uses ANOVA for understanding the impact of factors levels on performance measures. Let $Y_k$ be one of the performance measures previously defined (k = 1, 2, 3), let $x_i$ be the factors or treatments (with $x_i$ varying between the levels specified in table 4), let $\beta_{ij}$ be the coefficients of the model and let hypothesize a linear statistic input-output model to express $Y_k$ as function of $x_i$.

$$
\begin{aligned}
Y_k = \beta_{0,k} + \sum_{j=1}^{j=h} \beta_{j,k} x_{j,k} + \sum\sum_{i<j} \beta_{ij,k} x_{i,k} x_{j,k} + \sum\sum\sum_{i<j<m} \beta_{ijm,k} x_{i,k} x_{j,k} x_{m,k} + \\
+ \sum\sum\sum\sum_{i<j<m<n} \beta_{ijmn,k} x_{i,k} x_{j,k} x_{m,k} x_{n,k} + \varepsilon_k
\end{aligned}
\tag{14}
$$

$k = 1, 2, 3$ number of performance measures;
h = 1, 2, 3, 4 number of factors.
The Analysis of Variance allows to evaluate those factors that have a real impact on the performance measure considered or, in other words, evaluating all the terms in equation (14) eventually deleting insignificant factors from the input-output model. The Analysis of Variance decompose the total variability of $Y_k$ into components; each component is a sum of squares associated with a specific source of variation (treatments) and it is usually called treatment sum of squares. Without enter in formulas details, if changing the levels of a factor has no effect on $Y_k$ variance, then the expected value of the associated treatment sum of squares is just an unbiased estimator of the error variance (this is known as null hypothesis, $H_0$).
On the contrary, if changing the level of a factor has effect on $Y_k$, then the expected value of the associated treatment sum of squares is the estimation of the error plus a positive term that incorporates variation due the effect of the factor (alternative hypothesis, $H_1$). It follows that, by comparing the treatment mean square and the error mean square, we can understand which factors affect the performance measure $Y_k$. Such comparison is usually made by using a Fisher-statistic test. In addition, the ANOVA evaluates the coefficients of equation 14.

| Inventory Control Policy | Lead Time | Demand Intensity | Demand Variability | Run Order | Fill Rate | Average OHI - Item1 | Average OHI - Item2 | Average OHI - Item3 | Inventory Cost - Item1 [€] | Inventory Cost - Item2 [€] | Inventory Cost - Item3 [€] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| rR1 | 1 | Low | Low | 1 | 0,762 | 103 | 85 | 78 | 408,46 | 420,64 | 407,21 |
| rR1 | 1 | Low | Medium | 2 | 0,728 | 104 | 84 | 79 | 524,02 | 562,90 | 520,22 |
| rR1 | 1 | Low | High | 3 | 0,733 | 104 | 85 | 80 | 520,67 | 547,96 | 549,76 |
| rR1 | 1 | Medium | Low | 4 | 0,536 | 37 | 36 | 34 | 790,32 | 754,04 | 692,61 |
| rR1 | 1 | Medium | Medium | 5 | 0,533 | 38 | 36 | 35 | 770,76 | 749,73 | 696,53 |
| rR1 | 1 | Medium | High | 6 | 0,525 | 37 | 36 | 35 | 766,29 | 727,03 | 691,30 |
| rR1 | 1 | High | Low | 7 | 0,386 | 20 | 19 | 20 | 996,79 | 910,36 | 919,58 |
| rR1 | 1 | High | Medium | 8 | 0,385 | 20 | 18 | 19 | 881,84 | 1039,74 | 985,23 |
| rR1 | 1 | High | High | 9 | 0,374 | 21 | 19 | 20 | 891,43 | 921,24 | 873,29 |
| rR1 | 3 | Low | Low | 10 | 0,838 | 112 | 95 | 89 | 441,44 | 447,90 | 436,59 |
| rR1 | 3 | Low | Medium | 11 | 0,833 | 113 | 94 | 90 | 559,20 | 622,53 | 606,67 |
| rR1 | 3 | Low | High | 12 | 0,813 | 113 | 95 | 90 | 568,77 | 602,89 | 578,57 |
| rR1 | 3 | Medium | Low | 13 | 0,578 | 52 | 49 | 48 | 838,59 | 800,66 | 786,28 |
| rR1 | 3 | Medium | Medium | 14 | 0,554 | 53 | 50 | 51 | 768,47 | 754,35 | 774,04 |
| rR1 | 3 | Medium | High | 15 | 0,560 | 54 | 48 | 49 | 831,60 | 782,69 | 770,58 |
| rR1 | 3 | High | Low | 16 | 0,402 | 36 | 34 | 45 | 1038,40 | 975,13 | 988,23 |
| rR1 | 3 | High | Medium | 17 | 0,376 | 40 | 38 | 42 | 827,87 | 901,80 | 953,69 |
| rR1 | 3 | High | High | 18 | 0,379 | 41 | 42 | 35 | 933,43 | 961,85 | 811,90 |
| rR1 | 5 | Low | Low | 19 | 0,828 | 119 | 100 | 93 | 439,70 | 454,48 | 411,17 |
| rR1 | 5 | Low | Medium | 20 | 0,837 | 118 | 101 | 95 | 579,33 | 618,32 | 581,03 |
| rR1 | 5 | Low | High | 21 | 0,829 | 119 | 98 | 94 | 577,69 | 594,15 | 589,47 |
| rR1 | 5 | Medium | Low | 22 | 0,561 | 55 | 57 | 51 | 794,86 | 833,73 | 714,95 |
| rR1 | 5 | Medium | Medium | 23 | 0,581 | 58 | 56 | 58 | 785,19 | 852,77 | 808,67 |
| rR1 | 5 | Medium | High | 24 | 0,568 | 57 | 56 | 53 | 793,25 | 871,55 | 710,71 |
| rR1 | 5 | High | Low | 25 | 0,394 | 49 | 48 | 54 | 998,87 | 983,49 | 971,56 |
| rR1 | 5 | High | Medium | 26 | 0,399 | 54 | 49 | 51 | 969,71 | 1019,55 | 952,16 |
| rR1 | 5 | High | High | 27 | 0,399 | 48 | 49 | 42 | 952,87 | 990,75 | 1036,61 |

Table 5. Simulation results for Store #1 (rR1 inventory control policy, 3/20 items)

Table 6 consists of some results obtained using the statistical software Minitab: the fill rate ANOVA (table 6, upper part) and average on hand inventory ANOVA (table 6, lower part) of item #1 for store #1. In addition, table 6 reports all the terms of equation 14 (for both performance measures).

From the ANOVA theory it is well known that all the factors with a *p* value less or equal to the confidence level used for the analysis (α=0.05) have an impact on the performance measure. The *P*-value is the probability that the F-statistic test will take on a value that is at least as extreme as the observed value of the statistic when the null hypothesis *H*0 is true.

Let us discuss the results of the fill rate ANOVA reported in the upper part of table 6. Note that all factors levels have an impact on the fill rate. All the effects have to be taken into consideration: first order, second order, third order and fourth order effects. Such results show the high complexity of a supply chain and the strong interaction among the control policy used for inventory management and other critical factors such as demand intensity and variability and lead times (usually in many systems the third and fourth effects can be neglected).

For a better understanding of the fill rate analysis of variance (for store #1) we have plotted (see figures 10 and 11) the main effects and the second order interaction effects of equation (14). The inventory control policies have a different effect on store #1 fill rate. *rR1* and rR3 give as result an average fill rate of about 0.55 (mostly showing an analogous behavior); rR2gives an average fill rate of about 0.40 (the worst performance) and rR4 about 0.60 (the best one). The rR4 policy performs better than the other policies because it uses the policy parameters review period is based on cost optimization. The demand intensity has a strong impact on fill rate due to the greater number of required items: the average fill rates is about 0.80 in correspondence of low demand intensity, 0.50 in correspondence of medium intensity and 0.35 in case of high intensity. Lead times and demand variability cannot be considered as important as inventory control policy and demand intensity even if their effect on fill rate cannot be neglected.

Now let us focus on interaction effects (see fig. 11). The interaction between inventory control policies and lead times show a better behavior for rR1 and rR2 in correspondence of high lead times (the average fill rate increases in correspondence of higher lead times from 0.5 to 0.6 for rR1 policy and from 0.25 to 0.40 for rR2 policy). On the contrary, rR3 and rR4 show an opposite behavior and perform better with low lead-time values: the average fill rate decreases from 0.65 to 0.50 for rR3 policy and from 0.65 to 0.60 for rR4 policy. Note that the fill rate reduction with rR4 is smaller than the reduction with rR3. With regards to demand intensity rR1, rR3, rR4 policies show a similar trend in correspondence of low, medium and high demand intensity (the fill rate decrease from 0.90 to 0.40), whilst rR2 gives lower fill rate values (from 0.60 to 0.20). Similar results emerge when considering demand variability: rR1, rR3, rR4 policies show a similar trend (fill rate around 0.60 even if the rR4 performs better than rR1 and rR3), whilst rR2 gives the worst performance (fill rate about 0.40). All the remaining plots in figure 10 give useful information as well as help in understanding how the interaction among factors levels affect the store fill rate.

Both first order effect plots (figure 10) and interaction plots (figure 11) are obtained by using equation 14. The *Terms* columns (upper part of table 6) report all the values of the coefficients of equation 14. Such coefficients must be read per column and their order reflects the order of the experimental design matrix (i.e. consider the performance measure fill rate, $Y_1$, $\beta_{01}$=0.0022, $\beta_{11}$=-0.0010, etc.). Focusing only on fill rate, the best design solution for store #1 is rR4 inventory control policy and three days lead time.

| Fill rate ANOVA – Store #1 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Terms | Terms | Terms | Terms | Terms | Terms | Terms |
| $x_1$ | 3 | 2,87475 | 2,87475 | 0,95825 | 5832,04 | 0,000 | 0,7185 | 0,0022 | -0,0054 | -0,0253 | -0,0113 | 0,0051 | 0,0148 |
| $x_2$ | 2 | 0,07717 | 0,07717 | 0,03858 | 234,83 | 0,000 | 0,0314 | -0,0010 | -0,0051 | -0,0082 | -0,0084 | -0,0082 | 0,0159 |
| $x_3$ | 2 | 11,07926 | 11,07926 | 5,53963 | 33714,93 | 0,000 | -0,1575 | -0,0288 | 0,0115 | -0,0107 | 0,0065 | -0,0034 | -0,0258 |
| $x_4$ | 2 | 0,01681 | 0,01681 | 0,00841 | 51,16 | 0,000 | 0,0335 | -0,0158 | 0,0112 | 0,0046 | 0,0022 | 0,0072 | -0,0254 |
| $x_1$*$x_2$ | 6 | 0,41302 | 0,41302 | 0,06884 | 418,95 | 0,000 | -0,0192 | 0,0409 | -0,0058 | 0,0057 | 0,0054 | 0,0167 | 0,0132 |
| $x_1$*$x_3$ | 6 | 0,18962 | 0,18962 | 0,0316 | 192,34 | 0,000 | 0,0185 | -0,0005 | -0,0060 | -0,0068 | 0,0017 | -0,0016 | 0,0107 |
| $x_1$*$x_4$ | 6 | 0,03237 | 0,03237 | 0,00539 | 32,83 | 0,000 | 0,2402 | -0,0052 | 0,0016 | -0,0017 | 0,0070 | -0,0082 | |
| $x_2$*$x_3$ | 4 | 0,13543 | 0,13543 | 0,03386 | 206,07 | 0,000 | -0,0306 | -0,0051 | 0,0069 | 0,0028 | 0,0033 | 0,0113 | |
| $x_2$*$x_4$ | 4 | 0,0231 | 0,0231 | 0,00577 | 35,15 | 0,000 | 0,0057 | -0,0014 | -0,0040 | -0,0003 | 0,0034 | 0,0133 | |
| $x_3$*$x_4$ | 4 | 0,04209 | 0,04209 | 0,01052 | 64,05 | 0,000 | 0,0044 | 0,0096 | 0,0107 | 0,0290 | 0,0086 | -0,0094 | |
| $x_1$*$x_2$*$x_3$ | 12 | 0,19436 | 0,19436 | 0,0162 | 98,58 | 0,000 | -0,0139 | 0,0142 | -0,0593 | 0,0226 | 0,0025 | -0,0022 | |
| $x_1$*$x_3$*$x_4$ | 12 | 0,07523 | 0,07523 | 0,00627 | 38,16 | 0,000 | -0,0036 | -0,0309 | 0,0284 | -0,0140 | 0,0036 | 0,0113 | |
| $x_2$*$x_3$*$x_4$ | 8 | 0,05234 | 0,05234 | 0,00654 | 39,82 | 0,000 | -0,0555 | -0,0016 | 0,0113 | -0,0114 | -0,0126 | 0,0044 | |
| $x_1$*$x_2$*$x_4$ | 12 | 0,08415 | 0,08415 | 0,00701 | 42,68 | 0,000 | -0,0005 | 0,0172 | -0,0012 | -0,0068 | -0,0139 | -0,0049 | |
| $x_1$*$x_2$*$x_3$*$x_4$ | 24 | 0,16346 | 0,16346 | 0,00681 | 41,45 | 0,000 | 0,0460 | -0,0134 | 0,0271 | -0,0090 | -0,0146 | -0,0014 | |
| Error | 216 | 0,03549 | 0,03549 | 0,00016 | | | 0,0239 | -0,0026 | -0,0337 | 0,0030 | -0,0141 | -0,0274 | |
| Total | 323 | 15,48867 | | | | | -0,0196 | -0,0034 | 0,0091 | 0,0059 | 0,0134 | -0,0299 | |
| Item #1 on hand inventory ANOVA – Store #1 | | | | | | | | | | | | | |
| Source | DF | Seq SS | Adj SS | Adj MS | F | P | Terms | Terms | Terms | Terms | Terms | Terms | Terms |
| $x_1$ | 3 | 115183,2 | 115183,2 | 38394,4 | 6738,78 | 0,000 | 75,8025 | 1,3951 | -0,3272 | -0,1759 | -0,6728 | 1,8395 | 0,4722 |
| $x_2$ | 2 | 29430,7 | 29430,7 | 14715,3 | 2582,76 | 0,000 | -15,7284 | 3,9012 | -0,4846 | -0,9136 | -0,4599 | -0,3549 | 1,4167 |
| $x_3$ | 2 | 199587,1 | 199587,1 | 99793,5 | 17515,22 | 0,000 | -20,5679 | 1,8642 | 0,2469 | -0,3210 | 0,5216 | -1,1142 | -1,5370 |
| $x_4$ | 2 | 105,2 | 105,2 | 52,6 | 9,23 | 0,000 | 11,3333 | -11,8519 | 0,1728 | 0,1790 | 0,2068 | 1,3025 | -1,2315 |
| $x_1$*$x_2$ | 6 | 674,7 | 674,7 | 112,5 | 19,74 | 0,000 | -12,5617 | 3,1481 | -0,3642 | 0,8272 | -0,0895 | -0,2068 | 1,3796 |
| $x_1$*$x_3$ | 6 | 10050,3 | 10050,3 | 1675 | 293,99 | 0,000 | 2,0494 | 0,4321 | -0,1605 | -0,8272 | 0,5864 | 0,4043 | -0,0093 |
| $x_1$*$x_4$ | 6 | 138,8 | 138,8 | 23,1 | 4,06 | 0,001 | 34,8642 | -0,1327 | -0,4506 | -0,3086 | 0,0679 | -0,2438 | |
| $x_2$*$x_3$ | 4 | 2924,1 | 2924,1 | 731 | 128,31 | 0,000 | -13,9136 | -0,2840 | 0,3920 | 0,3765 | 0,2994 | 1,1790 | |
| $x_2$*$x_4$ | 4 | 92,2 | 92,2 | 23,1 | 4,05 | 0,003 | -0,8025 | -0,5525 | -0,9043 | 0,5062 | 0,1821 | -0,0617 | |
| $x_3$*$x_4$ | 4 | 26,1 | 26,1 | 6,5 | 1,15 | 0,336 | 0,4660 | 0,3704 | 0,0216 | 2,8148 | 0,3395 | -0,7747 | |
| $x_1$*$x_2$*$x_3$ | 12 | 995,3 | 995,3 | 82,9 | 14,56 | 0,000 | -0,1420 | 0,9537 | -1,3642 | 0,8148 | -0,4012 | -0,1265 | |
| $x_1$*$x_3$*$x_4$ | 12 | 426,2 | 426,2 | 35,5 | 6,23 | 0,000 | 0,7284 | 4,3395 | -0,0772 | -1,0185 | 0,8673 | 0,8457 | |
| $x_2$*$x_3$*$x_4$ | 8 | 236,3 | 236,3 | 29,5 | 5,18 | 0,000 | 3,0309 | 0,4228 | -0,7809 | -1,0741 | -0,6574 | 0,7438 | |
| $x_1$*$x_2$*$x_4$ | 12 | 469,9 | 469,9 | 39,2 | 6,87 | 0,000 | -1,1358 | -0,2438 | 0,4784 | -0,3395 | -1,4630 | -0,1636 | |
| $x_1$*$x_2$*$x_3$*$x_4$ | 24 | 786,6 | 786,6 | 32,8 | 5,75 | 0,000 | -0,5741 | 0,2006 | 3,5370 | -0,5432 | -0,6481 | 0,0401 | |
| Error | 216 | 1230,7 | 1230,7 | 5,7 | | | -0,5556 | 0,2006 | -1,3241 | 0,7994 | -1,1204 | -2,0556 | |
| Total | 323 | 362357,4 | | | | | 2,0988 | -0,2901 | 2,1574 | 0,4846 | 0,3765 | -2,0000 | |

Table 6. Analysis of Variance for Store #1 (*Fill Rate* and *item#1 Average On Hand Inventory*) and equation 14 coefficients

Let us consider now the analysis of variance of the average on hand inventory for store #1 and item #1 (lower part of table 6). All the factors have an impact on the average on hand inventory except for the interaction x3*x4 (Demand Intensity and Demand Variability). The lower right part of table 6 consists of terms of equation (14). Also in this case the equation 14 can be used for plotting first order and interaction effects and understanding, from a quantitative point of view, the average on hand inventory behavior.

Needless to say that similar results have been obtained for the third performance measure, the inventory cost. The same approach is followed for each item of store #1, for each store and for each distribution center. Note that the aim of the application example is not to find out the best configuration of the supply chain but to show the complexity of the inventory problem along the supply chain and the simulation potentials as decision-making tool for supply chain management. The high level of results detail (analysis of the fill rate for each supply chain node, analysis of on hand inventory and inventory costs for each item and in each supply node) helps in understanding simulation models capabilities as decision-making tool. In effect as reported in literature (refer to literature overview section) the supply chain decision process requires accurate analysis on the whole supply chain. In addition, the simulation model architecture jointly with Excel and Minitab spreadsheets guarantees high flexibility in terms of supply chain scenarios definition, high efficiency in terms of time for executing simulation runs and analyzing simulation results.

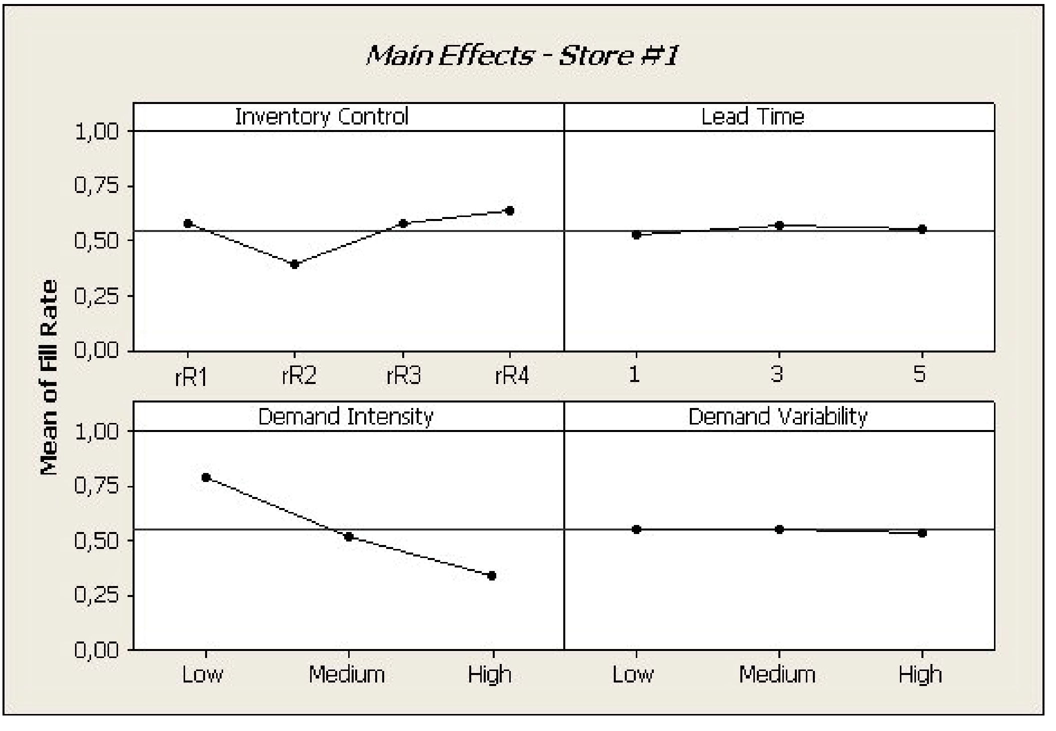



Fig. 10. Main effects plot: Store #1 fill rate versus inventory control policies, lead time, demand intensity and demand variability

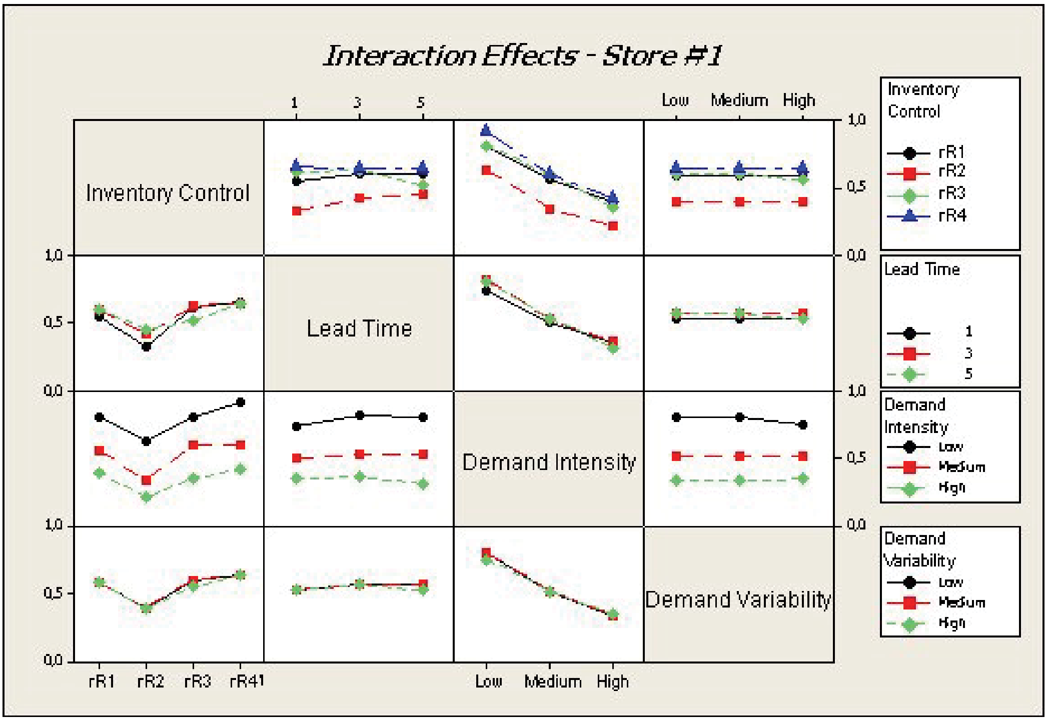



Fig. 11. Effects of factors interaction on fill rate

### 4.2 Testing the simulation results validity: residuals analysis

In using ANOVA for simulation results analysis, we strongly suggest to test ANOVA results validity. The Analysis of Variance assumes (as starting hypothesis) that the observations are normally and independently distributed, with the same variance for any combination of factors levels. These assumptions must be verified by means of the analysis of residuals for accepting the validity of the input-output analytical models (equation 14).

A residual is the difference between an observation of the performance measure and the corresponding average value calculated on the 3 replications. The assumption of normality can be tested by building a *normal probability plot* of residuals. If residuals approximately fall along a straight line passing form the centre of the graph, the assumption of normality can be accepted. In figure 12 (upper-left part) we observe that the deviation from normality is not severe (store #1, fill rate). The assumption of equal variance is tested by plotting residuals against the factors levels or against the fill rate: residuals variability must anyhow not depend on the level of factors or on the fill rate. Figure 12 (upper-right part) shows residuals versus the fitted values and do not show any particular trend; therefore, the equal variance hypothesis is accepted. Finally, the assumption of independence is tested by plotting residuals against the implementation order of simulation runs. A sequence of positive or negative residuals could indicate that observations are dependent among themselves. Figure 12 (lower part) shows that the hypothesis of independence of observations is accepted. The residuals analysis, as part of the Minitab standard tools, can be easily carried out for each supply chain scenario.

In case of starting hypothesis rejection, a linear statistical model (as the model in equation 14) must be rejected. A test for model curvature should be conducted.

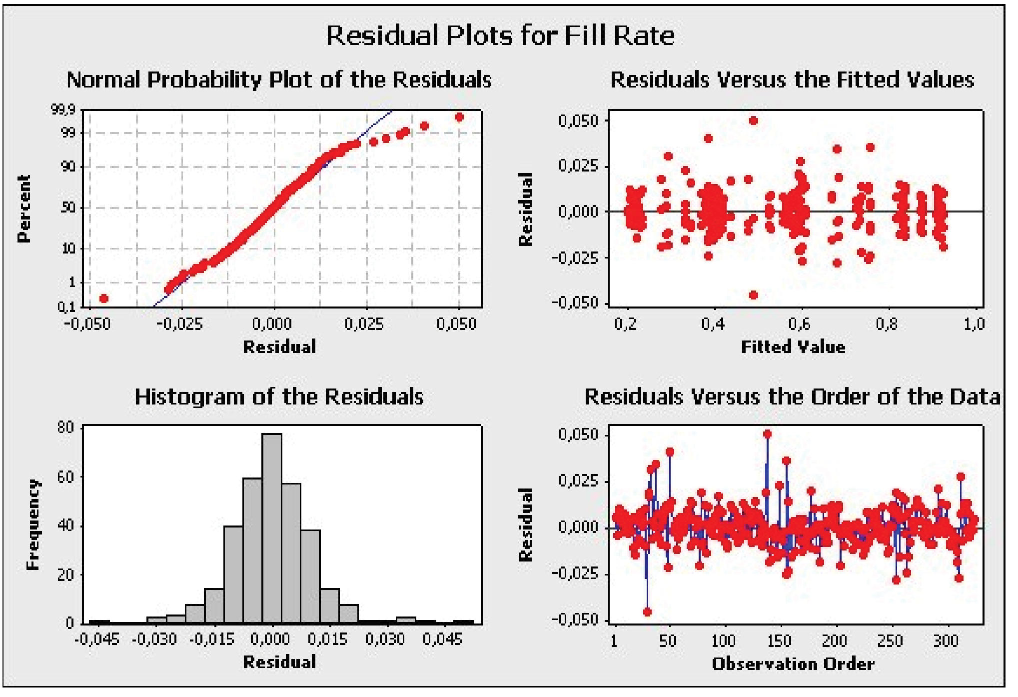



Fig. 12. Test of the simulation results validity: Residuals analysis

## 5. The Warehouse management problem: interactions among operational strategies, available resources and internal logistic costs

The survey of state of art proposed in section 2.2 highlights that, very often, models proposed are not able to recreate the whole complexity of a real warehouse system (including stochastic variables, huge number of items, multiple deliveries, etc). The application example proposed in this section investigates the effects of warehouse resources management on warehouse efficiency highlighting as the interactions among operational strategies and available resources strongly affect the internal logistic costs. In particular the simulation model of a real warehouse is presented. The simulator, called WILMA (*Warehouse and Internal Logistics Management*) has been developed under request of one of the major Italian company operating in the large scale retail sector.

### 5.1 Warehouse description and warehouse simulation model

As before mentioned, the warehouse belongs to one of the most important company operating in the large scale retail sector (in Italy) and it is characterized by:

- total surface: 13000 $m^2$;
- shelves surface: 5000 $m^2$;
- surface for packing and shipping operations: 3000 $m^2$;
- surface for unloading and control operations: 1800 $m^2$;
- three levels of shelves;
- eight types of products;
- capacity in terms of pallets: 28400 pallets;

- capacity in terms of pallets for each product: 3550 pallets;
- capacity in terms of packages: about one million packages.

Figure 13 shows the warehouse layout.

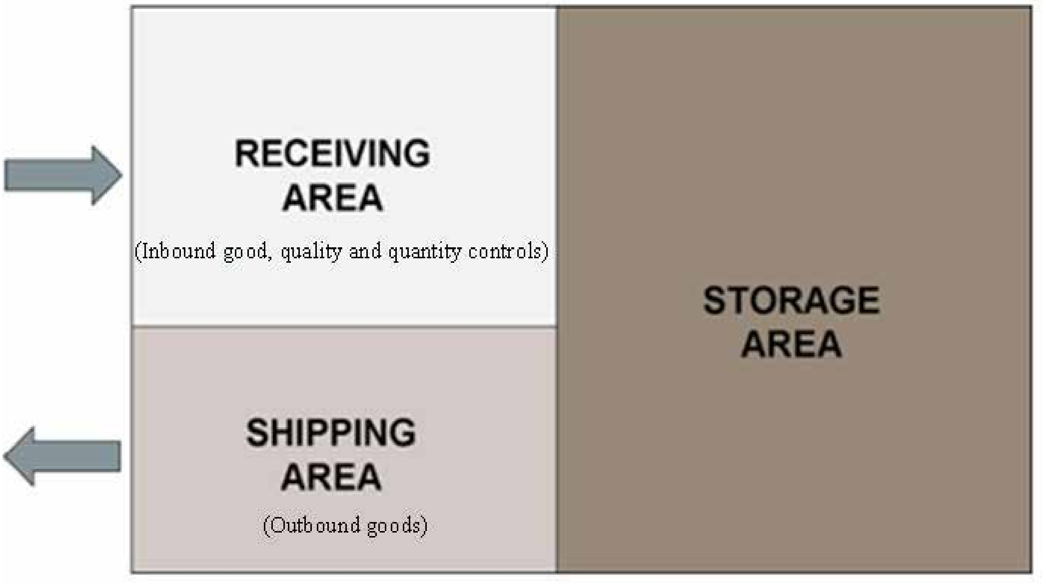



Fig. 13. The warehouse layout

The main modeling effort was carried out to recreate with satisfactory accuracy the most important warehouse operations:

- trucks arrival and departure for items deliveries (from suppliers to the warehouse and from the warehouse to retailers);
- materials handling operations (performed by using forklifts and lift trucks) including, trucks unloading operations, inbound quality and quantity controls, preparation for storage, storage operations, retrieval operations, picking operations, preparation for shipping, packaging operations, trucks loading operations and shipping;
- performance measures control and monitoring (a detailed description of performance measures will be provided later on).

The simulation software adopted for developing WILMA simulator is the commercial package Anylogic™ by *XJ Technologies*. Most of the logics and rules of the real warehouse are implemented by using ad-hoc Java routines. The description proposed below will be useful for those readers interested in developing similar simulation models. Figure 14 shows the simulation model Flow Chart.

In order to support scenarios investigation, the main variables of the WILMA simulator have been completely parametrized. To this end, the simulator is equipped with a dedicated Graphic User Interface (*GUI*) with a twofold functionality:

- to increase the simulation model flexibility changing its input parameters both at the beginning of the simulation run and at run-time observing the effect on the warehouse behavior (*Input Section*);
- to provide the user with all simulation outputs for evaluating and monitoring the warehouse performances (*Output Section*).

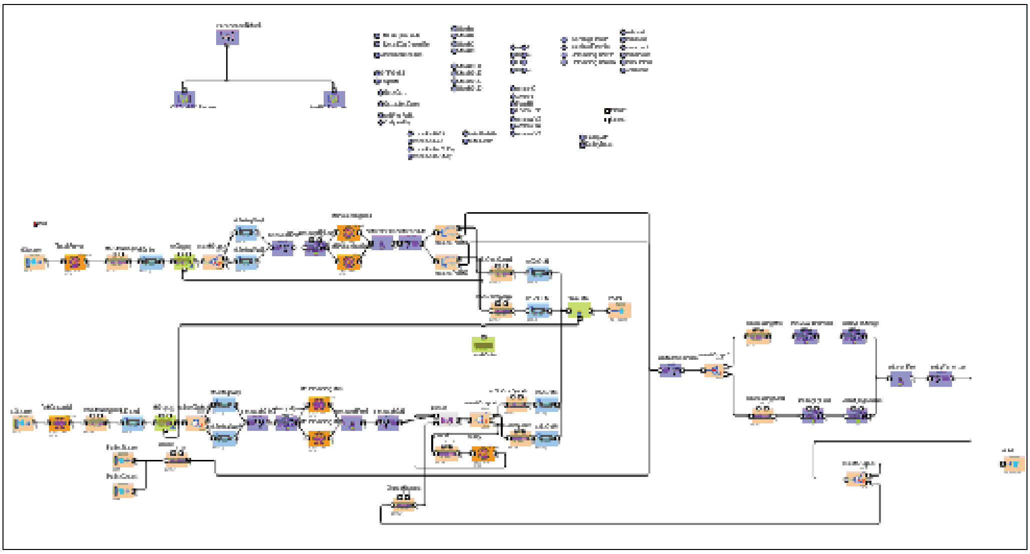


Fig. 14. The WILMA Simulation Model Flow Chart

The *Input Section* (figure 15) is in four different parts:

- The *Suppliers' Trucks* section which includes slider objects for changing the following parameters: suppliers' trucks arrival time, number of suppliers' trucks per day, time window in which suppliers' trucks deliver products;
- the *Retailers' Trucks* section includes slider objects for changing the following parameters: retailers' trucks arrival time, number of retailers' trucks per day, time window for retailers' trucks arrival, time for starting items preparation;


Fig. 15. The WILMA Input Section (part of the WILMA Graphic User Interface)

- the *Warehouse Management parameters* section which includes slider objects for changing the following parameters: shelves levels, number of forklifts, number of lift trucks, number of docks available for loading and unloading operations, forklifts and lift trucks efficiency, stock-out costs parameters;
- the *Logistics Internal Costs* section which includes slider objects for changing the following parameters: sanction fee for retailers/suppliers, time after which the warehouse has to pay a sanction fee to retailers for operations performed out of the scheduled period, time after which suppliers have to pay a sanction fee to the warehouse for operations performed out of the scheduled period.

The *Output Section* (figure 16) provides the user with the most important warehouse performance measures. The main performance measures include the following:

- forklifts utilization level;
- lift trucks utilization level;
- service level provided to suppliers' trucks;
- service level provided to retailers' trucks;
- waiting time of suppliers' trucks before starting the unloading operations;
- waiting time of retailers' trucks before starting the loading operations;
- number of packages handled per day (actual and average values);
- daily cost for each handled package (actual and average values).

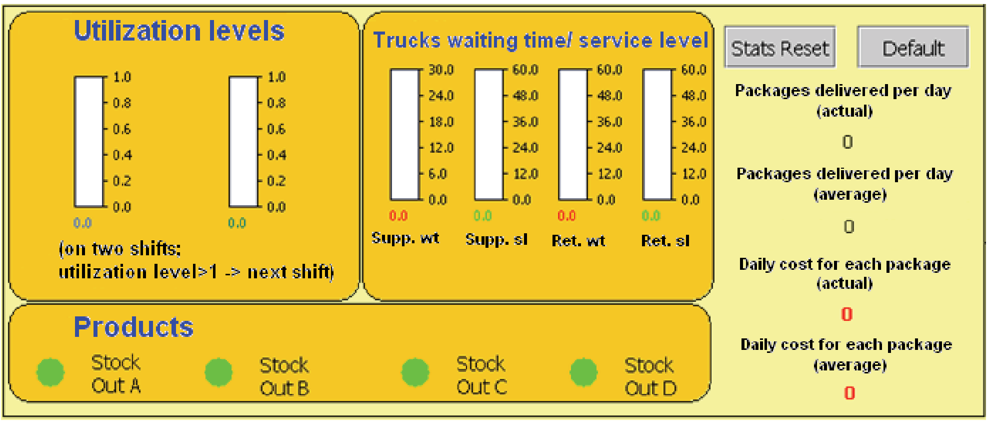



Fig. 16. The WILMA Output Section (part of the WILMA Graphic User Interface)

### 5.2 Internal logistics management: scenarios definition and simulation experiments

The WILMA simulation model has been used to investigate the effects of warehouse resources management on warehouse efficiency highlighting as the interactions among operational strategies and available resources strongly affect the internal logistic costs. The analysis carried out by using the WILMA simulator include the following:

- internal resources allocations versus number of packages handled per day;
- internal resources allocations versus the daily cost for each handled package;
- Internal resources allocations versus suppliers' waiting time and retailers' waiting time

In each case a sensitivity analysis is carried out and an input-output analytical model is determined. As in the first application example, the simulation approach is jointly used with the Design of Experiments and Analysis of Variance.

The input parameters (*factors*) taken into consideration are:

- the number of suppliers' trucks per day (*NTS*);
- the number of retailers' trucks per day (*NTR*);
- the number of forklifts (*NFT*);
- the number of lift trucks (*NMT*);
- the number of shelves levels (*SL*).

The variation of such parameters creates distinct operative scenarios characterized by different operative strategies and resources availability, allocation and utilization. The performance measures considered are:

- the average number of handled packages per day (*APDD*);
- the average value of the daily cost for each handled package (*ADCP*);
- the waiting time of suppliers' trucks before starting unloading operations (*STWT*);
- the waiting time of retailers' trucks before starting loading operations (*RTWT*).

The experiments planning is supported by the Design of Experiments (a Full Factorial Experimental Design is used). Table 7 consists of factors and levels used for the design of experiments.

| **Factors** | **Level 1** | **Level 2** |
|---|---|---|
| Number of suppliers' trucks per day, *NTS* ($x_1$) | 80 | 100 |
| Number of retailers' trucks per day, *NTR* ($x_2$) | 30 | 40 |
| Number of forklifts, *NFT*, ($x_3$) | 6 | 24 |
| Number of lift trucks, *NMT*, ($x_4$) | 12 | 50 |
| Number of shelves levels, *SL*, ($x_5$) | 3 | 5 |

Table 7. DOE Factors and Levels

As shown in Table 7, each factor has two levels: in particular, Level 1 indicates the lowest value for the factor while Level 2 its greatest value. In order to test all the possible factors combinations, the total number of the simulation runs is $2^5$. Each simulation run is replicated three times, so the total number of replications is 96 (32x3=96). The simulation results are studied, according to the various experiments, by means of the Analysis Of Variance (*ANOVA*) and graphic tools.

Let $Y_i$ be the i-th performance measure and let $x_i$ be the factors, equation 15 expresses the i-th performance measure as linear function of the factors.

$$Y_i = \beta_0 + \sum_{i=1}^{5} \beta_i x_i + \sum_{i=1}^{5}\sum_{j>i}^{5} \beta_{ij} x_i x_j + \sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5} \beta_{ijh} x_i x_j x_h + \sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5}\sum_{k>h}^{5} \beta_{ijhk} x_i x_j x_h x_k + \\ + \sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5}\sum_{k>h}^{5}\sum_{p>k}^{5} \beta_{ijhkp} x_i x_j x_h x_k x_p + \varepsilon_{ijhkpn} \quad (15)$$

where:

$\beta_0$ is a constant parameter common to all treatments;

$\sum_{i=1}^{5}\beta_i x_i$ are the five main effects of factors;

$\sum_{i=1}^{5}\sum_{j>i}^{5}\beta_{ij} x_i x_j$ are the ten two-factors interactions;

$\sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5}\beta_{ijh} x_i x_j x_h$ represents the three-factors interactions;

$\sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5}\sum_{k>h}^{5}\beta_{ijhk} x_i x_j x_h x_k$ are the three four-factors interactions;

$\sum_{i=1}^{5}\sum_{j>i}^{5}\sum_{h>j}^{5}\sum_{k>h}^{5}\sum_{p>k}^{5}\beta_{ijhkp} x_i x_j x_h x_k x_p$ is the sole five-factors interaction;

$\varepsilon_{ijhkpn}$ is the error term;

$n$ is the number of total observations.

In particular the analysis carried out aims at:

- identifying those factors that have a significant impact on the performance measures (*sensitivity analysis*);
- evaluating the coefficients of equation 4.2 in order to have an analytical relationship capable of expressing the performance measures as function of the most critical factors.

### 5.3 Internal resources allocations versus number of packages handled per day (*APDD*)

Table 8 reports the experiments design matrix and the simulation results in terms of average number of handled packages per day. The first four table columns show all the possible combinations of the factors levels while the last column reports the results provided by the WILMA simulation model for the APDD performance measure. Note that the APDD values reported in the last column of Table 8 are values obtained as average on three simulation replications.

According to the ANOVA theory, the non-negligible effects are characterized by *p-value* $\leq \alpha$ where $p$ is the probability to accept the negative hypothesis (the factor has no impact on the performance measure) and $\alpha = 0.05$ is the confidence level used in the analysis of variance. According to the ANOVA, the most significant factors are:

- NTS (the number of suppliers' trucks per day);
- NTR (the number of retailers' trucks per day);
- NFT (the number of forklifts);
- NMT (the number of lift trucks);
- NTR*NMT (the interaction between the number of retailers' trucks per day and the number of lift trucks);
- NTS* NTR* NFT (the interaction between the number of suppliers' trucks per day, the number of retailers' trucks per day and the number of forklifts).

| *NTS* | *NTR* | *NFT* | *NMT* | *SL* | *APDD* |
|---|---|---|---|---|---|
| 80 | 30 | 6 | 12 | 3 | 30370 |
| 80 | 30 | 6 | 12 | 5 | 30345 |
| 80 | 30 | 6 | 50 | 3 | 30439 |
| 80 | 30 | 6 | 50 | 5 | 30457 |
| 80 | 30 | 24 | 12 | 3 | 30421 |
| 80 | 30 | 24 | 12 | 5 | 30358 |
| 80 | 30 | 24 | 50 | 3 | 30387 |
| 80 | 30 | 24 | 50 | 5 | 30488 |
| 80 | 40 | 6 | 12 | 3 | 40574 |
| 80 | 40 | 6 | 12 | 5 | 40501 |
| 80 | 40 | 6 | 50 | 3 | 40603 |
| 80 | 40 | 6 | 50 | 5 | 40580 |
| 80 | 40 | 24 | 12 | 3 | 40551 |
| 80 | 40 | 24 | 12 | 5 | 40568 |
| 80 | 40 | 24 | 50 | 3 | 40553 |
| 80 | 40 | 24 | 50 | 5 | 40541 |
| 100 | 30 | 6 | 12 | 3 | 38528 |
| 100 | 30 | 6 | 12 | 5 | 37181 |
| 100 | 30 | 6 | 50 | 3 | 30361 |
| 100 | 30 | 6 | 50 | 5 | 30399 |
| 100 | 30 | 24 | 12 | 3 | 30388 |
| 100 | 30 | 24 | 12 | 5 | 30405 |
| 100 | 30 | 24 | 50 | 3 | 30416 |
| 100 | 30 | 24 | 50 | 5 | 30387,6 |
| 100 | 40 | 6 | 12 | 3 | 35846,1 |
| 100 | 40 | 6 | 12 | 5 | 37186,2 |
| 100 | 40 | 6 | 50 | 3 | 40498,8 |
| 100 | 40 | 6 | 50 | 5 | 40532,1 |
| 100 | 40 | 24 | 12 | 3 | 40550 |
| 100 | 40 | 24 | 12 | 5 | 35447,4 |
| 100 | 40 | 24 | 50 | 3 | 40530 |
| 100 | 40 | 24 | 50 | 5 | 40563,6 |

Table 8. Design Matrix and Simulation Results (APDD)

ANOVA results are summarized in table 9:

- the first column reports the sources of variations;
- the second column is the degree of freedom (*DOF*);
- the third column is the Sum of Squares;
- the 4th column is the Adjusted Mean Squares;
- the 5th column is the Fisher statistic;
- the 6th column is the p-value.

| *Source* | *DOF* | *AdjSS* | *AdjMS* | *F* | *P* |
|---|---|---|---|---|---|
| Main Effects | 4 | 50,30 | 125,75 | 23,22 | 0 |
| 2-Way interactions | 1 | 45,24 | 4,52 | 8,35 | 0 |
| 3-Way interactions | 1 | 24,84 | 2,48 | 4,59 | 0,04 |
| Residual Error | 25 | 13,53 | 0,54 | | |
| Total | 31 | | | | |

Table 9. ANOVA Results for APDD (most significant factors)

The input-output meta-model expressing APDD as function of the most important factors is the following:

$$APDD = 21777 + 21,46 * NTS + 348,74 * NTR - 167,083 * NFT + \\ -423,71 * NMT + 12,51 * (NTR * NMT) + 0,028 * (NTS * NTR * NFT) \quad (16)$$

Equation 16 is the most important result of the analysis: it is a powerful tool that can be used for correctly defining, in this case, the average number of packages handled per day in function of the warehouse available resources.

### 5.4 Internal resources allocations versus the daily cost for each handled package (*ADCP*)

The same analysis is carried out taking into consideration the average daily cost per handled packages (*ADCP*). Table 10 reports the design matrix and the simulation results. The normal

| *NTS* | *NTR* | *NFT* | *NMT* | *SL* | *ADCP* |
|---|---|---|---|---|---|
| 80 | 30 | 6 | 12 | 3 | 1,38 |
| 80 | 30 | 6 | 12 | 5 | 1,33 |
| 80 | 30 | 6 | 50 | 3 | 0,48 |
| 80 | 30 | 6 | 50 | 5 | 0,483 |
| 80 | 30 | 24 | 12 | 3 | 3,06 |
| 80 | 30 | 24 | 12 | 5 | 3,91 |
| 80 | 30 | 24 | 50 | 3 | 2,27 |
| 80 | 30 | 24 | 50 | 5 | 0,623 |
| 80 | 40 | 6 | 12 | 3 | 1,38 |
| 80 | 40 | 6 | 12 | 5 | 13,82 |
| 80 | 40 | 6 | 50 | 3 | 0,45 |
| 80 | 40 | 6 | 50 | 5 | 11,54 |
| 80 | 40 | 24 | 12 | 3 | 4,69 |
| 80 | 40 | 24 | 12 | 5 | 5,3 |
| 80 | 40 | 24 | 50 | 3 | 3,69 |
| 80 | 40 | 24 | 50 | 5 | 2,89 |
| 100 | 30 | 6 | 12 | 3 | 3,05 |
| 100 | 30 | 6 | 12 | 5 | 4,31 |
| 100 | 30 | 6 | 50 | 3 | 0,53 |
| 100 | 30 | 6 | 50 | 5 | 6,72 |
| 100 | 30 | 24 | 12 | 3 | 5 |
| 100 | 30 | 24 | 12 | 5 | 6,28 |
| 100 | 30 | 24 | 50 | 3 | 0,64 |
| 100 | 30 | 24 | 50 | 5 | 0,62 |
| 100 | 40 | 6 | 12 | 3 | 3,72 |
| 100 | 40 | 6 | 12 | 5 | 8,18 |
| 100 | 40 | 6 | 50 | 3 | 1,06 |
| 100 | 40 | 6 | 50 | 5 | 8,97 |
| 100 | 40 | 24 | 12 | 3 | 2,7 |
| 100 | 40 | 24 | 12 | 5 | 11 |
| 100 | 40 | 24 | 50 | 3 | 0,48 |
| 100 | 40 | 24 | 50 | 5 | 0,47 |

Table 10. Design Matrix and Simulation Results (ADCP)

probability plot in Figure 17 allows to evaluate the predominant effects (red squares): in this case the first order effects and some effects of the second order:

- NTR (the number of retailers' trucks per day);
- NMT (the number of lift trucks);
- SL (the number of shelves levels);
- NTR*SL (the interaction between the number of retailers' trucks per day and the number of shelves levels);
- NFT*SL (the interaction between the number of suppliers' trucks per day and the number of shelves levels).

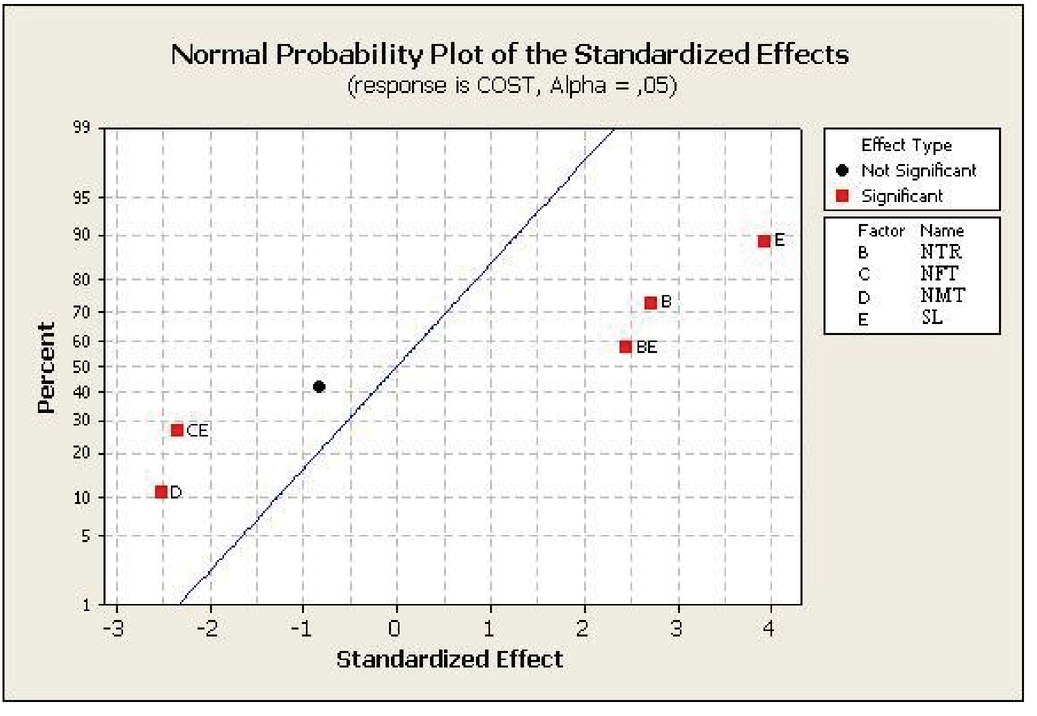



Fig. 17. The Most Significant Effects for the ADCP

Figure 18 shows the trend of ADCP in function of the main effects NTR, NMT and SL. As reported in Figure 18, when the number of lift trucks increases, the average daily cost for packages delivered decreases; the contrary happens with the shelves levels and the number of retailers' trucks variations.

Finally, Figure 19 presents the plots concerning the interaction effects between some couples of parameters (i.e NTR-NFT, NFT-SL). The results obtained by means of DOE and ANOVA allow to correctly arrange warehouse internal resources in order to maximize the average number of handled packages per day and to minimize the total logistics internal costs. In effect an accurate combination of the number of forklifts and lift trucks, help to keep under control both the number of handled packages per day and the total logistic costs.

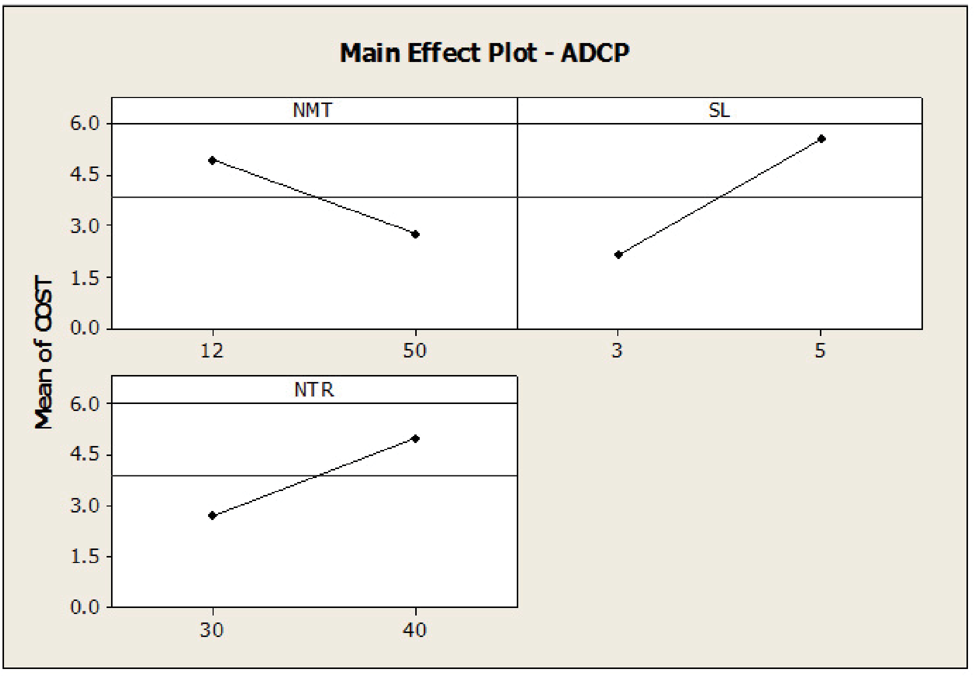



Fig. 18. ADCP versus Main Effects

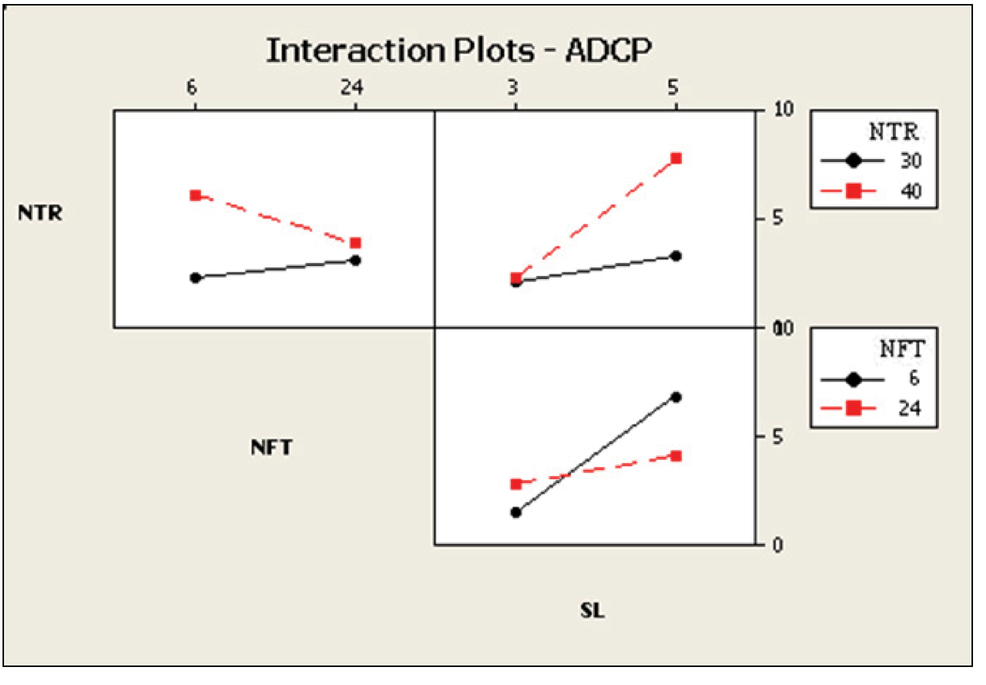



Fig. 19. Interactions Plots for the ADCP

### 5.5 Internal resources allocations versus suppliers' waiting time (STWT) and retailers' waiting time (RTWT)

This Section focuses on evaluating the analytical relationship between factors defined in Table 7 and the waiting time of suppliers' trucks before starting the unloading operation and the waiting time of retailers' trucks before starting the loading operation. Such relationships should be used for a correct system design.

The first analysis carried out aims at detecting factors that influence the waiting time of suppliers' trucks before starting the unloading operations (*STWT*). Adopting also in this case a confidence level α = 0.05, the Pareto Chart in Figure 20 highlights factors that influence STWT. These factors are:

- the number of retailers' trucks per day (*NTR*);
- the number of shelves levels (*SL*);
- the interaction factor between NTR and SL (*NTR*SL*).

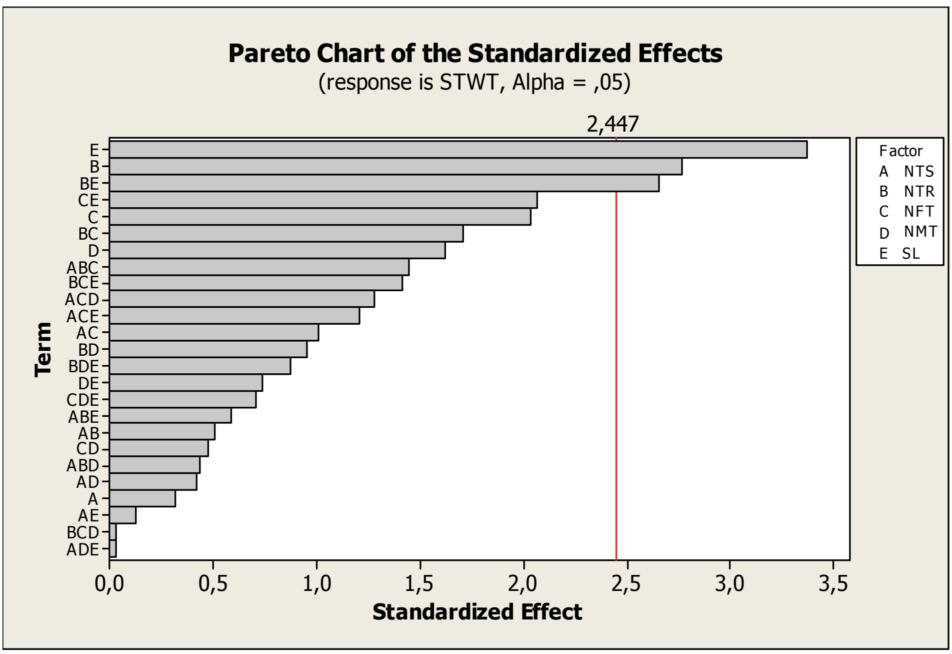



Fig. 20. The Pareto Chart for the STWT

Repeating the ANOVA for the most important factors, it is confirmed that factors are correctly chosen because their p-value is lower than the confidence level, as reported in Table 4.V.

| *Source* | *DF* | *AdjSS* | *AdjMS* | *F* | *P* |
|---|---|---|---|---|---|
| Main Effects | 2 | 14,38 | 7,19 | 8,26 | 0,002 |
| 2-Way interactions | 1 | 5,34 | 5,34 | 6,14 | 0,02 |
| Residual Error | 28 | 24,39 | 0,871 | | |
| Total | 31 | | | | |

Table 11. ANOVA Results for STWT

The input-output meta-model which expresses the analytical relationship between the STWT and the most significant factors is reported in equation 17.

$$STWT = 713{,}58 - 24{,}19 * NTR - 234{,}32 * SL + +8{,}17 * (NTR * SL) \quad (17)$$

This equation clearly explains how the waiting time of suppliers' trucks before starting the unloading operations depends on warehouse available resources.
The same analysis has been carried out taking into consideration the waiting time of retailers' trucks before starting loading operations (*RTWT*). Figure 21 (Normal Probability Plot of the Standardized Effects) helps in understanding those factors that have a significant impact on RTWT; in this case the first order effects and some effects of the second and third order:

- the number of retailers' trucks per day (*NTR*);
- the number of lift trucks (*NMT*);
- the number of shelves levels (*SL*);
- the interaction factor between NTS and NTR (*NTS*NTR*);
- the interaction factor between NTS and NFT (*NTS*NFT*);
- the interaction factor between NTR and SL (*NTR*SL*);
- the interaction factor between NFT and NMT (*NFT*NMT*);
- the interaction factor between NFT and SL (*NFT*SL*);
- the interaction factor between NTR, NFT and SL (*NTR*NFT*SL*);
- the interaction factor between NFT, NMT and SL (*NFT*NMT*SL*).

Table 12 reports analysis of variance results while equation 18 is the input-output analytical model that expresses RTWT as function of the predominant effects:

$$\begin{aligned} RTWT &= 261{,}843 - 13{,}125 * NTR + 3{,}159 * NMT - 166{,}299 * SL + 0{,}081 * (NTS * NTR) + \\ &-0{,}029 * (NTS * NFT) + 5{,}930 * (NTR * SL) + 0{,}122 * (NFT * NMT) + 1{,}027 * (NFT * SL) + \\ &-0{,}073 * (NTR * NFT * SL) - 0{,}022 * (NFT * NMT * SL) \end{aligned} \quad (18)$$

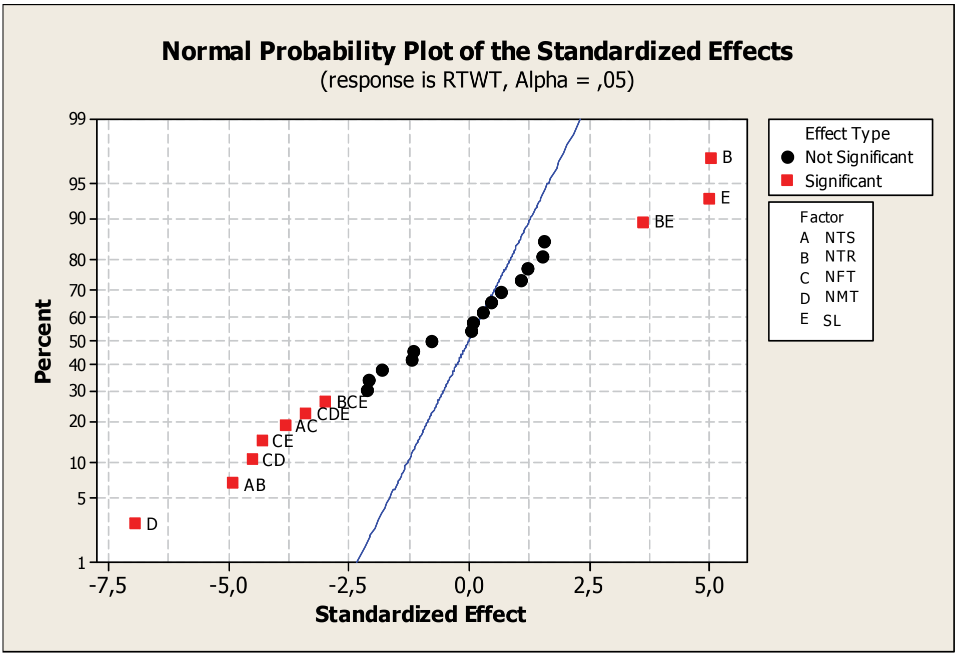



Fig. 21. The Normal Probability Plot for the RTWT

| *Source* | *DF* | *AdjSS* | *AdjMS* | *F* | *P* |
|---|---|---|---|---|---|
| Main Effects | 5 | 39,65 | 7,93 | 20,32 | 0,001 |
| 2-Way interactions | 10 | 39,46 | 3,94 | 10,11 | 0,005 |
| 3-Way interactions | 10 | 11,96 | 1,19 | 3,07 | 0,045 |
| Residual Error | 6 | 23,41 | 0,39 | | |

Table 12. ANOVA Results for RTWT

Figure 22 plots equation 18 in terms of main effects: each plot provides additional information about the effects of the most significant factors on the waiting time of retailers' trucks before starting loading operations.

Consider the NTR parameter, if the number of retailers' trucks per day increases the waiting time of retailers' trucks before starting the loading operations (*RTWT*) increases too because of trucks' traffic density. The same happens if the number of shelves levels (*SL*) changes from 3 to 5; on the other hand, when increasing the number of lift trucks (*NMT*) from its low to high value, the RTWT significantly decreases.

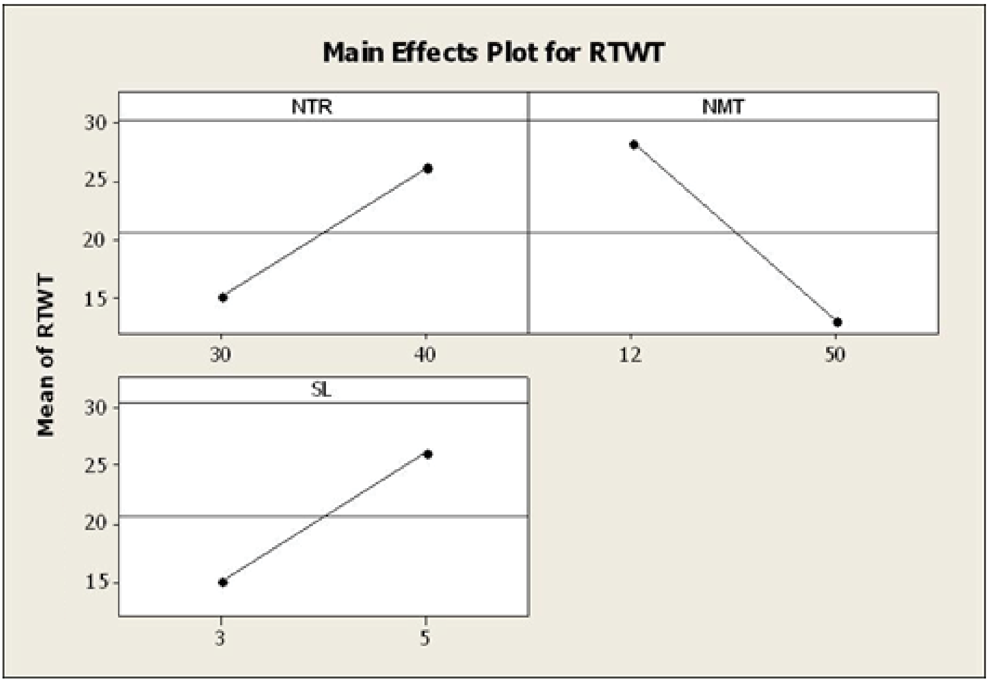



Fig. 22. Main Effects Plots for RTWT

Figure 23 shows simulation results for the RTWT parameter projected on a cube considering the NTR, NMT and SL parameters. At each corner of the cube the RTWT values are reported: NMT at its high value and NTR and SL at their low values are the best choice to obtain the lowest RTWT value.

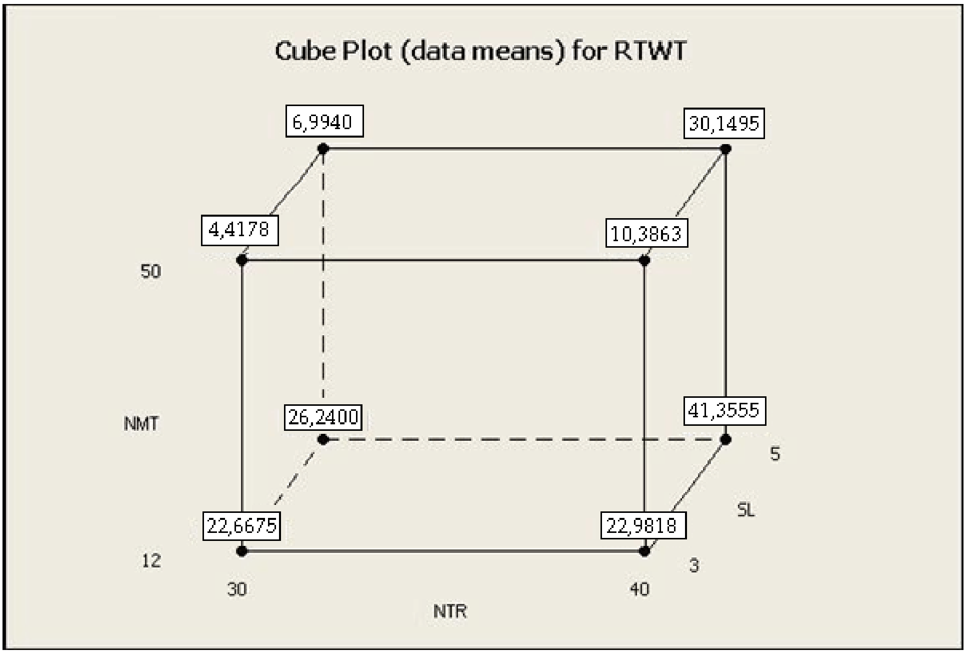



Fig. 23. Cube Plot for RTWT

Additional insights are provided by figure 24 that shows the three-dimensional surfaces of the RTWT in function of the different combinations of significant factors (NTR, SL, NMT).

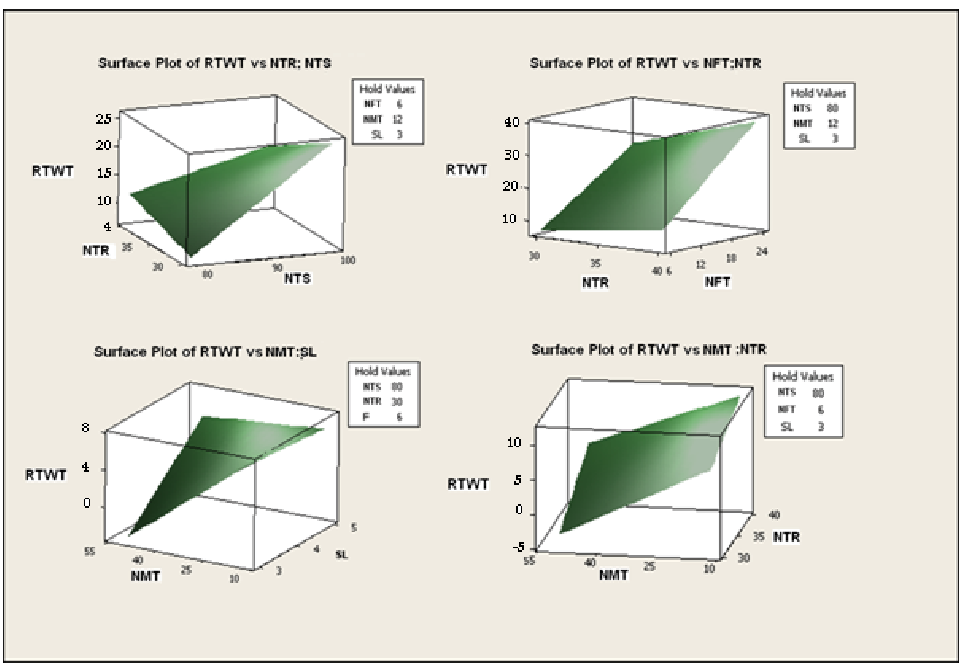



Fig. 24. Response Surfaces for RTWT

The analysis presented above show how Modeling & Simulation can be used for developing tailored solutions and tools for warehouse design and management. Input-Output analytical models and graphical tools allow to understand how changes in internal resources availability and operative strategies can affect technical and economic warehouse performances.

## 6. Conclusions

In this chapter the use of Modeling & Simulation as enabling technology is investigated, highlighting the contribution of this approach in supply chain management (with a specific focus on supply chain inventory and warehouse management). The literature in these two specific fields is surveyed and discussed highlighting approaches and solutions proposed during the years as well as lacks in research studies and critical issues still to be investigated.

Two application examples (based on real case studies) are then proposed. The application examples deal with advanced modeling approaches and simulation models for investigating the inventory management problem along the supply chain and the warehouse management problem within a single supply chain node. In both the application examples, simulators are decision-making tools capable of analyzing different scenarios by using approaches based on multiple performance measures and user-defined set of input parameters.

Lessons learned include operative procedures for developing supply chain simulation models, modus operandi for facing both the inventory and the warehouse management problem by using simulation for developing tailored solutions, joint use of simulation and advanced statistics techniques (DOE and ANOVA), limits and critical issues when using commercial simulation software as well as practical suggestions to overcome them.

It is not the intent of this chapter to investigate all the problems related to the inventory and warehouse management as well as to present all possible solutions. Indeed the literature review and the application examples should help the reader in understanding how Modeling & Simulation can be profitably used for recreating supply chains complexity and tackle specific problems with ad-hoc solutions.

## 7. References

Ashayeri, J., Gelders, L., Wassenhove, L.V., 1985. A microcomputer-based optimization model for the design of automated warehouses. *Production Research*, 23 (4), 825-839.

Axsäter, S. (2003). Optimal Policies for Serial Inventory Systems under Fill Rate Constraints. *Management Science*, 49(2), 247-253.

Azadivar, F., 1989. Optimum allocation of resources between the random access and rack storage spaces in an automated warehousing system. *Production Research*, 27 (1), 119-131.

Baganha, M. P., Cohen M. (1998). The stabilizing effect of inventory in supply chains. *Operations Research* 46 (3), S72-S73.

Balci, O. (1998). Verification, Validation and Testing. In *Handbook of Simulation*, edited by J. Banks, pp. 335-393, Wiley Interscience: New York.

Banks, J. (1998). *Handbook of simulation*, Wiley Interscience, New York.

Bartholdi, J.J., Eisenstein, D.D., Foley, R.D., 2000. Performance of bucket brigades when work is stochastic. *Operations Research*, 49 (5), 710-719.

Bassan, Y., Roll, Y., Rosenblatt, M.J., 1980. Internal layout design of a warehouse. *AIIE Transactions*, 12 (4), 317-322.

Bassin, W.M., 1990. A Technique for Applying EOQ Models to Retail Cycle Stock Inventories. *Small Business Management*, 28 (1), 48-55.

Beamon, B. M. (1998). Supply chain design and analysis: models and methods. *International Journal of Production Economics* 55 (3), 281-294.

Beamon, B. M. (1999). Measuring supply chain performance. *International Journal of Operations and Production Management* 19 (3), 275-292.

Berry, J.R., 1968. Elements of warehouse layout. *Production Research*, 7 (2), 105-121.

Bruzzone, A. G., F. Longo, M. Massei, S. Saetta (2006). The vulnerability of supply chain as key factor in supply chain management. In: Bruzzone A.G., Williams E., Proceedings of Summer Computer Simulation Conference (pp. 181-186), Calgary, Canada.

Bruzzone A.G, Longo F. (2010). An advanced System for supporting the decision process within large scale retail stores. Simulation: Transaction of SCS. ISSN: 0037-5497, doi: 10.1177/0037549709348801 (ahead of print).

Bruzzone, A.G., Bocca, E., Longo F., Massei, M. (2007). Logistics Node Design and Control over the Whole Life Cycle based on Web Based Simulation. *International Journal of Internet Manufacturing And Services*, vol. I (I); p. 32-50, ISSN: 1751-6048

Castilla I., Longo F. (2010). Modelling and Simulation Methodologies, Techniques and Applications: a State of the Art Overview. *International Journal of Simulation & Process Modelling*, vol. 6(1); p. 1-6, ISSN: 1740-2123

Chan, F.T.S., Chan, H.K. (2005). Simulation modeling for comparative evaluation of supply chain management strategies. *Journal of Advanced Manufacturing Technology* 25, 998–1006.

Chang, D.T., Wen, U.P., 1997. The impact of rack configuration on the speed profile of the storage and retrieval machine. *IIE Transactions*, 29, 525-531.

Chang, D.T., Wen, U.P., Lin, J.T., 1995. The impact of acceleration/deceleration on travel-time models for automated storage/retrieval systems. *IIE Transactions*, 27, 108-111.

Chen, J.H. (2003) *Theoretical Analysis of Multi-Objective Genetic Algorithms – Convergence Time, Population Sizing an Disequilibrium*, Report for IEEE NNS Walter Karplus Research Grant, Taichung, Taiwan.

Chopra, S., Meindl, P. (2001). *Supply chain management – Strategy, planning, and Operation*, Prentice-Hall, New Jersey.

Cimino A., Longo F., Mirabelli G. (2010). A General Simulation Framework for Supply Chain Modeling: State of the Art and Case Study. *International Journal of Computer Science Issues*, vol. 7(2); p. 1-9, ISSN: 1694-0784

Cimino, A., Longo F., Mirabelli G. (2010). A general framework on products return flows in inventory management: State of the Art Overview and a Supply Chain Simulator. In: *Proceedings of the 16th International Symposium on Inventories*. Budapest, Hungary, August 23-27ISIR

Cormier, G., 2005. Operational research methods for efficient warehousing. In: Langevin, A., Riopel, D. (Eds.), Logistics Systems: Design and Optimization. Springer, Berlin, 93-122.

Cormier, G., Gunn, E.A., 1992. A review of warehouse models. *Operational Research*, 58, 3-13.

Cormier, G., Gunn, E.A., 1996. On coordinating warehouse sizing, leasing and inventory policy. *IIE Transactions*, 28, 149-154.

Cox, B., 1986. Determining economic levels of automation by using a hierarchy of productivity ratios techniques. *Proceedings of 7th International Conference on Automation in Warehousing*.

Curcio D., Longo F. (2009). Inventory and Internal Logistics Management as Critical Factors Affecting the Supply Chain Performances. *International Journal of Simulation & Process Modelling*, vol. 5(4); p. 278-288, ISSN: 1740-2123.

D'Agostino R.B., Stephens, M.A. (1996). *Goodness of fit techniques*. Marcel Dekker: New York.

De Sensi G., Longo F., Mirabelli G. (2008). Inventory policies analysis under demand patterns and lead times constraints in a real supply chain. *International Journal of Production Research*, vol. 46(24); p. 6997-7016, ISSN: 0020-7543, doi: 10.1080/00207540701528776

Department of Defense, Deputy under Secretary of Defence, DoD modelling and simulation (M&S) management, *DoD Directive 5000.59*, 1994

Dunn R.H., (1987). The quest for software reliability, in *Handbook of software quality assurance*, edited by G.G. Schulmeyer and J.I. McManus, pp. 342 – 384, Van Nostrand Reynold: New york.

Fleisch, E., Tellkamp C. (2005). Inventory inaccuracy and supply chain performance: a simulation study of a retail supply chain. *International Journal of Production Economics* 95, 373–385.

Francis, R.L., 1967. On some problems of rectangular warehouse design and layout. *Industrial Engineering*, 18, 595-604.

Ganeshan, R., Boone, T., Stenger A. J. (2001). The impact of inventory and how planning parameters on supply chain performance: An exploratory study. *International Journal of Production Economics* 71, 111–118.

Goetschalckx, M., Ratliff, H.D., 1990. Shared storage policies based on the duration stay of unit loads. *Management Science*, 36 (9), 1120-1132.

Goetschalckx, M., Ratliff, H.D., 1991. Optimal lane depths for single and multiple products in block stacking storage systems. *IIE Transactions*, 23 (3), 245-258.

Goh, M., Ou, J., Teo, C.P., 2001. Warehouse sizing to minimize inventory and storage costs. *Naval Research Logistics*, 48 (4), 299-312.

Graves, S. C. (1999). A single inventory model for a non-stationary demand process, *Manuf. Serv. Op. Manag.*, 1, 50 – 61.

Graves, S.C., Hausman, W.H., Schwarz, L.B., 1977. Storage-retrieval interleaving in automatic warehousing systems. *Management Science*, 23 (9), 935-945.

Graves, S.C., Willems S. P. (2005). Optimizing the Supply Chain Configuration for New Product. *Management Science*, 51(8), 1165–1180.

Gray, A.E., Karmarkar, U.S., Seidmann, A., 1992. Design and operation of an order consolidation warehouse: models and applications. *Operational Research*, 58, 14-36.

Gu, J.X., Goetschalckx, M., McGinnis, L.F., 2007. Research on warehouse operation: A comprehensive review. *Operational Research*, 177 (1), 1-21.

Hackman, S.T., Frazelle, E.H., Griffin, P.M., Griffin, S.O., Vlasta, D.A., 2001. Benchmarking warehouse and distribution operations: An input–output approach. *Productivity Analysis*, 16, 79-100.

Hausman, W.H., Schwarz, L.B., Graves, S.C., 1976. Optimal storage assignment in automatic warehousing systems. Management Science 22 (6), 629–638.

Heragu, S.S., Du, L., Mantel, R.J., Schuur, P.C., 2005. Mathematical model for warehouse design and product allocation. *Production Research*, 43 (2), 327-338.

Hsieh, L.F., Tsai, L., 2006. The optimum design of a warehouse system on order picking efficiency. *Advanced Manufacturing Technology*, 28, 626-637.

Hung, M.S., Fisk, C.J., 1984. Economic sizing of warehouses – A linear programming approach. *Computers and Operations Research*, 11 (1), 13-18.

Hwang, H., Lee, S.B., 1990. Travel-time models considering the operating characteristics of the storage and retrieval machine. *Production Research*, 28 (10), 1779-1789.

Hwang, H., Song, Y.-K., Kim, K.-H., 2004b. The impacts of acceleration/deceleration on travel time models for carousel systems. *Computers and Industrial Engineering*, 46, 253-265.

Ingalls, R. G. (1998). The value of simulation in modeling supply chain. In: *Proceedings of the 1998 Winter Simulation Conference*, pp. 1371-1375, Washington D.C.

Ito, T., Abadi, J., Mousavi, S.M., 2002. Agent-based material handling and inventory planning in warehouse. *Intelligent Manufacturing*, 13 (3), 201-210.

Johonson N.L., Kotz, S., Balakrishnan, N. (1994). *Continuous Univariate Distributions*, Vol. 1, 2nd ed., Houghton Mifflin, Boston.

Johonson N.L., Kotz, S., Balakrishnan, N. (1995). *Continuous Univariate Distributions*, Vol. 2, 2nd ed., Houghton Mifflin, Boston.

Johonson N.L., Kotz, S., Kemp, A.W. (1992). *Univariate Discrete Distributions*, 2nd ed., Houghton Mifflin, Boston.

Karasawa, Y., Nakayama, H., Dohi, S., 1980. Trade-off analysis for optimal design of automated warehouses. *Systems Science*, 11 (5), 567-576.

Larson, N., March, H., Kusiak, A., 1997. A heuristic approach to warehouse layout with class-based storage. *IIE Transactions*, 29, 337-348.

Lee, H.S., 1997. Performance analysis for automated storage and retrieval systems. *IIE Transactions*, 29, 15-28.

Lee, Y. H., Cho, M. K., Kim, S. J., Kim, Y. B. (2002). Supply chain simulation with discrete continuous combined modeling. *Computer & Industrial Engineering*, 43, 375-392.

Levy, J., 1974. The optimal size of a storage facility. *Naval Research Logistics Quarterly*, 21 (2), 319-326.

Lin, C.H., Lu, I.Y., 1999. The procedure of determining the order picking strategies in distribution center. *Production Economics*, 301-307.

Linn, R.J., Wysk, R.A., 1990. An expert system framework for automated storage and retrieval system control. *Computers and Industrial Engineering*, 18 (1), 37-48.

Longo F., Oren T. (2008). Supply Chain Vulnerability and Resilience: A state of the Art Overview. In: *Proceedings of the European Modeling & Simulation Symposium*. Campora S.Giovanni (CS), Italy, 17-19 September, RENDE: A.Bruzzone-F.Longo-M.Piera-R.Aguilar-C.Frydman, pp. 527-533, ISBN/ISSN: 978-88-903724-0-7

Longo, F., A.G. Bruzzone (2005a). Modeling & Simulation applied to Security Systems. In: *Proceedings of Summer Computer Simulation Conference*, pp 183-188, Philadelphia, USA.

Longo, F., G. Mirabelli, E. Papoff (2005b). Modeling Analysis and Simulation of a supply chain devoted to support pharmaceutical business retail, In: *Proceedings of International Conference on Production Research*, Salerno, Italy.

Longo F. (2010). Design and Integration of the Containers Inspection Activities in the Container Terminal Operations. *International Journal of Production Economics*, vol. 125(2); p. 272-283, ISSN: 0925-5273 , doi: 10.1016/j.ijpe.2010.01.026

Longo F., Mirabelli G. (2008). An Advanced Supply Chain Management Tool Based on Modeling & Simulation. *Computers & Industrial Engineering*, vol. 54/3; p. 570-588, ISSN: 0360-8352, doi: 10.1016/j.cie.2007.09.008

Lowe, T.J., Francis, R.L., Reinhardt, E.W., 1979. A greedy network flow algorithm for a warehouse leasing problem. *AIIE Transactions*, 11 (3), 170-182.

Macro, J.G., Salmi, R.E., 2002. A simulation tool to determine warehouse efficiencies and storage allocations. *Proceedings of the 2002 Winter Simulation Conference*, 08-11 December, San Diego, California (USA), 1274-1281.

Malmborg, C.J., 1996. An integrated storage system evaluation model. *Applied Mathematical Modelling*, 20 (5), 359-370.

Malmborg, C.J., 2001. Rule of thumb heuristics for configuring storage racks in automated storage and retrieval systems design. *Production Research*, 39 (3), 511-527.

Malmborg, C.J., Al-Tassan, K., 2000. An integrated performance model for order picking systems with randomized storage. *Applied Mathematical Modelling*, 24 (2), 95-111.

Marsh, W.H., 1979. Elements of block storage design. *Production Research*, 17 (4), 377-394.

Marsh, W.H., 1983. A comparison with Berry. *Production Research*, 21 (2), 163-172.

Meller, R.D., Gau, K.Y., 1996. The facility layout problem: Recent and emerging trends and prospectives. *Manufacturing Systems*, 15 (5), 351-366.

Meller, R.D., Klote, J.F., 2004. A throughput model for carousel/VLM pods. *IIE Transactions*, 36 (8), 725-741.

Moder, J.J., Thornton, H.M., 1965. Quantitative analysis of the factors affecting floor space utilization of palletized storage. *Industrial Engineering*, 16 (1), 8-18.

Moinzadeh, K. (2002). A Multi-Echelon Inventory System with Information Exchange. *Management Science*, 48(3), 414-426.

Pandit, R., Palekar, U.S., 1993. Response time considerations for optimal warehouse layout design. *Engineering for Industry*, 115, 322-328.

Park, Y.H., Webster, D.B., 1989. Modelling of three-dimensional warehouse systems. *Production Research*, 27 (6), 985-1003.

Parker, R.P., Kapuscinski, R. (2004). Optimal Policies for a Capacitated Two-Echelon Inventory system, *Op. Res.*, 52(5), 739 – 755.

Perlmann, A.M., Bailey, M., 1988. Warehouse logistics systems – A CAD model. *Engineering Costs and Production Economics*, 13, 229-237.

Persson, F. , Olhager J. (2002). Performance simulation of supply chain designs. *International Journal of Production Economics*, 77, 231-245.

Petersen, C.G., 2000. An evaluation of order picking policies for mail order companies. *Production and Operations Management*, 9 (4), 319-335.

Pliskin, J.S., Dori, D., 1982. Ranking alternative warehouse area assignments: A multiattribute approach. *IIE Transactions*, 14 (1), 19-26.

Randhawa, S.U., McDowell, E.D., Wang, W.-T., 1991. Evaluation of scheduling rules for single- and dual-dock automated storage/retrieval system. *Computers and Industrial Engineering*, 20 (4), 401-410.

Randhawa, S.U., Shroff, R., 1995. Simulation-based design evaluation of unit load automated storage/retrieval systems. *Computers and Industrial Engineering*, 28 (1), 71-79.

Rao, A.K., Rao, M.R., 1998. Solution procedures for sizing of warehouses. *Operational Research*,108, 16-25.

Roberts, S.D., Reed, R., 1972. Optimal warehouse bay configurations. *AIIE Transactions*, 4 (3), 178-185.

Roll, Y., Rosenblatt, M.J., 1983. Random versus grouped storage policies and their effect on warehouse capacity. *Material Flow*, 1, 199-205.

Roodbergen, K.J., Vis, I.F.A., 2006. A model for warehouse layout. *IIE Transactions*, 38 (10), 799-811.

Rosenblatt, M.J., Roll, Y., 1984. Warehouse design with storage policy considerations. *Production Research*, 22 (5), 809-821.

Rosenblatt, M.J., Roll, Y., 1988. Warehouse capacity in a stochastic environment. *Production Research*, 26 (12), 1847-1851.

Ross, A., Droge, C., 2002. An integrated benchmarking approach to distribution center performance using DEA modeling. *Operations Management*, 20, 19-32.

Roundy, R. O., Muckstadt, J. A. (2000). Heuristic computation of periodic-review base stock inventory policies, *Management Science,* 46(1), 104 – 109.

Rowenhorst, B., Reuter, B., Stockrahm, V., Van Houtum, G.J., Mantel, R.J., Zijm, W.H.M., 2000. Warehouse design and control: Framework and literature review. *Operational Research*, 122, 515-533.

Schefczyk, M., 1993. Industrial benchmarking: A case study of performance analysis techniques. *Production Economics*, 32, 1-11.

Schwarz, L.B., Graves, S.C., Hausman, W.H., 1978. Scheduling policies for automatic warehousing systems: Simulation results. *AIIE Transactions*, 10 (3), 260-270.

Sharp, G.P., Vlasta, D.A., Houmas, C.G., 1994. Economics of storage/retrieval systems for item picking. Material Handling Research Center, Georgia Institute of Technology, Atlanta, Georgia.

Simchi-Levi, D., Kaminsky, P., Simchi-Levi, E. (2000). *Designing and managing the supply chain*, McGraw-Hill, Illinois.

Stadtler, H., Kilger, C. (2000). *Supply chain management and advanced planning*, Springer, Berlin.

Tagaras, G., Vlachos D. (2001). A Periodic Review Inventory System with Emergency Replenishments. *Management Science*, 47(3), 415-429.

Thonemann, U.W., Brandeau, M.L., 1998. Optimal storage assignment policies for automated storage and retrieval systems with stochastic demands. *Management Science*, 44 (1), 142-148.

Thor, C.G. (1994). Measures of success–creating a high performing organization. Essex Junction, VT: Oliver Wight.

Van den Berg, J.P., 1999. A literature survey on planning and control of warehousing systems. *IIE Transactions*, 31, 751-762.

Viswanadham, N. (1999). *Analysis and Design of Manufacturing Enterprises*. Kluwer Academic Publishers.

Wang, J.Y., Yih, Y., 1997. Using neural networks to select a control strategy for automated storage and retrieval systems (AS/RS). *Computer Integrated Manufacturing*, 10 (6), 487-495.

White, J.A., Francis, R.L., 1971. Normative models for some warehouse sizing problems. *AIIE Transactions*, 9 (3), 185-190.

Wikner, J., Towill, D. R., Naim, M. (1991). Smoothening supply chain dynamics. *Int. J. Prod. Econ.*, 3(3), 3 – 13.

Yoon, C.S., Sharp, G.P., 1996. A structured procedure for analysis and design of order pick systems. *IIE Transactions*, 28, 379-389.

Zhang, C., Zhang C. (2007). Design and Simulation of demand information sharing in a supply chain. *Simulation Modeling Practice and Theory*, 15, 32-46.

Zipkin, P. (2000). *Foundations of Inventory Management*. McGraw-Hill Higher Education, Boston.

6

# Supply Chain Process Benchmarking Using a Self-Assessment Maturity Grid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## 1. Introduction

Competitive advantage is more and more determined by the ability to respond to customer requirements. Research has shown that a well-organised supply chain that can meet these requirements is crucial to firm performance (2006; Ramdas & Spekman 2000; Spekman et al. 1998). Top performance in supply chain management will result into success at the organisational level (Green Jr et al. 2008). More than ever it is important to know what drives performance in a supply chain. As a result, many companies have reverted to benchmarking their supply chain activities. Benchmarking can be defined as a search for industry best practices that lead to superior performance (Camp 1989). Looking outwards to other companies enables companies to " learn from others and achieve quantum leaps in performance that otherwise could take years to achieve through internal incremental achievements" (Van Landeghem & Persoons 2001: 254). Such quantum leaps are often necessary to stay ahead of competition. Benchmarking is therefore more and more of strategic importance.

Benchmarking often consists of comparing performance outcomes with the outside world and the difference between the figures is considered the gap to close in the near future. However, comparing just figures bears certain dangers. Traditional approaches such as benchmarking lagging measures may be unreliable in rapidly changing business environments (Bourne et al. 2000). Furthermore, benchmarking first requires an understanding of processes benchmarked (Voss et al. 1994) and that is often not the case in traditional benchmarking approaches. Well functioning processes are a strategic asset for a company (Hammer 1990): they are crucial to achieving high performance levels and thus to achieve lasting competitive advantage. However, process benchmarking research, which focuses on finding and comparing process practices, largely remains descriptive with a focus on describing practices that successful companies have in place (Davies & Kochhar 2002). They provide companies with limited guidance in target setting as well as developing a roadmap how to get to these targets. In this paper we focus on benchmarking processes through maturity models and we develop a maturity model that can be used as a standard to compare processes across companies, set targets and define growth paths. Recent literature identified a need to develop such models that can be used as a standard to compare different companies within a branch (Lockamy III et al. 2008).

The concept of process maturity proposes that a process has a lifecycle that is assessed by the extent to which the process is explicitly defined, managed, measured and controlled

(Lockamy III & McCormack 2004a; Paulk et al. 1993). Process maturity can be defined as: "the degree to which a process/activity is institutionalized and effective" (Moultrie et al. 2006). For an overview we refer to Plomp and Batenburg (2010) who recently provided an overview of 22 published maturity models. Process maturity assessment has emerged as an effective way of capturing "good practices" knowledge on processes in a form that also supports improvement initiatives. According to Moultrie et al. (2006) maturity assessments help to predict an organisation's ability to meet its goals. They also provide guidance on targeting improvement by describing the progression of performance through incremental stages of development.

Process maturity assessment originates from the field of quality management to support quality improvement. Crosby (1979)) developed a so-called maturity grid that describe stages of progression in quality management processes, positing that organisations follow an evolutionary path in adopting quality management practices. Such a grid essentially describes typical stages of behaviour at different maturity levels for each activity or sub-process in scope. The grid thus codifies what can be regarded as good as well as bad practice along with a number of intermediate stages for each activity or sub-process in scope (Moultrie et al. 2006) and can thus be used for self-assessment purposes. An advantage of such an approach is that it enables companies to easily identify the current maturity stage for each activity (i.e., the description that fits the current situation best) and to develop target maturity levels and growth paths to reach targeted maturity levels. Typically, 4 to 5 intermediate stages are described. As such, a maturity grid provides a standardised way of analysing companies.

The use of these grids in quality management initiated the use of self-assessment maturity grids in several other disciplines, with well known examples in software development (Harter et al. 2000), project management (Ibbs & Kwak 2000; Kwak & Ibbs 2002) and product development (Fraser et al. 2002). Although supply chain process maturity has received an increased attention over the last few years, to date process maturity research in supply chain management has mainly focused on identifying the degree of presence of best practices using a five-point Likert scale, typically from 1 (e.g. "does not exist") to 5 ("always exists"). Using this approach, Lockamy and McCormack (2004b) investigate the use of SCOR based practices and identify clusters of practices that correlate with supply chain performance . McCormack et al (2008) further extend this model to investigate the Brazilian manufacturing industry. Lockamy et al. (2008) use a similar model with five maturity variables: process structure, documentation, jobs, measures and values/beliefs. In fact, this approach describes the extent to which a certain good practice is used by a company and derives maturity from the extent to which a practice is used. A maturity grid identifies intermediate stages towards a good practice or every single activity or sub-process in scope. As a result, identification of the current practice is easier but it also provides for the ability to show a company what a growth path could look like in order to reach a desired practice. To our knowledge, none of the existing supply chain maturity models is based on such a self-assessment maturity grid that also codifies intermediate stages. In our study we therefore set out to develop a self-assessment maturity grid for supply chain processes. We tested and applied it a among companies in the business-to-business segment that typically deliver a large variety of products from stock, such as wholesalers. We analysed the results of an application of the self-assessment grid in 57 such companies to identify how maturity of supply chain processes impacts supply chain performance. Using these results we show how our maturity model correlates with supply chain performance as there is a need for "…maturity models and roadmaps, which are proven to have direct correlation with performance" (Akyuz & Erkan 2009: 12).

In the remainder of this chapter, we elaborate on our research design and consecutively discuss the development of a self-assessment supply chain maturity grid. We then analyse and discuss results of the empirical application of this maturity grid. We provide conclusions and recommendations for further research in the last section.

## 2. Research design

We have focused our research on non-manufacturing processes due to a relatively large focus of prior research on best practices in manufacturing processes (cf. Whybark and Vastag (1993); Voss et al. (1994); Ungan (2005); Laugen et al. (2005); Swink et al. (2005) for best practice research results in manufacturing processes). We followed the guidelines of Voss et al. (1994) in setting up a self-assessment tool. They identified that the development of such a tool requires identification of best practices (Voss et al. 1994). A team of two supply chain consultants together with the author developed a maturity grid. We first used literature to identify non-manufacturing related process categories that impact supply chain performance. This resulted in 7 categories, depicted in Fig. 1 and described in section 3.

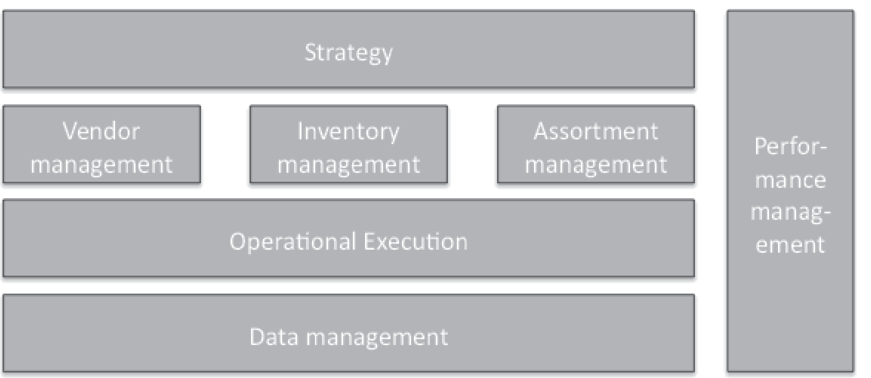


Fig. 1. Supply chain maturity processes.

We then assembled a first draft of process best practices based on a literature review and on consulting experiences within the team. Since a maturity model assumes that progress towards goal achievement comes in stages we also developed intermediate stages towards a best practice. We use five stages of maturity compared to the four that for example Voss et al. (1994) used, ranging from stage 1 “innocent”, identifying lack of attention to an activity, to stage 5 ”excellent” which identifies best in class. These phases can be compared to onionskins: stage five (“excellent”) covers stage 4, stage 4 covers stage 3 etc. We furthermore included questions general company characteristics such as company size, assortment size, inventory levels and average order fill rate. After several iterations within the team, we tested the tool in practice. It is particularly important to test tools developed to improve content validity (Voss et al. 1994). The test took place in two phases: during the first phase, two professors who were also highly experienced supply chain consultants provided input on the maturity grid. Their additions were used for an updated model that was thereafter tested in two companies (phase two). Two companies that were considered best in class volunteered to use the model in a self-assessment: a medium-sized supplier of the offshore industry with a global distribution network and a large wholesaler in building materials with a European focus. It was decided to use two different companies as it typically is advisable to use rather extreme types if limited situations can be studied (Eisenhardt 1989). This resulted in the final version, which has been administered in a survey to identify where and how supply chain maturity influences supply chain performance. We used a descriptive survey as this is a useful method to increase understanding of a phenomenon and understand its distribution in a population (Forza 2002). In the next section we formulate the contents of the maturity grid.

## 3. Self assessment supply chain maturity grid

We set out to develop a maturity grid that captures the process from ordering at a supplier to actual delivery at customer premises, from strategy to execution. In contrast to other supply chain maturity research, we did not use the SCOR model directly as we focus on non-manufacturing processes and SCOR has been conceived from a manufacturing perspective (Stewart 1997). Besides, literature showed that a broader scope of processes influences supply chain performance. We have focused on seven key process categories that according to literature affect supply chain performance (see Fig. 1)[1]. We developed a maturity grid using the results from existing maturity models such as developed by Lockamy and McCormack (2004a) and McCormack et al. (2008). The first process in the maturity grid is "Strategy". It has been shown that a link between strategy and operations is advantageous (Bendoly et al. 2007; Braam & Nijssen 2004; Swink et al. 2005). Lockamy and McCormack (2004a) found that more mature organisations are more effective in linking strategy to supply chain management. However, the challenge is how to achieve such strategic fit and that is not well understood (Melnyk et al. 2004). Using a self-assessment maturity grid may increase understanding of how to achieve such a fit. We furthermore included "Vendor Management", "Inventory Management" and "Assortment Management". Previous research by Ramdas and Spekman (2000) showed that high-performing companies used supplier evaluations more widely than low-performing companies. The management of vendors is more and more crucial to supply chain performance and more orientation on suppliers is generally considered to be positively related to performance (Shin et al. 2000). Van Ryzin and Mahajan (1999) conclude that assortments size has an impact on supply chain benefits. A large assortment leads to more satisfied customers but increases demand variability for each product variant due to increase product proliferation. Hendricks & Singhal (2008) show that excess inventory levels of companies can lead to strong negative market reactions; maturity in inventory management is therefore expected to be critical. We furthermore included processes focused on "Operational Execution" and "Data Management". Operational execution relates to the actual practices in the supply chain in operationally managing demand and supply and data management to maintaining up-to-date information and full data integrity needed to perform these processes. According to Lambert & Cooper (2000: 78) "…the kind of information and the frequency of information updating has a strong influence on the efficiency of the supply chain". Inefficient information systems, due to e.g. inaccuracies in data, are considered a key pitfall in supply chain management (Lee & Billington 1992). The effective use of information systems is essential to efficient and speedy business operations (Tummala et al. 2006). Last, we included "Performance Management" as the adequate measurement and management of performance is a key enabler for improvement (Bourne et al. 2002; Neely et al. 2000) and critical for high performance levels (Ramdas & Spekman

[1] The complete grid is available through www.supplychainmaturity.nl

2000). In the next section, we detail the results of an analysis of maturity grids filled out by companies.

## 4. Grid application and results

The maturity grid has been developed in the Dutch language and encompasses 54 items in the 7 process categories and an additional 10 general company characteristics. To shorten total data capture throughput time and to reduce misinterpretation in filling out the grid it has been decided to collect information from companies during a executive summer course for supply chain managers from distributors and manufacturers performing their own distribution function towards retailers. This is a particularly interesting audience due to a lack of attention in supply chain management research to distributive trade (Sharman 2003). Our sampling method is similar to Zirger and Maidique (1990) who performed an empirical test on product development among participants of an executive management course. We incorporated the self-assessment maturity grid in the summary that was published for the participants of the summer school (cf. Van Dijk et al. 2007). We handed out the maturity grid on the first day of the course and had a block of 1 hour reserved in the programme on the last day to handle questions. This not only enabled a verbal explanation of the grid as well as answering any questions that may arise about the content – which increases reliability of the data – but this also provided data in a very short time. It furthermore provided the opportunity to discuss the usefulness of the grid to companies in self-assessment benchmarking.

Such convenience samples are not uncommon (cf. Zirger & Maidique 1990) and may provide useful data with relatively limited effort compared to an extensive survey. In consumer research three criteria are used to judge whether convenience samples are applicable (Ferber 1977), which we translated for use in our situation. First, we ensured that the relevance of the sample was as targeted. The maturity grid is aimed at supply chain managers of companies delivering a relatively large assortment from stock to retailers, which was exactly the audience of the course. Secondly, the sample size must be adequate; all 57 companies completely filled out the maturity grid which is not very large but it is acceptable for such a study (Hair et al. 2006) and comparable in size to earlier research in supply chain maturity (Lockamy III & McCormack 2004b). Third, the subjects studied should be representative of the population studied, which are stockholding companies. The 57 companies present were mainly wholesalers (49) and a few manufacturers (8). We checked for equality of variance and mean between these two groups and concluded that there were no statistical differences between these two groups. We tested discriminant validity by checking bivariate correlations between process maturity and potentially confounding variables such as company size and company turnover. We did not find significant correlations.

We used the data of the 57 maturity grids that have been filled out to identify where process maturity is key in achieving high levels of supply chain performance. The resulting Cronbach alpha was .942, which is above the minimum acceptable criterion of .7 (Hair et al. 2006). The Kaiser-Meyer-Olin measure verified sample adequacy with KMO values for the categories >.62, which is above the acceptable limit of .5 (Kaiser 1974). We first applied factor analysis to examine patterns underlying our data and to investigate the extent to which our information can be condensed. This revealed the critical elements of the supply chain processes. The new composite dimensions were then used to develop a regression model. Each regression model contains one independent variable and therefore these models are equal to bi-variate correlations.

For our factor analysis, we conducted a principal component analysis on each of the seven categories of questionnaire items with orthogonal rotation (varimax). With our sample size of N=57, we used a factor loading threshold of 0.7 (Hair et al. 2006: 128-9). The results are depicted in Table 1.

| Factor | Item | Factor loading |
|---|---|---|
| Strategy | Degree to which a company is able to define and implement strategy | ,746 |
| | Presence of relation between strategy on the one hand and assortment, vendor and stock management on the other | ,720 |
| Assortment management | The extent to which product introductions are managed | ,787 |
| | Degree of joint promotions and promotion planning with partners | ,747 |
| | Extent of product introduction monitoring | ,730 |
| Stock management factor 1: risk analysis | The extent to which supply chain risks are understood and analysed | ,857 |
| Stock management factor 2: organisation | The level of coordination of stock over multiple sites | ,839 |
| | The extent to which stock responsibility is defined clearly | ,721 |
| Vendor management factor 1: vendor analysis | The depth and extent of measuring and managing vendor performance | ,824 |
| | The extent of analysing and managing risks in supply | ,813 |
| Vendor management factor 2: Vendor cooperation | Cooperative supply chain relations with vendors | ,869 |
| | Level of forecast and sales information exchange with suppliers | ,766 |
| Operational execution factor 1: up to date information | The extent to which forecasts are updated in a structured fashion | ,756 |
| Operational execution factor 2: customer cooperation | The level of joint replenishment planning with customers | ,777 |
| Data management | Level of standardisation in updating product data | ,746 |
| | Level of mutual data transparency between partners | ,734 |
| | Master data accuracy | ,728 |
| Performance management | Extent of internal and external communication about Key Performance Indicators | ,803 |
| | Extent to which performance measurement leads to performance improvement initiatives | ,761 |
| | Content diversity of performance metrics | ,760 |
| | Extent to which it is attempted to learn from others | ,748 |
| | Extent to which performance metrics are related to higher-level goals | ,745 |

Table 1. Factor analysis results

Our factor analysis on the variables related to Strategy showed two items representing critical elements of the strategy process: first, the degree to which a company is able to define and implement strategy; second, the presence of a relation between strategy and assortment, vendor and stock management. Factor analysis further revealed three items for Assortment Management: the extent to which product introduction are managed; the degree of joint promotions and promotion planning with partners, and the extent of product introduction monitoring.

We found two relevant factors in Stock Management. The first is focused on risk analysis and contains one item: the extent to which supply chain risks are understood and analysed. The second factor relates to organisational issues of managing stock and consists of two items: the level of coordination of stock over multiple sites and the extent to which stock responsibility is defined clearly.

In the category Vendor Management, two factors were found. The first relates to vendor analysis and contains the items "depth and extent of measuring and managing vendor performance" and "extent of analysing and managing risks in supply". The second Vendor Management factor deals with vendor cooperation and consists of two items as well: the cooperative supply chain relations with vendors and the level of forecast and sales information exchange with suppliers.

Operational Execution is split into two factors each consisting of one item. The first factor is "up to date information" and this consists of the extent to which forecasts are updated in a structured fashion. The second factor, dubbed "customer cooperation", consists of the level of joint replenishment planning with customers.

Data Management consists of one factor with three items: the level of standardisation in updating product data; the level of mutual data transparency between partners, and master data accuracy. In Performance Management, five items make up one factor: the extent of internal and external communication about key performance indicators; the extent to which performance measurement leads to performance improvement initiatives; the content diversity of performance metrics; the extent to which it is attempted to learn from others and the extent to which performance metrics are related to higher-level goals.

In the next step, we used single variable linear regression analysis to identify relationships between factors and performance levels indicated in the questionnaire. In order to select which performance variables to use we first developed a correlation table (see Table 2 on the next page).

We have selected the "order fill rate" to focus our analysis on correlates as this showed the strongest correlations with the maturity factors as well as the overall mean maturity score across all grid items. We developed a regression model for on the one hand each of the maturity factors as well as the overall mean score, and on the other the performance indicator "order fill rate". The results of this regression are depicted in Table 3.

## 5. Discussion

Our research corroborates earlier results of Lockamy and McCormack (2004b, 2004a) and McCormack et al. (2008) that higher levels of maturity are correlated with higher levels of performance. When examining the impact of maturity on the individual factors on performance levels, the factor Performance Management had the highest correlation with performance of all factors. This suggests that maturity in Performance Management has a stronger impact on actual performance levels than the other processes. This finding details earlier research that performance management not only has a positive effect of measuring

| | | Order fill rate | Mean maturity score | Strategy factor | Assortm. factor | Stock mngt factor 1 | Stock mngt factor 2 | Vendor mngt factor 1 | Vendor mngt factor 2 | Exec. factor 1 | Exec. factor 2 | Data mngt factor | Perf mngt factor |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Order fill rate | Pearson Correlation | 1 | ,526** | ,345** | ,463** | ,185 | ,445** | ,421** | -,054 | ,371** | ,217 | ,295* | ,538** |
| | Sig. (2-tailed) | | ,000 | ,009 | ,000 | ,168 | ,001 | ,001 | ,691 | ,005 | ,105 | ,026 | ,000 |
| Overall mean | Pearson Correlation | ,526** | 1 | ,801** | ,757** | ,532** | ,397** | ,600** | ,487** | ,428** | ,665** | ,590** | ,821** |
| | Sig. (2-tailed) | ,000 | | ,000 | ,000 | ,000 | ,002 | ,000 | ,000 | ,001 | ,000 | ,000 | ,000 |
| Strategy factor | Pearson Correlation | ,345** | ,801** | 1 | ,614** | ,286* | ,136 | ,432** | ,464** | ,165 | ,456** | ,417** | ,633** |
| | Sig. (2-tailed) | ,009 | ,000 | | ,000 | ,031 | ,312 | ,001 | ,000 | ,221 | ,000 | ,001 | ,000 |
| Assortment factor | Pearson Correlation | ,463** | ,757** | ,614** | 1 | ,209 | ,297* | ,379** | ,419** | ,087 | ,438** | ,304* | ,546** |
| | Sig. (2-tailed) | ,000 | ,000 | ,000 | | ,118 | ,025 | ,004 | ,001 | ,522 | ,001 | ,021 | ,000 |
| Stock mngt factor 1 | Pearson Correlation | ,185 | ,532** | ,286* | ,209 | 1 | ,000 | ,341** | ,142 | ,418** | ,438** | ,275* | ,470** |
| | Sig. (2-tailed) | ,168 | ,000 | ,031 | ,118 | | 1,000 | ,009 | ,294 | ,001 | ,001 | ,038 | ,000 |
| Stock mngt factor 2 | Pearson Correlation | ,445** | ,397** | ,136 | ,297* | ,000 | 1 | ,261* | ,111 | ,182 | ,245 | ,210 | ,360** |
| | Sig. (2-tailed) | ,001 | ,002 | ,312 | ,025 | 1,000 | | ,049 | ,412 | ,176 | ,067 | ,116 | ,006 |
| Vendor mngt factor 1 | Pearson Correlation | ,421** | ,600** | ,432** | ,379** | ,341** | ,261* | 1 | ,000 | ,252 | ,282* | ,384** | ,477** |
| | Sig. (2-tailed) | ,001 | ,000 | ,001 | ,004 | ,009 | ,049 | | 1,000 | ,059 | ,033 | ,003 | ,000 |
| Vendor mngt factor 2 | Pearson Correlation | -,054 | ,487** | ,464** | ,419** | ,142 | ,111 | ,000 | 1 | ,027 | ,456** | ,304* | ,184 |
| | Sig. (2-tailed) | ,691 | ,000 | ,000 | ,001 | ,294 | ,412 | 1,000 | | ,841 | ,000 | ,021 | ,171 |
| Execution factor 1 | Pearson Correlation | ,371** | ,428** | ,165 | ,087 | ,418** | ,182 | ,252 | ,027 | 1 | ,000 | ,196 | ,431** |
| | Sig. (2-tailed) | ,005 | ,001 | ,221 | ,522 | ,001 | ,176 | ,059 | ,841 | | 1,000 | ,144 | ,001 |
| Execution factor 2 | Pearson Correlation | ,217 | ,665** | ,456** | ,438** | ,438** | ,245 | ,282* | ,456** | ,000 | 1 | ,591** | ,475** |
| | Sig. (2-tailed) | ,105 | ,000 | ,000 | ,001 | ,001 | ,067 | ,033 | ,000 | 1,000 | | ,000 | ,000 |
| Data mngt factor | Pearson Correlation | ,295* | ,590** | ,417** | ,304* | ,275* | ,210 | ,384** | ,304* | ,196 | ,591** | 1 | ,368** |
| | Sig. (2-tailed) | ,026 | ,000 | ,001 | ,021 | ,038 | ,116 | ,003 | ,021 | ,144 | ,000 | | ,005 |
| Perf mngt factor | Pearson Correlation | ,538** | ,821** | ,633** | ,546** | ,470** | ,360** | ,477** | ,184 | ,431** | ,475** | ,368** | 1 |
| | Sig. (2-tailed) | ,000 | ,000 | ,000 | ,000 | ,000 | ,006 | ,000 | ,171 | ,001 | ,000 | ,005 | |

*. Correlation is significant at the 0.05 level (2-tailed); **. Correlation is significant at the 0.01 level (2-tailed)

Table 2. Correlation analysis

| Factor | Beta value | Significance level | Adjusted R2 |
|---|---|---|---|
| Performance management factor | ,538 | ,000 | ,276 |
| Mean maturity score | ,526 | ,000 | ,263 |
| Assortment management factor | ,463 | ,000 | ,200 |
| Stock management factor 2 | ,445 | ,001 | ,184 |
| Vendor management factor 1 | ,421 | ,001 | ,162 |
| Execution factor 1 | ,371 | ,005 | ,122 |
| Strategy factor | ,345 | ,009 | ,103 |
| Data management factor | ,295 | ,026 | ,071 |

Table 3. Regression analysis

performance on actual performance outcomes (Ittner 2008), it is in fact the most important process in our grid that a supply chain manager should pay attention to. This may also explain the importance that is typically adhered to measuring performance by many academics (Akyuz & Erkan 2009; Gunasekaran & Kobu 2007) as well as supply chain practitioners (Chae 2009). Our research furthermore suggests that it is not so much the just the definition of performance metrics that needs attention but the complete process from definition to using and managing with performance metrics in day-to-day activities. Key aspects addressed in the maturity grid for the factor Performance Management pertain to not only definition of indicators but also the extent to which they are communicated and the extent to which they are explicitly part of an improvement process. It is particularly the implementation and use of performance indicators that has a large impact on performance outcomes, and this requires more academic research (Bourne et al. 2000).

Linear regression furthermore suggested that maturity in product assortment management plays a key role in managing and improving supply chain performance. Van Ryzin and Mahajan (1999) already indicated that assortment size influences performance; our research extends this finding by showing that also the maturity of the process of managing product assortments is key to supply chain performance. In the realm of Efficient Consumer Response (ECR), managing assortments has received significant attention, though that is mainly with the objective to optimise productivity of inventories and store-space at the consumer interface (Svensson 2002). Our detailed findings suggest that the more mature process an organisation has for managing assortments, by means of closely managing and monitoring product introductions and a joint assortment planning with partners, the higher the expected performance will be. This supports the statement of Homlström et al. (2002) who argue that ECR contains a missing link as each entity in the chain still plans assortments independently. All in all, in the supply chain realm, research on assortment management so far has mainly focused on issues related to variety of the assortment, such as depth and width of product ranges required. However, given its effect on supply chain performance, research is particularly needed on the process of managing the assortment from a supply chain perspective. Holmström (1997) concluded that assortment management is an overlooked area of supply chain management. We contend that this gap has not yet been filled sufficiently.

Stock management factor 3 (organisation), vendor management factor 1 (vendor analysis) and execution factor 1 (up to date information) have about an equally strong relation with order fill rate. Stock management factor 3 consists of clear and detailed specifications of responsibilities over inventory and clear division of tasks across sites about who is doing what positively influence performance. This shows that the organisational aspects of managing inventory need to be carefully considered. Unclear organisational aspects such as responsibilities, managerial commitment and conflicting policies may be a significant barrier to effective supply chain management (Fawcett et al. 2008).

In managing vendors, particularly measuring vendor performance and understanding and managing risks on the supply side impacts performance. Fawcett et al. (2008) found that a lack of willingness to manage risks jointly was perceived as an obstacle to effective supply chain management; managing these risks is therefore critical in achieving high performance levels. This also suggests that managing performance is particularly relevant across partners, not just within a company. This confirms Lockamy and McCormack (2004b) who found a positive impact of collaboration, measurement and integration across partners on supply chain performance.

The fact that the process of developing and reviewing a strategy is related to order fill rate confirms and extends earlier research that strategy is key to business performance (Bendoly et al. 2007); however we only find a weak relation. Data management is only weakly related to performance, supporting the finding of Lockamy and McCormack (2004b: 1210) that "…information technology solutions are only part of the answer to improved supply chain performance".

Last, we have calculated an overall mean score by averaging the maturity scores on all practices. It turns out that the overall mean maturity score has a nearly equally strong relation with performance as the factor Performance Management. Estimated changes in average maturity score on our instrument may thus be a guide for assessing effects on future supply chain performance.

## 6. Conclusions and implications

Self-assessment of supply chain process maturity is a type of benchmarking that has benefited little from academic contributions (Akyuz & Erkan 2009). In this chapter, we have described the development and application of a self-assessment supply chain maturity grid. We have used the data from 57 companies that filled out the assessment grid to understand how supply chain maturity assessment can contribute to the improvement of companies, which is ultimately the goal of a benchmarking exercise.

The data used from a maturity model such as discussed in this chapter enables companies to define target maturity levels and compare target to actual maturity levels. As such, a maturity model is a powerful tool to support strategies of a company, particularly because target and actual maturity in different processes can be compared easily with a spider diagram. Fig. 2 provides an example of such a spider diagram.

Managerial implications of our study are twofold. First, our results suggest that performance management is key in achieving high performance levels, particularly across organisational boundaries. Performance management should be the first and foremost process a supply chain manager pays attention to if high levels of supply chain performance are strived for. Aspects that managers should focus on are an introduction of a Plan-Do-Check-Act cycle to guide process improvement, communication of performance metrics to stakeholders, ensuring a balance of metrics, a focus on learning from one another and in particular a cross-organisational view on measuring performance.

Secondly, our analysis shows the importance of assortment management across companies. The extent to which product introductions are managed and monitored and the degree of

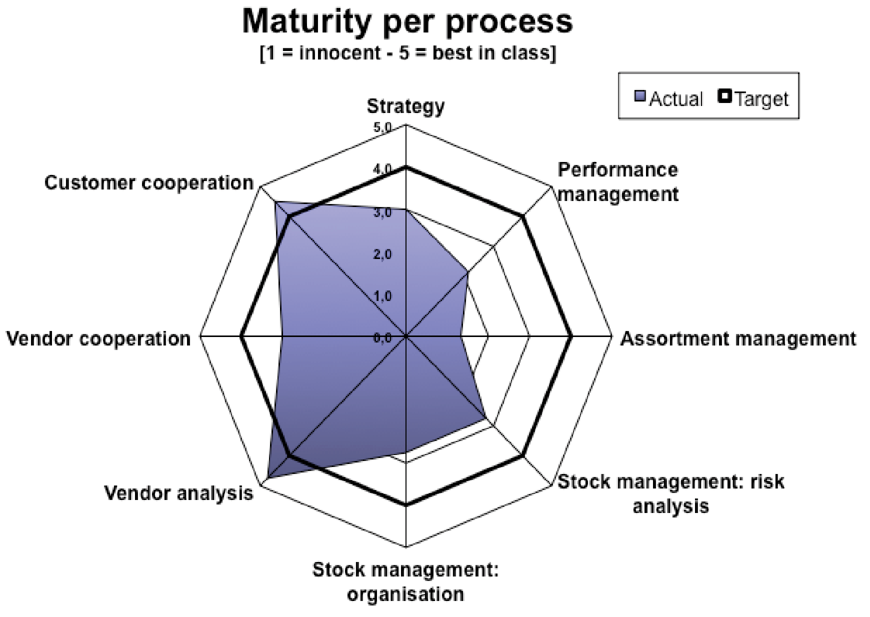


Fig. 2. Sample maturity spider diagram

joint planning together with partners in the supply chain are practices that contribute significantly to achieving high performance levels. It is not uncommon in business practice that the number of stock keeping units grows quite rapidly based on desires of sales departments to introduce new product versions. Our results suggest that this should be done in close cooperation with partners to have the right product versions available. They furthermore suggest that the process be managed closely and that there be quick feedback mechanisms in place to judge the success of a new product quickly and take decisions accordingly.

The theoretical implications of our results are the following. First, literature asserts that it is not so much the definition of performance metrics that requires attention but in particular the process of implementation (Bourne et al. 2000). Our analysis confirms that maturity in measuring and managing performance in a company plays a key role in achieving high levels of supply chain performance. Practices that support this, such as the implementation of a PDCA cycle and communication about performance metrics turn out to support reaching high performance levels. As such, our results provide further evidence that particularly the human elements such as communication are critical in successfully developing and implementing a performance measurement system.

Secondly, our research shows the importance of maintaining a cross-company perspective in managing processes, particularly in managing performance and managing assortments. Previous research has shown that companies that are integrated with partners in the supply chain perform better (Frohlich & Westbrook 2001; Singh & Power 2009); our research provides further guidance by identifying relevant practices for such integration.

Thirdly, our results show the importance of managing assortments, an area that has received ample marketing attention but relatively scant attention in the context of supply chain management. The debate in the supply chain domain so far has mainly focused on depth and width of an assortment, not on the process of managing assortments as such.

Our research findings are limited by the size of the sample and the section of industry we have focused on. A larger sample may be useful to expand findings. We furthermore focus on companies delivering a significant variety from stock, with a large representation of wholesalers in our sample. The need for good assortment management in such companies may be not surprising at first hand due to typical assortment sizes in these companies. However, we did not find any effect of assortments size on performance in our sample. A replication of this research in other industry segments may provide additional directions.

Discussions during the summer course event where companies filled out the grid revealed that they found it a very useful exercise to go through such a grid. Companies argued that it evoked discussion and can provide concrete guidance to improvement in supply chain processes. In the weeks and months after this summer course, we received many requests from summer course participants to make the maturity grid available in a digital format. Upon further inquiry, it turned out that many had started to use the maturity grid in their companies as an instrument to develop a growth path for their supply chain, which is exactly what the self-assessment grid has been intended for. Several of these companies used the grid to develop a supply chain strategy together with selected suppliers and customers. As such, the grid was a useful facilitating tool for goal setting with supply chain partners. Though we have not performed a formal evaluation among course participants, we believe the above is a good indication for the usefulness of a self-assessment grid in practice.

There are several interesting avenues for future research besides the application of the grid on a larger and wider sample. First of all, a longitudinal study on a company applying the grid and using the grid for defining an improvement strategy would show if and how the use of a maturity model can induce performance improvement. Secondly, research on process maturity across partners in a supply chain would enable the detection of which practices truly matter from a cross-company perspective. This could be done by for example following a product from raw materials to finish product and investigate triads of companies that are supplier/customer of each other in that supply chain and that are involved in making and distributing that product.

Albeit we have not been able to obtain data from a large sample with a variety of industries, our research shows that there is a need to further research self-assessment supply chain maturity grids: both academia and practice are in need of validated maturity assessment instruments.

## 7. References

Akyuz, G.A. and Erkan, T.E. [2009], 'Supply chain performance measurement: a literature review', *International Journal of Production Research*, First published on: 25 August 2009 (iFirst).

Bendoly, E., Rosenzweig, E.D., and Stratman, J.K. [2007], 'Performance Metric Portfolios: A Framework and Empirical Analysis', *Production and Operations Management,* Vol. 16, No. 2, pp. 257-76.

Bourne, M., Neely, A., Platts, K., and Mills, J. [2002], 'The success and failure of performance measurement initiatives', *International Journal of Operations & Production Management,* Vol. 22, No. 11, pp. 1288-310.

Bourne, M., Mills, J., Wilcox, M., Neely, A., and Platts, K. [2000], 'Designing, implementing and updating performance measurement systems', *International Journal of Operations and Production Management,* Vol. 20, No. 7, pp. 754-71.

Braam, G.J.M. and Nijssen, E.J. [2004], 'Performance effects of using the Balanced Scorecard: a note on the Dutch experience', *Long Range Planning,* Vol. 37, No. 4, pp. 335-49.

Camp, R.C. [1989], Benchmarking - The Search for Industry Best Practices that lead to Superior Performance (Milwaukee: ASQ Quality Press).

Chae, B.K. [2009], 'Developing key performance indicators for supply chain: an industry perspective', *Supply Chain Management: An International Journal,* Vol. 14, No. 6, pp. 422-28.

Crosby, P.B. [1979], *Quality is free: The art of making quality certain* (New York: New American Library New York).

Davies, A.J. and Kochhar, A.K. [2002], 'Manufacturing best practice and performance studies: a critique', *International Journal of Operations & Production Management,* Vol. 22, No. 3, pp. 289-305.

Eisenhardt, K.M. [1989], 'Building Theory from Case Study Research', *Academy of Management Review,* Vol. 14, No. 4, pp. 532-50.

Fawcett, S.E., Magnan, G.M., and McCarter, M.W. [2008], 'Benefits, barriers, and bridges to effective supply chain management', *Supply Chain Management: An International Journal,* Vol. 13, No. 1, pp. 35-48.

Ferber, R. [1977], 'Research by convenience', *Journal of Consumer Research,* Vol. 4, No. 1, pp. 57-58.

Forza, C. [2002], 'Survey research in operations management: a process-based perspective', *International Journal of Operations & Production Management,* Vol. 22, No. 2, pp. 152-94.

Fraser, P., Moultrie, J., and Gregory, M. (2002). The use of maturity models/grids as a tool in assessing product development capability. IEEE International Engineering Management Conference, Cambridge, IEMC.

Frohlich, M.T. and Westbrook, R. [2001], 'Arcs of integration: an international study of supply chain strategies', *Journal of Operations Management,* Vol. 19, No. 2, pp. 185-200.

Green Jr, K.W., Whitten, D., and Inman, R.A. [2008], 'The impact of logistics performance on organizational performance in a supply chain context', *Supply Chain Management: An International Journal,* Vol. 13, No. 4, pp. 217-27.

Gunasekaran, A. and Kobu, B. [2007], 'Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995-2004) for research and applications', *International Journal of Production Research,* Vol. 45, No. 12, pp. 2819-40.

Hair, J.F., Black, W.C., Babin, B.J., Anderson, R.E., and Tatham, R.L. [2006], *Multivariate data analysis* (6 edn.; Upper Saddle River, NJ: Pearson Prentice Hall).

Hammer, M. [1990], 'Reengineering work: don't automate, obliterate', *Harvard Business Review,* Vol. 68, No. 4, pp. 104-12.

Harter, D.E., Krishnan, M.S., and Slaughter, S.A. [2000], 'Effects of process maturity on quality, cycle time, and effort in software product development', *Management Science,* Vol., pp. 451-66.

Hendricks, K.B. and Singhal, V.R. [2008], 'Demand-supply mismatch and stock market reaction: Evidence from excess inventory announcements', (Atlanta: Working paper, Georgia Institute of Technology).

Holmstrom, J., Framling, K., Kaipia, R., and Saranen, J. [2002], 'Collaborative planning forecasting and replenishment: new solutions needed for mass collaboration', *Supply Chain Management: An International Journal,* Vol. 7, No. 3, pp. 136-45.

Holmström, J. [1997], 'Product range management: a case study of supply chain operations in the European grocery industry', *Supply Chain Management: An International Journal,* Vol. 2, No. 3, pp. 107-15.

Ibbs, C.W. and Kwak, Y.H. [2000], 'Assessing project management maturity', *Project Management Journal,* Vol. 31, No. 1, pp. 32-43.

Ittner, C.D. [2008], 'Does measuring intangibles for management purposes improve performance? A review of the evidence', *Accounting and Business Research,* Vol. 38, No. 3, pp. 261-72.

Kaiser, H.F. [1974], 'An index of factorial simplicity', *Psychometrika,* Vol. 39, No. 1, pp. 31-36.

Kim, S.W. [2006], 'Effects of supply chain management practices, integration and competition capability on performance', *Supply Chain Management: An International Journal,* Vol. 11, No. 3, pp. 241-48.

Kwak, Y.H. and Ibbs, C.W. [2002], 'Project Management Process Maturity (PM) Model', *Journal of Management in Engineering,* Vol. 18, pp. 150-5.

Lambert, D.M. and Cooper, M.C. [2000], 'Issues in supply chain management', *Industrial Marketing Management,* Vol. 29, No. 1, pp. 65-83.

Laugen, B.T., Acur, N., Boer, H., and Frick, J. [2005], 'Best manufacturing practices', *International Journal of Operations & Production Management,* Vol. 25, No. 2, pp. 131-48.

Lee, H.L. and Billington, C. [1992], 'Managing supply chain inventory: pitfalls and opportunities', *Sloan Management Review,* Vol. 33, No. 3, pp. 65-73.

Lockamy III, A. and McCormack, K. [2004a], 'The development of a supply chain management process maturity model using the concepts of business process orientation', *Supply Chain Management: An International Journal,* Vol. 9, No. 4, pp. 272-78.

Lockamy III, A. and McCormack, K. [2004b], 'Linking SCOR planning practices to supply chain performance; an exploratory study', *International Journal of Operations and Production Management,* Vol. 24, No. 12, pp. 1192–218.

Lockamy III, A., Childerhouse, P., Disney, S.M., and Towill, D.R. [2008], 'The impact of process maturity and uncertainty on supply chain performance: an empirical study', *International Journal of Manufacturing Technology and Management,* Vol. 15, No. 1, pp. 12-27.

McCormack, K., Ladeira, M.B., and de Oliveira, M.P.V. [2008], 'Supply chain maturity and performance in Brazil', *Supply Chain Management: An International Journal,* Vol. 13, No. 4, pp. 272-82.

Melnyk, S.A., Stewart, D.M., and Swink, M. [2004], 'Metrics and performance measurement in operations management: dealing with the metrics maze', *Journal of Operations Management,* Vol. 22, No. 3, pp. 209.

Moultrie, J., Clarkson, P.J., and Probert, D. [2006], 'A tool to evaluate design performance in SMEs', *International Journal of Productivity and Performance Management,* Vol. 55, No. 3/4, pp. 184.

Neely, A., Mills, J., Platts, K., Richards, H., Gregory, M., Bourne, M., and Kennerley, M. [2000], 'Performance measurement system design: developing and testing a process-based approach', *International Journal of Operations and Production Management,* Vol. 20, No. 9/10, pp. 1119-145.

Paulk, M.C., Curtis, B., Chrissis, M.B., and Weber, C.V. [1993], 'Capability maturity model, version 1.1', (10), pp. 64.

Plomp, M. and Batenburg, M.R.S. [2010], 'Measuring chain digitisation maturity: An assessment of Dutch retail branches', *Supply Chain Management: An International Journal,* Vol. 15.

Ramdas, K. and Spekman, R.E. [2000], 'Chain or shackles: understanding what drives supply-chain performance', *Interfaces,* Vol., pp. 3-21.

Sharman, G. [2003], 'Building the successful multinational distributor', *Supply Chain Forum: An International Journal,* Vol. 4, No. 1, pp. 28-34.

Shin, H., Collier, D.A., and Wilson, D.D. [2000], 'Supply management orientation and supplier/buyer performance', *Journal of Operations Management,* Vol. 18, No. 3, pp. 317-33.

Singh, P.J. and Power, D. [2009], 'The nature and effectiveness of collaboration between firms, their customers and suppliers: a supply chain perspective', *Supply Chain Management: An International Journal,* Vol. 14, No. 3, pp. 189-200.

Spekman, R.E., Kamauff, J.W., and Myhr, N. [1998], 'An Empirical Investigation into Supply Chain Management: a Perspective on Partnerships', *Supply Chain Management: An International Journal,* Vol. 3, No. 2, pp. 53-67.

Stewart, G. [1997], 'Supply-chain operations reference model (SCOR): the first cross-industry framework for integrated supply-chain management', *Logistics Information Management,* Vol. 10, pp. 62-67.

Svensson, G. [2002], 'A firm's driving force to implement and incorporate a business philosophy into its current business activities: the case of ECR', *European Business Review,* Vol. 14, No. 1, pp. 20-30.

Swink, M., Narasimhan, R., and Kim, S.W. [2005], 'Manufacturing practices and strategy integration: effects on cost efficiency, flexibility, and market-based performance', *Decision Sciences,* Vol. 36, No. 3, pp. 427-57.

Tummala, V.M.R., Phillips, C.L.M., and Johnson, M. [2006], 'Assessing supply chain management success factors: a case study', *Supply Chain Management: An International Journal,* Vol. 11, No. 2, pp. 179-92.

Ungan, M. [2005], 'Management support for the adoption of manufacturing best practices: key factors', *International Journal of Production Research,* Vol. 43, No. 18, pp. 3803-20.

Van Dijk, E., de Leeuw, S., and Durlinger, P. [2007], *Voorraadbeheer in Perspectief; zeven invalshoeken van het vak (in Dutch)* (Deventer: Slimstock B.V.).

Van Landeghem, R. and Persoons, K. [2001], 'Benchmarking of logistical operations based on a causal model', *International Journal of Operations and Production Management,* Vol. 21, No. 1/2, pp. 254-66.

van Ryzin, G. and Mahajan, S. [1999], 'On the relationship between inventory costs and variety benefits in retail assortments', *Management Science,* Vol. 45, No. 11, pp. 1496-509.

Voss, C.A., Chiesa, V., and Coughlan, P. [1994], 'Developing and testing benchmarking and self-assessment frameworks in manufacturing', *International Journal of Operations and Production Management,* Vol. 14, pp. 83-101.

Whybark, D.C. and Vastag, G. (eds.) [1993], Global manufacturing practices - a world-wide survey of practice in production planning and control (Amsterdam: Elsevier).

Zirger, B.J. and Maidique, M.A. [1990], 'A Model of New Product Development: An Empirical Test', *Management Science,* Vol. 36, No. 7, pp. 867-83.

# 7

# Supply Chain Resilience Using the Mapping Approach

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## 1. Introduction

The supply chain environment is changing. Globalisation and changes demanded by stakeholders have influenced the attitudes of supply chain entities. These entities are becoming more professional, showing ever increasing levels of complexity, and adopting philosophies and management practices with the objective of increasing their levels of competitiveness.
Competitiveness is a critical factor in the success of a supply chain. Disturbances increase supply chain and may reduce it performance and competitiveness. It is therefore fundamental for a supply chain to be resilient to disturbances.
The chapter begins by defining and discussing the central concepts of resilience and disturbance, within the scope of supply chain management. Based on a mapping approach, a methodology is proposed for improving the supply chain's resilience to a disturbance proactively. After the selection of a supply chain disturbance, and the supply chain mapping, a mitigation strategy is chosen to make the supply chain resilient to this disturbance. A case study is presented to illustrate how the mapping approach support managers in the decision making process to make the supply chain resilient.

### 1.1 Background

In recent years, there has been an increase in the likelihood of the occurrence of disturbances. Natural catastrophes, such as what happened on the island of Madeira (Portugal) in February 2010, serious accidents resulting from technical faults, such as the oil spill that is taking place in the Gulf of Mexico, and economic crises, such as the one we are going through now with the international financial crisis caused by the failure of Lehman Brothers, are examples of events that cause disturbances that can have an adverse impact on supply chain management.
These disturbances can have characteristics that make them difficult to anticipate, and they can have severe negative consequences, not only in the supply chain entities where they directly occur, but also in the supply chains where the entities are integrated, since they generally lead to a cascade effect.
Disturbances may cause disruptions in flows of information, materials and/or finance in one or more supply chain entities. These disruptions may have a negative influence on a supply chain's normal operations, thus making it vulnerable and reducing its performance and competitiveness. Therefore, it is fundamental to make a supply chain resilient to disturbances.

The resilience of a supply chain entity is defined as the ability of that entity to be able to react to disturbances and return to its original state or a more desirable one (Christopher & Peck, 2004; Ponomarov & Holcomb, 2009). So, to make a supply chain resilient to disturbances, it is essential to understand the network that connects the supply chain entities. Therefore, it is essential to have an overall vision of the supply chain and of the principal characteristics regarding its entities and flows.

Supply chain mapping is a tool that allows for a macro-graphic representation of the supply chain (current state). When subjected to a disturbance, through this current state it is possible to build a potential future state. With the current state and the future state, we have the ability to identify if the supply chain is resilient to such disturbance. If the supply chain is not resilient to the disturbance, managers may take appropriate measures to respond to this disturbance, i.e., they may adopt mitigation policies, strategic or operational policies, to reduce the adverse effects of such disturbance and make the supply chain resilient.

The evaluation of the impact of the adoption of mitigation policies, in terms of supply chain performance and efficiency, will provide support to managers in decision making concerning the selection of the mitigation policy that needs to be adopted in order to increase the supply chain's resilience to a disturbance.

### 1.2 Objective

The main purpose of this study is twofold:

i. To show that the mapping of the supply chain makes it possible to identify if the supply chain is resilient to a specific disturbance, and
ii. Support managers in making decisions concerning the adoption of mitigation policies, in the strategic as well as operational areas, in order to make the supply chain more resilient to certain disturbances.

To illustrate the way in which supply chain mapping can help managers to identify the most appropriate management strategy (mitigation policy) to make a supply chain resilient to a disturbance, a case study is presented based on a real supply chain in the automotive industry, considering a disturbance on the supply side. Consequently, we will discuss proactive and reactive mitigation policies that can be adopted by the supply chain to make it resilient to disturbances on the supply side. The case study represents a small part of the supply chain. In fact, in light of the objectives of this work and the complexity inherent in a real supply chain, it is sufficient to analyse only a small part of the supply chain.

## 2. Supply chain disturbances

The occurrence of disturbances that negatively affect a supply chain is an unavoidable fact, whereby all supply chains are inevitably at risk (Craighead et al., 2007). In this context, it is crucial for supply chain survival that managers identify, in a proactive manner, the disturbances that may potentially affect the supply chain and take measures, developing, for example, mitigation and/or contingency plans that help make the supply chain more resilient (i.e., less vulnerable).

Supply chain management in the face of disturbances is a subject that, in recent years, has motivated the interest of numerous researchers and practitioners. The works of Sheffi, Zsidisin and Svensson are examples of this.

In recent years there has been an increase in disturbances affecting the normal operation of the supply chain entities. According to Craighead et al. (2007), this is the greatest source of pressure on supply chain entities intending to compete in the global market. They become vulnerable, which consequently reduces their performance and causes them grave financial difficulties. The supply chains thus lose their competitiveness. Competitiveness is a critical factor to the success of an organisation and/or a supply chain, so it is fundamental to make the supply chain able to be resilient to those disturbances.

A disturbance is a consequential situation that significantly threatens the normal course of operations of the affected supply chain entities (Zsidisin, 2000). Typically, this situation implies taking decisions/actions in order to minimize such effects.

The authors who have studied this subject do not reach consensus over the definition of disturbance, with it often being confused with the definition of disturbance source. In the context of this chapter, the term disturbance is defined as a foreseeable or unforeseeable event which affects the usual operation and stability of an organisation or a supply chain (Barroso et al., 2008). This is similar to Svensson's (2000), Hendricks' et al. (2008) and Kleindorfer & Saad's (2005) supply chain disturbance definition, an unplanned and unanticipated event that disrupts the normal flow of goods and materials in a supply chain.

For example, the supplier of automotive parts was severely affected by an earthquake that occurred on July 16, 2007 in Japan. As a consequence, one of its customers, a Japanese automotive manufacturer suffered a halt for several days (Pettit, 2008). An interruption in the operations of the supplier of automobile parts and of the automobile manufacturer is a disturbance example.

According to a study carried out by Autoeuropa, a Portuguese automotive assembler (Redmont, 2007, as cited in Azevedo et al., 2008), "some of the main disturbances identified by the principal partners in the supply chain are supplier delays (51%), others (25%), variations in production quantity (14%), quality problems (6%), problems in collection (3%) and damage in transport (1%)", Figure 1. Other disturbances frequently mentioned in the bibliography are:

i. an unexpected increase in demand from a customer;
ii. a general strike by drivers in a country;
iii. and infrastructure problems (roads, ports and communications). Regardless of the type of disturbance, the final result is always the same, unfulfilled orders.

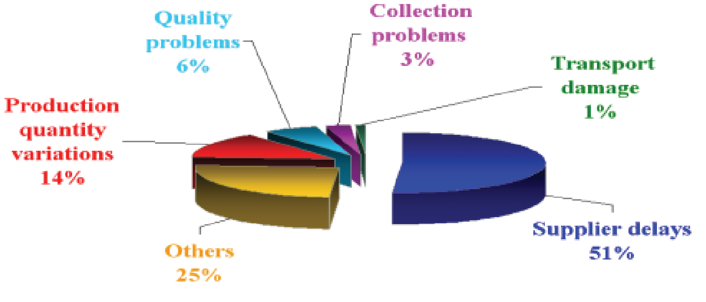


Fig. 1. Disturbances in an automotive SC entity in Portugal

The authors do not reach consensus over the term used to designate a disturbance. Some authors refer to disturbances as "disruptions" (Ponomarov & Holcomb, 2009; and Tuncel & Alpan, 2010), while others refer to it as "risk" (Chopra & Sodhi, 2004; and Goh et al., 2007), "uncertainty" (Mason-Jones & Towill, 1998) or even as "crisis" (Natarajarathinam et al., 2009). In this chapter, the term used is disturbance.

A disturbance may be characterized based on some criteria, particularly, i) it may be critical for a SC, ii) it may occur during a short or long period of time, iii) it may have a local or a global impact, and iv) it may be foreseen a greater or lesser time in advance of its occurrence (Barroso et al., 2008).

A disturbance may occur: i) within an organisation (for example, a machine breakdown or a strike), ii) outside an organisation but internal to the supply chain (for example, a supply delay or distorted information throughout the supply chain), or iii) external to the supply chain (for example, an earthquake or a flu epidemic).

The occurrence of a disturbance may have severe negative effects only on the supply chain entity it directly impacts, or may also affect, in whole or in part, the supply chain of which the entity forms a part. In fact, the negative effects of the disturbances frequently cascade through the supply chain, due to dependencies (time, functional and relational) between supply chain entities (Svensson, 2004). This behaviour affects the capacity of the entities that constitute the supply chain to fulfil commitments made, reducing their service level.

The effect of a disturbance on a supply chain may involve different degrees of severity. Severity is defined as the number of entities in a supply chain whose outbound and inbound flow is affected by an unplanned event (Craighead et al., 2007). The degree of severity of a certain disturbance depends on factors specific to the structure of the supply chain (density, complexity, and node criticality), and supply chain mitigation capabilities (recovery and warning).

In the light of a disturbance with negative effects for a supply chain, the level of competitiveness of the supply chain previously reached (before the disturbance occurrence) is compromised. The ideal solution is for managers of the supply chain entity or the supply chain to formulate proactive recovery plans to minimize the negative effects of the disturbances that may affect the supply chain. But, in the absence of this, at least a reactive recovery plan should be in place. Although this is not the ideal solution, it is better than having no recovery plan.

The performance of a supply chain that is not resilient to a disturbance shows a typical profile that was defined by Asbjørnslett & Rausand (1999), Figure 2. In general, the performance of a supply chain entity or a supply chain when subject to a disturbance drops sharply, taking some time to recover until it reaches the same performance level as before the disturbance occurred (line A). In the event of a disturbance mitigation policy being adopted, the drop in performance is not so sharp, the period of time that the supply chain takes to recover its performance being shorter and the final performance level (before maintaining stability) can be the same as before the disturbance occurred (line B) or even greater (line C).

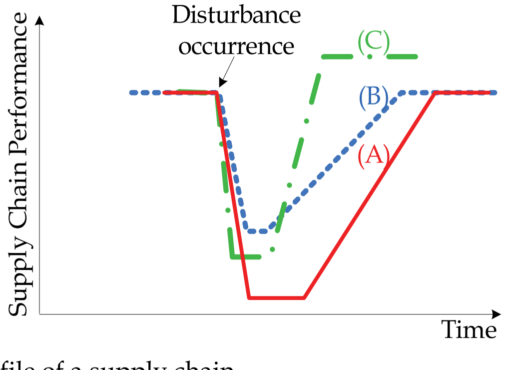


Fig. 2. Performance profile of a supply chain

So, it is crucial that managers identify the likelihood that disturbances will occur and then take the appropriate measures to respond to each disturbance. The adoption of measures suitable for the management of supply chain disturbances will give the supply chain the ability to quickly return to its original state, or even a better state (Peck, 2005; Ji & Zhu, 2008; and Carvalho & Cruz Machado, 2007), and thereby demonstrate resilience. The measures to be taken to limit the negative effects of a disturbance can be of 3 types: i) to reduce the likelihood that such a disturbance will occur, ii) to reduce the negative effect of the disturbance, or iii) both.

## 3. Supply chain resilience

Supply chain resilience is a relatively new area of management research. Although in the available literature it is possible to find some definitions of resilience in different contexts, in the supply chain context some researchers, namely Peck (2005) and Mitroff & Alpasan (2003), define supply chain resilience by associating it with the ability to recover from or adjust easily to adversity or change, i.e., supply chain disruptions caused by disturbances. Fiksel (2006) proposes an identical definition, but considers that a resilient system will have the ability not only to "survive and adapt in face of turbulent change", but also "grow".

The traditional tool to manage uncertainty is risk management. According to Pettit (2008), the "traditional risk assessment approach cannot deal with unforeseeable events", the concept of supply chain resilience filling this gap.

Using multidisciplinary perspectives, Ponomarov & Holcomb (2009) propose the following definition of supply chain resilience: "The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function." This definition considers several key elements when a supply chain disruption occurs, namely, response and recovery to the same or a better state, and retention (or maintenance of) the same control over structure and function.

The concept of supply chain resilience is, in this chapter, defined as the supply chain's ability to react to the negative effects caused by disturbances that occur at a given moment in order to maintain the supply chain's objectives.

A resilient supply chain entity or supply chain recovers better from hardships (Mitroff & Alpasan, 2003). However, resilience is more than simply the ability to recover. It also implies a certain level of flexibility and the ability to adapt to environmental influences. Therefore, resilience is one of the prerequisites for sustainable economic development (Hamel & Valikangas, 2003). It may also be viewed as a source of competitive advantage. Resilience is the key to developing a strategic plan that is sustainable and capable of producing results that are better than those of less resilient competitors (Stoltz, 2004).

### 3.1 Mitigation policies

One way for a supply chain to become resilient is through the implementation of adequate mitigation policies.

The awareness and need for supply chain disturbance management has grown rapidly this century, driven by regulatory compliance requirements and stakeholders' demands. Also, there is a greater understanding of the real costs of supply chain disturbances. Consequently, supply chain disturbance management has become one of the major concerns of many

organisations and supply chain managers who direct their efforts to improving the resilience of their supply chain entities or supply chains. Accordingly, adequate management policies must be defined in order to a supply chain entity or supply chain become resilient, meaning an entity or supply chain with the abilityand the means to reduce negative disturbance effects.
When main disturbances occur, many supply chains tend to break down. In this case recovery takes a long time. Certain policies will enable a supply chain to effectively manage the inherent fluctuations regardless of the occurrence of major disturbances. These policies will allow a supply chain to become more resilient in the face of major disturbances (Tang, 2006).
The mitigation policies can be defined according to the moment at which actions are taken to mitigate the disturbance effects, Figure 3. Tomlin (2006) describes two general approaches for dealing with disturbances: mitigation and contingency policies. Both are defined prior disturbance occurring, however, mitigation policies are employed prior to disturbances, whereas contingency policies are generally post-disturbance techniques. In the case of mitigation policies, the supply chain entity takes some action in advance of a disturbance (and so incurs the cost of the action regardless of whether a disturbance occurs). With contingency policies, the supply chain entity takes action only in the event of a disturbance occurring. So, mitigation policies are essentially more proactive in nature, while contingency policies are more reactive (Craighead et al., 2007).

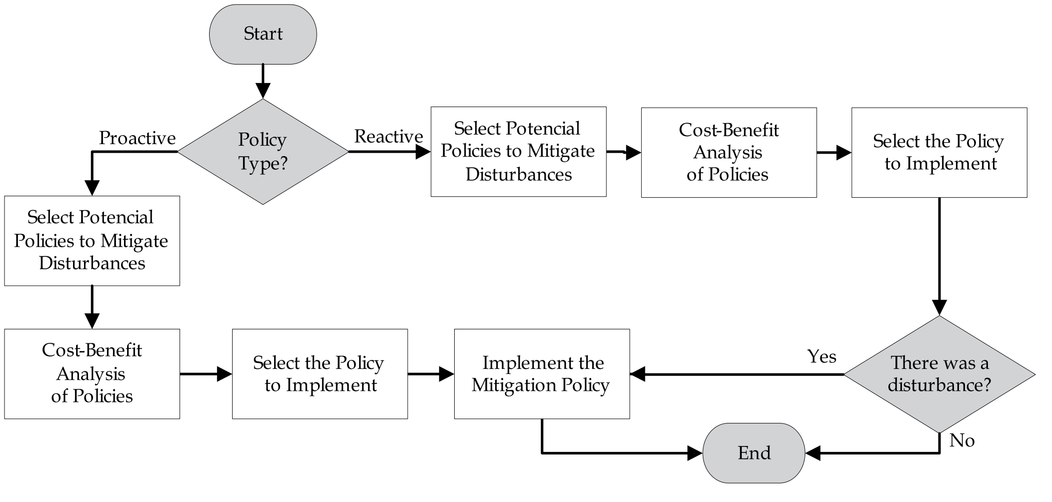


Fig. 3. Framework to mitigation policies implementation

A proactive policy emphasizes preventive plans for what can be done to avoid specific disturbances or prevent their occurrence as far as possible. For those unavoidable disturbances, the emphasis is to mitigate their negative consequences and transform them into business opportunities and/or increased value for the customer.
A reactive policy to disturbances emphasizes supply chain readiness. The focus is on how to increase the supply chain's capacity to respond to the disturbance faced individually and collectively.
The selection of which policy to adopt generally depends on the negative potential consequences to the supply chain of the disturbance or the likelihood of the disturbance occurring. Many policies for the management of disturbances are in conflict with the supply chain's traditional goals and processes, and vice-versa. Consider, for example, the trade-off

between efficiency and redundant inventory: building redundant inventory in the supply chain will function as a buffer to maintain continuous operations. However, it will also drive up costs and lead to lower efficiency.

A review of available literature provides a huge number of policies used to mitigate the negative effects of supply chain disturbances. Since the disturbances most cited by managers in the automotive industry (section 2) are from the supply side, in this chapter only disturbances with this characteristic will be analysed.

Consider the disturbance source "supplier failure". Failures with inbound materials and services can arise from a supplier failure. An example of the ramifications of supply failure would be the shutdown of production lines due to a lack of incoming materials from a supplier, which can then result in the loss of business and customer goodwill. Some authors propose different policies to mitigate supplier failures (Table 1).

| Mitigation policy | References |
|---|---|
| Safety stock | Baker (2007); Zsidisin et al. (2000) |
| Multi-sourcing | Baker (2007); Zsidisin et al. (2000); Svensson (2003) |
| Collaboration with supplier | Zsidisin et al. (2000); Christopher & Peck (2004) |
| Coordinate relationships in the supply chain | Giunipero & Eltantawy (2004) |
| Increase information sharing | Giunipero & Eltantawy (2004); Li et al. (2006) |
| Supplier selection process | Levary (2007) |
| Well stocked pipeline | Zsidisin et al. (2000) |
| Supply chain reengineering | Christopher & Peck (2004) |
| Create a supply chain disruptions management culture | Christopher & Peck (2004) |

Table 1. Supply side mitigation policies

The use of inventory redundancy in situations of supply uncertainty is, in most cases, recognized as a possible mitigation policy. For example, Chopra & Sodhi (2004) cite "increase inventory" as a mitigation policy, whilst Stoltz (2004) states that "the strategic disposition of additional capacity and/or inventory at potential 'pinch points' can be extremely beneficial in the creation of resilience within the supply chain".

The creation of redundancies or flexibilities is one of the main policies for resilience design: the redundancy capacity may or may not be used; it is this additional capacity that would be used to replace the capacity loss caused by a disturbance. Flexibility, on the other hand, entails restructuring previously existing capacity.

The sourcing policy should be employed considering the fact that there is an overall association between the sourcing and the occurrence of disturbances in firms' inbound and outbound logistical flows. However, due the interdependencies among groups of suppliers, the buying organisation that wants to adopt multiple sourcing policies for disturbance mitigation should create a portfolio of suppliers that do not maintain relationships with one another.

The supplier selection process, the use of collaboration with the various entities involved working together, the increase of information sharing, and the use of safety stock to buffer against variations in supply are also policies to which reference is frequently made.

Typically, supplier selection is based on the acquisition price. However, for the organisation to be resilient, the supplier selection criteria should also be extended to other issues such as quality and organisational parameters/capabilities.

Intense collaboration among the various supply chain entities is crucial in order to attain a resilient supply chain in the turbulent business environment in which they currently operate. It may also facilitate upgrading suppliers' performance and allow them to become more capable. However, such a policy is difficult to implement. Only a small number of collaboration initiatives will be successful, and collaboration appears more and more difficult to achieve.

Increasing information sharing among supply chain entities will improve supply chain resilience, since the negative impact of lack of visibility in the supply chain is reduced.

Some authors also refer other policies, such as building a level of trust among trading partners, coordinating relationships with supply chain entities, passing the responsibility for the consequences of disturbances on to suppliers, having a well-stocked supply pipeline, performing supply chain re-engineering, and creating both an agile supply chain and a culture of disruption management.

## 4. Supply chain mapping

### 4.1 Traditional value stream mapping

Value Stream Mapping, referred to at Toyota as material and information flow mapping (Rother & Shook, 1999), is based on the fundamental principle of Lean Manufacturing, and has been used in several organisations as a powerful tool to identify and reduce waste, and to help to design production systems incorporating the lean concept. It is a relatively simple tool and has been widely applied to processes in need of performance improvement (Jones & Womack, 2002).

This tool illustrates material and information flows across the entity by focusing on production activities, working backwards from the entity's shipping dock to the entity's receipt of materials. Through value stream mapping a common set of tools, metrics and language is produced, facilitating systems analysis and decision making. The process of developing the value stream map makes understanding the product, material and information flows, value stream metrics and the interaction of processes possible. It is a big picture view of the system and aims to improve the whole value stream and not just to optimize parts of the value.

So, value stream mapping can be used as a road map that reveals the obstacles to continuous flow and the opportunities for reducing waste through the use of other lean techniques. As it explains how lean techniques can reduce waste in the value stream, it is known primarily as a communication tool. However, it is also used as a strategic planning tool, and a change management tool.

Many authors have studied the implementation of Value Stream Mapping effectively, namely, Ohno (1988), Womack et al. (1990), Womack & Jones (1998), and Rother & Shook (1999).

### 4.2 Extended value stream mapping

Over time, the most simple supply chain will begin to change. New entities and/or flows, such as suppliers, end-users, and parts or materials, can be added or excluded as changes that are not part of original planning. For that reason, a supply chain map of the current state is an indispensable managerial document, as it helps visualize the network that connects the business to its suppliers and to its downstream customers, and allows the identification of problematic areas and support process decisions. It can be seen as the starting point to improving supply chain management, increasing both efficiency and cost-saving efforts, allowing the identification of places where likely cost savings can be made due, namely, to excess or scarce inventories, inefficient processes, unnecessary actions, expedited shipments, lost visibility, and correct them.

Extended value stream mapping is a tool that takes material and information flows and effectively illustrates them across the supply chain. As an extension of the mapping process, supply chain mapping allows a clear view and understanding of the supply chain entities' actual capabilities as well as the whole chain dynamics. In general, supply chain mapping efforts focused on the flow of a specific product or product family (Lambert, 2008) and covers two echelons of the supply chain.

Gardner & Cooper (2003) define a supply chain map as a visual representation of the linkages and entities of a supply chain, and all of the process and decision points that occur throughout a supply chain, both upstream and downstream. According to Craighead et al. (2007) the mapping process should illustrate the different entities that are connected by the material flow, the relationships between entities, and the direction of the material flow (unidirectional or bidirectional). In line with Schroeder (2000), in supply chain mapping all processes may be included and the mapping focuses on how material, information and money flow in the upstream and downstream directions, and also within supply chain organisations.

Discussion on supply chain mapping cases is found in both the work of academics and practitioners (Hines & Rich, 1997; Naim et al., 2002; Childerhouse & Towill, 2003).

### 4.3 Supply chain map

In supply chains with multi-country operations, the manager may not have a clear view of the exact flow of material, information, and money. Developing a supply chain map which clearly shows suppliers, their contributions, the various flow types, and the way the business is organized, can lead to supply chain decision making more effective. Given the complexity of supply chains, supply chain mapping may exclude non-critical entities to keep the map simpler. Although a map of the supply chain is a simplified representation of the system, with respect to both entity relationships and types and direction flows, the essence of the environment in which the supply chain operates is captured.

A supply chain map should be easy to build and use, sufficiently comprehensive but not excessively detailed, intuitive in its use of visuals, and effective in building alternatives. Thus, a map would have standardized icons to allow easy identification of supply chain entities and also understanding of the flows between each entity (Farris II, 2010). It is important to note the role of the size, shape and colour of the assorted icons as a means of visual communication. Gardner & Cooper (2003) present a set of conventions, albeit incomplete, derived from the lean manufacturing model (Rother & Shook, 1999).

The choice of what to represent from what viewpoint can have a profound effect on supply chain strategy. The processes of both developing and disseminating the map should lead to a common understanding of the supply chain that would include what was deemed important to managing or monitoring the chain, as well as what the supply chain structure is or will be.

A supply chain map can either form an integral part of the planning process or a tool for implementing the supply chain strategy. Thus, according to Gardner & Cooper (2003), it may alert to possible constraints and offers a basis for: i) enhancing the strategic planning process, ii) easing the distribution of key information, iii) facilitating supply chain redesign

or modification, iv) clarifying channel dynamics, v) providing a common perspective, vi) enhancing communications, vii) enabling monitoring of supply chain strategy, and viii) providing a basis for supply chain analysis. So, a supply chain map provides a supply chain interrelationships framework, but does not provide the detail that allows to manage it.
Despite the fact that the mapping process can be used and found in many scientific areas, the map's appearance may vary significantly.
According to Gardner & Cooper (2003) three main distinctions are made between supply chain mapping and process mapping: i) orientation, ii) level of detail represented in the map, and iii) purpose for creating the map, Table 2.

| | Supply chain mapping | Process mapping |
|---|---|---|
| **Orientation** | • Focuses on how material, information, and money flow: i) in both the upstream and downstream directions, and ii) through an organisation. | • Can be defined as the focus of the mapping procedure.<br>• Generally directs its attention to a single operation or system within an organisation. |
| **Detail** | • Emphasizes high-level measures such as volume, cost, or lead time. | • Tends to break down a process into activities and steps. |
| **Purpose** | • Is strategic.<br>• Is used i) to help create a supply chain that conforms to a strategy, or ii) as a check to make sure the current chain is set up properly to fulfil that strategy. | • Is typically tactical.<br>• The origin of that map comes from the recognition of a problem area and an attempt to improve operating efficiency. The goal is to make changes to the current operations of the organisation. |

Table 2. Supply chain and process mapping

### 4.4 Type of maps

Supply chain maps can be built from a descriptive or prescriptive perspective (Gardner & Cooper, 2003). However, the purpose of the mapping is to gain an intimate understanding of the supply chain. There are different techniques and tools used to develop maps, and there are different types of map.
When someone refers to the expressions "supply chain" and "mapping", remembers the Supply Chain Operations Reference model. The Supply Chain Council (2006) has developed the Supply Chain Operations Reference model for representing a supply chain configuration by capturing the state of five core processes of its constituent entities: i) plan, ii) source, iii) make, iv) deliver, and v) return. Thus, it provides a unique framework that links business processes, metrics, best practices and technological features into a unified structure to support communication among supply chain entities, and also to improve the effectiveness of supply chain management and related supply chain improvement activities. This model allows the buy-make-deliver operations of a supply chain entity to be improved, and extends it beyond a single entity's boundaries.
The maps can depict organisations, flows, facilities, and/or processes (Gardner & Cooper, 2003), and results from the collection of different kinds of data. Therefore, Fine (1998) suggests three different types of map depending on the type of information they represent:

i. Organisations (e.g., focal organisation),
ii. Technologies (e.g., engine valve), and
iii. Capabilities (e.g., Just In Time delivery and supply chain management).

Supply chain maps may or may not depict geographical relationships. When supply chain maps are drawn on geographic maps, they allow spatial visualization. While cartographers might insist that a true map has spatial relationships depicted, for a supply chain map this information may be present or absent (Juga, 1995).

## 5. Research methodology

The purpose of a supply chain is to bring to its customers the product and services they need where and when necessary. All business processes within the supply chain must focus directly or indirectly on this goal. As competitiveness is a critical factor in the success of a supply chain, it is vital for a supply chain to be resilient to disturbances. Supply chain resilience to a disturbance can be achieved by redesigning the supply chain, which, in turn, can be done using the mapping approach as it allows both the supply chain to be understood and problematic areas identified. Therefore, in the context of this study, after identifying a potential disturbance that cause changes in the normal operation of the supply chain (reducing its competitiveness), it is necessary to redesign the supply chain (through the adoption of proactive and/or reactive policies), to mitigate adverse impacts and speed recovery.

Different policies may entail different implementation costs and different effectiveness to mitigate the adverse impact of a disturbance on the supply chain. Therefore, the selection of the mitigation policy to be implemented must take into consideration a cost-benefit analysis in relation to all the policies likely to being adopted.

To determine a future state of supply chain management and the progression from 'what is the current state?' to 'what should the redesigned supply chain be?', a methodology comprising six phases is proposed, Figure 4. Phases 4, 5 and 6 of the methodology are performed only if the supply chain is not resilient to the disturbance selected in phase 2.

**Phase 1 - Mapping the current supply chain**

To obtain a transparent overview of the related organisations and processes, the supply chain should be described and visualized. Thus, the first phase of the methodology is to provide a map of the supply chain under analysis. The mapping of the supply chain should be developed in pictorial form using diagrams. The most important information for each supply chain entity must be captured, such as products and materials sourced or bought, costs and prices, quantities, replenishment lead time and whether or not it is a sole or single source or a key customer, respectively. Sources of information used should be provided by each supply chain entity.

The supply chain map allows to identify i) the main supply chain constraints, ii) the relative importance of each supply chain entity, and iii) their main characteristics. Additionally, it should allow to identify iv) the supply chain dynamics, and v) their complexity (the complexity depends on both the entities that comprise it and the flow of materials that circulates between them). Thus, a supply chain map allows to illustrate the core processes that must be considered when trying to improve the resilience of a supply chain to a disturbance. Six major dimensions for supply chain maps can be considered: i) supply chain entities; ii) relational links between supply chain entities; iii) material flows; iv) information flows; v) management policies; and vi) lead times.

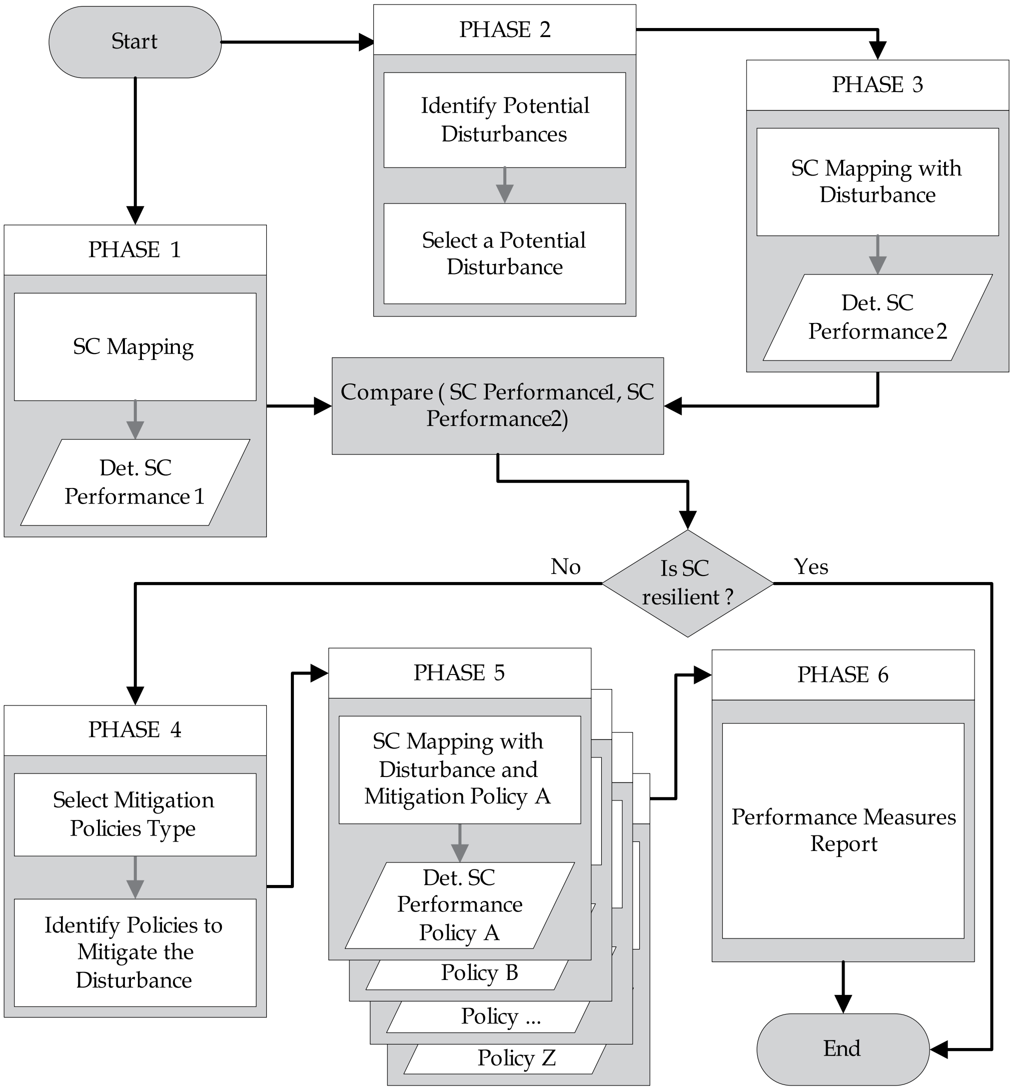


Fig. 4. Research methodology proposed

**Phase 2 - Identifying a potential disturbance in the supply chain**

The second phase is to identify potential disturbances in the supply chain that make it vulnerable. These vulnerabilities are related to specific events that have the potential to cause a break in the supply chain. Their disturbance source could lie within the supply chain, such as a strike, or externally, such as a severe weather event. Whatever the source, the adverse impact of disturbances on supply chain performance may be different. Thus, associated with a supply chain disturbance, there is a risk that depends on the likelihood of it occurring and the negative impact that it may have on supply chain performance. Accordingly, this phase is mainly focused on the selection of the disturbances that may occur in the supply chain in the near future, and that have higher probability of occurring and/or high negative impact on the supply chain.

**Phase 3 - Mapping the supply chain considering the impact of the potential disturbance identified in phase 2**

The third phase builds upon work conducted in the previous two phases of the methodology. A map of possible future state of the supply chain under analysis is formulated from the mapping of the current state of the supply chain (performed in phase 1) and the selected disturbance (from phase 2). At phase 3, it is possible to visualise the negative effects of the disturbance on supply chain performance and verify if the supply chain is resilient to the disturbance. If the supply chain is not resilient to the chosen disturbance, it is necessary to proceed to phase 4 to choose actions that may allow to move towards supply chain resilience.

**Phase 4 - Identifying a set of reactive or proactive policies, to mitigate the supply chain management problems caused by the chosen disturbance**

The fourth phase of the methodology allows, as a first step, to decide what type of mitigation policies to adopt, and as a subsequent step, to choose some policies to be implemented to make the supply chain resilient to the selected disturbance (phase 2).

**Phase 5 - For each mitigation policy chosen, mapping the supply chain considering the negative impact of the potential disturbance identified in phase 2 on the supply chain**

In the fifth phase, some supply chain mapping scenarios (of potentials future states) are built. These scenarios result from the adoption/implementation of mitigation policies chosen in the previous phase (phase 4). This allows to investigate if each scenario makes the supply chain resilient to the selected disturbance.

**Phase 6 - Performance measurement report for all supply chain mapping scenarios**

Finally, in the sixth phase of the methodology, a report outlining performance measures determined for each scenario is presented. This report allows a comparative analysis of the various scenarios. At this phase, each scenario is characterized by some performance measures aimed at the end customer, including the service level and lead time. Supply chain cost, which includes the costs associated with the adoption/implementation of mitigation policy, is also considered, where appropriate, as is the production cost in the supply chain entities and the transportation costs between supply chain entities that contribute to satisfying the end customer.

The methodology proposed supports decision making within supply chain management. It allows the manager to act in a proactive manner, trying different scenarios (implementing mitigation policies) to make the supply chain resilient to disturbances.

## 6. Case study

To illustrate the way in which supply chain mapping allows to improving proactively the supply chain's resilience to the negative effects of disturbances at the supply side, a case study was developed based on a real supply chain in the automotive industry. AutoEuropa (an automotive assembler) and some of its Portuguese suppliers make up the supply chain, and were involved in a research project named "Supply Chain Management: Design for Resilient Systems", which is being developed in Portugal.

To support proactive decision making in the selection of the mitigation policy to be implemented, the methodology proposed in section 5 was applied to the case study.

**6.1 Description**

The case study represents a small part of a supply chain in the automotive industry. In fact, in the light of the objectives of this chapter and the complexity inherent in the actual supply chain, the analysis of only a small part of the supply chain is enough.
The supply chain is defined by five entities: the customer, the assembler, and three parts suppliers (1st Tier A, 1st Tier B, and 1st Tier C), Figure 5.
The supply chain is responsible for the production and distribution of product X, which consists of three parts (A, B and C), in accordance with the materials tree, Figure 6.

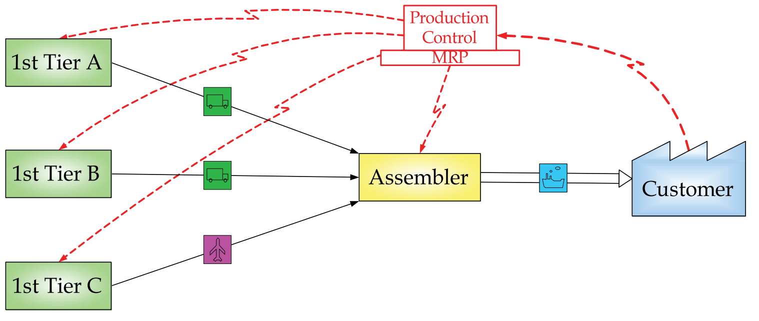


Fig. 5. Case study supply chain

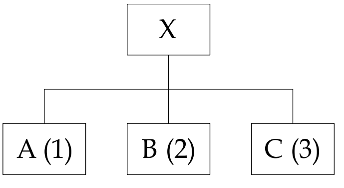


Fig. 6. Product X materials tree

In light of the location of the suppliers' and assembler's facilities, and the pre-established supply conditions between the supply chain entities, road and air transport are used to transfer the parts from the suppliers to the assembler. The transport of product X from the assembler to the customer is undertaken by sea. All transports have a cost which depends on a fixed cost, and a variable cost. In turn, the variable cost depends on the quantity of product transported, the unit cost of the transport, and the transport time.
On a daily basis, the customer places orders of 100 units of product X to the assembler. Customer demand is pulled through the supply chain. From the application of Material Requirements Planning (MRP), the requirements for parts are generated and immediately transmitted to their suppliers. Each part of product X is supplied by a single supplier.
The assembler, along with its suppliers, works according to the Just In Time philosophy and no middle inventories are held.
For simplification proposes, the capacity of the assembler and all the suppliers is considered unlimited, and it is assumed that the customer will wait for the order to be delivered even when a stockout exists.
The assembler produces daily the quantity of the product necessary to satisfy the order place by the customer. The quantity to be produced is determined considering that the proportion of parts produced correctly is 98%. The period of time from the moment the assembler receives an order to the moment it is shipped, the lead time, is 1 day. The cost to the assembler of

producing 1 unit of product X is 5 UM. The inventory cost tax is 20% per unit per year. If a stockout occurs, there will be a backorder cost of 1,52 UM per unit per day.
The 1st Tier A produces part A daily. The quantity produced depending on the order placed daily by the assembler, and the proportion of parts produced correctly (95%). Regarding part A, the number of parts per product unit X is 1. The production lead time is 1 day. The production of 1 unit of part A represents for 1st Tier A a cost of 1 UM. In the event of a stockout, there will be a backorder cost of 0,30 UM per unit per day.
All entities in the supply chain work 22 days a month and do not interrupt their work for holidays.
The characteristics of the assembler and the three suppliers are shown in Table 3.

| Entity | N_Part (Units) | Yield (%) | Lead Time (Day) | Production Cost (UM/Unit) | Backorder Cost (UM/Unit.Day) |
|---|---|---|---|---|---|
| Assembler | 1 | 98 | 1 | 5 | 1,52 |
| 1st Tier A | 1 | 95 | 1 | 1 | 0,30 |
| 1st Tier B | 2 | 100 | 1 | 1 | 0,30 |
| 1st Tier C | 3 | 99 | 1 | 2 | 0,61 |

Table 3. Supply chain entity characteristics

The transport time from the assembler to the customer is 2 days. The number of shipments per day is unitary. The fixed cost of transport is 50 UM per shipment and the variable cost is estimated from the quantity of product X transported, the unit cost of 0,01 UM, and the transport time.
The 1st Tier A order is transported to the assembler by road. The lead time is 1 hour (0,125 days). The frequency of the order transport is twice daily. The other item flow characteristics between all entities are shown in Table 4.

| Flow from ... to ... | Transport mode | Lead Time (Days) | Cost t (UM) | Fix Cost (UM) | Frequency (per Day) |
|---|---|---|---|---|---|
| Assembler → Customer | Sea | 2,0 | 0,01 | 50 | 1 |
| 1st Tier A → Assembler | Road | 0,125 | 0,02 | 100 | 2 |
| 1st Tier B → Assembler | Road | 0,125 | 0,01 | 80 | 1 |
| 1st Tier C → Assembler | Air | 0,5 | 0,10 | 200 | 1 |

Table 4. Flow characteristics between entities

### 6.2 Performance measures

In order to make the supply chain resilient proactively, it is necessary, in a first step, make a diagnosis regarding the performance of current state. Then, using the same performance measures, it is necessary to assess potential future states, those resulting from the disturbance occurrence and/or those resulting from the implementation of mitigation policies.
So, to compare the current state and the potential future states (considering a disturbance) performances, two performance measures were defined, supply chain cost (SC Cost) and supply chain lead time (SC Lead Time).

For an order h, the supply chain cost includes all relevant costs, namely, the ones associated with production and holding inventory (Prod_Holding Cost), stockout (Backorder Cost), and transportation of the product (Transportation Cost).

$$SC\,Cost_h = Prod\_Holding\;Cost_h + Backorder\;Cost_h + Transportation\;Cost_h \tag{1}$$

For an order h of product X, the production and holding inventory cost at the supply chain is defined as follows:

$$Prod\_Holding\,Cost_h = \sum_{i=1}^{I}\left[\begin{array}{l}\left(Prod\,Quant_{hi} \times Cost_{hi}\right) + \\ +\left(Inventory_{hi} \times Inventory\,Cost_{hi} \times Lead\;Time_{hi}\right)\end{array}\right] \tag{2}$$

where,

I is the number of supply chain entities;

$ProdQuant_{hi}$ is the number of units produced of order h, at entity i;

$Cost_{hi}$ is the unit cost of production of order h, at entity i;

$Inventory_{hi}$ is the average inventory level, at entity i;

$InventoryCost_{hi}$ is the cost of holding inventory for one unit of the product h over a unit time period, at entity i;

$LeadTime_{hi}$ is the period of time required to produce the order h, at entity i.

In the event of a stockout affecting an item, it is assumed that the customer awaits restocking. The backorder cost depends on the cost of shortage of one unit, the number of units that are stockout per unit of time, and the time necessary to satisfy the customer's order. Thus, for an order h, the backorder cost is defined as follows:

$$Backorder\,Cost_h = \sum_{i=1}^{I}\left[B\_order\;Cost_{hi} \times \sum_{z=1}^{Time} Quant_{hiz}\right] \tag{3}$$

where,

Time is the period of time between the moment that the order h should have been delivered and the moment at which it is delivered to entity i;

$Quant_{hiz}$ is the quantity of an item of h stockout per unit of time z, at entity i;

$B\_order\ Cost_{hi}$ is the shortage cost of an unit of h by unit of time, at entity i.

The products flow between entities of the different echelons. So, there are product transportation costs. The transportation cost has two components, the fixed cost and the variable cost. The fixed cost is incurred whenever a shipment is dispatched, regardless of the quantity transported. The variable cost is a function of the transported quantity, the transportation time, the transportation frequency, and the unit transportation cost per unit time.

As there is no product flow between all entities in the supply chain, a dummy variable must be employed with a value of 1 if there is a flow of products between two entities and a value of 0 if there is no flow. So, the transportation cost of an order h is defined as follows:

$$\begin{aligned}Transportation\;Cost_h &= \sum_{i=1}^{I-1}\sum_{k=1}^{I}\left(Flow_{hik} \times Fix\,Cost_{hik} \times Freq_{hik}\right) + \\ &+ \sum_{i=1}^{I-1}\sum_{k=1}^{I}\left(Flow_{hik} \times Cost\,t_{hik} \times Transp\,Quant_{hik} \times LeadTime\_t_{hik} \times Freq_{hik}\right)\end{aligned} \tag{4}$$

where,

$Flow_{hik}$ is a dummy with a value of 1 if there is a flow of h from entity i to entity k, or 0 otherwise;

$Fix\ Cost_{hik}$ is the fixed cost associated with transport of order h from entity i to entity k;

$Cost\_t_{hik}$ is the unit cost associated with transport of order h from entity i to entity k;

$TranspQuant_{hik}$ is the number of units transported from entity i to entity k;

$LeadTime\_t_{hik}$ is the period of time from the moment at which the order h is shipped by entity i and the moment at which entity k receives the order;

$Freq_{hik}$ is the number of shipments of order h per unit time from entity i to entity k.

The lead time associated with the customer's order depends on the lead time associated with all the activities that are necessary along the supply chain to fulfil the order, both value added and not added. In order to simplify calculation of the supply chain lead time, it is assumed that products only flow between consecutive echelons of the supply chain. So, for a customer order h, the supply chain lead time is defined as follows:

$$SC\ Lead\ Time_h = \sum_{e=1}^{E-1} \left[ \underset{\forall i \in e; k \in e+1}{Max} \left( Lead\ Time_{hi} + LeadTime\_t_{hik} \right) \right] \quad (5)$$

where,

E is the number of echelons in the supply chain.

### 6.3 Following the methodology

The application of the methodology proposed results in the construction of scenarios. The base case scenario (1) corresponds to the current state of the supply chain. After identifying a potential disturbance, scenario (2) was defined, in order to identify the performance behaviour of the supply chain when subjected to the disturbance. If supply chain is not resilient to the disturbance, scenarios (3) to (6) are constructed from scenarios (1) and (2) with the implementation of policies to mitigate the negative effects of the disturbance. The performance of a supply chain when subject to a disturbance drops, taking some time to recover. The supply chain disturbance is verified at 1st Tier B, from day 3 to day 6. Then, for each scenario, the performance indicators SC Cost and SC Lead Time were determined, for a period of 10 days, to involve the entire recovery period.

To represent the supply chain from a macro perspective, the Value Stream Mapping (VSM) method was used with the eVSM(TM) software, version 5.21. The experiments were performed with a connection to Microsoft Excel. Input data were collected from Excel and output data were stored in the same worksheet.

The eVSM(TM) software was designed to complement lean implementation methodologies and focus on process analysis rather than supply chain entities. Because this software is used to gather a macro view of a supply chain, it is necessary to establish analogies between processes and supply chain entities. Therefore, each supply chain entity can be moulded as a process with specific characteristics. By replicating the entities models and linking the material and information flows, a supply chain representation can be obtained.

#### 6.3.1 Phase 1 - mapping the current supply chain

The supply chain mapping, base case scenario (1) was carried out in accordance with the characteristics of the entities involved, the material and information flows and the modes of transport used, shown in section 6.1.

The management of a supply chain entity involves costs. For example, associated with fulfilling an order of product X, the assembler may have production, holding and/or backorder costs.
The average cost of production of 102 units of product X, with a unit production cost of 5 UM, is 510,00 UM. During the day, the average stock of product X is 51 units. The unit cost of production is 5 UM, and the annual rate of cost of ownership is 20% per unit. Thus, ownership of a product for 1 day, at the assembler's facilities, costs 18,94 UM. So, the average production and holding inventory cost (i.e., considering all supply chain entities) is 528,94 UM, for an order of 100 units of product X.
In this phase, which corresponds to the base case scenario, no stockout is considered to exist. The frequency of the deliveries to the customer is 1 order per day, and the dummy variable associated with the transport between the two entities is 1.
The transportation cost of an order between the assembler and the customer, defined by the fixed cost and the variable cost, is 52,00 UM. The average transportation cost of a customer order of 100 units of product X through the supply chain (i.e., considering the flows between all supply chain entities) is 547,81 UM.
A graphical view of the supply chain was obtained, Figure 7. In the bottom right-hand corner it can be seen that the period of time between the moment at which the customer places an order and the moment at which the customer receives it is 4,17 days, and that the average cost of managing 1 order along the supply chain is 2041 UM.
For the period analysed (10 days), the SC Cost is 20405,22 UM (Table 5).

| Entity | Prod_Holding Cost (UM) | Transportation Cost (UM) | SC Cost (UM) |
|---|---|---|---|
| Assembler | 5289,39 | 520,00 | 5809,39 |
| 1st Tier A | 1108,64 | 2002,55 | 3111,19 |
| 1st Tier B | 2117,27 | 802,55 | 2919,82 |
| 1st Tier C | 6411,82 | 2153,00 | 8564,82 |
| Supply chain | 14927,12 | 5478,10 | 20405,22 |

Table 5. Scenario (1) costs for the analysed period of 10 days

### 6.3.2 Phase 2 - identifying a potential disturbance in the supply chain

In this phase it is necessary to define the disturbance whose effects are intended to be analysed. Taking into consideration that "supply delay" is the main disturbance that affects the supply chain under study (as mentioned in Section 2), this disturbance was chose. It was considered that a failure in the 1st tier B, supplier of part B, on the third day of the period of analysis (10 days), generates an increase in the production lead time from 1 to 4 days.

### 6.3.3 Phase 3 - mapping the supply chain considering the disturbance impact

To analyse supply chain performance when a disturbance occurs, scenario (2) was built. Under this scenario, in addition to production, holding inventory, and transportation costs, the supply chain cost also takes backorder cost into consideration.
For the assembler, the average backorder cost is 151,52 UM per day, given that the shortage cost of 1 unit per day of product X is 1,52 UM and that, as a consequence of a delay of 4 days in the delivery of part B, during this period of time there is a stockout of 100 units of product X.

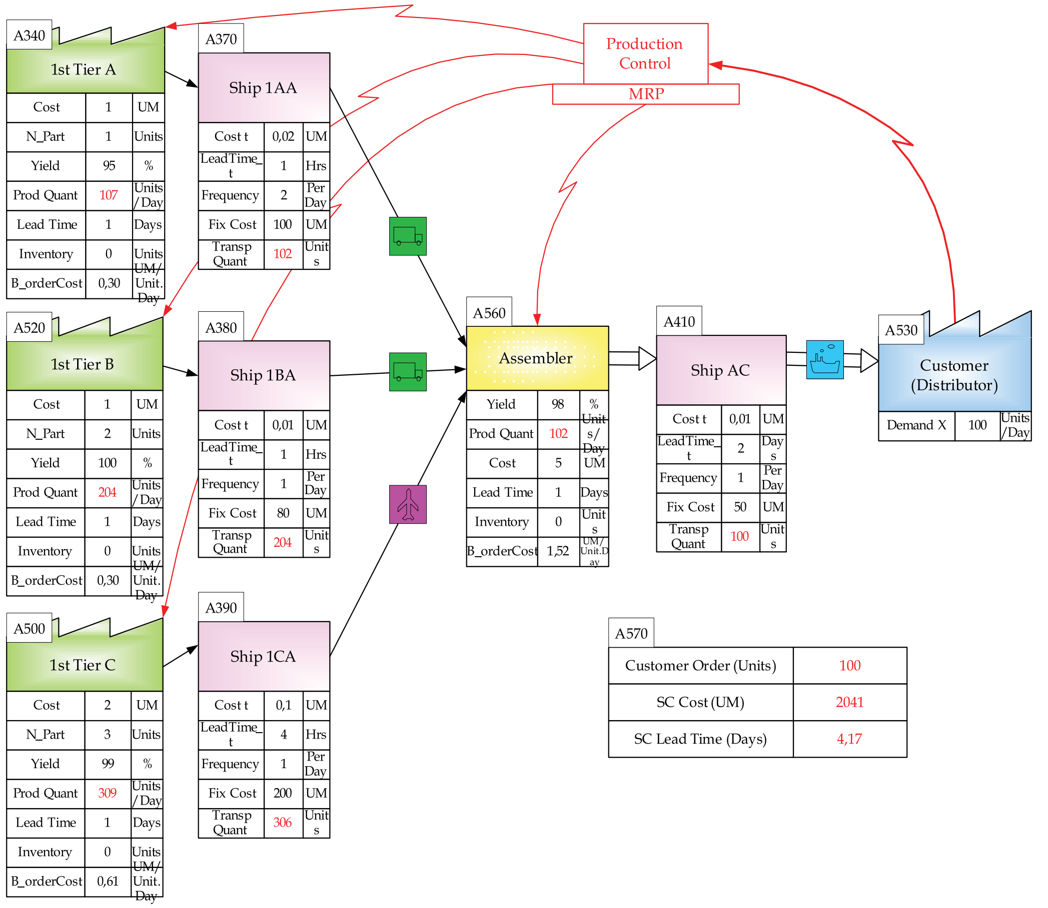


Fig. 7. Scenario (1) for an customer order of 100 units of product X

Under scenario (2), as a consequence of the disturbance at 1st Tier B, the maximum SC Lead Time increases by 93% in relation to scenario (1) (from 4,17 to 8,04 days). For the analysed period of 10 days, the SC Cost increases by 7,9% in relation to scenario (1) (from 20405 to 22019 UM), Table 6.

| Entity | Prod_Holding Cost (UM) | Transportation Cost (UM) | Backorder Cost (UM) | SC Cost (UM) |
|---|---|---|---|---|
| Assembler | 5289,39 | 320,00 | 1515,15 | 7124,55 |
| 1st Tier A | 1108,64 | 2002,55 | - | 3111,19 |
| 1st Tier B | 2117,27 | 482,55 | 618,18 | 3218,00 |
| 1st Tier C | 6411,82 | 2153,00 | - | 8564,82 |
| Supply chain | 14927,12 | 4958,10 | 2133,33 | 22018,55 |

Table 6. Scenario (2) costs for the analysed period of 10 days

### 6.3.4 Phase 4 - identifying policies to mitigate the disturbance

Through the analysis of scenario (2), it is possible to notice that:

i. The assembler has no alternative suppliers for part B. An identical situation is found for all the other parts.

ii. Like the assembler, the 1st Tier B has no buffer stock. There is no inventory of raw materials, work in progress, and final products.

It is therefore possible to say that the occurrence of a disturbance in 1st Tier B prevents the supply of part B to its direct customer, the assembler. It may also be noted that, due to this fact, the assembler cannot supply its customer. In other words, given the characteristics of the supply chain, a disturbance in one entity of the supply chain causes a cascading effect on all the entities that depend, directly or indirectly, on that part.

In order to analyse the resilience of the supply chain when mitigation policies are applied to the disturbances, in phase 4 of the methodology, two proactive policies are chosen: (P1) holding of a buffer stock and (P2) having two suppliers for part B.

### 6.3.5 Phase 5 - supply chain mapping considering the mitigation policies

In phase 5, scenarios (3) and (4) were constructed from scenario (1), and scenarios (5) and (6) from scenario (2). Mitigation policy (P1) was applied to scenarios (3) and (5), i.e., it was considered that 1st Tier B holds a buffer stock of the quantity necessary to satisfy two days of assembler demand. Under scenarios (4) and (6) mitigation policy (P2) was applied. Part B orders are subdivided equally by two suppliers. Each supplier has unlimited capacity, so, if necessary, each supplier can provide the total demand for part B.

### 6.3.6 Phase 6 - performance measurement report for all scenarios

A summary of the performance measurements results for the six scenarios built are presented in Table 7.

| Scenario | Characterisation | | Performance Measures (10 days) | |
|---|---|---|---|---|
| | Disturbance | Mitigation Policy | SC Cost (UM) | Max (SC Lead Time) (Days) |
| 1 | - | - | 20405 | 4,17 |
| 2 | ✓ | - | 22019 | 8,04 |
| 3 | - | P1 | 20714 | 4,17 |
| 4 | - | P2 | 21311 | 4,17 |
| 5 | ✓ | P1 | 20933 | 6,04 |
| 6 | ✓ | P2 | 20991 | 4,17 |

Table 7. Scenarios results

### 6.4 Results analysis

The performance measures analysis obtained from each scenario, Table 7, allows the decision maker to assess the behaviour of the supply chain in different situations and decide which policy to adopt to mitigate (or not) the negative effects of the disturbance.

As revealed by the case study results, if a “supply delay” occurs at a 1st Tier supplier, delaying the items availability (scenario (2)), the maximum SC Lead Time would increase by 93% (from 4,17 to 8,04 days) compared to base case scenario, scenario (1), if no mitigation policy has been implemented.

If a mitigation policy using multiple suppliers (policy P2) is implemented, scenario (6), the maximum SC Lead Time can be reduced from 8,04 to 4,17 days (the same as scenario (1)), and SC Cost will decrease by about 4,7% (from 22019 to 20991 UM). However, the policy P2 implementation will represent in the SC Cost an increase of 2,87%, if no disturbance occur (scenario (4)). It is also possible to verify that, relatively to policy P2, the policy P1 implementation represents a lower SC Cost (20933 *versus* 20991 UM), and a lower reduction in the maximum SC Lead Time (6,04 *versus* 4,17 days), relatively to scenario (2).

## 7. Conclusion

Nowadays, supply chains are rooted within a turbulent environment, being subject to numerous events that cause disturbances in their management. Supply chain disturbances are increasing in number and frequency, affecting the normal operation of supply chains and, consequently, their ability to meet commitments.

Regardless of the disturbance that affects the supply chain, the final effect observed in the supply chain is unfulfilled customer orders. Therefore, supply chains must be resilient to disturbances and must react effectively to their negative effects. Otherwise they can loose competitively.

Supply chain resilience to a disturbance can be achieved by redesigning the supply chain to mitigate adverse impacts and speed recovery. To determine a future state of supply chain management and the progression from 'what is the current state?' to 'what should the redesigned supply chain be?', a methodology is proposed. The methodology, comprising six phases, supports managers in making decisions, in a proactive manner, trying different scenarios from the implementation of mitigation policies, to make the supply chain resilient to a selected disturbance. The methodology is based on the mapping approach.

A case study is developed based on a real supply chain in the automotive industry. The methodology proposed is applied to the case study. Supply chain mapping is carried out based on the characteristics of the entities involved, on the material and information flows and on the modes of transport used. For each entity, some relevant management characteristics are identified. Also, the flow of materials between entities is characterised by some attributes. To represent the supply chain from a macro perspective, the Value Stream Mapping (VSM) method is used with the eVSM(TM) software, version 5.21. The experiments are performed with a connection to Microsoft Excel.

Through the application of the proposed methodology to the case study it is possible to verify that supply chain mapping allows to have a clear view and understanding of the supply chain entities' actual capabilities. It is also possible to verify that the supply chain is not resilient to the “supply delay” disturbance due to its management characteristics, namely, absence of inventories and adoption of a single supplier policy. The built of different scenarios allow yet to analyse the supply chain behaviour considering two proactive mitigation policies.

## 8. Acknowledgment

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## 9. References

Asbjørnslett, B. & Rausand, M. (1999). Assess the vulnerability of your production system. *Production Planning and Control*, Vol. 10, No. 3, (219–229), ISSN 0953–7287

Azevedo, S., Machado, V., Barroso, A. & Cruz Machado, V. (2008). Supply chain vulnerability: environment changes and dependencies. *International Journal of Logistics and Transport*, Vol. 2, No. 1 (April), (41-55), ISSN 1906-0521

Baker, P. (2007). An exploratory framework of the role of inventory and warehousing in international supply chains. *The International Journal of Logistics Management*, Vol. 18, No. 1, (64-80), ISSN 0957-4093

Barroso, A., Machado V. & Cruz Machado V. (2008). A supply chain disturbances classification, *Proceedings of the International Conference on Industrial Engineering and Engineering Management*, (8-11), ISBN 9781424426294, Singapore, December 2008, IEEM, Singapore

Carvalho, H. & Cruz Machado, V. (2007). Designing principles to create resilient supply chains, *Proceedings of the Industrial Engineering Research Conference*, (186-192), 2007, IIE, Atlanta

Childerhouse, P. & Towill, D. (2003). Simplified material flows holds the key to supply chain integration. *Omega*, Vol. 31, 17–27, ISSN 0305-0483

Chopra, S. & Sodhi, M. (2004). Managing risk to avoid supply chain breakdown. *Sloan Management Review*, Vol. 46, No. 1, (53-62), ISSN 1532-9194

Christopher, M. & Peck H. (2004). *Marketing Logistics*, Elsevier, 2ed., ISBN 0-7506-5224-1, Great Britain

Craighead, C., Blackhurst, B., Rungtusanatham, M. & Handfield, R. (2007). The severity of supply chain disruptions: design characteristics and mitigation capabilities. *Decision Sciences*, Vol. 38, No. 1, (131-156), ISSN 1540-5915

Farris II, M. (2010). Solutions to strategic supply chain mapping issues. *International Journal of Physical Distribution & Logistics Management*, Vol. 40, No. 3, (164-180), ISSN 0960-0035

Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. *Sustainability: Science, Practice & Policy*, Vol. 2, No. 2, (1-8), ISSN 1548-7733

Fine, C. (1998). *Clockspeed: Winning Industry Control in the Age of Temporary Advantage*, Reading: MA: Perseus Books, ISBN 0-7382-0153-7, Massachusetts

Gardner, J. & Cooper, M. (2003). Strategic supply chain mapping approaches. *Journal of Business Logistics*, Vol. 24, No. 2, (37-64), ISSN 0735-3766

Giunipero, L. & Eltantawy, R. (2004). Securing the upstream supply chain: a risk management approach. *International Journal of Physical Distribution & Logistics Management*, Vol. 34, No. 9, (698-713), ISSN 0960-0035

Goh, M., Lim, J. & Meng, F. (2007). A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research*, Vol. 182, (164-173), ISSN 0377-2217

Hamel, G. & Valikangas, L. (2003). The quest for resilience, *Harvard Business Review*, (September), (52-63), ISSN 0017-8012

Hendricks, K., Singhal, V. & Zhang, R. (2008). The effect of operational slack diversification and vertical relatedness on the stock market reaction to supply chain disruptions. *Journal of Operations Management*, Vol. 27, No. 3 (233-246), ISSN 0272-6963

Hines, P. & Rich, N. (1997). The seven value stream mapping tools. *International Journal of Operations & Production Management*, Vol. 17, No. 1, (46-64), ISSN 0144-3577

Ji, G. & Zhu C. (2008) Study on supply chain disruption risk management strategies and model", *Proceedings of the International Conference on Service Systems and Service Management*, (1-6), ISBN 978-1-4244-1671-4, Australia, 2008, IEEE, Melbourne

Jones, D. & Womack, J. (2002). *Seeing the Whole: Mapping the Extended Value Stream*, Lean Enterprise Institute, Inc., ISBN 0-9667843-5-9, Cambridge, MA USA

Juga, J. (1995). Redesigning logistics to improve performance. *The International Journal of Logistics Management*, Vol. 6, No. 1, (75-84), ISSN 0957-4093

Kleindorfer, P. & Saad, G. (2005). Managing disruption risks in supply chains. *Production and Operations Management*, Vol. 14, No. 1, (53-68), ISSN 1059-1478

Lambert, D. (2008). *Supply Chain Management: Processes, Partnership, Performance*, Supply Chain Management Institute, Douglas M. Lambert, ISBN 978-0-9759949-3-1, USA

Levary, R. (2007). Ranking foreign suppliers based on supply risk. *Supply Chain Management: An International Journal,* Vol. 12 , No. 6, (392-394), ISSN 1359-8546

Li, G., Lin, Y., Wang, S. & Yan, H. (2006). Enhancing agility by timely sharing of supply information. *Supply Chain Management: An International Journal,* Vol. 15, No. 5, (425-435), ISSN 1359-8546

Lian, Y.H. & Van Landghem, H. (2007). Analysing the effects of lean manufacturing using a value stream mapping-based simulation generator. *International Journal of Production Research*, Vol. 45, No. 13, (3037–3058), ISSN 0020-7543

Mason-Jones, R. & Towill, D. (1998). Shrinking the supply chain uncertainty circle. *Institute of Operations Management Control Journal*, Vol. 24, No. 7, (17-23), ISSN 0266-1713

Mitroff, I. & Alpasan, M. (2003). Preparing for the evil. *Harvard Business Review,* (April), (109-115), ISSN 0017-8012

Naim, M., Childerhouse, P., Disney, S. & Towill, D. (2002). A supply chain diagnostic methodology: determining the vector of change. *Computers & Industrial Engineering*, Vol. 43, (135–157), ISSN 0360-8352

Natarajarathinam, M., Capar, I. & Narayanan, A. (2009). Managing supply chains in times of crisis: a review of literature and insights. *International Journal of Physical Distribution & Logistics Management*, Vol. 39, No. 7, (535-573), ISSN 0960-0035

Ohno, T. (1988). *The Toyota Production System: Beyond Large-scale Production*, Productivity Press, ISBN 0-915299-14-3, USA

Peck, H. (2005). Drivers of supply chain vulnerability: an integrated framework. *International Journal of Physical Distribution & Logistics Management*, Vol. 35, No. 4, (210-232), ISSN 0960-0035

Pettit, T. (2008). Supply Chain Resilience: Development of a Conceptual Framework, an Assessment Tool and an Implementation Process. Dissertation for the Degree Doctor of Philosophy, The Ohio State University

Ponomarov, S. & Holcomb, M. (2009). Understanding the concept of supply chain resilience. *The International Journal of Logistics Management*, Vol. 20, No. 1, (124-143), ISSN 0957-4093

Rother, M. & Shook, J. (1999). *Learning to See: Value Stream Mapping to Add Value and Eliminate Muda*, Lean Enterprise Institute, Inc., ISBN 0-9667843-0-8, Boston

Schroeder, R. (2000). *Operations Management: Contemporary Concepts and Cases*, Irwin McGraw-Hill, ISBN 0-07-249891-9, Boston

Stoltz, P. (2004). Building resilience for uncertain times. *Leader to Leader*, (Winter), (16-20), ISSN 1531-5355

Svensson, G. (2000). Conceptual framework for the analysis of vulnerability in supply chains. *International Journal of Physical Distribution & Logistics Management*, Vol. 30, No. 9, (731–749), ISSN 0960-0035

Svensson, G. (2003). Sub-contractor and customer sourcing and the occurrence of disturbances in firms' inbound and outbound logistics flows. *Supply Chain Management: An International Journal*, Vol. 8, No. 1, (41-56), ISSN 1359-8546

Svensson, G. (2004). Key areas, causes and contingency planning of corporate vulnerability in supply chains: A qualitative approach. *International Journal of Physical Distribution & Logistics Management*, Vol. 34, No. 9, (728-742), ISSN 0960-0035

Tang, C. (2006). Robust strategies for mitigating supply chain disruptions. *International Journal of Logistics. Research and Applications*, Vol. 9, (33–45), ISSN 1367-5567

The Supply Chain Council, Inc. (2006). *Supply-Chain Operations Reference-model: Overview of SCOR*, Pittsburgh, 16th September 2010, Available from: <http://www.supply-chain.com>

Tomlin, B. (2006). On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science*, Vol. 52, No. 5, (639-657), ISSN 0025-1909

Tuncel, G. & Alpan, G. (2010). Risk assessment and management for supply chain networks: a case study. *Computers in Industry*, Vol. 61, No. 3, (250-259), ISSN 0166-3615

Womack J., Jones D. & Roos D. (1990), *The Machine that Changed the World: The Story of Lean Production*, Simon & Schuster, ISBN 0-7432-9979-5, New York

Womack, J. & Jones, D. (1998). *Lean Thinking: Banish Waste and Create Wealth in your Corporation*, Simon & Schuster, ISBN 0-684-81035-2, New York

Zsidisin, G., Panelli, A. & Upon, R. (2000). Purchasing organisation involvement in risk assessments, contingency plans, and risk management: an exploratory study. *Supply Chain Management: An International Journal*, Vol. 5, No. 4, (187-197), ISSN 1359-8546

# 8

# Capacity Collaboration in Semiconductor Supply Chain with Failure Risk and Long-term Profit

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## 1. Introduction

A large proportion of the product mix of the semiconductor manufacturer is of relatively short life cycle (one or two years, typically), and a semiconductor chip may loses 60 percent of value within the first half year of its life cycle (Mallik, 2007). The increasingly challengeable environment of a semiconductor can be characterized by randomly periodic demand, high manufacturing lead time, the expensive set-up costs, and the rapid change of technology, all of which mean significant capital and big risk. The effective capacity scheme of the semiconductor supply chain is of one major measure in order for less capital waste and lower failure risk.

Silicon is the initial and most critical raw material of the semiconductor industry. Today, most semiconductor chips and transistors are created with silicon. The first step in the production of semiconductor silicon device is the drawing of ingots of silicon. These ingots are sliced into wafers. After several layers of semiconductor material are placed on the wafers, they are cut into individual chips. Depending on the complexity of the circuits involved, each wafer may yield between 10 and 100,000 chips. The individual chips can then be measured against one or more dimensions of electrical performance and classified as different products. Then, the final products are finished after dozens of manufacturing processes. A more detailed description of the production process can be found in several references (Kothari, 1984; Bitran & Tirupati, 1988).

Capacity management and planning is always central to the competitiveness of a semiconductor manufacturer. Unlike other high capital requirement industries, the semiconductor industry is competing in the environment of short product life cycles, near-continuous technological innovation and the changing customer demands. A semiconductor supply chain must produce a variety of products in a number of different production facilities as they endeavour to meet the requirements of the customers and capture market share. Because the low flexibility of the equipments, one critical puzzle turns up: how should the existing capacity be configured in order to meet customer demand? This problem

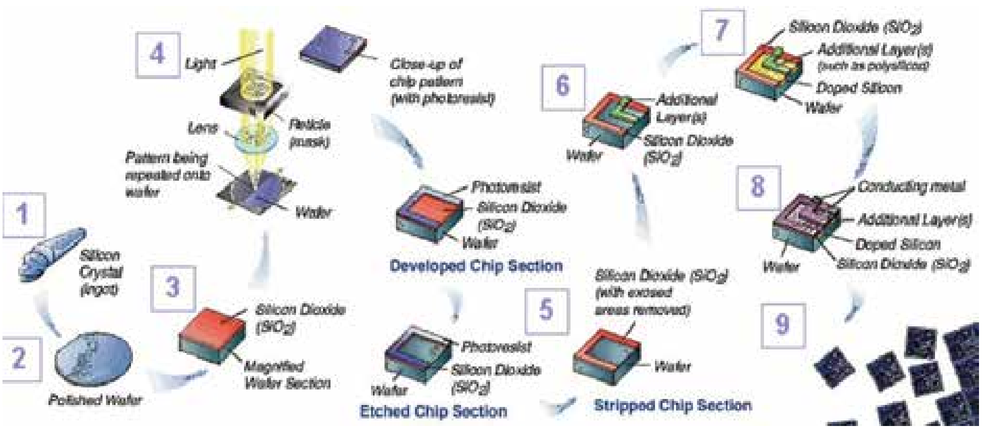


Fig. 1. Semiconductor manufacturing processes (SEMATECH Inc.[1])

of capacity planning becomes especially challenging during the recent economic crisis. However, effective capacity management tools are not applied in semiconductor industry, many intensive investments have been done by an Indian research institute (see figure 2).

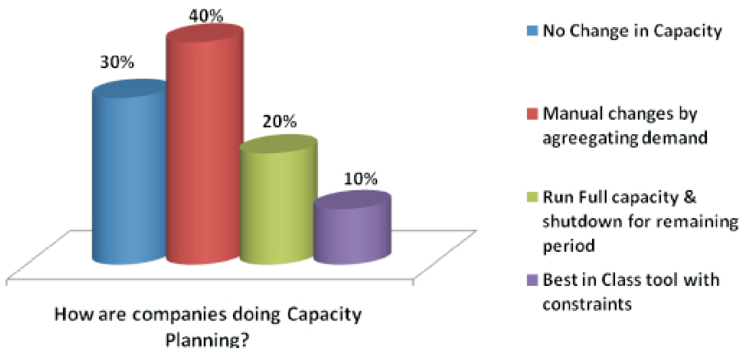


Fig. 2. Capacity management in semiconductor firms (Tata consultancy[2])

According to their researches, most of the semiconductor manufacturers have best-of-breed advance planning systems to aggregate an optimized plan for capacity management. 40 percent respondents agreed to incorporation of manual overrides in capacity planning. Now, capacity model in capacity planning solution has been relaxed to adapt the current downturn depending on the solution used and the capability of the solution to model manufacturers' capacity.

This paper considers a simple and typical semiconductor integrated manufacturing and allocating system, which consists of one silicon material suppler, multiple manufacture manufacturers and multi-demand (see figure 1). The raw material (silicon) supplier offer silicon to the manufacturers, then several classes of products are made. We attempt to

[1] SEMATECH settled at Texas, traces its history back to 1986, she focuses on improving the industry infrastructure, particularly by working with domestic equipment suppliers to improve their capabilities.

[2] Tata Consultancy Services (TCS) (BSE: 532540) is a Software services consulting company headquartered in Mumbai, India. TCS is the largest provider of information technology and business process outsourcing services in Asia.

determine the optimal quantity of the material input of the material supplier and the capacity of each manufacturer.

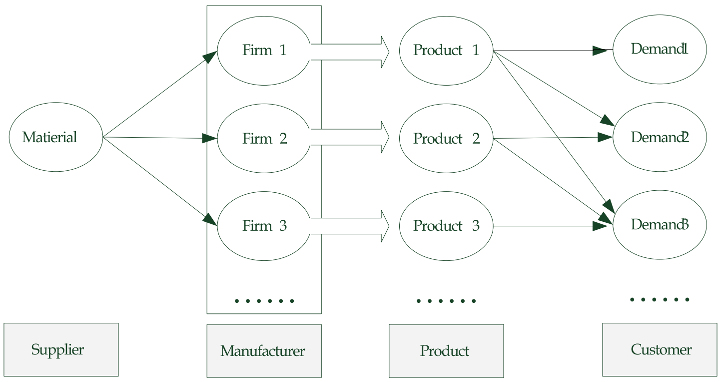


Fig. 3. The semiconductor supply chain

The contributions of this paper are threefold. First, it extends the previous research to a multi-products, random demands semiconductor manufacture and allocation system with downward substitution. Second, we settle an integrated model of the capacity decision problem, and find its several characters. Third, an effective method is designed to solve the proposed stochastic programming model.

The rest of the paper is organized as follows. Section 2 gives an exhaustive literature review, summarizes the exiting researches in the field. Section 3 describes the basic model, which is a stochastic programming model. In section 4, we prove several characters of the model and show that the single-step substitution policy is not necessarily be the optimal rule for allocating products among different demand classes. In section 5, an effective solution method is designed to solve the proposed programming model. Section 6 concludes the paper.

## 2. Literature review

Some literatures have focused on capacity coordination problem of a manufacture and distribution integrated system with the view of information asymmetry or symmetry, for example, designing an incentive mechanism by a manufacturer to encourage all retailers provide their private information to the manufacturer (Cachon & Lariviere, 1999). The decision of capacity allocation is based on supply and demand in the market, however, the information from production department and marketing department may be opposite, that is the production department aims to meet the demand of orders while the sales manager aims to carry out the sales targets. Then, some researchers study the incentive mechanism for the production department and the marketing department by information screening method to make the optimal decision of capacity allocation (Mallik, 2007). Meanwhile, capacity allocation problem of two-echelon supply chain under information symmetry is studied by some researchers. For example, a few references present a similar problem of capacity allocation decision with the change rate of the linear price under the capacity reservation contract (Erkoc & Wu, 2005), or make the capacity reservation contract according to the changing demands to maximize the total profit (Brown & Lee, 1998).

In addition to the literatures above, some researchers have focused on the capacity coordination problem with the perspective of supply chain structure. By means of the theoretical analysis and model deduction, some references discuss the benefits of supply chain capacity coordination and give some suggestions on the management (Corbett & Rajaram 2006). There are also some literatures study the issue of semiconductor wafer manufacturer's capacity allocation decision problems and establish the network flow model of capacity allocation through a heuristic algorithm ( oktay & Uzsoy, 1998). Then, other researches extend a mathematical model to compute the number of retailers for the supply chain profit maximization and several examples prove the validity of the model (Netessine & Rudi, 2003). However, their objective is only to maximize the profit of manufacturer, the supply chain profit may not be optimal. In order to optimize the supply chain performance, a few literatures study a specific capacity allocation problem with the deterministic supply chain capacity (Rupp & Ristic, 2000), and then analysis capacity coordination problems among semiconductor wafer plants under the deterministic capacity with discrete event simulation approach (Gan et al., 2007). They show that the capacity coordination among plants can reduce the supply chain response time. Thus, the CRPS system (Capacity Requirements Planning System) is established towards the problem to decrease the computation burden (Chen et al., 2008). Generally, mathematical programming method is one of normal methods in settling the capacity coordination problems (Wu et al., 2009). A comparative study on semiconductor plants capacity coordination models shows that the capacity coordination among plants on the same supply chain stage can increase total production capacity ability for more than 3% (Chen & Chien, 2010).

In general, most of the researches consider the supply chain coordination mechanisms (e.g. contract mechanism) and their decision variables are mostly the supply chain output rather than capacity. Some other literatures focus on the capacity allocation problem of a manufacturer and the corresponding solving methods always be the situational theory and intelligent algorithms. Most of researches about capacity coordination problem of the supply chain recently mainly focus on the parallel coordination issues, and the common solving method is mathematical reasoning and intelligent simulation approach (Chien & Hsu, 2006; Chien et al., 2007). In this work, we study the coordination of the whole semiconductor supply chain.

Actually, substitution problems with random demand are common in the semiconductor industries. Because the nature performance of a product is highly sensitive to the production equipment and the manufacturing line is less of flexibility, the nature performance of the products made by different manufacturers is probably different. The products can be classified and indexed by the metrical performance, and then be allocated to the corresponding demands. The demands for one certain type of product can be upgraded when its corresponding product has been depleted. The manufacture processes are very complex and the nature performance is sensitive to the production conditions, so the products that are original planed to supply to the customer may be failed. The monopolistic material supplier controls the critical material of silicon, so she can control the yield of each manufacturer, in other words, she is able to control the supply of whole supply chain network.

## 3. Modelling

### 3.1 System dynamics simulations

Many management efforts are to enhance the specific manufacturing processes through statistical and experimental analysis, but they fail to manage the yields of overall manufacturing processes. Some researches on yield management mainly based on the price-setting problem, because the price policies always carried out in conjunction with other options such as inventory control (Curry, 1990; Wollmer, 1992; Brumelle, 1990; Robinson, 1994), revenue management (Bassok & Ernst1, 1995; Feng & Xiao, 2000; Bitran & Gilbert, 1996), and so on. A few papers discuss the system approaches to solve manufacturing problems(Doniavi, Mileham & Newnes, 1996) and to determine the effects (Sack, 1998).They analysis the workflow of the manufacturers(see figure 4) and involve a series of models on the integrated system and the discrete subsystems, then solve the problem step by step by mathematical method. As for the semiconductor manufacturing industry, yield is usually considered as one of the most important performance indices (Horton, 1998). A few researches use system simulation method to solve yield problems in integrated manufacturing systems, but a simple and effective methodology is still under development.

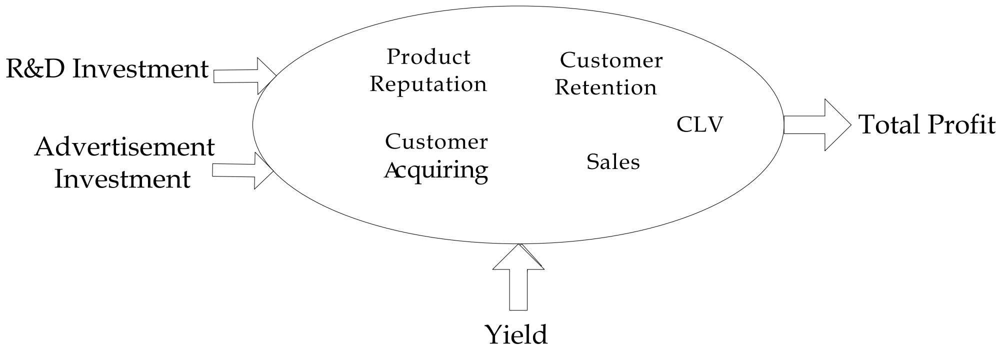


Fig. 4. The capacity decision network of a manufacturer

### 3.2 Forecasting model

The main sources of uncertainty include demand forecast and capacity estimation, among others. Many manufacturers use the forecasting tools to do capacity plans. An America semiconductor manufacturer once made a five-year capacity decisions only basing on the results from forecasting tools, they find that there is a great gap between the forecast data and the realized data (Christie & Wu, 2002)(see table 1.and table 2.).

| Technology code | Demand | | | | |
|---|---|---|---|---|---|
| | Year | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| 1 | - | - | 114 | 845 | 1310 |
| 2 | - | - | 51 | 792 | 1353 |
| 3 | 156 | 1348 | 2001 | 1616 | 1307 |
| 4 | - | 165 | 1550 | 1668 | 1366 |
| 5 | 849 | 747 | 485 | 417 | 395 |
| 6 | 359 | 572 | 6457 | 359 | 443 |
| 7 | 2708 | 1982 | 1092 | 763 | 614 |
| 8 | 684 | 669 | 433 | 290 | 250 |
| 9 | 175 | 120 | 75 | 56 | 19 |

Table 1. Capacity forecast

| Technology code | Gap between capacity forecast and the realized results | | | | |
|---|---|---|---|---|---|
| | Year | | | | |
| | 1 | 2 | 3 | 4 | 5 |
| 1 | - | - | 84 | 159 | 535 |
| 2 | - | - | 51 | 731 | 670 |
| 3 | 57 | 235 | 276 | 55 | 622 |
| 4 | - | 76 | 227 | 248 | 134 |
| 5 | 69 | 100 | 196 | 355 | 395 |
| 6 | 27 | 85 | 101 | 6 | 46 |
| 7 | 659 | 570 | 743 | 1072 | 1221 |
| 8 | 14 | 61 | 295 | 438 | 479 |
| 9 | 150 | 174 | 194 | 213 | 251 |

Table 2. The gap between capacity forecast and the realized results

### 3.3 Mathematical modeling

We assume that the total material quantity which the silicon supplier determined to input is $Q$, and the production output quantities of manufacturers are proportional to the input quantity. The production system has a fixed yield coefficient for each of the products, which we collectively denote by $e_1, e_2, \ldots, e_n$. If $Q_i$ is the material input quantity for manufacturer $i$, then the production output quantity is $e_iQ_i$。 We consider a downward substitution structure of the products that classes are numbered so that the class with superior quality is numbered 1 and the class with inferior quality is numbered $n$, so that product $i$ can substitute for product $j$ if $i \le j$. The demand for each class maybe random, but we assume that the probability distributions of the demands are known. To demonstrate the problem clearly and intently, we give a strict assumption that each demand comes from only one customer. We consider the following costs: production cost, usage cost, shortage cost and expected failure cost, meanwhile, we also consider the following revenues: selling price, the customer lifetime value that result from the satisfied demand. All costs and revenues are assumed to be proportional with their respective quantities. We use the following notation in the paper.

| | |
|---|---|
| $i, j$ | The product and demand class index |
| $p_i$ | Price that the customer will offer towards demand $j$ per unit. |
| $v_i$ | Penalty cost of demand $j$ if unsatisfied. |
| $u_i$ | Usage cost of product $i$ per unit. |
| $d_i$ | Demand quantity for product $j$. |
| $Q_i$ | Material quantity supplied to manufacturer $i$. |
| $Q$ | Total material supplied to the system. |
| $e_i$ | Yield coefficient of product $i$. |
| $U_j$ | Customer life time value of customer $j$. |
| $I_i$ | Residual quantity of product i before manufacturing rotation. |
| $C$ | Total cost of product $i$ before finished, including manufacturing and material expenses. |
| $k_i^t$ | The probability of the customer $i$ is belongs to type $t$. |
| $y_{i,j}$ | The quantity of products $i$ that are used to satisfy demand $j$. |

$f_{i,j}$ The failure risk that use product *i* to satisfy demand *j*.
$\alpha_{i,j}$ Contribution margin for satisfying a demand of class j with product *i*.
$t$ The customer type, *t*=1,2,or3.
$f_j^t(r_j)$ Customer lifetime value of customer *j* type *t*.
$r_j$ The quantity of the realized demand class *j*.
$h_i$ The holding cost of product *i* per unit.
$\Pi(Q)$ The total profit of the integrated supply chain.
$a_1$, $b_1$, a, b, $a_2$, $b_2$ The constants in CLV function

### 3.3.1 The customer lifetime value

In marketing, customer lifetime value (CLV) is the present value of the future cash flows attributed to the customer relationship. Use of customer lifetime value as a marketing metric tends to place greater emphasis on long-term customer satisfaction, rather than on maximizing short-term sales. CLV is directly influenced by customer satisfaction, which is positively related to the fulfil rate of the demand. The customer satisfaction is an inside feeling, so it may be different among individuals. We assume that $U_j=f_j\ (r_j)$ based on utility curves theory (Becker et al. 1964), where $r_j$ denotes fulfil rate of demand *j*. The CLV curve is depicted in the following figure.

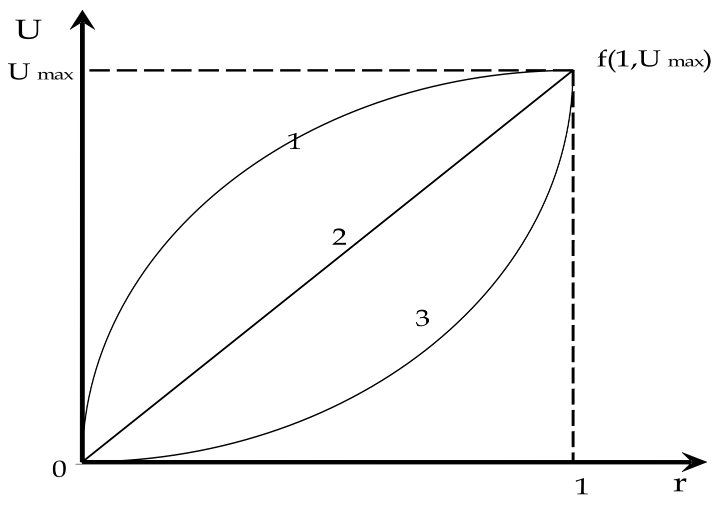


Fig. 5. Relationship between demand fulfil rate and CLV value

In figure 5, curve 1 denotes the CLV of positive customer, curve 2 demotes the CLV of neutral customer and curve 3 denotes the CLV of conservative customer. It is obviously that the CLV values are identical among all types of customers when their demands are fulfilled. The probability of the customer *j* is belongs to type *t* is $k_j^t$ (*t*=1,2,3), so $\sum k_j^t = 1$. We assume the CLV functions $f_j^1(r_j), f_j^2(r_j), f_j^3(r_j)$ along with customer types based on the utility curves theory (Becker et al. 1964). The functions equal to $a_1 - b_1 e^{r_j}, a + br_j, a_2 + b_2 e^{r_j}$, respectively, and the parameters *a*, *b*, $a_1$, $b_1$, $a_2$, $b_2$ are constants. The functions have the following relationships: $f_j^1(1) = f_j^2(1) = f_j^3(1) = 0$ and $f_j^1(1) = f_j^2(1) = f_j^3(1) = U_{max}$. If $0 < r_j < 1$, we have $f_j^1(r_j) > f_j^2(r_j) > f_j^3(r_j)$.

$$f_j(r_j) = \begin{cases} a_1 - b_1 e^{r_j} & (neutral\ customer, t = 1) \\ a + br_j & (positive\ customer, t = 2) \\ a_2 + b_2 e^{r_j} & (conservative\ customer, t = 3) \end{cases}$$

### 3.3.2 The failure risk cost

System failure risk is often happened in the semiconductor supply chains, and they always result to great capital losses. Failure risks of the stochastic manufacture system mainly come from the equipment failure, the shipping failure in transport, or the high technology demands. In the system, there is always a probability that each piece of ordered product will not be supplied to the customer. In this chapter, we use $f_{ij}$ to describe the probability of the failure of one unit of product shipment: use product $i$ to satisfy the demand class $j$. If we planed to use product $i$ to satisfy the demand $j$ for $q$ piece, the expect failure cost of the supplement is $qf_{ij}$.

### 3.3.3 Other costs and revenues

In the manufacture and allocation system, the material supplier must buy the materials from the outside of the system. Then, the manufacturing process starts, the manufacturers spent the consumables to conduct manufactures. If the products are not fully sold, it will be hold in stock and allocate in the next selling period. The fulfilled demand will increase the customer life time value, because the fulfilled customer may suggest others to purchase or will maintain the bought products. When the demands are not fulfilled, the retailer should pay the shortage cost to the customers. So, on the view of the integrated system, the other costs are the material cost, holding cost, shortage cost. At the same time, the system gains the revenue from products' selling.

### 3.3.4 Model constraints

The system faces some constraints. For example, the demand constraint: the supplied quantity to a certain demand should not exceed the need, that is, $\sum_i y_{i,j} \le d_i$ . At the same time, all the realized demand fulfilled by the one type of product should not exceed the total quantity in inventory, that is, $\sum_i y_{i,j} \le e_i Q_i + I_i$ .

### 3.3.5 Model construction

Generally, higher classes of products have higher revenue and usage costs, so it is reasonable that the revenue ($p_j$+$v_j$) and usage cost $u_j$ decrease with the index $j$ . Then we have:

$$p_j + v_j > p_i + v_i\ ,\ u_j > u_i \ \text{ for } \ j < i \tag{1}$$

$$\alpha_{i,j} = p_j + v_j - u_i + U_j / \sum_i y_{i,j}\ , \tag{2}$$

Let $\Pi(Q)$ be the profit function of the supply chain in the whole manufacturing and selling rotation. In the production stage the supplier determines the optimal material quantity that will be input in the manufacturing system, then, varieties products are manufactured and shipped to the customers under a proper allocation policy. Our objective is to determine the optimal material quantity and the capacity of each manufacturer in order to maximize the profit function. We formulate this problem as a programming model, and it is as follows:

$$\Pi(Q) = \underset{d_1,\ldots,d_n,k_j^t}{E} \max[(\sum_{i,j} \alpha_{i,j} y_{i,j} - \sum_i v_i d_i) + \sum_j U_j - CQ - f_{i,j} y_{i,j} - h_i(e_i Q_i + I_i - \sum_j y_{i,j})] \quad (3)$$

Where,

$$U_j = k_j^t f_j(r_j) \quad (4)$$

$$f_j\ (r_j) = \begin{cases} a_1 - b_1 e^{r_j} & \text{(neutral customer, } t=1) \\ a + b r_j & \text{(positive customer, } t=2) \\ a_2 + b_2 e^{r_j} & \text{(conservative customer, } t=3) \end{cases}$$

$$r_j = \sum_i y_{i,j} \quad (5)$$

$$\sum_i y_{i,j} \le d_i \quad (6)$$

$$\sum_j y_{i,j} \le e_i Q_i + I_i \quad (7)$$

$$Q = \sum_i Q_i \quad (8)$$

$$f_j^t(0) = 0,\ f_j^t\ (1) = U_{\max} \quad (9)$$

$$y_{i,j}, Q_i \in R^+, i, j \in (1,2,\ldots,n)$$

$\Pi(Q)$ in equality (3) includes five parts: the total profit in the allocation stage, the CLV value, the material and manufacturing cost, the expected failing risk cost, and the holding cost of the residual products. $a, b, a_1, b_1, a_2, b_2, I_i$ and $U_{\max}$ are constants. $f_{i,j}$ is the failure risk of one unit of product *i*, which is used to fulfil demand *j*, so $0 \le f_{i,j} \le 1$ . Equalities (4) and (9) are the CLV function and the corresponding restraint. Equality (5) is the fulfilled demand *i*. Inequalities (6) and (7) are the demand constraint and supply constraint, respectively. Equality (8) states that all the materials are allocated to manufacturers.

## 4. Model analysis

Substitution in semiconductor industry is very common in practice, because the nature performance of the same type of products even in one batch may be different. But the practice is always hard to describe in mathematical modelling, little has been done on the impact of the demand substitution to the supply chain network. Substitution can help to remit the bullwhip effect and gives the supply chain with flexibility. A number of papers have studies substitution policy in a product allocation system (Chen & Plambeck, 2008; Shumsky & Zhang, 2009). The dissertation applies and studies the impact of the demand substitution to a semiconductor supply chain network.

In this manufacture and allocation system, the whole rotation can be divided into two stages: the production stage and the allocation stage (see figure 1). At the production stage, the supplier determines the optimal materials input, while at allocation stage the manufacturers allocate the products. The allocation policy determines not only the revenue of the allocation stage, but also the materials inputs at the production stage.

Let $N$ be the difference between the actual demand and available product, then we have:

$$N = (N_1, N_2, ..., N_n) = ((e_1Q_1 + I_1 - d_1), (e_2Q_2 + I_2 - d_2), ..., (e_nQ_n + I_n - d_n))$$

Obviously, $N_i$ $(i = 1,...,n)$ can be positive, negative, or zero. For $i = 1,...,n$, if $N_i^t > 0$ and $N_j^t < 0$, then $y_{i,j}$ units of product *i* can be offered for upgrading. The realized upgraded quantity is non-negative and does not exceed the quantity that product *i* can provide. That is,

$$0 \le y_{i,j} \le \min(\left|N_j\right|, N_i)$$

Single-step upgrade can deliver most of benefit of more complex substitution schemes (Jordanand 1995) and some literatures consider the single-step upgrade as the optimal allocation policy (Shumsky & Zhang, 2009). The single-step upgrade allocation policy states that the substitution can be allowed between two neighbour product classes where the high class products are in stock (see figure 6.).

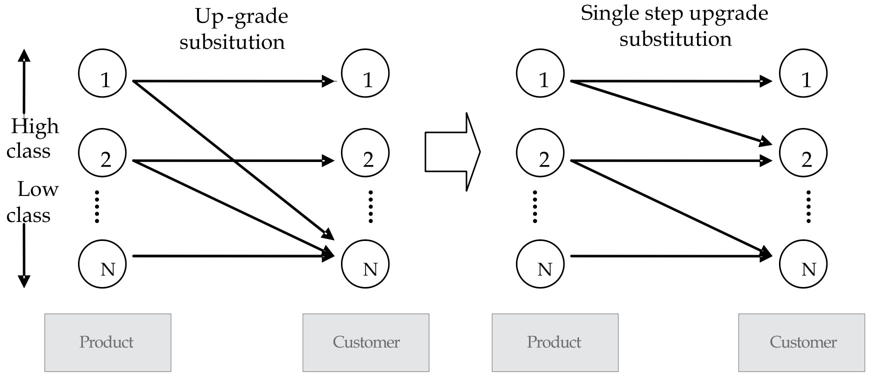


Fig. 6. Single step upgrade substitution

**Proposition 1.** Traditional substitution policy is not the optimal allocation policy of the integrated system.

In our paper, we take customer life time value in to account as one evaluation indicator when make allocation decisions. When $N_i^t > 0, N_j^t < 0$, *i*<*j*, and $N_{j+1}^t < 0$, we may choose the residual quantity product *i* to satisfy the demand class of *j* or demand class *j*+1 or even both the demands, but the puzzle is that which is the optimal choice of the three substitution policies. Based on equation (2), the difference between contribution margin $\alpha_{i,j}$ and contribution margin $\alpha_{i,j+1}$ are,

$$\begin{aligned}\Delta\alpha &= \alpha_{i,j} - \alpha_{i,j+1} \\ &= (p_i + v_i - u_j + U_j / \sum_i y_{i,j}) - (p_{i+1} + v_{i+1} - u_j + U_{j+1} / \sum_i y_{i,j+1}) \\ &= (p_i - p_{i+1} + v_i - v_{i+1}) + (U_j / \sum_i y_{i,j} - U_{j+1} / \sum_i y_{i,j+1})\end{aligned} \tag{10}$$

In equality (10), $\Delta\alpha$ consists of two part, the first part $p_i - p_{i+1} + v_i - v_{i+1}$ is obviously positive because of equality (1). The values of $U_j / \sum_i y_{i,j}$ and $U_{j+1} / \sum_i y_{i,j+1}$ are depend on the customer type and the realized quantity of demand, so we can not estimate the size of the second part of the right-hand-side of equality (10) until the allocation decisions are made. Thus, $\Delta\alpha$ is not necessarily positive or negative. It means that the traditional single-step upgrade allocation policy is not the optimal in this integrated system.

Lemma 1. $\Pi(Q)$ is concave in $Q$.

Proof. The programming model can be simplified and transformed as,

$$\Pi(Q) = \underset{d_1,\dots,d_n,k_j^t}{E} \Pi(Q_\mathrm{i})$$

$$\Pi(Q_\mathrm{i}) = \max[(\sum_{i,j} \alpha_{i,j} y_{i,j} - \sum_i v_i d_i) + k_j^t \sum_j f_j^t (\sum_i y_{i,j}) - C \sum_i Q_i - f_{i,j} y_{i,j} - h_i (e_i Q_i + I_i - \sum_j y_{i,j})]$$

s.t.

$$\sum_i y_{i,j} \le d_i \tag{11}$$

$$\sum_j y_{i,j} \le e_i Q_i + I_i \tag{12}$$

$$y_{i,j}, Q_i \in R^+, i, j \in (1,2,\dots,n)$$

$\Pi(Q_i)$ is a linear program model of Q*i* (*i*=1,…,*n*) with the constraints of inequalities (11) and (12). Obviously, $\Pi(Q_i)$ is concave in Qi because a linear program is concave in variables that determine the right-hand-side of its constraints. Van Slyke and Wets (1966) prove that concavity is preserved over the expectation operator, so $\Pi(Q)$ is concave in Q*i*. Because is a positive linear function in $Q_i$, so $\Pi(Q)$, as the function of $Q_i$, is also concave in $Q$ (Rockafeller,1970).

## 5. Solution method and numerical experiment

### 5.1 Solution method

The decision model is a stochastic programming model, the demand distributions for the products are modelled not by their analytic functions but rather by a finite number of randomly generated demand scenarios that are statistically identical to the joint probability distribution of the demands. It should be noted that a finite number of scenarios can model only an approximation of continuous distributions, but that a model with a sufficiently large number of scenarios can approach the actual distributions. Let $M$ denote the number of scenarios and superscript each of the following parameters and variables by the scenario index m: $d_i^m$ and $k_j^{tm}$. Monte Carlo sampling is often used in stochastic linear program to maximize the expected profit over the scenarios. Each scenario may be given a probability weight wm.

We now have the following formulation for the problem that models $d_i^m$ and $k_j^{tm}$ distributions using the $M$ scenarios:

$$\Pi'(Q\ ) = \max[\sum_{i,j}\alpha_{i,j}y_{i,j} - \sum_m w_m(\sum_i v_i d_i^m) + \sum_m w_m(k_j^{tm}\sum_j f_i^{tm}(\sum_i y_{i,j}))$$

$$-C\sum_i Q_i - f_{i,j}y_{i,j} - h_i(e_iQ_i + I_i - \sum_j y_{i,j})]$$

s.t.

$$\sum_i y_{i,j} \le d_j \tag{13}$$

$$\sum_j y_{i,j} \le e_iQ_i + I_i \tag{14}$$

$$y_{i,j}, Q_i \in R^+,\ 0 < \text{m} \le M$$

The solution steps for the objective function (3) are shown in figure 7.

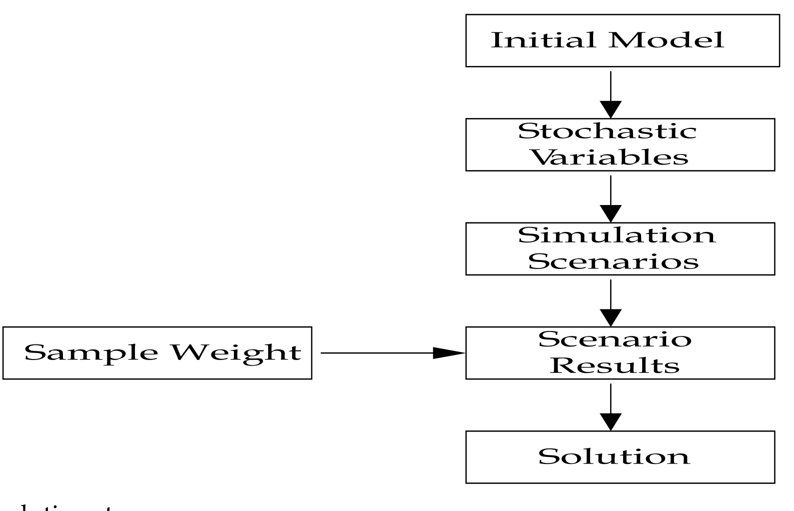


Fig. 7. The solution steps

There are several basic steps to conduct the sample simulation.

Step 1. Analysis the programming model, and determine the stochastic variables in the model.

Step 2. Generate the stochastic samples.

Step 3. Solve the model based on each sample series.

Step 4. Determine the weight of each sample series.

Step 5. Calculate the optimal value of the decision variables.
In the simulation, the choice of the number of scenarios $M$ is important when the scenarios in the model can only approximate the demand distributions. As the value of scenarios $M$ increase, there is a trade-off between the increased computing time and the improved accuracy as a result of a better approximation of the model.

### 5.2 A simple numerical experiment

Using the above formulation, we can obtain an optimal material quantity and the optimal capacity of each manufacture by solving the program. As an example, we consider a problem with five products ($n$=5) and the following are the parameters (see table 3.):

| Product | $p_i$ | $v_i$ | $e_i$ | $h_i$ | $I_i$ | $u_i$ |
|---|---|---|---|---|---|---|
| 1 | 7 | 13 | 20 | 7 | 22 | 0.5 |
| 2 | 6 | 10 | 24 | 4 | 34 | 0.43 |
| 3 | 5 | 8 | 32 | 6 | 21 | 0.39 |
| 4 | 4 | 7 | 31 | 3 | 41 | 0.35 |
| 5 | 3 | 5 | 27 | 5 | 32 | 0.25 |

Table 3. The values of parameters

We assume a= 3, b=2.4, C=2.3, M=5000, $w_m$=1. The value of $f_{i,j}$ is shown in table 4.

| | Demand 1 | Demand 2 | Demand 3 | Demand 4 | Demand 5 |
|---|---|---|---|---|---|
| Product 1 | 0.01 | 0.02 | 0.021 | 0.024 | 0.028 |
| Product 2 | | 0.012 | 0.023 | 0.024 | 0.027 |
| Product 3 | | | 0.01 | 0.013 | 0.017 |
| Product 4 | | | | 0.012 | 0.021 |
| Product 5 | | | | | 0.009 |

Table 4. The value of $f_{i,j}$

In this example, we assume that the demands are normally distributed with the given mean and standard deviation: $d_1 \sim n(34,42)$, $d_2 \sim n(53,69)$, $d_3 \sim n(52,18)$, $d_4 \sim n(73,37)$ $d_5 \sim n(64,15)$. We also assume $k_j^1$ ($j$=1,2,3,4,5) follows beta distribution, and $k_i^{tm}$ is generated as follows (table 5.):

| | $k_1^t$ | $k_2^t$ | $k_3^t$ | $k_4^t$ | $k_5^t$ |
|---|---|---|---|---|---|
| $t$=1 | $B$ (3,5) | $B$ (4,7) | $B$ (4,6) | $B$ (5,4) | $B$ (4,4) |
| $t$=2 | $B$ (2,4)* $k_1^1$ | $B$ (2,2)* $k_2^1$ | $B$ (5,4)* $k_3^1$ | $B$ (2,9)* $k_4^1$ | $B$ (7,2)* $k_5^1$ |
| $t$=3 | 1- $k_1^1$ - $k_1^2$ | 1- $k_2^1$ - $k_2^2$ | 1- $k_3^1$ - $k_3^2$ | 1- $k_4^1$ - $k_4^2$ | 1- $k_5^1$ - $k_5^2$ |

Table 5. The value of $k_i^{tm}$

As has been studied in the theory of Monte Carlo sampling, 5000 iterations of simulation is enough to get a relatively accurate result. After 5000 iterations, we get the optimal material quantity $Q$=136.29. The optimal capacity of manufacturers are $Q_1$=18.23, $Q_2$=24.72, $Q_3$=26.58, $Q_4$=29.15, $Q_5$=37.61.

## 6. Conclusion

In this work we study a capacity determination problem of the manufacture and allocation integrated supply chain in semiconductor industry. The material supplier invests in materials (e.g. silicon) before the actual demands are known. All the manufacturers produce one type of output, but the nature performances of the outputs produced by different manufacturer are distinctive because of the different technical and equipment conditions. The outputs are classified to different products by the nature performances and then allocated to customers. Customers can be divided into three types (the positive customers, neutral customers and the conservative customers), and their long-term profit functions are different. The demands can be upgraded when a particular type of the product has been depleted. We show that the traditional one-step substitution policy is not the optimal in our system, and we prove that the objective function of the stochastic model is concave in material quantity and the manufacturer's capacity. A solution method of the model is proposed and tested by numerical experiment.

## 7. References

Bassok, Y. & Ernst, R.(1995). Dynamic allocations for multi-product distri- bution Transportation Science, Vol.29, No.3, pp. 256-266. ISSN 0041-1655

Becker, G.M. & DeGroot MH., Marschak J.(1964). Measuring utility by a single-response sequential method. Behavioral Science, Vol.9, No.3, pp. 226-232. ISSN 0021-8863

Bitran, G.R. & Tirupati, D.(1988). Planning and scheduling for epitaxial wafer production facilities. Operational Research, Vol.36, No.1, pp. 34-49. ISSN 0030-364X

Bitran, G.R. & Gilbert, S.M.(1996). Managing hotel reservations with uncertain arrivals. Operations Research Vol.44, No.1, pp.35-49. ISSN 0030-364X

Brown, A. & Lee, H.(1998). Optimal "pay to delay" capacity reservation with application to the semiconductor industry. Working paper, Stanford University, Stanford, CA.

Brumelle, S.L. & McGill, J.I., Oum T.H., Sawaki K. Tretheway M.W.(1990). Allocation of airline seats between stochastically dependent demands. Transportation Science, Vol.24, No.3, pp. 183-192. ISSN 0041-1655

Cachon, G.P. & Lariviere, M.A.(1999). Capacity Allocation Using Past Sales: When to Turn-and-Earn. Management Science, Vol.45, No.5, pp.685-703. ISSN 0025-1909

Charles, J.C., Rajaram, K.(2006). A Generalization of the Inventory Pooling Effect to Non-normal Dependent Demand. MANUFACTURING & SERVICE OPERATIONS MANAGEMENT, Vol.8, No.4, pp. 351-358. ISSN 1523-4614

Chen, W.C. & Chien, C.F.(2010). Evaluating capacity pooling strategy in semiconductor manufacturing: a productivity perspective study. International Journal of Production Research, Vol.28, No.4, pp.566-588. ISSN 0020-7543

Chen, J.C., Fan, Y.C. & Chen, C.W.(2008). Capacity requirements planning for twin fabs of wafer fabrication. International Journal of Production Research. Vol. 41, No. 16, pp. 3921-3941. ISSN 0020-7543

Chen, L. & Plambeck, E. L.(2006). Dynamic Inventory Management with Learning About the Demand Distribution and Substitution Probability. Manufacturing & Service Operations Management, Vol.10, No.2, pp.236-256. ISSN 1523-4614

Chien, C.F. & Hsu, C.(2006). A novel method for determining machine subgroups and backups with an empirical study for semiconductor manufacturing. Journal of Intelligent Manufacturing, Vol.17, No.4, pp.429–440. ISSN 0956-5515

Chien, C.F. & Hsu, C.(2007). Construct the OGE for promoting tool group productivity in semiconductor manufacturing. International Journal of Production Research, Vol.45, No.3, pp.509–524.. ISSN 0020-7543

Christie, R.M.E & Wu, S.D.(2002).Semiconductor capacity planning: stochastic modeling and computational studies.(Statistical Data Included). IIE Transactions. February 1

Corbett, C.J. & Rajaram, K.(2006). A generalization of the inventory pooling effect to nonnormal dependent demand. Manufacturing and Service Operations Management, Vol.84, No.4, pp. 351–358. ISSN 1523-4614

Curry, R.E.1990. Optimal airline seat allocation with fare classes nested by origins and destinations. Transportation Science, Vol.24, No.3, pp.193-204. ISSN 0041-1655

Doniavi, A. Mileham, A.R. & Newnes, L.B.(1996). 12th National Conference on Manufacturing Research, pp. 111-115, ISBN 185790031, Bath,UK, September.

Erkoc, M. & Wu, D.(2005). Managing high-tech capacity expansion via reservation contracts. Production, Operation & Management, Vol.14, No.2, pp.232–251. ISSN 0144-3577

Feng, Y.Y. & Xiao, B.C.(2000). Optimal policies of yield management with multiple predetermined prices. Operations Research, Vol.48, No.2, pp.332-343. ISSN 0030-364X

Gan, B.P.(2007). Analysis of a borderless fab using interoperating AutoSched AP models. International Journal of Production Research, Vol.45, No.3, pp. 675–697. ISSN 0020-7543

Horton, D.(1998). A CMOS-compatible Process for Fabricating Electrical Through-vias in Silicon. Solid State Technology, Vol.41, No.1, pp.109-119. ISSN 0038111X.

Jordan, W.C. & Graves, S.C.(1995). Principles on the benefits of manufacturing process flexibility. Management Science, Vol.41, No.4, pp.577-598. ISSN 0025-1909

Kothari, V.(1984). Silicon wafer manufacture. Unpublished thesis, Sloan school of management, MIT, Cambridge, Mass.

Mallik, S.(2007). Contracting over multiple parameters: Inventory allocation in semiconductor manufacturing. European Journal of Operational Research, Vol.182, No.1, pp. 174-193. ISSN 0377-2217

Netessine, S. & Rudi N.(2003). Centralized and competitive inventory models with demand substitution. Operations Research. Vol.51, No.2, pp.329-335. ISSN 0030-364X

Robinson, L.W.(1994). Optimal and Approximate Control Policies for Airline Booking with Sequential Non-monotonic Fare Classes. Operations Research, Vol.45, No.2, pp.252-263. ISSN 0030-364X

Rockafellar, R.T. (1970). Convex Analysis. Princeton University Press, Princeton, New Jersey.

Rupp, T. M. & Ristic, M..(2000). Fine Planning for Supply Chains in Semiconductor Manufacture, Journal of Materials processing Technology, Vol.107, pp.390-397. ISSN 0924-0136

Sack, E.A.(1998). Method and apparatus for characterizing a semiconductor device. Solid State Technology, Vol.41, No.1, pp.81-85. ISSN 0038111X

Shumsky, R.A. & Zhang, F.Q.(2009). Dynamic Inventory Management with Substitution. Operational Research, Vol.57, No.3, pp. 671-684. ISSN 0030-364X

Smith, S.A. & Agrawal, N.(2000). Management of multi-item retail inventory systems with demand substitution. Operations Research, Vol.48, No.1, pp. 50-64. ISSN 0030-364X

Toktay, L.B. & Uzsoy, R..(1998). A Capacity Allocation Problem with Integer Side Constraints. European Journal of Operational Research, Vol..109, No.1, pp.170-182. ISSN 0020-7543

Van, Slyke R. & Wets, R..(1966). Programming under uncertainty and stochastic optimal control. SIAM Journal on Control, Vol.4, No.1, pp. 179-193. ISSN 0363-0129

Wollmer, R.D.(1992). An airline seat management model for a single leg route when lower fare classes book first. Operations Research, Vol.40, No.1, pp.26-37. ISSN 0030-364X

Wu, M.C., Chen, C.F. & Shih, C.F., (2009). Route planning for two wafer fabs with capacity sharing mechanisms. International Journal of Production Research, Vol.47, No.16, pp.5843–5856. ISSN 0020-7543

9

# A Cost-based Model for Risk Management in RFID-Enabled Supply Chain Applications

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## 1. Introduction

Radio Frequency IDentification (RFID) is a dedicated short range communication (DSRC) technology that enables a physically linked world where every object is identified, catalogued, and tracked through the use of a RFID tag, comprised of an IC (Integrated Circuit) chip and antenna that sends information to the RFID reader in response to a wireless probe. In contrast to barcodes, RFID does not require line of sight or contact between readers (also known as interrogators) and tagged objects. The main advantages of RFID systems are price efficiency and accuracy of stock management. In addition to emerging applications in retail and distribution, RFID has gradually been adopted and deployed in other service industries, including aircraft maintenance; baggage handling; laboratory procedures; security; and healthcare. Although RFID technology has obvious advantages, including increased visibility and fast identification, there are still some problems, including limitation of RFID tag's hardware storage and memory; threat of counterfeiting; and other security and privacy issues (Juels, 2006).

This study focuses on the counterfeiting problem of RFID technology in supply chain management (SCM). This problem appears as RFID tag cloning and fraud attacks (Gao *et.al*, 2004) that lead to financial losses and loss of trust and confidence. The RFID tag cloning and fraud attacks can hinder the adoption and acceptance of RFID technology (Choi *et.al*, 2008; Lehtonen, 2007). Therefore trust management plays an important role as an instrument of decision making whether a system is worthwhile to be used with a minimal risk (Kutvonen, 2005). The tradeoff of trust is considered against risk handling, security and privacy management. The significance of trust in the new emerging ubiquitous technology in a context of RFID is critical. Supply chain involves open network connectivities, physical products transportation, and transaction management, where trust counts in the selection of partners; the selection of software and hardware infrastructure; as well as the adoption of communication systems (Derakshan *et.al*, 2007).

Public acceptance of RFID implications systems is still an open question due to its current limitations and vulnerabilities, (Lehtonen, 2007). In our previous work (Mahinderjit-Singh & Li, 2009; Mahinderjit-Singh & Li 2010), we proposed a novel seven layers trust framework for RFID-enabled supply chain management (SCM). Our seven-layer trust framework provides an approach to establish trustworthiness of large scale tracking systems and usefulness of RFID systems. This framework suggests a few prevention and detection mechanisms for a variety of security attacks. Also Mirowski & Harnett (2007) believe that RFID cloning and fraud attacks necessitate countermeasures beyond static preventive mechanisms. As most existing research studies focused on static preventive models without much success, we agree with Mirowski & Harnett (2007) that the detection of cloning and fraud attacks is the first line of defense in eliminating these security attacks.

Our study includes minimization of RFID technology error rates, as well as the minimization of predictions of incorrect class labels and the improvement of detection accuracy. We argue that a cost-sensitive approach is essential to reduce the risk of counterfeiting in SCM. For example, in medical diagnosis of cancer disease, where presence of cancer is regarded as either positive (cancer) or negative (no cancer). In this scenario, a false–negative (FN) error is much more serious (and costly) than a false-positive (FP) error. The patient could risk his/her life because of this FN error and missing out of the early detection and treatment. Similarly, in RFID clone and fraud detection, false-negative or failure of detecting fraud tags is very expensive (e.g. counterfeiting associated loss of billions–dollar businesses). This study focuses on closing a current gap in RFID tag cloning detection systems, that has not been dealt with in previous studies, namely the analyses of system costs in FN and FP errors.

The objective of a cost-sensitive model in an intrusion detection system (IDS) is to formulate the total expected cost for the detection of an intrusion. A cost model should consider the trade-offs among all relevant cost factors and provides a basis for making appropriate cost-sensitive prediction decisions. A cost model should comply with the well-known Pareto principle or the commonly regarded 80-20 rule. Pareto rule or 80-20 rule specifies an unequal relationship between inputs and outputs (Shulmeyer & Thomas, 1999). More generally, the Pareto Principle is the observation (not law) that most things in life are not distributed evenly. For instance, the efforts of 20% for using cost model for counterfeit wines detection system could drive 80% of the firm's profits through elimination of counterfeit wines bottles in a supply chain. By applying the Pareto distribution rule, we may eliminate 80% percent of counterfeiting by dealing with the causal factors of the top 20% of the reported RFID cloned and fraud tags. In our hypothesis, we denote that solving FN cost is more important than solving false positive (FP) cost, and that 20% of effort put into detecting the FN cost will lead to an overall system cost reduction of 80%. Our cost model does not involve the cost for products reduction due to an attack; for instance losses in wine prices due to counterfeit attack. We believe that the usage of a cost model in a cloned detector system is able to reduce the chances of counterfeiting as early as in the supply chain plant itself. By doing so, there will be zero counterfeit products after any POS (Point of Sale) at the retailer site.

Risk Management (Lin & Varadharajan, 2006) is a process used to identify possible risks and setting procedure to avoid the risk, or minimise its impact or setting up a strategy to control the risks. Risk management often involves a multi-criteria decision making process in which factors such as economic, health, legal and others are appropriately weighted on a course of action. Because the decision making process can be complex, there is no one decision criterion that must be or is always used. In order to build cost-sensitive IDS models, we discuss the relevant cost factors and the metrics used to define them. Cost-sensitive modeling for intrusion detection must be performed periodically because cost metrics need to deal with changes in information assets and security policies (Lee *et.al*, 2002). It is therefore important to develop tools that can automatically produce cost-sensitive computations for given cost metrics. The three main costs: damage, response, and operational cost, must be evaluated and quantified based on factors such as cloning attack types and the RFID system environment. Damage cost is a measured loss to the supply chain business which has lost the financial benefits due to cloning and fraud attacks. Response cost is the cost to countermeasures the cloning and fraud attack in a supply chain business. Operational cost is distinguished by the cost of running the detection engine providing function in detecting and responding to both cloning and fraud attacks in a RFID enabled supply chain environment. Hence, the main aim of this chapter is to construct and quantify a cost sensitive model for RFID enabled SCM. The RFID tag cloning and fraud attacks are used in simulating the security attacks and in defining the cost factors in the RFID-enabled supply chain.

We use the Multi Criteria Decision Making (MCDM) (Satty, 1990) model to calculate the costs and decisions. We have use Analytic Hierarchy Process (AHP) technique, which is a MCDM tool in distinguishing the best approach and algorithm for preventing and testing for RFID tag cloning attacks in SCM. The second aim is to extend the MCDM tool through the use of criteria used by supply chain owners when selecting RFID tag cloning and fraud prevention techniques. These criteria include acceptance; cost; security; and complexity. This cost model is the first of its kind with the aim to counter security attacks such as counterfeiting in RFID enabled SCM. The main challenges in the development of the cost model are to represent and identify the different types of costs involved in the detection of the attacks and to maintain responsiveness to changes in these cost factors. Finally, we distinguish the cost properties in a SCM RFID environment. Even though our work is focused on RFID tag cloning and fraud, our trust framework and the cost model will be transferable for countering other types RFID security attacks.

The rest of this chapter is constructed as follows. Section 2 gives a literature review and describes the related cost models. It also introduces some background on countering RFID cloning and fraud attacks. Section 3 explains the design of our cost model for RFID tag cloning and fraud detection system. In section 4 we present on how can use MCDM tool to quantify the related costs and maintain responsiveness to RFID tag cloning and fraud attacks. Section 5 introduces RFID tag cloning and fraud prevention techniques using AHP and MCDM tools. Sections 6 discuss the applicability of the proposed models. Section 7 provides the conclusion and views on future work.

## 2. Backgrounds and related work

In this section we provide an overview of cost sensitive learning and define cloning, fraud and counterfeiting problems. We define both RFID tag detection classification and cost matrices. Finally, we explain how we could integrate RFID detection and our cost model in our proposed seven-layer trust framework.

Cost-Sensitive Learning is a type of learning in data mining that takes misclassification and other types of cost into consideration (Turney, 2002). The goal of this type of learning is to minimise total cost. The key difference between cost-sensitive learning and cost-insensitive learning is that cost-sensitive learning treats different misclassifications differently (Turney, 2002). Cost insensitive learning does not take misclassification costs into consideration. The goal of this type of learning is to pursue high accuracy when classifying examples into a set of known classes.

Credit card fraud detection, cellular phone fraud detection and medical diagnoses are examples of intrusion detection because intrusion detections deal with detecting abnormal behaviour and are typically motivated by cost-saving, and thus typically use cost-sensitive modeling techniques. Previous work in the domains of credit card fraud (Lee, W., et.al, 1999) and cellular phone fraud (Fawcett & Provost, 1997) have applied cost metrics in evaluating systems and alternative models, and in formalizing the problems to which one may wish to apply data mining technologies. The cost model approach proposed by Lee et.al (2000) formulate the total expected cost of an IDS, and present cost-sensitive machine learning techniques that can produce detection models that are optimized for user-defined cost metrics. The detection technique used by Fan et.al (2000) and Lee et.al (2002) uses an inductive rule learner, Repeated Incremental Pruning to Produce Error Reduction (RIPPER). Their cost model is based on a combination of several factors: The cost of detecting the intrusion; the amount of damage caused by the attack; and the operational cost of the reaction to the intrusion. Lee et al (2002) claimed that the IDS should have minimal costs. However, their work did not consider any related administrative testing costs. Their work has been extended by Chen et.al (2008), who claimed that their approach could potentially lower the consequential cost in current IDSs. Although the generation of fingerprints as a means of authentication increases operational costs associated with the use of IDSs, experimental results show that these incremental costs are limited and that overall cost is much lower than with the Lee et.al (2002) approach.

We adopted the two proposed models above. Since our cloned detector will become a component integrated in the existing Global Electronic Product Code (EPCglobal) Standard, we should be able to use the cost model designed for IDS. Differences include the technique used to quantify the cost model and the detection technique and authentication method used in our cloned detector. We analyse various authentication methods used for supply chain partners and RFID tags by using the MCDM approach. Next, we define cloning, fraud and counterfeiting attacks in a RFID system.

## 2.1 Problem definition

### 2.1.1 Cloning, fraud and counterfeiting definition

RFID tags clone occurs in the form of cloned tags on fake products or clone tags on genuine product. Both types are similar in term of the cloned tags.

- An RFID tag is a cloned when the tag identification number (TID) and the form factors is copied to an empty tags (Lehtonen et.al, 2009). Hence there will be a same tags data structure on two different products.
- In contrast, fraud is an act of using the cloned tags and adding the serial numbers of future EPC codes. These future EPC codes are the codes in the systems, which are yet to be tagged to the products.
- Counterfeiting on the other hand is a more generalised term which includes both the act of cloning and fraud of RFID tags and tagging onto fake products in the market for personal benefit.

There are four different attacks that contribute to cloning attack in a RFID system (Mahinderjit-Singh & Li, 2009; Mahinderjit-Singh & Li 2010). Skimming attack occur when RFID tag are read directly without anyone knowledge. Eavesdropping attack happens when an attacker sniffs the transmission between the tag and reader to capture tags data. On the other hand, man in the middle attack occurs when a fake reader is used to trick the genuine tags and readers during data transmission. RFID tag data could also be altered using this technique and as a result, fraud tags could be generated too. Physical attack which requires expertise and expensive equipment takes places in laboratory on expensive RFID tags and security embedded tags.

We will give a definition of clone, fraud and counterfeiting in RFID tag. Let assume set Ti contain the RFID genuine tags and Tx contain cloned tags derived from Ti. A genuine tag is known as TG and a cloned tag is known as TC. *I* denote an intruder. A list of attacks (*S*) includes Skimming (*S1*), Sniffing (*S2*), Active Attack (*S3*), Reverse Engineering (*S4*) and Cryptanalysis (*S5*)

Thus;

Ti= {TG1, TG2, TG3}

Tx= {TC1, TC2}

S = {S1, S2, S3, S4, S5}.

| Attack Types | Attack Pattern | Attack Levels | Model features |
|---|---|---|---|
| **Skim**<br>(Juel.A,2005)<br>(Dimitriou,2005) | Copy → Cloned | Low<br>( Tag, Reader) | Content<br>Timestamp/TTL<br>R/W on Tag & Reader |
| **Eavesdrop**<br>(Bolotnyy et.al, 2007)<br>(Duc & Park, 2006) | Copy → Cloned | Low<br>( Tag, Reader, DB) | Content<br>Timestamp/TTL<br>R/W on Tag & Reader<br>Location |
| **Man-In- The middle**<br>(Juels, 2006)<br>(Gao et.al, 2007) | Copy → Cloned<br>Alter → Fraud | High<br>( Tag, Reader, DB) | Content<br>Timestamp/TTL<br>R/W on Tag & Reader<br>Location |
| **Physical**<br>(Bono.S, 2005)<br>(Nohl.K, 2008) | Copy → Cloned<br>Alter → Fraud | High<br>( Tag, Reader, DB) | Content<br>Timestamp<br>R/W on Tag & Reader<br>Location |

Table 1. RFID Cloning and Fraud attacks

Hence TC1 is a clone of TG1; if and only if both tags have identical TIDs (tag identifier) and share the same form of characteristics. Once the TIDs are the same, all the data and structure of the tag's EPC code such as header, manufacturer id, object class and serial number are identical, i.e., |TG| = |TC|. A TC exists when *I* performs *S* either a single *S* or a combinations of *S* against TG. *S* will produce cloning attack. RFID Cloning is a process of injecting imitated EPC tags in a normal genuine EPC tags batch $TG \subseteq$ BG and $TC \subseteq$ BC. Table 1 shows RFID attacks patterns and its model.

By analysing the model features of the different attacks types, we can distinguish different types of RFID security attacks, different levels of attack (high, low) and the different associated compromised RFID components. This model is important for the precise understanding of cloning vs. fraud attacks. A cloning attack is generalised as an act of copying tag data and structure, whereas a fraud attack involves both copying and altering tag data and structure. Based on Table 1, RFID tags compromised by 'Eavesdropping', 'Man in the middle' and 'Physical' attacks will demonstrate deviants in RFID tag data and structure namely tag content tag time ( e.g. timestamp and time to live (TTL) ( Li *et.al*, 2009) and tag locality. Next, we define RFID tag cloning and fraud detection classification and a cost sensitive model that can be used for RFID tagging.

### 2.1.2 RFID tag cloning and fraud detection classification and cost sensitive modeling

Before applying a cost sensitive model to RFID tagging, a RFID dataset is pre-processed to feed into a cloned detector that is based on a classification concept. Suppose that we have a collection, I, of RFID Tags, each labelled as either good or bad, depending on whether or not it is associated with legitimate or fake products. The set of all possible classes can thus be defined as C = {good, bad}. Bad tags could be either cloned or fraudulent/fake tags. We approximate the unknown target function, *F: I × C = {1, 0}*. The value of *f(i, c)* is equal to one if the RFID tag, *i*, belongs to the class c and equal to zero if not. It is now possible to define a classifier as an approximation function, *M: I ×C = {1, 0}*. The objective of the learning task is to generate a classifier that produces results as close to that of F as possible. Compute a model or classifier, *C*, by some learning algorithm *L* that is predicted from the features:

*<fn,……fn-1>*

The target class label is *fc*, 'cloned' .
Hence, *C* = *L(T)*, where *L* is a learning algorithm . Each *t* ∈ *T* is a vector of features, where we denote *f1* as the 'transaction amount' (tranamt), and *fn* as the target class label, where the denoted clone *(t)* = 0 (legitimate transaction) or 1 (cloned or fraudulent transaction). Given a 'new unseen' transaction, x, with an unknown class label, we compute *fn(x)* = *C(x)*. *C* serves as a clone detector. Within the context of financial transactions, cost is naturally measured in dollars (e.g. US dollar is used in his chapter). However, any unit of measure of utility applies here. Hence, the cost model for this domain is based on the sum and average of loss caused by cloned and fraudulent tags. We define a set of transactions S, a fixed overhead amount, and a cloned detector *C* (or classifier, *C*). The overhead amount is the cost of running the IDS operation. The total potential loss is the transaction amount (tranamt) losses for both cloning and fraudulent transactions. The cost matrix outcomes such as FN, FP, hit and true negative (TN) is as shown in Table 2 and is used for distinguishing whether the cost is a 'tranamt' (*t*) or an overhead.

$$\text{Total Potential Loss (S)} = \sum_{t\epsilon\, SCLONED(t)\ \&\ t\epsilon\, SFRAUD(t)=true} tranmt\ (t) \qquad (1)$$

| Outcomes | Cost (t, Overhead) | |
|---|---|---|
| Miss ( False Negative, FN) | tranamt (t) | |
| False Alarm ( False Positive, FP) | Overhead<br>0 | If tranamt (t) > overhead<br>If tranamt (t) ≪ overhead |
| Hit ( True Positive , TP) | Overhead<br>0 | If tranamt (t) > overhead<br>If tranamt (t) ≪ overhead |
| Normal ( True Negative, TN) | 0 | |

Table 2. Prediction of Cost model using tranmt (t) and overhead

## 2.2 Trust framework and IDS

The deviation of RFID technology based trust takes places when simple soft trust (including experience and reputation) is taken up to a higher level known as hybrid trust. Hybrid trust in a RFID system is more than just a hard or security trust based on authentication of soft

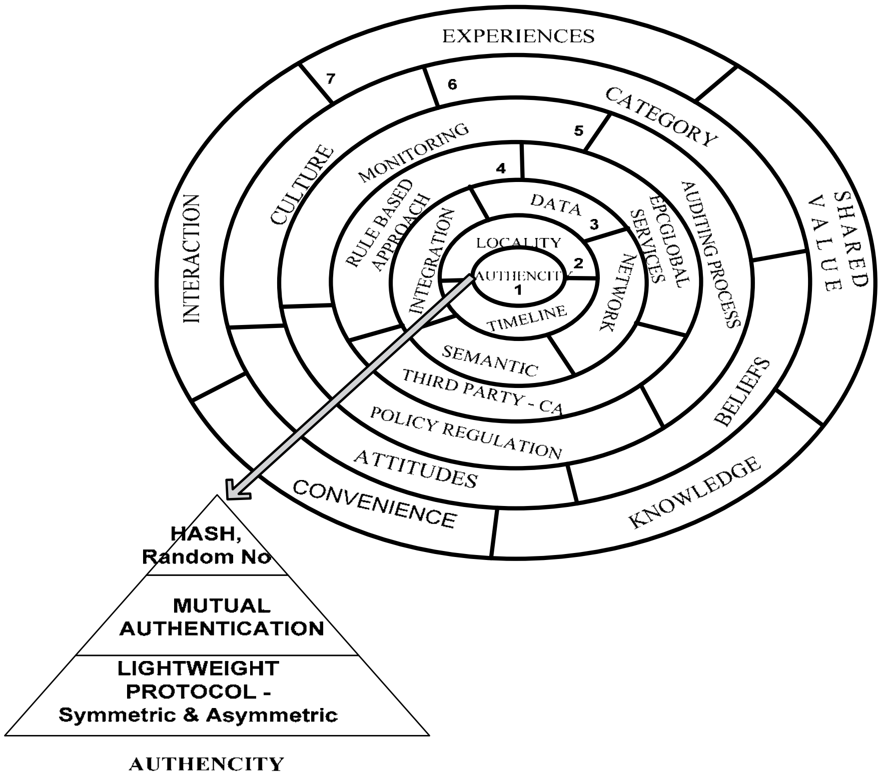


Fig. 1. Seven Layer Trust Framework [8]

trust as argued by Lin and Varadharajan (2007). In our definition, trust in a RFID technology system is defined as a comprehensive decision making instrument that joins security elements in detecting security threats with preventing attacks through the use of basic and extended security techniques such as cryptography and human interaction with reputation models. Since a trust model that disperses privacy is a weak and non-usable model, our trust framework ensures privacy and does not compromise security measurements. In addition, we argue that a trust model for a technological system should always include human interaction through the use of a feedback and ranking model. Our trust framework provides a theoretical solution for the trust gaps discussed in Section 1. In addition, our proposed trust framework (Figure 1) functions as :

- a solution to optimising trustworthiness by employing core functions at three main levels:
  a. The RFID system physical level (i.e. tags and readers) security and privacy level core functions;
  b. The RFID service core functions at the middleware level through utilisation of multiple data integration platforms such as the EPC trust services (http://www.epcglobalinc.org ) and third party software systems such as intrusion detection systems (IDS) which can also be used; and
  c. The core functions at application level through use of reputation systems based on user interaction experiences and beliefs and

- to provide guidelines for designing trust in solving open system security threats.

### 2.3 EPCglobal network

EPCglobal (http://www.epcglobalinc.org), a subsidiary of GS1, has used EPC naming conventions to identify and trace products movement using RFID technology . This application is named the EPCglobal Network. The EPCglobal Network introduces a few dedicated components, such as the Object Naming Service (ONS) and the EPC Information Services (EPCIS) that may or may not be needed for future applications (Ranasinghe et.al, 2007). The ONS functions as an EPC resolution service that provides a look up a service to resources that provide further information about an item identified by a particular EPC. The ONS uses the standard Domain Name Service (DNS) for resolving EPCs. EPCIS permit applications to share and use EPC data across different enterprises. In each application, each local company will have its own local database and local EPC-IS. In addition, a Discovery Service (DS) (still under development) is a registry which registers incoming and outgoing products (Ranasinghe. and Cole, 2007) and functions as a item-level tagging server.

### 2.4 Architecture of our cost based cloned detector

In this section we design a cost based RFID tag cloning detector into our proposed trust framework and into the EPCglobal service. Figure 2 gives an outline on how our proposed detection system will work in a supply chain environment and in an EPCglobal network.
The following is a list of assumptions used in our system:

1. By utilising our proposed seven-layer trust framework, detection functions take place in layer-4.
2. Our trust framework is placed in EPCglobal services.
3. Local EPC-IS only share information that can be assessed by all assigned supply chain partners. Distributed network architecture is employed. Distributed network architecture eliminates the problem of information overload and makes it easier to exchange information. Manufacturer s and trading partners create and store their own serialised information about each and every product in their own local EPC-IS. The manufacturer manages and hosts a database that stores information about the generation of their products. Trading partners manages their local EPC-IS and store information about products movement through the supply chain. This local EPC-IS is accessible by all supply chain partners. Each involved partner makes this information available to authorised parties using the internet.
4. The Discovery service (DS) record incoming and outgoing product sand track products by using item-level tagging. DS functions as a key management server in which it generates public keys for System Administrator (SA) testing purposes. EPCglobal DS is equipped with a key management mechanism using a specific cryptography algorithm for public key encryption (RSA). It stores access control policies that comply with the role based access system. A role-based access control (RBAC) system has two phases in assigning privileges to an employee: first the employee is assigned one or more roles, and hen the role(s) are checked against the requested operation.
5. Supply Chain (SC) partner authentication is done through a certificate authority (CA) service using our trust framework. The partners that need to access the clone detector to provide their local certificate to the CA server installed in our trust framework.

6. The Object Naming Service (ONS) could be used to point to an address in the EPCglobal network where information about the product being questioned is stored. This service is important if a product need to be traced and tracked.
7. Item-level tagging is employed in our scenarios.
8. Attackers could be either from the organisation or outsiders.They are mainly 8 different points used by attacker to inject cloned and fraud in the SCM.

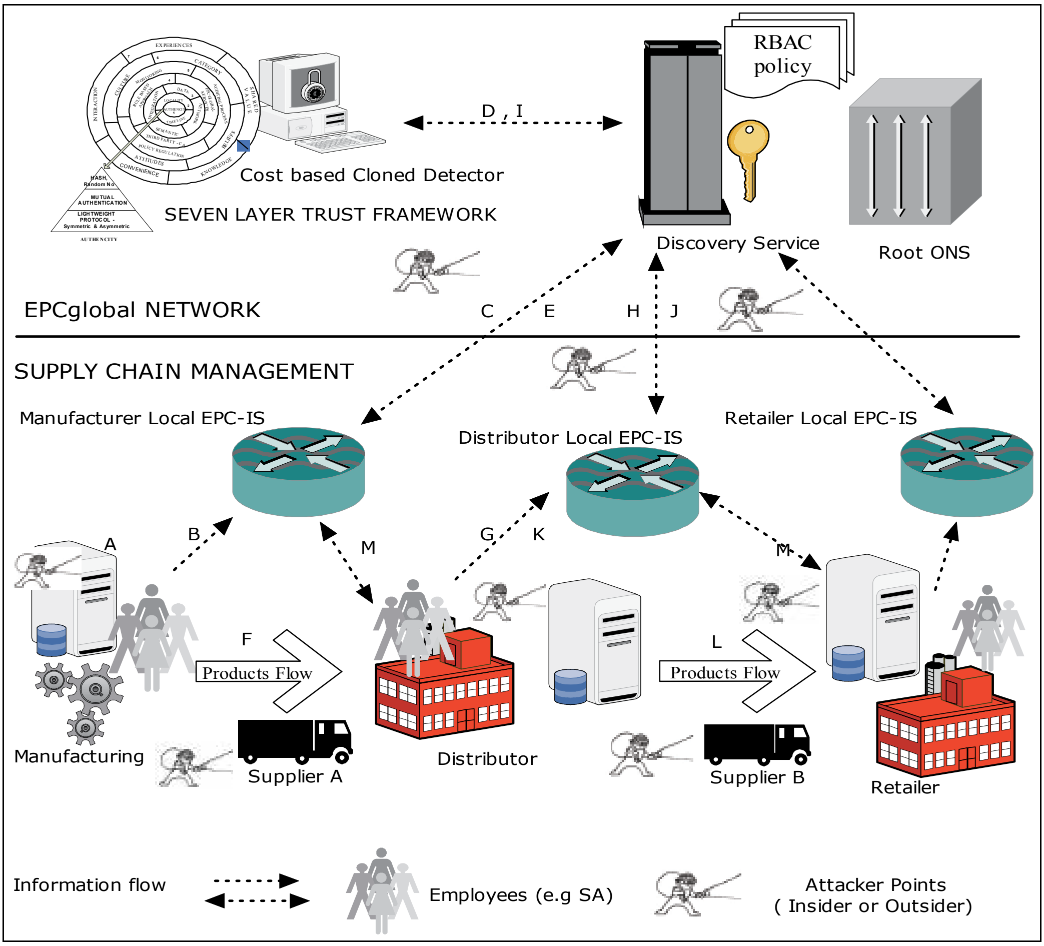

Fig. 2. Cost based Cloned Detector in a Supply Chain Management and EPCglobal Network environment.

a. An EPC lifecycle begins when a manufacturer tags a product. At the manufacturer's place, EPC tags are fixed to products. These EPC tags are furnished with codes and KILL/ACCESS passwords, upfront.
b. A manufacturer records products information into the local EPC-IS.
c. The EPC-IS registers EPC knowledge with EPC Discovery Services (DS).
d. Before the product leaves the manufacturer's site, the product is fed into the cloning detector.

e. The result is sent to the manufacturer's local EPC-IS. If a cloned tag is detected, a trigger is sent to the manufacturer's SA.
f. If not, the supplier is requested to move the product to the distributor's front door.
g. At the front door, the distributor records the product into their local EPC-IS.
h. The EPC-IS records with the EPC DS where tags are next fed into the cloning detector.
i. If a clone is detected, the distributor's SA is triggered. The alarm log is kept in the DS.
j. The alarm log is sent to distributor's local EPC-IS.
k. Before the products leaves the Distributor's site (at the back door), the RFID tags are fee into the cloning detector again to check for if there have been any cloning or fraudulent processes at the distributor site.
l. Once confirmed as genuine tags, distributor sends the tagged products to the retailer site. The same process takes place at the retailer site.
m. Any supply chain partner can access any other partner's EPC-IS for tracking and tracing purposes.

### 2.5 Testing process by system administrators

In this section we discuss how RFID tag cloning and fraud detection as well as cost modelling are supported by our proposed trust framework (Mahinderjit-Singh & Li, 2009; Mahinderjit-Singh & Li 2010). In supply-chain-wide RFID systems, increasingly large data volumes are being exchanged, which in turn increases the risk for competitors to intercept this information (Gao et.al, 2004). Trust relationships between supply chain suppliers and distributors curb cheap RFID tag cloning. RFID tag cloning and fraud detection can be detected in a supply chain at an initial stage if there is proper transfer of ownership with secure and authorised information exchange. We extend our proposed trust framework to establish a cloning and fraud detection system that has an integrated cost sensitive model.

Our RFID detection system has three main components: collection; detection; and response. Collection is the component that collects a RFID event set *E* that is supplied by different supply chain partners. RFID event sets are then sent to the detection component where the information sources are analysed. Several detection functions are performed in this component, such as pattern matching; traffic or protocol analysis; finite state transition; etc. The response component notifies the system administrator where and when an intrusion takes place. Two types of roles, an attacker and a system administrator (SA), are considered in current IDSs and are defined below.

**Attackers** attempt to gain unauthorised access to computer systems, tend to be malicious and possess a wide range of tools such as unauthorised RFID readers for performing the unethical acts of reading and manipulating genuine RFID tags to produce fake tags. Their behaviour is potentially harmful to the supply chain system. Almost 80% of attackers are the employees within a supply chain (P.Marcellin , 2009)

**System administrators (SAs)** take charge of protecting the system and are minimising the costs of network management; system maintenance; and excessive use of resources. They are appointed and authorised to examine enterprise networks from attackers' perspectives, and use vulnerability testing tools that are the same as or similar to those used by hackers. Their objectives are to help an enterprise evaluate its security level, and identify the vulnerable elements that need to be repaired.

Employment of layer 5 of our trust framework, the auditing module, supports the testing functions performed by SAs. Authentication and identification processes, applied through any authentication method or strong security protocol for identification purposes, begin prior to the SA accessing the system. After accessing the system, the SAs perform security tests and use testing techniques to identify malicious RFID tags. The security protocol concurrently calculates the key within the Discovery Service (DS) and matches it with any malicious RFID tag keys (a pre-shared secret managed by the SA). The tags are then sent to a cost based cloning detector for security testing.

When the cloning detector finds a cloned tag, the alert system is triggered: First, the system tests for the existence of a secret key in the tag. If present, it treats it as a security-testing tag and executes the second step. If not, the tag is considered as cloned and the response component starts to inform the SA. In the second step, with the tag treated as a security testing tag, the validating algorithm is used to verify whether the shared and secret keys are identical. If they are identical, the response component does not generate an alarm to alert the SA, but logs the occurrence. If they are not identical, the security-testing tag is considered as a malicious attempt to forge the secret key. An alarm is generated to alert the SA to the attack of the protected system and suitable actions are taken to avoid system loss. Section 3 presents our proposed cost model.

## 3. Proposed cost model for RFID cloning detector

In this section, we discuss our proposed cost sensitive cost model and how we derived its algorithm. We use Bayes rule to forms the foundation of pattern recognition and embodies the definition of conditional probability. Bayes theorem is essentially an expression of conditional probabilities. More or less, conditional probabilities represent the probability of an event occurring given evidence. To better understand, Bayes Theorem can be derived from the joint probability of *ci* and $x$ (i.e. *P*(*ci,x))* as follows:

$$P(ci, x) = P\,(ci\,|\,x)P(x)\,;\, P(x,ci) = P(x\,|\,ci)\,P(ci) \tag{1}$$

where $\boldsymbol{P(ci\,|\,x)}$ is referred to as the *posterior*; $\boldsymbol{P(x\,|\,ci)}$ is known as the likelihood, P(ci) is the prior and $P(x)$ is generally the evidence and is used as a scaling factor. Therefore, it is handy to remember Bayes Rule as:

$$P\,(ci, x)= \frac{P(ci)\,P(ci|x)}{P(x)} \tag{2}$$

In practice, the same type of misclassification error may have different cost impacts depending on the object to be classified, contrary to the fixed misclassification cost approach, where costs remain constant regardless of the data to be classified. As a caveat, we have used US dollars (US$) as a measure when discussing the RFID domain, but these costs can be converted to some other meaningful unit of measure of utility that may be more appropriate for the IDS case.

$$R(\alpha i|x) = \sum_{j=1}^{n} Cij(x)P\,(cj|x) \tag{3}$$

$$R(\alpha i|x) = \sum_{j=1}^{n} Mij(x)P\,(cj|x) \tag{4}$$

where the $Cij$ is the misclassification cost function taking into account the properties of the data point $x$ and $Mij$ is the test cost function taking into account the properties of the data point $x$

We examine the major costs factors associated with a SCM cloned tag detector, which include: misclassification cost due to successful intrusions initiated by attackers; Response Cost due to these intrusions; and the Testing costs associated with SA testing of authentication methods. We identify the following major cost factors associated to intrusion detection: Damage Cost; Response Cost; and Operational Cost.

a. Damage Cost (*Dcost*) characterises the amount of Damage to a target resource caused by an attack when intrusion detection is unavailable or ineffective. There are two different Damage Costs, *DcA*(e) and *DcS*(e). *DcA*(e) is the Damage caused by hackers and may harm the system. *DcS*(e)is the amount of security testing cost associated with the SA's function that may Damage the system.
b. Response Cost (*Rcost*) is the cost of acting upon an alarm or log entry that indicates a potential intrusion. There are two different Response Costs, *RcA*(e) and *RcS*(e). *RcS*(e) is the Response Cost for recovery from the testing performed by the SA.
c. Operational Cost (*OpCost*) is the cost of processing the stream of events that are monitored by an IDS and of analyses of related activities, made available through the application of intrusion detection models.

The detection outcome *e* is one of the following: false negative (*FN*); false positive (*FP*); true positive (*TP*); or true negative (*TN).* The costs associated with these outcomes (outlined in Table 3) are known as consequential costs (*CCost*), as they are incurred as a consequence of prediction. *CCost* is the cost summation of Damage and Response Costs. The terms used in our cost model are as following:

| Detection Outcomes | CCost | Condition |
|---|---|---|
| FN′ | $\sum_{e \in E'A} DcA\ (e) + \sum_{e \in E'S} E3\ DcS\ (e)$<br>$0 \leq E3 \leq 1$ | |
| FP′ | $\sum_{e \in E'A} RcA + \sum_{e \in E'NORM} P(e)$<br>0 | If *DcA* (e) ≥ *RcA* (e), e ∈ E′A<br>If *DcA* (e) < *RcA* (e), e ∈ E′A |
| TP′ | $\sum_{e \in E'A} RcA + \sum_{e \in E'S} E4\ DcS(e)$<br>$0 \leq E4 \leq 1$<br>$\sum_{e \in E'A} DcA\ (e)$<br>$\sum_{e \in E'SA} E3\ DcS(e)$ +<br>$\sum_{e \in E'NORM} P(e)$<br>$0 \leq E3 \leq 1$ | If *DcA* (e) ≥ *RcA* (e), e ∈ E′A<br>If *DcA* (e) < *RcA* (e), e ∈ E′A<br>∀ ∈ E′ SA |
| TN′ | 0 | |

Table 3. Cost Model associated with FN, FP, TP , and TN outcome as Consequential Cost (CC)

$E'A$ = *Event by Attackers*
$E'S$ = *Event by System administrator*
$DcA$ : Damage cost of attacker
$DcS$ : Damage cost of system administrator
$RcA$ : Response cost of attacker
$OcA$ : Operation cost of attacker
$OcS$ : Operation cost of SA
$P$ : Penalty cost rate of positive false detection
$q1$ : Negative false detection rate
$q2$ : Positive false detection rate

Our proposed decision tree algorithm objective is in reducing misclassification cost for the cloned and fraud detection problem. Once the algorithm have achieved this objective, the cost model which calculates the total cost for cloning and fraud tags will be employed.A decision tree algorithm could be made cost sensitive by selecting those attributes that have highest gain at each stage of the tree building process (Ling et, al, 2006). The gain is defined as:

$$\text{Gain} = \text{priorCost} - \text{cCost} - \text{attribCost} \times \text{N} \tag{5}$$

priorCost = cost of misclassification before the split
cCost = cost of misclassification after the split
attribCost = cost of evaluating the attribute over which the split is taking place.
N = number of instances.

$$\text{currentCost} = \sum_{i=0}^{n} \sum_{j=0}^{n} (N * distj) * Cjk \tag{6}$$

where: n is the number of values that the attribute can take ,
N is the number of instances or RFID tags ,
D is the number of attributes,
distj is the probability of class value j
$Cjk$ is the cost of misclassifying an instance of class j as that of class
k, where k is the dominating class of the split.
T is training dataset

Given a distribution for c classes, the dominating class I for that node is calculated as follows:

$$\text{arg min cost} = \sum_{j=0}^{c} \text{distj} * Cji \tag{7}$$

We would not explain further on our proposed algorithm and its evaluation in this chapter and focus more on the cost model instead.

We can now define the cost model for the cloning detection system .When evaluating a system over some labelled test set $E$, where each event, $e \in E$, has a label of normal or one of the cloned , we define consequential cost ( CCost) and cumulative cost of the IDS as follows:

$$\text{Consequential Cost (CC)} = \sum_{e \in E} ( DcA + RcA ) \tag{8}$$

$$\text{Total Cost (E)} = \sum_{e \in E} ( CCost(e) + OpCost(e)) \tag{9}$$

$$\text{TotalCost (e)} = current\ cost * \sum_{i=1}^{N}(\sum_{j=1}^{T} DcA\ (e) + \text{RcA(e)} + \text{OcA(e)}) \quad (10)$$

$$\text{TotalCost (e)} = currentcost * \sum_{i=1}^{N}(\sum_{j=1}^{T} DcS\ (e) + \text{OcS(e)}) \quad (11)$$

$$DcA\ \text{(e)} \geq RcA\ \text{(e), e} \in \text{E'A} \quad (12)$$

It may not always be possible to fold Damage and Response Costs into the same measurement unit. Instead, each should be analysed using its own relative scale. We must, however, compare and then combine these costs so that we can compute *CCost(e)* for use in the calculation of Cumulative Cost as shown in (2) and (3). Cost total is categorised in two parts:

- the total costs associated with attacks; and
- the total cost associated with SA testing.

Based on equations (7) and (8), N is the number of training datasets and T is the number of tags attacked. The overall total cost is calculated as a sum of all costs associated with all compromised RFID tags. In Table 4 and Table 5 extends the cost matrix outcome to predict the total cost of detection vs. non-detection of an attack vs. no attack. Table 4 shows the misclassification cost matrix for attackers and Table 5 displays the test cost matrix associated with the SA role. The explanations are discussed below.

*Misclassification cost ( Cij)*

| | ***Attack*** | ***No Attack*** |
|---|---|---|
| ***Detection*** | $RcA + OcA$ | $RcA + OcA + Pe$ |
| ***No detection*** | $DcA + OcA$ | $OcA$ |

Table 4. 2x2 cost matrix for attacks detection

*SA testing cost ( Mij)*

| | ***Attack*** | ***No Attack*** |
|---|---|---|
| ***Detection*** | $DcS + Pe + OcS$ | $0$ |
| ***No detection*** | $DcS$ | $OcS$ |

Table 5. 2x2 cost matrix for SA testing detection

Detection algorithms of all kinds often create false positives. For example, an RFID IDS may detect a 'cloned' where there are only some RFID tags that look like a ‘cloned’ to the algorithm is being used. When developing detection algorithm, the trade-off between false positives and false negatives threshold values can be varied to make the algorithm more restrictive or more sensitive. Restrictive algorithms risk rejecting true positives while more sensitive algorithm risk accepting false positives.

Detection algorithms of all kind often create misses as well. For example, if in a medical diagnosis, if a doctor fails to detect cancer in a patient that is a false negative. When developing detection algorithms or tests, a balance must be chosen between the risks of false negative and false positives. Usually there is a threshold of how close a match to a given sample must be achieved before the algorithm reports a match. The higher this threshold is, the more false negatives and fewer false positives exist. The description on each value of true positive (TP), false negative (FN), false positive (FP) and true negative (TN) costs are listed below:

**TP Cost**

If an attack occurs and the IDS detects it successfully, the associated cost is $((1-q1))$ *RcA* + *OcA*. *TP Cost* is incurred in the event of a correctly classified cloned tag, and involves the cost of detecting the clone and possibly responding to it. To determine whether a response will be needed, *RCost* and *DCost* must be considered. If the Damage done by the attack to resource *r* is less than *RCost*, then ignoring the attack reduces the overall cost. Therefore, if *RCost(e)* > *DCost(e)*, the intrusion is not responded to other than logging its occurrence, and the loss is *DCost(e)*. If *RCost(e)* ≪ *DCost(e)*, the intrusion is acted upon and the loss is limited to *RCost(e)*. Because this state is the opposite state to a false negative detection, the detection rate can be derived as $(1 - q1)$. *OcA* is the default cost if the IDS is settled and the *RcA* is generated because the IDS detects malicious tags.

**FN Cost**

*FN Cost* is the cost of not detecting a cloned attack. When the system falsely decides that a RFID tag is not cloned and does not respond to it, the attack will succeed, and the target resource will be Damaged. The *FN Cost* is therefore defined as the Damage Cost associated with the attacker (*DcA* ) or the Damage Cost associated with the system administrator *DcS,* related to event *e.* The expected cost in this scenario is $q1$ (*DcA* + *OcA*). *OcA* is the default cost if the IDS is settled and *DcA* occurs because the IDS fails to detect malicious packets. $q1$ is a negative false detection rate.

**FP Cost**

*FP Cost* is incurred when an event is incorrectly classified as an attack, i.e., when *e* = (*normal*, *p*, *r*) is misidentified as *e′* = ( *a′*, *p′*, *r′*) for some attack *a*. If *RCost*(*e′*_) ≪ *DCost*(*e′*), a response will ensue and the Response Cost, *RCost*(*e′*), must be accounted for. In this instance, since normal activities may be disrupted due to an unnecessary response, a false alarm should be penalized. For our discussion, we use *PCost*(*e*) to represent the penalty cost of treating a legitimate event *e* as an intrusion. For example, if *e* is aborted, *PCost*(*e*) can be the Damage Cost of a *DOS* attack on resource *r*, because a legitimate user may be denied access to *r*. The expected cost in this state is $q2$(*RcA* + *OcA* + *Pe*). Because 'false positive detection' is a false detection the same as in case 2, the generated cost is expected to be *Rcj* + *OcA*. However, this scenario causes an additional penalty cost *Pe* due to a false response. $q2$ is a false negative detection rate.

**TN cost**

*TN Cost* is always 0, as it is incurred when a system correctly decides that an event is normal. This decision is therefore associated with no Damage Cost, as only Operating Cost for maintaining the IDS is required. Section 4 discusses how MCDM is used to quantify costs in our cost model.

The detection algorithm that is embedded within the cost sensitive model is based on the description of our proposed cost matrix outcome as described earlier. Figures 3 and 4 demonstrate our proposed cost model within an improvised decision tree

```
Input: Training data: T= {t1,… tm} where each example Ti has attributes {pi,….pn) and a class ci
      : Classifier C with learning algorithm L
      : Misclassification cost, Cij

Output: W: the predicted test class, alarm log, response
For ∀ T ∈{ti, … tm}
        C ◄── L(T)
 Create a Root node for the tree
Initialize all the weights in T, Wi=1/N, where N is the total number of the examples.
Calculate the prior probabilities P(Cj) for each class Cj in T. P (Cj) = Σ_Ci Wi / Σ_{i=1}^{n} Wi
Calculate the conditional probabilities P (Aij | Cj) for each attribute values in T. P (Aij | Cj) = P (A)
/ Σ_Ci Wi
Calculate the posterior probabilities for each example in D.P(ei | Cj) = P(Cj) Π P(Aij | Cj)
Update the weights of examples in D with Maximum Likelihood (ML) of posterior probability
P(Cj|ei);  Wi= PML (Cj|ei)

        If (all the examples in T are in the same class ci)
        {
                Return (the single node tree Root with label ci)
        }
        Else
        {
          Let a be the Best attribute (T)
          For (each possible value v of a) do
             {
              Add a new tree branch below Root, which correspond to the test a = v
              If (Dv is empty)
                  {
                    Below this branch add a new leaf node with label equal to the common class
                    Value in D.
                  }
                   Else
                    {
                     Below this branch add the subtree (Dv,A-a)
                    }
                  }
        }
        Return Root
        End learning phase

C = {Ti , Tx}
 For ∀ Tx ∈{Cloned, Fraud}
        Calculate the expected misclassification cost R(αi /x) by equation (10)
        W= arg minj R(αi /x)
If DCost > RCost, response is triggered
 Else store in alarm log
```

Fig. 3. Pseudo code for misclassification cost by attackers using Decision Tree

*Input : Training data : T= {t1,…….., tm} where each example Ti has attributes {pi,….pn) and a class ci*
*: Classifier C with learning algorithm L*
*: Test cost, Mij*
*: SA test : Ts = {t1,…….., tm} where each example Ti has attributes {pi,….pn) and a class ci*

*Output: W : the predicted class*
*For T ∈{ti, … tm}*
*C ⟵ L(T)*
Create a Root node for the tree
Initialize all the weights in T, Wi=1/N, where N is the total number of the examples.
Calculate the prior probabilities P(Cj) for each class Cj in T. P (Cj) = $\sum_{Ci}$ Wi / $\sum_{i=1}^{n}$ Wi
Calculate the conditional probabilities P (Aij | Cj) for each attribute values in T. P (Aij | Cj) = P (A) / $\sum_{Ci}$ Wi
Calculate the posterior probabilities for each example in D.P(ei | Cj) = P(Cj) Π P(Aij | Cj)
Update the weights of examples in D with Maximum Likelihood (ML) of posterior probability P(Cj|ei); Wi= PML (Cj|ei)

*For ∀ T ∈{Ts}*
*Calculate the expected test cost R(αi /x) by equation (11)*

Fig. 4. Pseudo code for test cost by attackers using Decision Tree

## 4. Quantifying cloning and fraud cost using MCDM tool

In this section we use the MCDM approach in quantifying costs. For our purposes, we define decision making as the process of choosing among optional alternatives based on multiple criteria. For each of these decisions, we consider several factors or criteria and we also consider several optional alternatives. In group decision making these criteria and alternatives are more complex and must be determined prior to the development of related judgment scores or evaluation values. We adopted the simplest method for MCDM, using cross tabulation and weighting methods. The following equation describes how cross tabulation and weighting is represented:

$$\text{Normalized score}, Zk(Oi) = \frac{1}{2}\left(1 - \frac{sum}{totalsum}\right) \quad (13)$$

$$U(Oi) = \sum_{k=1}^{M} Zk(Oi) \times w(Ck) \quad (14)$$

where *Zk(Oi)* is the normalised score of option *Oi* under criterion *Ck* and *w(Ck)* is the normalised weighting for criterion *Ck*. The summation of the damage, response and operational costs will always be for the representation of ten tags for any conditions such as cloned, fraud or for the purpose of testing by SA. Section 4.1 discusses how MCDM is used to quantify cost for a RFID tag cloning attack. Section 4.2 describes the evaluation of the cost of a fraud attack.

### 4.1 MCDM for RFID tags cloning attack

This section introduces how costs associated with cloning attacks by attackers are quantified in a RFID system. Attacker Damage Cost (*DcA*) and attacker Response Cost (*RcA*) are the two costs discussed here. *DcA* is the amount of cost related to the Damage to target resources if intrusion detection is unavailable. Two main factors, criticality and lethality (Lindqvist & Jonsson, 2007); (Northcutt, 1999) are used to measure and define these costs.

Criticality measures the importance of the targeted resource of an attack and evaluates it in terms of cost to replace, including unavailability and disclosure costs. For instance, the cost of replacing cloned RFID tags is much less than the cost of replacing the complete organisation database. *DcA* is a result of combining criticality with the attack category. Based on cost measurements factors and based on our problem definition, we use the simplest method of applying MCDM, using a cross table with target resources in RFID systems (tags, readers, database and RFID network) as criteria; and types of security cloning attacks as alternatives. Table 1 displays the *ADCost* for RFID cloning attack.

| Attacks \| Target Resources | Skimming | Eavesdropping | MIM | Physical | SUM |
|---|---|---|---|---|---|
| **Tags** | 30 | 15 | 25 | 30 | 100 |
| **Readers** | 20 | 30 | 40 | 10 | 100 |
| **Database(local)** | 20 | 30 | 35 | 15 | 100 |
| **Network** | 10 | 40 | 40 | 10 | 100 |
| **Sum** | **80** | **115** | **140** | **65** | **400** |
| **Normalized Score** | **20.0%** | **28.8%** | **35.0%** | **16.3%** | **100%** |

Table 6. Criticality of RFID components in term of replacing, unavailability and disclosure for Damage cost

| | Tags | Reader | Database | Network | Sum |
|---|---|---|---|---|---|
| **Importance Level** | 20 | 15 | 30 | 35 | 100 |
| **Importance Weight** | 20.0% | 15.0% | 30.0% | 35.0% | 100.0% |

Table 7. Weight Importance of RFID components

| Attacks \| Costs | Weights | Skimming | Eavesdropping | MIM | Physical attack | |
|---|---|---|---|---|---|---|
| **Tags** | 20.0% | 6.00 | 3.00 | 5.00 | 6.00 | |
| **Readers** | 15.0% | 3.19 | 4.79 | 6.38 | 1.60 | |
| **Database(local)** | 30.0% | 1.58 | 2.36 | 2.76 | 1.18 | |
| **Network** | 35.0% | 0.99 | 3.96 | 3.96 | 0.99 | |
| **Sum** | **100.0%** | **11.8** | **14.1** | **18.1** | **9.8** | **53.7** |
| **Normalized Score** | | **21.9%** | **26.3%** | **33.7%** | **18.2%** | **1** |

Table 8. Damage Cost (*DcA*) Evaluation based on scores of attacks and target resources factors

Based on Table 8, we could distinguish the damage cost for each attack using different RFID components.For instance, the damage cost for skimming attack on ten RFID tags is USD

6.00.'Man in the middle' attack has the highest associated Damage Cost, followed by that associated with 'eavesdropping' attack. 'Man in the middle' attack high Damage Cost is related to its related probability that all RFID components, especially tags and the network, have been compromised. The related impact on the organisation is greater than simply replacing the components with new ones. The disclosure of information from the tags and database could lead to further losses due to unavailability costs and to future related serious security attacks, such as fraud, that could jeopardize the complete RFID system. RFID tags are generally exploited more than RFID readers, as they are more vulnerable to attack. This fact is supported by RFID tags typically having little or no security measures. In the supply chain management environment, RFID tags take up less storage space and are of low cost compared to RFID readers.

*RcA* is the Response Cost associated with acting upon an alarm. A Response Cost can be either manual or automatic and is determined based associated IDS capabilities and organisation policies; attack types; and target resources. Measurement of a Response Cost is similar to that of a Damage Cost, and includes the factors of criticality and attack category. Table 9 displays a Response Cost for a RFID cloning attack.

| Attacks \| Target Resources | Skimming | Eavesdropping | MIM | Physical | Range |
|---|---|---|---|---|---|
| **Tags** | 15 | 15 | 30 | 40 | 100 |
| **Readers** | 15 | 35 | 40 | 10 | 100 |
| **Database(local)** | 20 | 25 | 35 | 20 | 100 |
| **Network** | 20 | 30 | 35 | 15 | 100 |
| **Sum** | **70** | **105** | **140** | **85** | **400** |
| **Normalized Score** | **17.5%** | **26.3%** | **35.0%** | **21.3%** | **100%** |

Table 9. Criticality of RFID components in term of replacing, unavailability and disclosure for Response cost

| Attacks \| Costs | Weights | Skimming | Eavesdropping | MIM | Physical attack | |
|---|---|---|---|---|---|---|
| **Tags** | 20.0% | 3.00 | 3.00 | 6.00 | 8.00 | |
| **Readers** | 15.0% | 2.39 | 5.59 | 6.38 | 1.60 | |
| **Database(local)** | 30.0% | 1.58 | 1.97 | 2.76 | 1.58 | |
| **Network** | 35.0% | 1.98 | 2.97 | 3.46 | 1.48 | |
| **Sum** | **100.0%** | **8.9** | **13.5** | **18.6** | **12.7** | **53.7** |
| **Normalized Score** | | **16.7%** | **25.2%** | **34.6%** | **23.6%** | **1** |

Table 10. Response Cost (*RcA*) Evaluation based on scores of attacks and target resources factors

Based on Table 10, we can conclude that a simpler attack such as a 'skimming' attack has a much lower Response Cost compared to a complex attack (such as a 'physical' attack). This is because a 'physical' attack requires more complex mechanisms for an effective response.

In addition, we have totaled up the relative cost for the Damage and Response Cost to calculate the *CCost* based on formula (2). From Table 11, we could conclude that 'man in the middle' attack has the highest normalized score.

| Costs \| Attacks | Skimming | Eavesdropping | MIM | Physical | Sum |
|---|---|---|---|---|---|
| **Damage** | 11.8 | 14.1 | 18.1 | 9.8 | 53.7 |
| **Response** | 8.9 | 13.5 | 18.6 | 12.7 | 53.7 |
| **Sum** | 20.7 | 27.6 | 36.7 | 22.4 | 107.5 |
| **Normalized Score** | **19.3%** | **25.7%** | **34.2%** | **20.9%** | **100%** |

Table 11. Consequential Cost (CC) Evaluation for summation between Damage and Response Cost

### 4.2 Operational cost

Operational Cost (*OcA)* includes the default cost of running an IDS. This could include the amount of time and amount of computing resources needed to extract and test features from the raw data stream that is being monitored. In practice, *OcA* is associated with time. For instance, time should be minimised in the detection of a security problem and related generation of an alarm, as the longer the time taken, the higher the associated cost. There are two cost factors which need careful examining: 1) the computing resource cost per each of the four attack types); and 2) the time taken per attack type. To compute the computing resource related cost, the different events and transactions that occur in a supply chain need to be taken into account. Table 12 depicts the time taken to handle each attack type and Table 13 the test features, based on their computing resource related cost. It takes more time to handle a 'physical' attack than other attack types. This is because a 'physical' attack requires understanding of cryptanalysis techniques and is associated with a greater amount of laboratory work. We have analysed *OcA* related to the four different cloning attack types based on a typical RFID system in an integrated RFID EPCglobal service (Ranasinghe & Cole, 2007, Verisign Inc, 2007).

| | Skimming | Eavesdropping | MIM | Physical | Sum |
|---|---|---|---|---|---|
| **Importance Level** | 15 | 35 | 45 | 60 | 155 |
| **Importance Weight** | 9.7% | 22.6% | 29.0% | 38.7% | 100.0% |

Table 12. Operational cost relative to time taken in handling 4 cloned attacks.

The main cost inherent in the operation of an IDS is the amount of time and the computing resources needed to extract and test features from the raw data stream that is being monitored. We classify features into four relative levels, based on their computational costs:

- Level 1 features can be computed at the beginning of the service (e.g. tagging)
- Level 2 features can be computed at any point during the transaction of RFID tags in a single plant or site; e.g. Movement of tags in a distributor plant (shipping , receiving)
- Level 3 features can be computed at the end of a single supply chain tag transaction at the end of the plant movement; e.g. Movement and transactions of tags from manufacturer to retailer plant

| Levels | L1: Computed from the beginning of service (e.g tagging) | L2: Computed at any events of RFID movement between two plants. ( e.g shipping, receiving). | L3 : Computed at all the events in a single SCM from manufacturer to retailer(e.g tagging, pack, shipping, receiving) | L4:Computed at the overall of operation of interconnected EPCglobal network (EPCIS, DNS) such as tracing and tracking. (Involves L1,L2 and L3) | Sum |
|---|---|---|---|---|---|
| **Importance Level** | **1** | **5** | **10** | **100** | **116** |
| **Importance Weight** | **0.9%** | **4.3%** | **8.6%** | **86.2%** | **100.0%** |

Table 13. Four relative levels of test features based on their computing resources cost for Operating Cost (*OcA)*.

- Level 4 features can be computed at the end of multiple supply chain plants in a interconnected network connection, but potentially require access to data of many prior connections. These are temporal and statistical features and are the most costly to compute. The computation of these features may require values of the lower level (i.e., levels 1, 2, and 3) features. Table 10 depicts the four relative test features for different attacks.

| Features \| Attacks | Weights | Skimming | Eavesdropping | MIM | Physical attack | |
|---|---|---|---|---|---|---|
| **L1** | 0.9% | 10.00 | 15.00 | 15.00 | 10.00 | |
| **L2** | 4.3% | 11.01 | 11.01 | 13.21 | 8.81 | |
| **L3** | 8.6% | 21.46 | 17.17 | 25.76 | 17.17 | |
| **L4** | 86.2% | 21.41 | 21.41 | 26.77 | 21.41 | |
| **Sum** | **100.0%** | **63.9** | **64.6** | **80.7** | **57.4** | **266.6** |
| **Normalized Score** | | **20.7%** | **20.9%** | **26.1%** | **32.4%** | **1** |

Table 14. Operational Cost (*OcA*) Evaluation based on scores of test features and cloning attacks types

Test features look into the computing resources used in a counter measuring attack. 'Physical' attacks require more testing of raw features and are harder to counter than other attack types. In order to calculate Cumulative Cost or overall cost by using formula (3), the end result is based on two scenarios: The first scenario is the summation of *CCost* (Damage and Response Cost) with Operational Cost, relative to the cost of the time taken in handling the attacks. This is shown in Figure 15.

Based on Figure 7, Cumulative Cost for a 'man in the middle' attack is the highest, followed by that for a 'physical' attack. 'Skimming' attacks have low overall costs because the attack requires less expertise and a lower Response Cost.

| Features \| Attacks | Weights | Skimming | Eavesdropping | MIM | Physical attack | |
|---|---|---|---|---|---|---|
| **Features** | 70.0% | 19.2 | 19.4 | 24.2 | 30.3 | |
| **Time** | 30.0% | 0.9 | 2.0 | 2.6 | 3.5 | |
| **Sum** | **100.0%** | **20.0** | **21.4** | **26.8** | **33.8** | **102.0** |
| **Normalized Score** | | **19.6%** | **21.0%** | **26.3%** | **33.1%** | **100.0%** |

Table 15. Operational Cost (*OcA*) Evaluation based on weight for test features and time

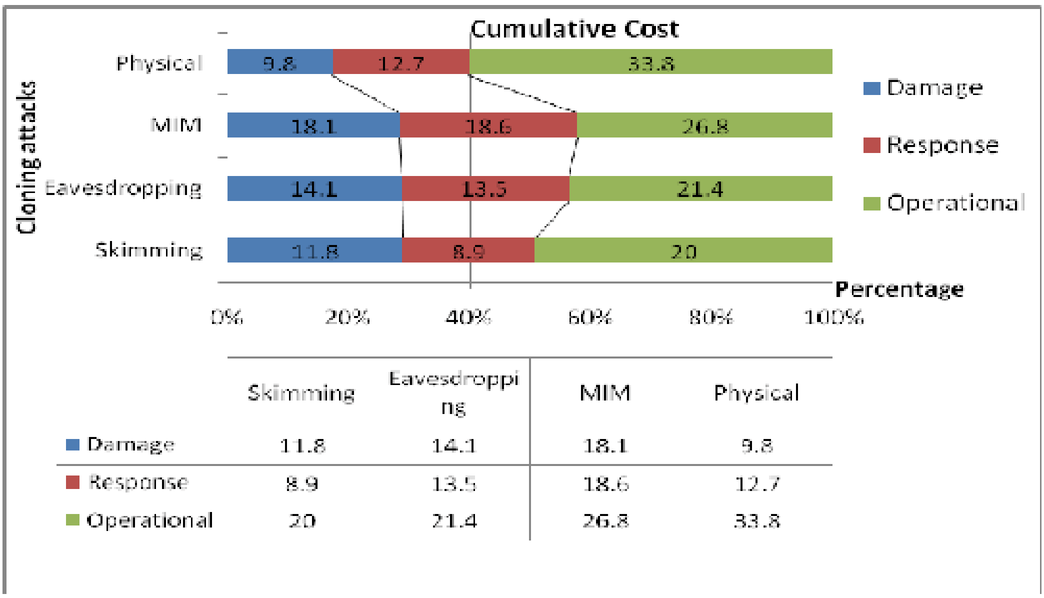


Fig. 7. Overall Cost Evaluation for summation between Consequential Cost and Operational Cost

#### 4.3 Quantifying RFID tag fraud attack and system administrator testing

This section looks at *DcA* and *RcA* the respective Damage and Response Costs in detecting a fraudulent act. Fraud involves injection of products with future EPC codes or past batch EPC codes. It involves first cloning and then modifying existing EPC codes. The cost types for fraudulent events are similar to that of cloning attacks. The difference is the need to monitor the progress of the attack when calculating Damage Cost and Response Cost, as a fraud attack has a greater impact on the performance of the system than a cloning attack. The contributing factors for its greater impact include:

a. An inconsistent number of tags and readers
b. A higher bandwidth
c. Unauthorized locations /sites visited by tags (as obtained from tracking and tracing processes)
d. The transaction time – greater or smaller than a given transaction time range.

We consider fraud attacks and SA testing damage (*DcS)* together since they have similar cost impact factors. In a real-time situation, a fraud attack is potentially in progress by the time it is detected, meaning that its measured Damage Cost at a point in time is potentially only a part of its total Damage Cost. This is represented by the formula '**Progress X Damage Cost'**, where attack progress is represented by the percentage of the attack's progress. We use the simpler 'skimming' attack cost ($11.80) obtained from Table 8 when calculating fraud attack Damage and Response Costs. Table 16 displays relative costs for fraud attacks and associated SA testing.

| **Progress of attacks \| Attacks** | **Progress attack** | **Damage Cost (Fraud)** | **Progress attack for SA** | **Damage Cost (SA)** | **Sum** |
|---|---|---|---|---|---|
| **Tags Count** | 1 | 11.8 | 1 | 11.8 | |
| **Location** | 0.8 | 9.44 | 0.5 | 5.9 | |
| **Time** | 0.8 | 9.44 | 0.5 | 5.9 | |
| **Bandwidth** | 0.5 | 5.9 | 0.5 | 5.9 | |
| **Sum** | | **36.6** | | **29.5** | **66.0** |
| **Normalized Score** | | **55%** | | **45%** | **100%** |

Table 16. Cost relative to Damage Cost for fraud attack and SA test and Progress attack value

There is no reason to calculate Response Cost for SA testing, since SA testing is done using an upfront authentication mechanism and requires secure identification of a system administrator, thus preventing their injection of cloned or fraudulent tags in the system. Response Cost is thus associated only with fraud attacks, and not with SA tests. Table 17 shows the Response Cost for fraud attack and response cost used is similar to response to handle skimming attack. The amount of Response Cost is related to the number of affected tags.

| **Progress of attacks \| Attacks** | **Progress attack** | **Response Cost (Fraud)** | **Sum** |
|---|---|---|---|
| **Tags Count** | 1 | 8.9 | |
| **Location** | 0.8 | 7.12 | |
| **Time** | 0.8 | 7.12 | |
| **Bandwidth** | 0.3 | 2.67 | |
| **Sum** | | **25.8** | **25.8** |
| **Normalized Score** | | **100%** | **100%** |

Table 17. Cost relative to Response Cost (Attacks vs. Target resources) and Progress attack value

We analyse *CCost* in terms of its difference between cloning and fraud attacks. The cloning Damage and Response Costs are captured from section 4.1. Based on these results, we are able to conclude that cloning attacks have higher Damage as well as Response Costs than fraud attacks. This occurs because a fraud attack is only part of a cloning attack. A cloning attack needs to occur before a fraud attack can occur.

| Costs \| Attacks | Cloning | Fraud | Range |
|---|---|---|---|
| **Damage** | 53.7 | 36.6 | 1-100 |
| **Response** | 53.7 | 25.8 | 1-100 |
| **Sum** | 107.4 | 62.4 | 170.02 |
| **Normalized Score** | **63.2%** | **36.8%** | **100%** |

Table 18. Consequential Cost (CC) Evaluation for summation between Damage and Response Cost

Operating cost for fraud attack will follows the similar formulation in section 4.2. Table 19 and Table 20, compares both time taken in handling fraud and cloning and test features for fraud and cloning. Detection of fraud is much simpler than any cloning attack. This is because in practical and based on our theory, fraud tags will have identifiers which are not in the system. Thus simple similarity test is good enough to distinguish the EPC tags stored in the database. By using similar weight in cloning attack operational example in Table 12, we have allocated an average of 30 minutes to detect a fraud attack and features test used for skimming attack.

| Features \| Attacks | Weights | Skimming | Eavesdropping | MIM | Physical attack | Fraud attack | |
|---|---|---|---|---|---|---|---|
| **L1** | 0.9% | 10.00 | 15.00 | 15.00 | 30.00 | 63.90 | |
| **L2** | 4.3% | 11.01 | 11.01 | 13.21 | 17.62 | 28.14 | |
| **L3** | 8.6% | 21.46 | 17.17 | 25.76 | 25.76 | 27.43 | |
| **L4** | 86.2% | 21.41 | 21.41 | 26.77 | 26.77 | 17.10 | |
| **Sum** | **100.0%** | **63.9** | **64.6** | **80.7** | **100.1** | **136.6** | **445.9** |
| **Normalized Score** | | **14.3%** | **14.5%** | **18.1%** | **22.5%** | **30.6%** | **1** |

Table 19. Operational Cost (*OcA*) Evaluation based on scores of test features for cloning and fraud attacks

| Features \| Attacks | Weights | Skimming | Eavesdropping | MIM | Physical attack | Fraud attack | |
|---|---|---|---|---|---|---|---|
| **Features** | 70.0% | 19.2 | 19.4 | 24.2 | 30.3 | 19.2 | |
| **Time** | 30.0% | 0.9 | 2.0 | 2.6 | 3.5 | 1.7 | |
| **Sum** | **100.0%** | **20.0** | **21.4** | **26.8** | **33.8** | **20.9** | **122.9** |
| **Normalized Score** | | **16.3%** | **17.4%** | **21.8%** | **27.5%** | **17.0%** | **100.0%** |

Table 20. Operational Cost Evaluation based on scores of test features and cloning attacks types

Cumulative Cost calculations for fraud attack are different based on two scenarios. In this scenario *CCost* is added to the relative cost of different test features for computing resource related cost and time taken in handling attack (as shown in Figure 20). We have compared Cumulative Cost for both cloning and fraud attacks, and though the difference is not great, cloning attacks take up more operating time due to related countermeasures, which causes it to have a slightly greater cost. The operational cost for SA testing purposes will be a constant figure of 20.0, similar to operational cost to handle skimming attack.

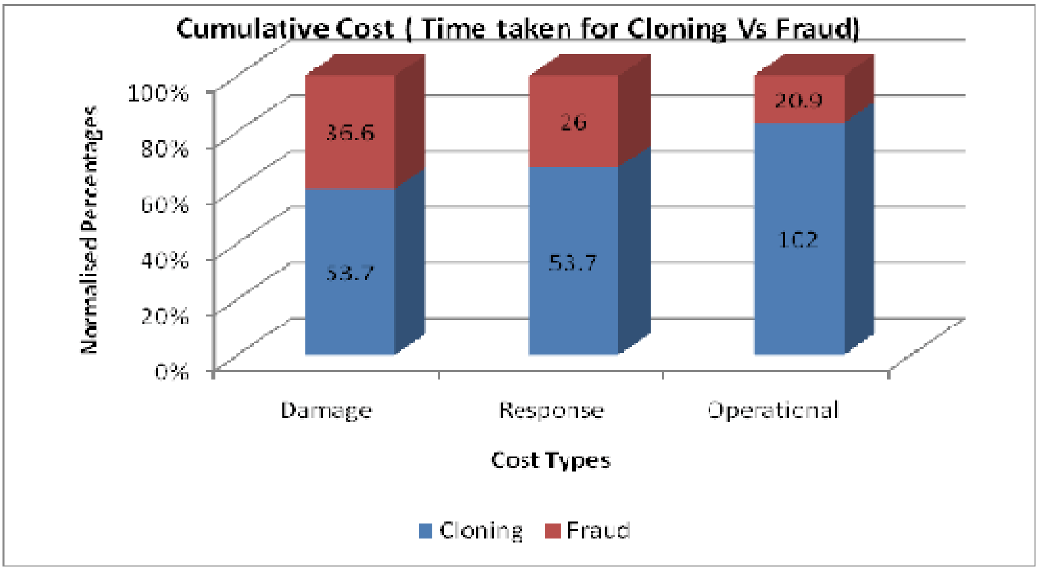


Fig. 8. Overall Cost Evaluation for summation between Consequential Cost and Operational Cost (Time taken to handled fraud and cloning attacks)

### 4.4 Cost model calculation

This section contains an analysis of cost sensitive and cost insensitive models, and introduces a cost model input cost matrix for a detection system.Assuming that we have a cloned detection system that functions upfront, we could feed the cost matrix result in our cost model. Since our cost system is quantified using the MCDM tool and is based on the cost model calculation in Table 3 and Table 4 which are calculated using MCDM in section 4.1 and 4.3, we could list estimated Damage, Response and Operational Costs according to this cost model. The difference between a cost sensitive and cost insensitive model is that a cost sensitive method initiates a response if $DCost \geq RCost$ and corresponds to the cost model, whereas a cost insensitive method responds to every predicted intrusion and is representative of current brute-force approaches to intrusion detection. Table 21 displays the overall cost model calculation for a cloning attack and Table 22 displays the overall cost model calculation for a fraud attack.

Table 23 shows the difference between cost sensitive and cost insensitive models for both cloning and fraud attacks. For instance, in a supply chain environment where both fraud and cloning are the act of counterfeiting, the total potential loss is estimated based on formula (1) in our model and is calculated to be US$1692.90. If this cost sensitive model is calculated for cloning attack for 'skimming attack ' for ten RFID tags, we will obtained a cost reduction of $US77.8 compare to cost insensitive model which gives us $US193.20. On average, the risk for our cost sensitive model on 'skimming attack' on each RFID tag over skimming attack will be estimated at $US7.80. Table 24 displays the cost of $US139 that should be bear by an organsation for every ten RFID tags tested. This testing cost is much lesser than 10% of the overall cost of counterfeiting and worth to be considered as well in any intrusion detection system.

| **Cost types \| Cost matrice** | **FN** | **FP (DCost ≥ Rcost)** | **TP (DCost ≥ Rcost)** | **TP (DCost < Rcost)** | **TP (∀ ∈ E′ SA)** | **TN** | **Sum** |
|---|---|---|---|---|---|---|---|
| **ADCost(Cloning)** | 53.7 | | | 53.7 | 53.7 | 0 | |
| **Operational Cost** | 102 | 102 | 102 | 102 | 102 | 102 | |
| **ARCost(Cloning)** | | 53.7 | 53.7 | | | 0 | |
| **Penalty** | | **20** | | | 20 | **0** | |
| **Sum** | 155.7 | 175.7 | 155.7 | 155.7 | 175.7 | 102 | 920.5 |
| **Normalized Score** | **16.9%** | **19.1%** | **16.9%** | **16.9%** | **19.1%** | **11%** | 100.0% |

Table 21. Overall cost calculation for ten cloned attack

| **Cost types \| Cost matrice** | **FN** | **FP (DCost ≥ Rcost)** | **TP (DCost ≥ Rcost)** | **TP (DCost < Rcost)** | **TP (∀ ∈ E′ SA)** | **TN** | **Sum** |
|---|---|---|---|---|---|---|---|
| **ADCost (fraud)** | 36.6 | | | 36.6 | 36.6 | 0 | |
| **Operational Cost** | 20.9 | 20.9 | 20.9 | 20.9 | 20.9 | 20.9 | |
| **ARCost(fraud)** | | 26 | 26 | | | 0 | |
| **Penalty** | | **20** | | | **20** | **0** | |
| **Sum** | 57.5 | 66.9 | 46.9 | 57.5 | 77.5 | 20.9 | 327.2 |
| **Normalized Score** | **17.6%** | **20.4%** | **14.3%** | **17.6%** | **23.7%** | **6.4%** | **100%** |

Table 22. Overall cost calculation for fraud attack

| **Attacks \| Cost model** | **Cost Insensitive** | **Cost Sensitive** | **Sum** |
|---|---|---|---|
| **Cloning** | 920.5 | 331.4 | |
| **Fraud** | 327.2 | 113.8 | |
| **Counterfeiting (Sum)** | 1247.7 | 445.2 | 1692.9 |
| **Normalized Score** | **73.7%** | **26.3%** | **100%** |

Table 23. Cost Model for cloning, fraud and counterfeiting

| Cost types \| Cost matrice | FN | FP (DCost ≥ Rcost) | TP (∀ ∈ E′ SA) | TN | |
|---|---|---|---|---|---|
| **SDCost** | 29.5 | | 29.5 | 0 | |
| **Operational** | 20 | | 20 | 20 | |
| **Penalty** | | | 20 | **0** | |
| **Sum** | 49.5 | | 69.5 | 20 | 139 |
| **Normalized Score** | **35.6%** | **0.0%** | **50.0%** | **14.4%** | **100.0%** |

Table 24. Cost Model calculated for SA testing (using matrix in table 5)

## 5. RFID tag prevention techniques using MCDM

In this section we apply Analytical Hierarchy Process (AHP) and MCDM approaches (for different units of range) to select optimal supply chain authentication techniques and RFID tag authenticity verification methods.

AHP is a structured technique for dealing with complex decision making. AHP is a decision making tool that can describe a general decision making process by decomposing a complex problem into a multi- level hierarchical structure of objectives, criteria, sub criteria and alternatives, and is a well-known decision theory model developed by Saaty (1990). Its primary attribute is quantifying relative priorities for a given set of alternatives on a ratio scale, based on the judgment of the decision-maker. It provides an easy way to incorporate multiple experts' opinions and control of consistency in judgments. In addition, the AHP method ensures high repeatability and scalability controls. Applications of AHP have been reported in numerous fields such as conflict resolution, project selection, budget allocation, transportation, health care, and manufacturing (Harker, 1989).

AHP determines the criteria weightings indirectly based on scores of relative importance for each in pair-wise comparisons. The comparison ratings are on a scale of 1 to 9, resulting in a ratio of importance for each pair with the maximum difference that one criterion is 9 times more important than another. A matrix of pair-wise comparisons is determined in this way (where *Ci / Cj* is just shorthand for the relative importance of *Ci* to *Cj*). In AHP, the final weightings for the criteria are the normalised values of the eigenvector that is associated with the maximum eigenvalue for this matrix. Saaty (1980) suggests that this procedure is the best way to minimise the impact of inconsistencies in the ratios. Consistency Ratio is a comparison between Consistency Index and Random Consistency Index, or, in formula:

$$CR = \frac{CI}{RI} \tag{15}$$

We utilise the AHP tool in distinguishing the best approach and algorithm for preventing RFID tag cloning attacks in supply chains, and which is also suitable for use in testing processes used by SAs. In addition, we extend the MCDM tool based on criteria that best suit supply chain owners' needs when selecting RFID tag cloning and fraud prevention techniques. Among the defined criteria are acceptance, cost, security and complexity.

### 5.1 AHP tool for SA prevention techniques

In this section, we observe two different approaches. The first approach show the different methods used by SAs to handle authentications and select of algorithms. The second approach uses trust analysis based on tag cloning and fraud prevention techniques. The MCDM model can also be used in selecting the best tag cloning and fraud prevention approaches and the best approach for authentication that can be used by the System Administrator (SA) in testing the system.

Authentication is an essential element of a typical security model. It is the process of confirming the identification of a user (or in some cases, a machine) that is trying to log on or access resources. While authentication verifies the user's identity, authorisation verifies that the user in question has the correct permissions and rights to access the requested resource. The two work together: Authentication occurs first, then authorisation. In a RFID enabled supply chain management tracking and tracing system website, authentication and authorisation are essential. Based on organisational role, role based access control can be employed in which the administrator at each site are responsible for their own site. For instance, an administrator is only able to view other supply chain partner reports and not able to edit or delete them. In an IDS system, one of the SA tasks are to monitor and maintain the availability and execution of the detection system.

In addition, SAs are also responsible to test the system to ensure the IDS system is still relevant and able to detect cloned and fraud tags precisely. Thus, appropriate and secure modes of authentication approaches are required to ensure that the SA account is always protected. SAs can be authenticated by entering a password, inserting a smart card and entering the associated PIN, providing a fingerprint; voice pattern sample; retinal scan;, or using some other means to prove to the system that they are who they claim to be. Biometrics such as fingerprints, voice patterns or retinal scans are just a few of human traits known to be uniquely used in authentication. Biometric authentication is normally the most secure and the hardest to be compromised or cracked.

Single Sign-On (SSO) is a feature that allows a user to use one password (or smart card) to authenticate to multiple servers on a network without re-entering credentials. IP Security (IPSec) provides a means for users to encrypt and/or sign messages that are sent across the network to guarantee confidentiality, integrity, and authenticity. IPSec transmissions can use a variety of authentication methods, including the Kerberos protocol or using public key certificates issued by a trusted certificate authority (CA). By using AHP approach, we have analysed the authentication alternatives against criteria such as processing time, cost, security and complexity. These criteria are the required validation factors for any authentication method .Table 25 shows an example on how to calculate overall weight for alternatives using AHP. The AHP model results as shown in Table 25 indicates that the biometrics method provides the most appropriate authentication mode in terms of security and minimal time in processing the public key fingerprint.

Pair-wise comparison generally refers to any process of comparing entities in pairs to judge which entity is either preferred; or is found to have a greater amount of some quantitative property. The normalized principal Eigen vector is also called the **priority vector.** Since it is normalized, the sum of all the elements in priority vector is 1. The priority vector indicates the elements' relative weights.

A comparison of the different authentication methods used by supply chain partners indicates the following authentication results: Sign on (38.08%); biometrics (41.74%) and IPSec (15.86%). Biometrics is most popular authentication method, followed by the sign on method. The Consistency Ratio of these figures is less than 10%, which is acceptable due to the subjective nature of the measurement factors. The subjective judgment needs to be revised if the Consistency Ratio is greater than 10%.

| Criterias | Processing Time | Cost | Security | Complexity |
|---|---|---|---|---|
| Processing Time | 1 | 1 | 5 | 1 |
| Cost | 5 | 1 | 7 | 1 |
| Security | 0.2 | 0.14285714 | 1 | 3 |
| Complexity | 1 | 0.11 | 0.14 | 1 |
| Sum | 7.2 | 2.25 | 13.14 | 6 |

| Criterias | | | | | Sum | Priority Vector |
|---|---|---|---|---|---|---|
| Processing | 0.14 | 0.44 | 0.38 | 0.17 | 1.13 | 28.25% |
| Cost | 0.69 | 0.44 | 0.53 | 0.17 | 1.84 | 45.94% |
| Security | 0.03 | 0.06 | 0.08 | 0.50 | 0.67 | 16.68% |
| Complexity | 0.14 | 0.05 | 0.01 | 0.17 | 0.37 | 9.13% |
| Sum | 1.00 | 1.00 | 1.00 | 1.00 | 4.00 | 100.00% |

| Techniques | Sign on | Biometrics | IPSEC |
|---|---|---|---|
| Sign on | 1.00 | 1.00 | 7.00 |
| Biometrics | 1.00 | 1.00 | 3.00 |
| IPSEC | 0.14 | 0.33 | 1.00 |
| Sum | 2.14 | 2.33 | 11.00 |

| Normalised Matrix for Only Processing Time Criterion | | | | Sum | Priority vector |
|---|---|---|---|---|---|
| | 0.467 | 0.429 | 0.636 | 1.532 | 51.05% |
| | 0.467 | 0.429 | 0.273 | 1.168 | 38.93% |
| | 0.067 | 0.143 | 0.091 | 0.300 | 10.01% |
| Sum | 1.000 | 1.000 | 1.000 | 3.000 | 100.0% |
| | | | | | |

| | | |
|---|---|---|
| **lambda max** | **3.104** | |
| **consistency index (CI)** | **5.20%** | **n =** 3 |
| **consistency ratio (CR)** | **8.97%** | |

| | Processing Time | Cost | Security | Complexity | Overall Weight |
|---|---|---|---|---|---|
| Weight | **36.69%** | **36.69%** | **7.47%** | **2.17%** | |
| Sign on | 51.05% | 25.78% | 30.01% | 61.44% | **38.08%** |
| Biometrics | 38.93% | 44.40% | 42.82% | 22.50% | **41.74%** |
| IPSEC | 10.01% | 21.40% | 23.35% | 32.87% | **15.86%** |
| | | | | | |
| **Overall Consistency of Hierarchy** | | | **5.64%** | | |

Table 25. SA Criteria's and Techniques for Testing Cost Using AHP tool

| | MD5 | SHA | PKI | Overall Weight |
|---|---|---|---|---|
| **Weight** | **22.30%** | **22.30%** | **55.40%** | |
| **MD5** | 40.98% | 40.98% | 40.98% | **40.98%** |
| **SHA** | 47.36% | 47.36% | 47.36% | **47.36%** |
| **PKI** | 11.66% | 11.66% | 11.66% | **11.66%** |

Overall Consistency of Hierarchy: 7.06%

Table 26. SA Criteria's and Algorithms for Testing Cost Using AHP tool

We have evaluated three different public key algorithms (PKI, MD5 and SHA) that can be used in different algorithm approaches by applying AHP approach as shown in Table 24. Certificate services are part of a network's Public Key Infrastructure (PKI); have been applied in EPC global service; and are applicable to RFID systems (EPCGlobal Certificate Profile, 2008). Standards for the most commonly used digital certificates are based on X.509 specifications. In a public key cryptography, a 'fingerprint' is created by applying the keyboard hash function to a public key. SHA and MD5 are examples of 'fingerprint' algorithms.

Theoretically, MD5 and SHA1 are algorithms for computing a 'condensed representation' of a message or a data file. This uniqueness enables the message digest to act as a 'fingerprint' of the message. Among the algorithms used for SA authentication, SHA is the best algorithm to use (as shown in table 26). This is because SHA provides more strength of security compare to MD5 algorithm. However the disadvantage of the SHA algorithm is that it requires more storage space for its key management functionality.

### 5.2 MCDM for tag's authenticy

The second part is an evaluation of different tag authentication methods through the use of various supply chain criteria, applying the MCDM approach (usage of ranking with different range). The supply chain criteria are selected based on the assumption that a supply chain company that is willing to spend minimal whilst still maintaining the appropriate security features standard for their low cost tags; and curbing both cloning and fraud attacks on their tags. Table 27 displays the most appropriate tag authentication for a supply chain based on our analysis (M.Mahinderjit Singh & L.Xue., 2009).

| Criterias \| Techniques | EPC Design | Tags Design | Lightweight Protocol | Lightweight ECC | Steganography | |
|---|---|---|---|---|---|---|
| **Acceptance** | 3 | 4 | 1 | 2 | 5 | |
| **Cost** | 3 | 5 | 1 | 2 | 4 | |
| **Security** | 1 | 2 | 5 | 3 | 4 | |
| **Complexity** | 2 | 1 | 3 | 4 | 5 | |
| **Sum** | **9** | **12** | **10** | **11** | **18** | **60** |
| **Normalized Score** | **21.25%** | **20.00%** | **20.83%** | **20.42%** | **17.50%** | **100%** |

1 = Best ; 2 = Good ; 3 = Fair ; 4 = Weak ; 5 = Bad

Table 27. Evaluation based on rank scores of Tag's authencity Techniques for Various Supply Chain Criterias

The value of each row is either 1,2,3, 4 or 5 and represent the rank (shown in Table 27). Since smaller rank value is more preferable than higher rank value. Table 28 indicates that each criterion has a different range. For instance, the range for cost is in indicated in dollars in contrast to that for acceptance which is indicated in rank. It is not viable to the sum of the values of the different multiple criteria does not deliver a valid result. We need to transform the score of each factor according to its range value so that all factors have comparative ranges.

| Criterias \| Techniques | EPC Design | Tags Design | Lightweight Protocol | Lightweight ECC | Steganography | Range |
|---|---|---|---|---|---|---|
| **Acceptance** | 3 | 4 | 1 | 2 | 5 | 1-5 |
| **Cost** | 1.5 | 5 | 0.5 | 1 | 2 | $0.5 - $5.00 |
| **Security** | 1 | 0.8 | 0.3 | 0.6 | 0.5 | 0.3-1 |
| **Complexity** | 2 | 1 | 3 | 4 | 5 | 1-5 |
| **Sum** | **7.5** | **10.8** | **4.8** | **7.6** | **12.5** | **43.2** |
| **Normalized Score** | **20.66%** | **18.75%** | **22.22%** | **20.60%** | **17.77%** | **100%** |

Table 28. Evaluation based on range scores of Tag's authencity Techniques for Various Supply Chain Criterias

We transform the score value of each factor to have the same range value of 0 to 1. A formula based on the simple geometry of a line segment is used to linearly convert the score of each factor from table 28 to table 30 to a single shared range.

$$\textit{new score} = \frac{nub - nlb}{oub - olb}(\textit{original score} - olb) + nlb \tag{16}$$

Each factor has different importance weightings based on its organisation's priorities. Since the weighting is a subjective value, the result changes with changes to the factors' weightings. Table 29 displays an example of organisation 'A 'are weighting priorities in selecting their most appropriate tag authentication methodology.

| | Acceptance | Cost | Security | Complexity | Sum |
|---|---|---|---|---|---|
| **Importance Level** | 20 | 40 | 30 | 10 | 100 |
| **Importance Weight** | 20.0% | 40.0% | 30.0% | 10.0% | 100.0% |

Table 29. Supply Chain Criteria's Weight of Importance

Table 30 shows the end result of normalizing the weighting of each factor, demonstrating the opportunity for an organization to compare different based factors based on a normalised range where individual factors are weighed according to the organization's personal requirements and needs. We are able to demonstrate that, for a organisation 'A' that emphasizes cost factors over security factors, a lightweight ECC would be the most appropriate technique for securing their low cost tags. This result contraindicates the prediction that lightweight ECC might be the preferred way in the future for securing low cost tags. This prediction is based on the fact that lightweight ECC uses only 64K of RFID tag storage and provides strong authenticity comparable to that of any other lightweight public key infrastructure.

| Criterias \| Techniques | Weights | EPC Design | Tags Design | Light-weight Protocol | Lightweight ECC | Stegano-graphy | |
|---|---|---|---|---|---|---|---|
| **Acceptance** | 20.0% | -0.100 | -0.100 | -0.200 | -0.150 | 0.200 | |
| **Cost** | 40.0% | 0.011 | -0.067 | 0.033 | 0.022 | -0.033 | |
| **Security** | 30.0% | -0.071 | -0.043 | 0.029 | -0.014 | -0.029 | |
| **Complexity** | 10.0% | 0.150 | 0.200 | 0.100 | 0.050 | -0.200 | |
| **Sum** | **100.0%** | **-0.010** | **-0.010** | **-0.038** | **-0.092** | **-0.062** | **-0.212** |
| **Normalized Score** | | **4.9%** | **4.5%** | **18.0%** | **43.4%** | **0.292134831** | **100.0%** |

Table 30. Supply Chain Criteria's and Techniques Weighted scores

## 6. Applicability discussions

In this section, we analyze how well MCDM quantified costs associated with cloning and fraud attacks. In the first part we discuss on the MCDM quantified cost result for cloning attack. The second part discusses the cost results obtained for fraud attacks, and for SA tests and authentication exercises. Finally, we analyze the validity of using cost sensitive and cost insensitive models for costing purposes.

### 6.1 RFID Tag cloning attack

Based on the result obtained from the MCDM approach, a 'man in the middle' attack has the highest Damage Cost of all attacks. This shows that a high Damage Cost is not associated with highly complex attacks (e.g. 'physical' attacks) or with easy attacks (e.g. 'skimming' attacks), but with specific techniques used in and means of the attack taking place. Although unavailability and disclosure Damage associated with 'man in the middle' attacks has an high risk impact on the occurrence of future cloning and fraud attacks, simpler attacks have a much lower Response Cost.

A comparison of consequential costs (the summation of Damage and Response Costs) indicate that both 'eavesdropping' and MIM attacks have a higher consequential cost than other attacks. Time factors are used in the ranking system, correspondent to the level of complexity in detecting and responding to the attack, to calculate Operational Costs associated with an IDS handling a cloning or fraud attack. MCDM criteria include extracted test features from raw RFID streams. There are four different levels of extracting test features. Our results indicate that highest rank extracted test features are from an interconnected supply chain partner's organisation within an EPCglobal service, due to the difficulty in obtaining shared computing resources between different partners and establishing various EDI services among them.

Cumulative Cost calculations indicate the association of the highest cumulative Operational Costs with 'man in the middle' attacks and of the lowest costs with 'skimming' attacks. Based on this information, we conclude that 'man in the middle' cloning attacks cause the greatest overall losses in terms of money, time and computing resources. This result implies that measures to prevent 'man in the middle 'cloning attacks in a supply chain management is likely to minimise the impact of counterfeiting on an organisation.

The prevention measures that could be taken in eliminating MIM attacks include: 1) refresh the tag secret key immediately after a reader has been authenticated; 2) maintain tag output changes, as this minimises opportunities for replay attacks and the related risk of a faked tag; 3) keep the number of communication rounds and operation stages minimal to avoid redundant operations; maintain scalability and eliminate the risk of 'man in the middle; and 4) design the coordinating global item tracking server to include a timely tracking system that maintains freshness necessary due to the randomness of keys used in inter-organisational item-tracking activities.

### 6.2 RFID tag fraud, SA testing and authentication techniques

The main differences between fraud and cloning attacks in regards to the similar Damage; response; and Operational Cost types, are based on the criteria factors used in applying a MCDM tool to calculate these costs. Fraud attack costs are associated with the progress of the attack rather than with the type of attack that contributed to it. This is due to the fact that a fraud attack occurs only after a tag has successfully been cloned after one or more previous attacks. The progress of a fraud attack is closely associated with inconsistency of tag count, related to the travel of tags to unauthorised locations:; the need for a higher bandwidth for fraud detection in unauthorised locations; and inconsistencies between travel timeframes associated with illegal tags. Similar criteria factors are used to calculate costs associated with SA testing.

In a comparison of *CCost* for cloning and fraud attacks, the latter attack type has significantly lower associated *CCost*. This is due to the fact that fraud attacks are a part of cloning attack SA test costs are calculated using only Damage Cost, as SAs do not have malicious intentions towards the system and are able to use the system only after their system authentication, which is transparent during system audit procedures, classified as usage by a legal and authorised user.

Biometric authentication methods are the most secure and suitable method for use by supply chain partners in supply chain management, as indicated by the AHP tool. The SHA algorithm can be used to create a 'fingerprint' for the public key of this biometric application. Tag authentication methods that minimise storage needs and use minimal key bits are preferred, such as lightweight public cryptography (e.g. ECC and lightweight protocol).

### 6.3 Cost sensitive vs. Cost insensitive

We have extended the MCDM tool for evaluating *CCost* (Damage and Response Costs) calculations in our cost model. The aim for calculating both Damage and Response Costs is the evaluation the cost impact of a cost sensitive vs. that of a cost insensitive cost model. The difference between the cost impact of a cost sensitive and cost insensitive model is that a cost sensitive model initiates an SA alert only if $DCost \geq RCost$ and if it corresponds to the cost model. Cost insensitive methods, in contrast, respond to every predicted intrusion and are demonstrated by current brute-force approaches to intrusion detection.

Estimation of losses indicates that it could be reduced by up to 73% if a cost sensitive model is used in a system.

This impressive result is obtained using quantified cost for counterfeiting; and indicate that to optimally curb both cloning and fraud attacks, it is necessary to aim to minimise false negative in a system rather than to optimise accuracy of detection and elimination of false positives. The underlying principle for every business model should remain to minimise financial losses without compromising system security or product quality.

In addition our RFID cost model also included testing cost operated on the detector system by supply chain employee; the system administrator. The result display that testing cost only takes up less than 10% for every misclassifications cost reported. As the role of testing indicates the relevance of IDS and boost the accuracy of the dataset rules, the component of testing should never be compromised on the ground of losses in dollar.

The result also indicates the significance of calculating both misclassification and testing cost in any cost model.

## 7. Conclusions and future research

In this chapter, we have proposed cost-based approach using MCDM tool to quantify cost when curbing counterfeiting in RFID-enabled SCM. We have extended this tool to analyze the different authentication approaches, including for tag authentication, which can be used by system administrators. We have shown that the MCDM approach could be used for implementing a practical cost-sensitive model, as validated by our analytical results. We contend that the definitions of damage; response; and operational costs are complex, especially when applying theoretical attack criticality and progress attack in determining cloning and fraud costs. Our future work will focus on the implementation of our cost model and on development of robust RFID tag detectors for cloning and fraud attacks. We will use the cost model to estimate costs to predict total financial losses related to RFID tag cloning and fraud.

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## 9. References

S. Bono *et al.*: Security Analaysis of a Cryptographically-Enabled RFID Device. In P. McDaniel, ed., *USENIX Security '05*, pp. 1-16. 2005.

E.Y. Choi, D.H. Lee and J.I. Lim: Anti-cloning protocol suitable to EPCglobal Class-1 Generation-2 RFID systems, *Computer Standards and Interfaces* 31 (6) (2009), pp. 1124–1130.

L. Bolotnyy, G. Robins: Physically Unclonable Function-Based Security and Privacy in RFID Systems, percom, pp.211-220, *Fifth IEEE International Conference on Pervasive Computing and Communications (PerCom'07), 2007*

D.N. Duc, Park, J., Lee, H., Kim, K.: Enhancing Security of EPCglobal GEN-2 RFID Tag against Traceability and Cloning. In: *Symposium on Cryptography and Information Security, Hiroshima, Japan (January 17-20, 2006)*

T. Dimitriou., "A Lightweight RFID Protocol to protect against Traceability and Cloning attacks" in *Security and Privacy for Emerging Areas in Communications Networks, 2005.*

*SecureComm 2005. First International Conference on* (05-09 September 2005), pp. 59-66.

R. Derakhshan, M. E. Orlowska, and X. Li. (2007). RFID data management: Challenges and opportunities. In: D. W. Engels, *IEEE International Conference on RFID 2007. IEEE International Conference on RFID 2007, Grapevine, Texas, USA, (pp 175-182). 26-28 March, 2008*

W .Fan, Lee, W., Stolfo, S., Miller, M.: A multiple model cost sensitive approach for intrusion detection. In*: Proc. Eleventh European Conference of Machine Learning, Barcelona Spain, pp. 148–156 (2000)*

X.Gao Gao, Hao Wang, Jun Shen, Jian Huang, Song, "An Approach to Security and Privacy of RFID System FOR Supply Chain," Proceedings of the *IEEE International Conference on E-Commerce Technology for Dynamic E-Business (CEC-East'04), pp 164-168, 2004.*

P.T.Hacker: The art and science of decision making: The analytic hierarchy process. In: Golden, B.L., Wasil, E.A., Harker, P.T. (Eds.), *The Analytic Hierarchy Process: Applications and Studies. Springer, Berlin, pp. 3–36.*

A. Juels:RFID security and privacy: a research survey, *IEEE Journal on Selected Areas In Communications, VOL. 24, NO. 2, FEBRUARY 2006, vol. 24, pp. 381-394, 2006.*

A. Juels: Strengthening EPC Tags Against Cloning, (M. Jakobsson and R. Poovendran, eds.), *ACM Workshop on Wireless Security (WiSe), pp.67-76. 2005.*

S. Kutvonen: Trust management survey, Proccedings of iTrust 2005, number 3477 in *LNCS, pp 77--92 , Springer-Verlag.*

W.Lee , Fan, W., Miller, Matt, Stolfo, Sal, Zadok, E.: Toward cost sensitive modeling for intrusion detection and response. *J. Comput. Security 10, pp 5-22 (2002)*

W.Lee, Sal Stolfo and Kui Mok, A Data Mining Framework for Building Intrusion Detection Models. Proceedings of the *IEEE Symposium on Security and Privacy, Oakland, CA, pp. 120-132. 1999.*

M.Lehtonen, et.al: Trust and Security in RFID-Based Product Authentication System , *Systems Journal, IEEE, vol. 1, pp. 129-144, 2007.*

M.Lehtonen., Michahelles, F., Fleisch, E.: How to Detect Cloned Tags in a Reliable Way from Incomplete RFID Traces. *In 2009 IEEE International Conference on RFID, Orlando, Florida, April 27-28, 2009, pp. 257 - 264.*

X. Li, J. Liu, Q. Z. Sheng, S. Zeadally, and W. Zhong: TMS-RFID: Temporal Management of Large-Scale RFID Applications*, International Journal of Information Systems Frontiers, Springer, July 2009,*

C. Lin, V.Varadharajan .: A Hybrid Trust Model for Enhancing Security in Distributed Systems. *In: Proceedings of International conference on availability, reliability and security (ARES 2007), Vienna, pp. 35–42 (2007) ISBN 0-7695-2775-2*

C.Lin and V. Varadharajan: Trust Based Risk Management for Distributed System Security - A New Approach, in *Proceedings of the First International Conference on Availability, Reliability and Security*: IEEE Computer Society, pp 6-13 2006.

C.X Ling, V.S Sheng, Q. Yang, "Test Strategies for Cost-Sensitive Decision Trees," *IEEE Transactions on Knowledge and Data Engineering, pp. 1055-1067, August, 2006*

U. Lindqvist and E. Jonsson: How to systematically classify computer security intrusions, in *Proceedings of the IEEE Symposium on Research in Security and Privacy*, Oakland CA, May 1997.

M. Mahinderjit- Singh and X. Li , "Trust Framework for RFID Tracking in Supply Chain Management," Proc of *The 3rd International Workshop on RFID Technology – Concepts, Applications, Challenges (IWRT 2009), Milan, Italy, pp 17-26 , 6-7 May 2009*.

M. Mahinderjit- Singh and X. Li (2010): Trust in RFID-Enabled Supply-Chain Management, in International *Journal of Security and Networks (IJSN), 5, 2/3 (Mar. 2010), 96-105. DOI= http://dx.doi.org/10.1504/IJSN.2010.032208.*

M.2008, EPCglobal Certificate Profile [online]," Available http://www.epcglobalinc.org/standards/cert/cert_1_0_1-standard-20080514.pdf

L. Mirowski, & Hartnett, J.: Deckard: A system to detect change of RFID tag ownership. *International Journal of Computer Science and Network Security, 7(7), 89–98.*

P. Marcellin: Attacks from within can be worse than those from without [online], Available on: http://www.themanager.org/resources/Attacks_from_within.htm

K. Nohl, D. Evans, Starbug, and H. Pl¨otz: Reverse-engineering a cryptographic RFID tag, in *USENIX Security Symposium*, July 2008, pp. 185–194.

S. Northcutt. *Intrusion Detection: An Analyst's Handbook*, New Riders, 1999.

C. Pei-Te and L. Chi-Sung: IDSIC: an intrusion detection system with identification capability, *Int. J. Inf. Secur.*, vol. 7, pp. 185-197, 2008.

D.C. Ranasinghe, and M.G. Harrison, and Cole, P.H.: *EPC network architecture* In: Cole, P.H. and Ranasinghe, D.C., (eds.) *Networked RFID Systems and Lightweight Cryptography: Raising Barriers to Product Counterfeiting. Springer; 1 edition. pp. 59-78 ISBN 9783540716402*

T. Saaty: An exposition of the AHP in reply to the paper remarks on the analytic hierarchy process. Management Science 36 (3), 259–268.

G. G. Shulmeyer and J. M. Thomas: The Pareto principle applied to software quality assurance, in *Handbook of software quality assurance (3rd ed.)*: Prentice Hall PTR, 1999, pp. 291-328.

F. Tom and P. Foster: Adaptive Fraud Detection, *Data Min. Knowl. Discov.*, vol. 1, pp. 291-316, 1997.

P.Turney: Types of cost in inductive concept learning. In *Workshop on Cost-Sensitive Learning at ICML*. Stanford University, California; 2000:15-21.

VeriSign Inc: EPC Network Architecture , http://interval.hu- berlin.de/downloads/rfid/IT_Infrastruktur/013343.pdf (2004).

# 10

# Inventories, Financial Metrics, Profits, and Stock Returns in Supply Chain Management

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## 1. Introduction

This chapter studies the role of inventory in supply chain management and in its impact in the book value and market value of firms. We elaborate on the idea that inventory models can be useful for implementing inventory policies for the different stages of a supply chain. In section 2, the role of inventory in supply chain management is discussed. In section 3, we provide a discussion of existing inventory models that have been developed to model real systems.Many authors have proposed mathematical models that are easy to implement in practical situations. We provide a simple classification of these models based on stocking locations and type of demand.

In section 4, we address the empirical question of whether inventory level decisions should be focused on efficiency (i.e., minimum inventory levels) or on responsiveness (i.e., maximum product availability). To answer this, we analyze the US agribusiness (food) sector during 35 years. This sector weights about 10% of the complete US market, and has been chosen by the authors for two reasons. Inventory levels in agribusinesses could be considered more critical due to the highly perishable nature of food products, and because the sample includes firms considered as mature (Jensen (1988)). Mature firms are expected to have already fine tuned their inventory level positions. Using regression analysis, empirical results show that both, the growth in inventories[1] and capital expenditures in year *t*, negatively affect stock returns in *t+1* at 1% level of significance. Further, while property, plant and equipment represents 70% of total invested capital compared to inventories representing 30%, a 1% change in inventories has an economic impact similar to a 1% investment in capital expenditures. This emphasizes the economic importance of managing inventories.

## 2. The role of inventory in supply chain management

According to Chopra and Meindl (2007), inventory is recognized as one of the major drivers in a supply chain, along with facilities, transportation, information, sourcing, and pricing. In

[1] Inventories and inventory level are used interchangeably

this chapter we investigate the relationship between inventories and the value of firms (i.e., as measured by financial accounting metrics and stock prices returns). It turns out that the investment in inventory is an important component of Return of Invested Capital (ROIC) and of its corresponding weighted average cost of capital. We elaborate on those measurements, emphasizing their relationship with inventories, in section 4.

Inventory exists in the supply chain because there is a mismatch between supply and demand. In any supply chain there are at least three types of inventories: raw materials, work-in-process, and finished products. The amount of these types of inventories held at each stage in the supply chain is referred to as *the inventory level*. In general, there are three main reasons to hold inventory (Azadivar and Rangarajan (2008)):

1. Economies of scale: placing an order usually has a cost component that is independent of the ordered quantity. Therefore, a higher frequency of orders may increase the cost of setting up the order. This may even cause higher transportation costs because the cost of transportation per unit is often smaller for larger orders.
2. Uncertainties: as products are moved within the supply chain, there exists variability between the actual demand and the level of inventories being produced and distributed. Therefore, inventories help mitigate the impact of not holding sufficient inventory where and when this is needed.
3. Customer service levels: inventories act as a buffer between what is demanded and offered.

So, one of the main functions of maintaining inventory is to provide a smooth flow of product throughout the supply chain. However, even if all the processes could be arranged such that the flow could be kept moving smoothly with inventories, the variability involved with some of the processes would still create problems that holding inventories could resolve.

From the above reasons, it becomes clear that the level of inventory held at the different stages of the supply chain has a close relationship with a firm's competitive and supply chain strategies. For instance, inventory could increase the amount of demand available to customers or it could reduce cost by taking advantage of economies of scale that may arise during production and distribution. Moreover, we argue that the inventory held in a supply chain significantly affect the value of the firm, as it will be discussed in section 4.

### 2.1 Supply chain strategy

As we have discussed, determining inventory levels at the different stages of the supply chain is an important part of the supply chain strategy, which in turn, must be aligned with the firm competitive strategy. Fisher (1997) presents an interesting framework that helps managers understand the nature of the demand for their products and devise the supply chain strategy than can best satisfy that demand. This framework lays out a matrix that matches product characteristics as follows: between *functional products* (e.g., predictable demand, like commodities) and *innovative products* (e.g., unpredictable demand, like technology-based products); and supply chain characteristics: *efficient supply chains* (whose primary purpose is to supply predictable demand efficiently at the lowest possible cost) and *responsive supply chains* (whose primary purpose is to respond quickly to unpredictable demand in order to minimize stock-outs, forced markdowns, and obsolete inventory). This idea is illustrated in Figure 2.1.

From Fisher's framework it becomes clear that a supply chain cannot maximize cost efficiency and customer responsiveness simultaneously. This framework identifies a market-driven basis for strategic choices regarding the supply chain drivers. Therefore, as far as inventory, some questions arise as to whether inventory strategies should be focused on efficiency (minimizing inventory levels) or on responsiveness (maximizing product availability). This is the empirical question addressed in this chapter (section 4), but before that inventory systems and models are discussed in section 3.

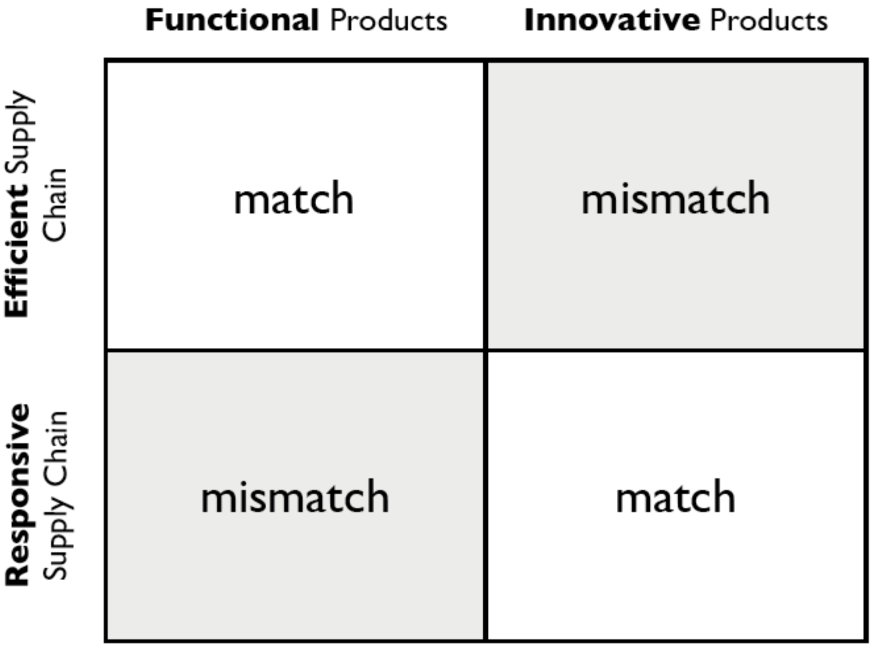


Fig. 2.1. Matching supply chain with products (adapted from Fisher (1997))

## 3. Design of the appropriate inventory systems in a supply chain

In designing an inventory system, there are two main decisions to make: how often and how much to order. The goal is to determine the appropriate size of the order without raising cost unnecessarily; otherwise the firm value might deteriorate.

A major criterion in determining the appropriate level of inventory at each stage in the supply chain is the cost of holding the inventory. In trying to avoid disruptions, this cost might exceed the potential loss due to shortage of goods. On the other hand, if lower levels are maintained in order to decrease the holding cost, this might result in more frequent ordering as well as losses of customer trust and losses due to disruptions in the supply chain. Thus, designing an inventory system to determine the appropriate level of inventory for each stage in the supply chain requires analyzing the trade-off between the cost of holding inventory and the cost of ordering (typically known as setup cost).

Azadivar and Rangarajan (2008) present an interesting discussion of factors in favor of higher and lower inventory levels. Some of their discussion is summarized in Figure 3.1.

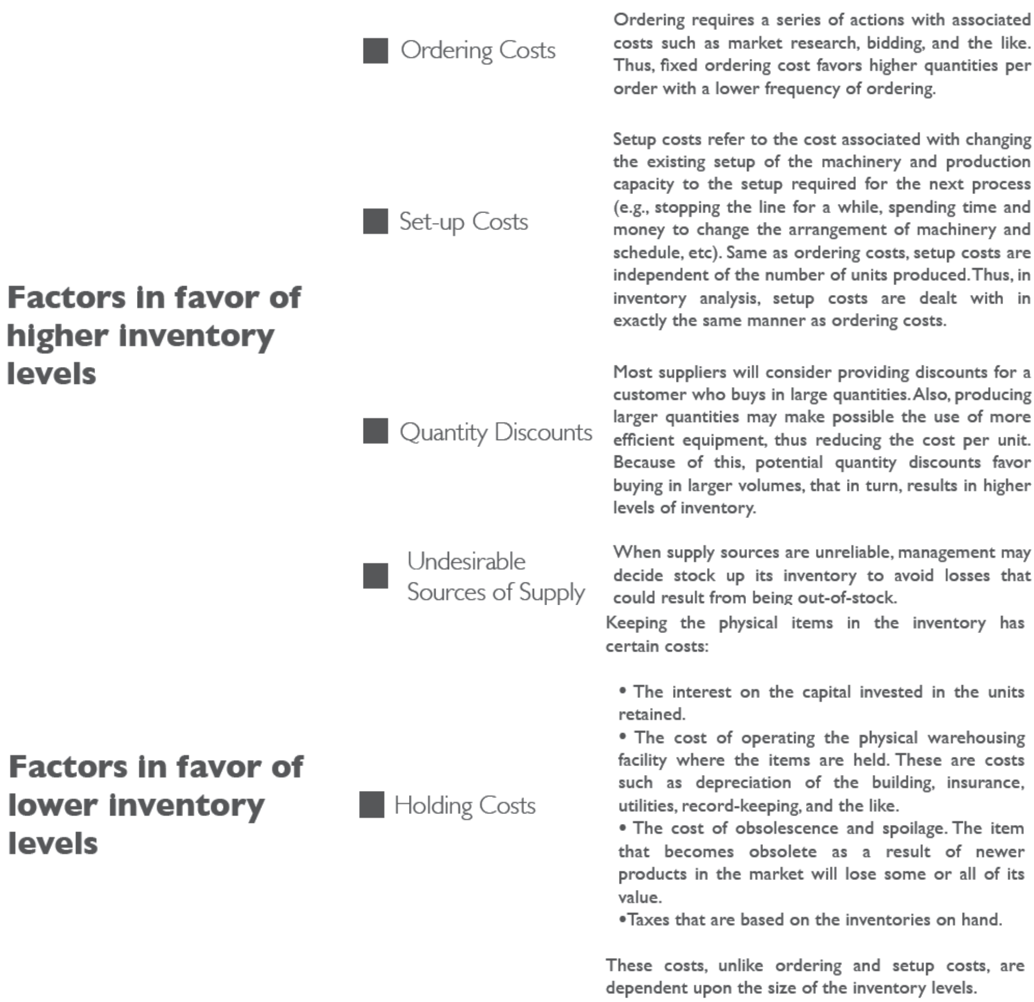


Fig. 3.1. Factors affecting the level of inventory (summarized from Azadivar and Rangarajan (2008))

### 3.1 A classification framework of inventory models

Inventory models are mathematical models of real systems and are used as a tool for calculating inventory policies for the different stages of a supply chain. Currently, small and medium companies seem to be characterized by the poor efforts they make optimizing their inventory management systems through inventory models. They are mainly concerned with satisfying customers' demand by any means and barely realize about the benefits of using scientific models for calculating optimal order quantities and reorder points, while minimizing inventory costs and increasing customer service levels. As far as large companies, some of them have developed stricter policies for controlling inventory. Though, most of these efforts are not supported by scientific (inventory) models either. Many authors have proposed mathematical models that are easy to implement in practical situations and can be used as a basis for developing inventory policies in real systems. This section presents a brief discussion of existing inventory models that have been developed to model real systems. We provide a simple classification of these models based on the following two criteria (a table summarizing the literature on inventory models is presented at the end of the section):

1. Stocking locations: this criterion refers to the number of stages used as a stocking location. That is, when inventory is held at only one stage, this system is referred to as a single-stage model. When more than one stage is considered as stocking location, these systems are called multi-echelon[2] inventory models (or supply chain inventory models).
2. Type of demand: this refers to customer demand. It may be deterministic or stochastic. The first is when the demand is fixed and known. In stochastic demand, uncertainties are considered and modeled using some known probability distribution.

### 3.1.1 Deterministic inventory systems

In this type of models it is assumed that the demand is fixed and known. The most fundamental of all inventory models is the so-called Economic Order Quantity (EOQ). EOQ was first introduced by Ford Whitman Harris in 1913, an engineer at Westinghouse Electric Co. (Harris (1990)), and is used to determine purchasing or production order quantities while considering the trade-off between fixed ordering and holding costs. The basic EOQ model assumes that the demand rate (demand per time unit) is constant, inventory shortages are not allowed, and replenishments leadtimes are constant.

Let us now explain how this system is designed. In inventory management, in addition to considering the purchasing unit cost of an item ($c$), managers must also consider the fixed cost of ordering (placing) an order and the cost of holding the inventory at the warehouse. The order cost ($k$), is the sum of all the fixed costs incurred every time an order is placed. This cost is also known as purchase or setup cost. According to Piasecki (2001), "these costs are not associated with the quantity ordered but primarily with physical activities required to process the order". The order cost comprises issues such as the cost for entering the order, approval steps, processing the receipt, vendor payment, time inspecting incoming products, time spent searching and selecting suppliers, phone calls, etc. The holding cost ($h$) represents the cost of having inventory on hand (e.g., investment and storage) and is calculated as follows,

$$h = I \times c \,, \tag{3.1}$$

where $c$ is the unit cost of the item and $I$ is an annual interest rate that usually includes: opportunity cost, insurances, taxes, storage costs, and spoilage, damage, obsolescence and theft risk costs.

As shown by Harris (1990), these costs significantly affect the order quantity decision ($Q$). For example, in order to take advantage of quantity discounts offered by some suppliers, companies tend to purchase large volumes each time they order. Nevertheless, while this approach may minimize the fixed cost of placing the order, it increases the cost of holding that amount of inventory. Therefore, it is important to study the trade-off between these costs. Figure 3.2 illustrates this concept.

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[2] Hillier and Lieberman (2010) define an echelon of an inventory system as "each stage at which inventory is held in the progression through a multi-stage inventory system".

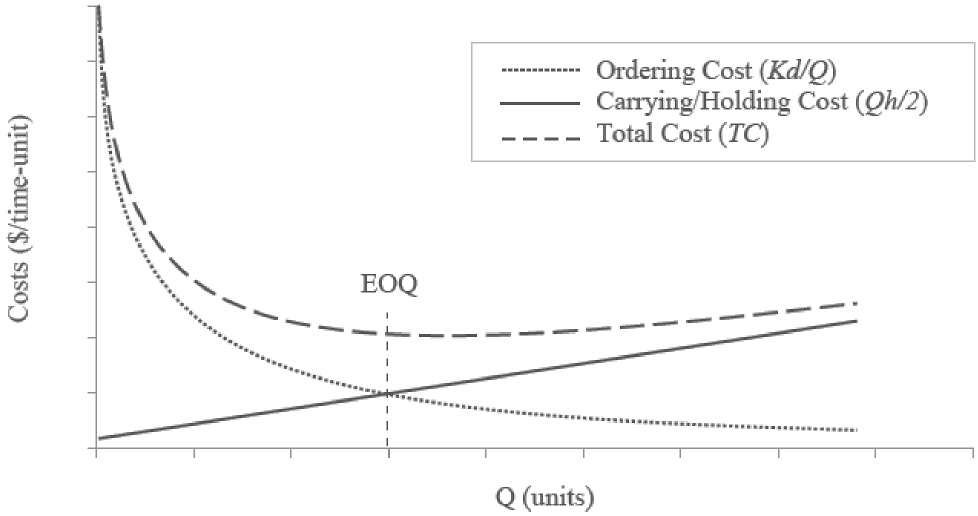


Fig. 3.2. The inventory costs tradeoff

From Figure 3.2, the total cost per time unit is the sum of the ordering and the holding costs. The ordering cost per time unit is calculated as the product between the ordering cost ($k$) and the number of orders placed in a time unit ($d/Q$), where $d$ represents the demand per time unit The holding cost per time unit is computed as the product between the average inventory level ($Q/2$) and the holding cost ($h$). The objective is to minimize the Total Cost per time unit ($TC$),

$$TC(Q) = \frac{kd}{Q} + \frac{hQ}{2}. \tag{3.2}$$

It can easily been shown that the order quantity that minimizes the total cost per time unit is the minimum value of the $TC$ function. That is, the point at which the tangent or slope of the curve is zero. The optimum order quantity ($Q^*$) is then given by,

$$Q^* = \sqrt{\frac{2kd}{h}}\ , \tag{3.3}$$

and, since the demand rate is constant, the time between orders (e.g., how often an order of size $Q$ is to be placed) can be calculated as follows,

$$T^* = \frac{Q^*}{d}. \tag{3.4}$$

An important characteristic of the EOQ formula is its robustness [3] (Silver, Pyke and Peterson (1998)). Observe from Figure 3.2 that the total cost curve is significantly flat in the region

[3] Robustness refers to the insensitiveness of the EOQ to errors in the input parameters

surrounding the EOQ. This implies that a reasonable positive or negative deviation from the optimal quantity does not have a big impact on the total cost per time unit. Due to this, it is safe to assume that the EOQ is very insensitive to misestimates on the input parameters. Additionally, the EOQ represents a good starting solution for more complex models (Nahmias (2001)). This is why the EOQ represents a simple, yet effective way of determining an inventory policy. Moreover, although the basic EOQ model assumes a deterministic demand, some authors have shown that using it in stochastic environments, instead of more sophisticated approaches, does not result in a considerable increase in the cost of policies. Zheng (1992) demonstrates that the maximum relative error bound is 12.5%. Furthermore, Axsäter (1996) states that the increase is no more than 11.80%. Considering the cost and time required to develop inventory policies with more complex methodologies and software, we found that it is perfectly justified to take advantage of the simplicity of the deterministic EOQ formula even in stochastic situations.

Extensions to the basic EOQ include the consideration of shortage costs, inclusion of quantity discounts, and the extension to the case of finite production rate. The reader is referred to Chopra and Meindl (2007), Nahmias (2001), Hillier and Lieberman ( 2010), and Silver, Pyke and Peterson (1998) for more detailed texts on these extensions. Finally, the EOQ has been applied successfully by some companies. For instance, Presto Tools, at Sheffield, UK, obtained a 54% annual reduction in their inventory levels (Liu and Ridgway (1995)).

*Leadtime and Reorder Point*

Another important parameter to consider when designing an inventory system is the so-called leadtime. Since orders are not received at the time they are placed, the time between when an order is placed and the time when is received is called leadtime. If a company waits until the inventory is completely depleted, the inventory will be out of stock during the leadtime. Therefore, orders need to be placed before the inventory level reaches zero. In order to overcome this situation, the order is placed whenever the inventory level reaches a level called the reorder point. In deterministic inventory models (e.g., EOQ), it is assumed that the leadtime is constant and known. In stochastic inventory systems, the leadtime could be a random variable (this will be discussed in section 3.1.2). According to Azadivar and Rangarajan (2008), two methods can be used to determine when an order should be placed: (1) the time at which the inventory will reach zero is estimated and the order is placed a number of periods equal to the leadtime earlier than the estimated time; (2) the second approach is based on the level of inventory. In this approach, the order is placed whenever the inventory level reaches a level called the reorder point (ROP). This means that if the order is placed when the amount left in the inventory is equal to the reorder point, the inventory on hand will last until the new order arrives. Thus the reorder point is that quantity sufficient to supply the demand during the leadtime. If we assume that both the leadtime ($L$) and the demand are constant, the demand during the leadtime is constant too, and the ROP can be calculated as follows:

$$ROP = L \times d \; . \tag{3.5}$$

This concept is illustrated in Figure 3.3.

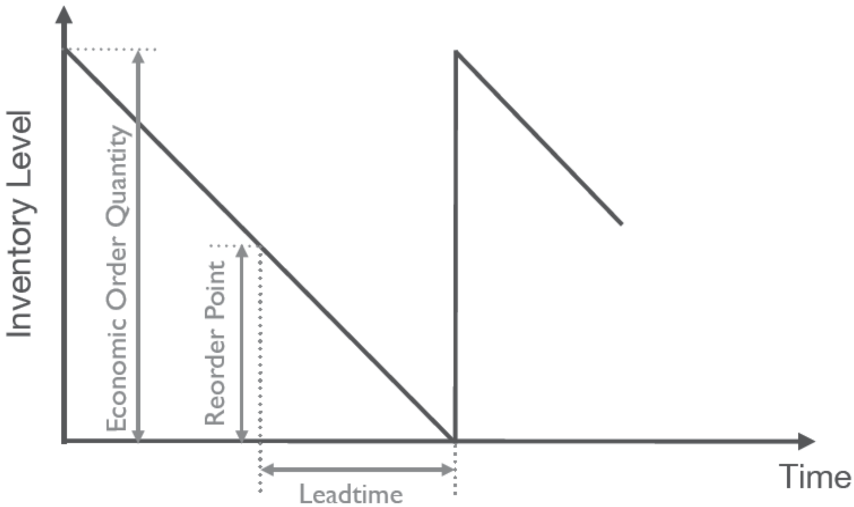


Fig. 3.3. Graphical representation of the reorder point and leadtime

### 3.1.2 Stochastic inventory systems

In section 3.1.1, it was assumed that the demand rate is constant and known. Also, it was assumed that the quantity ordered would arrive exactly when expected. These assumptions eliminated uncertainties and allowed simple solutions for designing inventory systems. In this section, we now study the case when uncertainties are present in modeling the inventory system, as in most real situations. For instance, if new orders do not arrive by the

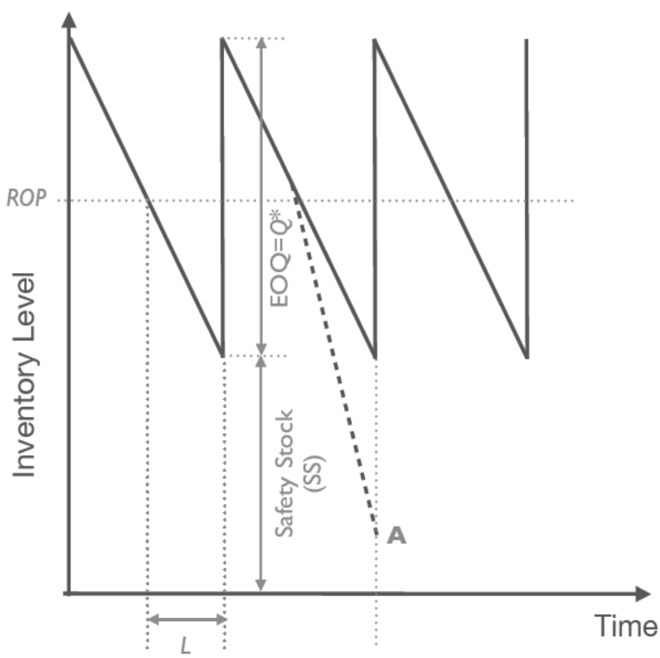


Fig. 3.4. Illustration of the concept of SS

time the last unit in the inventory is used up, then the company will be short for the next person demanding units from inventory (this is called stockout). And, if customers are not willing to wait for the next order arrival, this will cause loss of goodwill, and therefore loss of profit. Stockouts occur whenever the leadtime exceeds the reorder point. In order to overcome this situation, companies need to design inventory systems so they carry sufficient inventory to satisfy demand when the forecast has been exceeded due to system variability. The amount of inventory carried for these situations is called safety stock (SS). Chopra and Meindl (2007) formally define the SS as the "inventory carried to satisfy demand that exceeds the amount forecasted for a given period". Figure 3.4 illustrates the SS concept.

As shown in Figure 3.4, when the ordered units ($Q^*$) arrive, there are still a number of units left in inventory (equivalent to *SS*). Point **A** indicates the possible variation of demand. Observe that even if demand changes (as in the dotted line ending in point A), the SS would still act as a buffer to maintain sufficient inventory to satisfy possible demands.

The appropriate level of *SS* is determined by two factors: (1) uncertainty of both demand and supply (e.g., leadtime). In this case, a company is exposed to uncertainty of demand during the leadtime. Thus, in designing inventory models for this situation, one must estimate the uncertainty of demand during the leadtime; and (2) the desired level of product availability. Product availability is generally measured in two ways: product fill rate and service level. Product fill rate is the fraction of product demand that is satisfied from product in inventory. This is equivalent to the probability that product demand is supplied from available inventory. Service level is the desired probability of not having stockouts during the leadtime.

Notice that when the SS is considered, the ROP is calculating as follows:

$$ROP = Ld + SS \,. \tag{3.6}$$

Unlike Eq. (3.5), the *SS* term is added to account for the variability in the system, as explained before. As the factor directly affecting our decision is the reorder point rather than the safety stock, we usually determine the best reorder point before finding the *SS*. Additionally, since stochastic behavior is considered, the *SS* could be better defined as:

$$SS = ROP - \text{Expected value of demand during the leadtime.} \tag{3.7}$$

That is, one way of dealing with uncertain demand is to increase the reorder point to provide some safety stock if higher-than-average demands occur during the leadtime. So, to deal with uncertainties in a stochastic system, we would need to characterize the stochastic behavior of the system. In particular, we are interested in knowing the probability distribution of demand during the leadtime. The problem is that this is not an easy task. For example, if the probability density function of demand per day is denoted as $f(x)$, the density function for demand during the leadtime of $n$ days is not always a simple function of $f(x)$(Azadavir and Rangarajan (2008)). In order to illustrate the logic for calculating the SS, in this chapter, we present a case when a normal probability distribution provides a good approximation of the demand during the leadtime. The reader is referred to Azadivar and Rangarajan (2008) and Silver, Pyke and Peterson (1998) for the analysis of more complex stochastic systems.

*Continuous Review Model*

There are several review schemes that integrate a variable demand, such as the Continuous Review Model and the Periodic Review Model. In the Continuous Review Model or ($Q$, $R$)

model, an order of $Q$ units is placed when the reorder point ($ROP$) is reached. When a normal probability distribution provides a good approximation of the demand during the lead time, the general expression for the reorder point is as follows,

$$ROP = \mu_{LTD} + z \cdot \sigma_{LTD} \,, \tag{3.8}$$

where $\mu_{LTD}$ is the average demand during the leadtime, $\sigma_{LTD}$ is the standard deviation of the demand during the leadtime and $z$ is the number of standard deviations necessary to achieve the acceptable service level (the probability of not having stockout during leadtime). Notice that $z{\cdot}\sigma_{LTD}$ represents the safety stock.
The terms $\mu_{LTD}$ and $\sigma_{LTD}$ are obtained, respectively, as follows:

$$\mu_{LTD} = \mu_t L \,, \tag{3.9}$$

$$\sigma_{LTD} = \sigma_t \sqrt{L} \,, \tag{3.10}$$

where $\mu_t$ is the average demand on a time $t$ basis, $\sigma_t$ is the standard deviation of the demand during $t$ and $L$ is the supply leadtime.
Notice that the determination of the reorder point is based on the so-called Inventory Position ($IP$). The $IP$ provides an accurate value of the actual inventory position of a product and is calculated as follows,

$$IP = OH + SR - BO, \tag{3.11}$$

where $SR$ represents scheduled receipts (units already ordered and pipe-line inventory), $BO$ refers to back-orders and $OH$ to the actual inventory on-hand. If the control system only considers the on-hand inventory, every unit below the reorder point will trigger a purchasing order of $Q^*$ units, an undesirable and counterproductive situation (as it increases holding costs unnecessarily).

### 3.1.3 Multi-stage inventory systems

The focus of sections 3.1.1 and 3.1.2 was on single-stage models. These types of models have provided a strong foundation for subsequent analyses of multi-stage systems. However, one may ask what happens if the manufacturer is out of the stock and the rest of the supply chain relies on this manufacturer to offer finished products to its customers. Then, we see the need to extend those basic results already studied for single-stage systems to the entire supply chain. Thus, this section focuses on analyzing inventory models at multiple locations. These types of models are referred to as supply chain inventory management models or as multi-echelon inventory models, in the research literature. Figure 3.5 shows a general multi-echelon network.
One of the core challenges of managing inventory at multiple locations, as one may see in Figure 3.5, is the dependency between the different stages of the supply chain. These dependencies make the coordination of inventory difficult. The analysis of the research in this area, presented next, provides some models for different supply chain configurations.

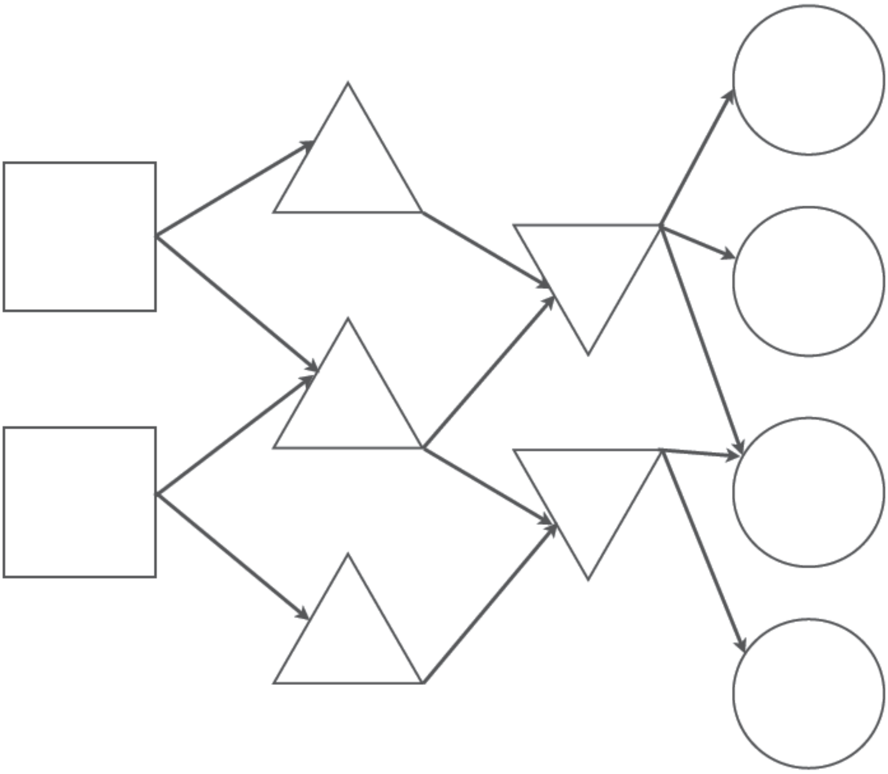

Fig. 3.5. A general multi-echelon network (extracted from Azadivar and Rangarajan, 2008).

The first inventory policies for multi-stage systems were presented by Clark and Scarf (1960) and Hadley and Whitin (1963). Determination of optimal inventory policies for multi-stage inventory systems is made difficult by the complex interaction between different levels, even in the cases where demand is deterministic. Given this, several researchers have developed different approaches to find effective solutions to these problems. Schwarz (1973) concentrated on a class of policies called the basic policy and showed that the optimal policy can be found in a set of basic policies. He proposed a heuristic solution to solve the general one-warehouse multi-retailer problem. Rangarajan and Ravindran (2005) introduced a base period policy for a decentralized supply chain. This policy states that every retailer orders in integer multiples of some base period, which is arbitrarily set by the warehouse. Recently, Natarajan (2007) proposed a modified base period policy for the one warehouse, multi-retailer system. He formulated the system as a multi-criteria problem and considered transportation costs between the echelons.

Roundy (1985) introduced the so-called power-of-two policies. He presented a 98% effective power-of-two policy for a one-warehouse, multi-retailer inventory system with constant demand rate. In this class of policies, the time between consecutive orders at each facility is a power-of-two of some base period. Several researchers have used the power-of-two policies for multi-stage inventory systems that do not incorporate supplier selection. These policies have proven to be useful in supply chain management since they are computationally efficient and easy to implement. Maxwell and Muckstadt (1985) developed a power-of-two policy for a production-distribution system. Roundy (1986) extended his original 98% effective policy to a general multi-product, multi-stage production/inventory system where a serial system is a special case. Federgruen and Zheng (1995) introduced algorithms for finding optimal power-of-two policies for production/distribution systems with general joint setup cost. For the stochastic cases, Chen and Zheng (1994) presented lower bounds for the serial, assembly, and one-warehouse multi-retailer systems.

For the serial inventory system, Schwarz and Schrage (1975) and Love (1972) proved that an optimal policy must be nested and follow the zero-ordering inventory policy. A policy is nested provided that if a stage orders at any given time, every downstream stage must order at this time as well. The zero-ordering inventory policy refers to the case when orders only occur at an inventory level of zero. Muckstadt and Roundy (1993) developed a power-of-two policy for a serial assembly system and proved that such a policy cannot exceed the cost of any other policy by more than 2% for a variable base period. They introduced an algorithm to solve the problem along with the corresponding analysis of the worst-case behavior. Sun and Atkins (1995) presented a power-of-two policy for a serial system that includes backlogging. They reduced the problem with backlogging to an equivalent one without backlogging and used Muckstadt and Roundy's algorithm to solve this transformed problem. For serial systems with stochastic demand, an echelon-stock $(R,nQ)$ policy for compound Poisson demand was introduced by Chen and Zheng (1998).

Most recently, Rieksts, Ventura, Herer and Daning (2007) developed power-of-two policies for a serial inventory system with a constant demand rate and incremental quantity discounts at the most upstream stage. They provided a 94% effective policy for a fixed base planning period and a 98% effective policy for a variable base planning period. Mendoza and Ventura (2010) presented a mathematical model for a serial system. This model determines an optimal inventory policy that coordinates the transfer of items between consecutive stages of the system while properly allocating orders to selected suppliers in stage 1. In addition, a lower bound on the minimum total cost per time unit is obtained and a 98% effective power-of-two (POT) inventory policy is derived for the system under consideration. This POT algorithm is advantageous since it is simple to compute and yields near optimal solutions.

Some authors have considered multi-criteria approaches to multi-stage inventory systems. Thirumalai (2001) modeled a supply chain system with three companies arranged in series. He studied the cases of deterministic and stochastic demands and developed an optimization algorithm to help companies achieve supply chain efficiency. DiFillipo (2003) extended the one-warehouse multi-retailer system using a multi-criteria approach that explicitly considered freight rate continuous functions to emulate actual freight rates for both centralized and decentralized cases. Natarajan (2007) studied the one-warehouse multi-retailer system under decentralized control. The multiple criteria models are solved to generate several efficient solutions and the value path method is used to display tradeoffs associated with the efficient solutions to the decision maker of each location in the system.

Finally, Table 3.1 provides a simple classification of the inventory models discussed in this chapter. Notice that this table is not intended to cover the vast literature on inventory models, and it is rather presented to summarize the literature discussed in this chapter.

| Author(s) | Stocking Locations | | Type of Demand | |
|---|---|---|---|---|
| | Single | Multiple | Deterministic | Stochastic |
| Axsäter (1996) | X | | | X |
| Chen and Zheng (1994) | | X | | X |
| Chen and Zheng (1998) | | X | | X |
| Clark and Scarf (1960) | | X | X | |
| Federgruen and Zheng (1995) | | X | X | |
| Harris (1990) | X | | X | |
| Love (1972) | | X | X | |
| Maxwell and Muckstadt (1985) | | X | X | |
| Ventura and Mendoza (2009) | X | | X | |
| Mendoza and Ventura (2010) | | X | X | |
| Muckstadt and Roundy (1993) | | X | X | |
| Natarajan (2007) | | X | X | X |
| Rangarajan and Ravindran (2005) | | X | | X |
| Rieksts et al. (2007) | | X | X | |
| Roundy (1985) | | X | X | |
| Roundy (1986) | | X | X | |
| Schwarz (1973) | | X | X | |
| Schwarz and Schrage (1975) | | X | X | |
| Sun and Atkins (1995) | | X | X | |
| Thirumalai (2001) | | X | X | X |
| Zheng (1992) | X | | X | X |

Table 3.1. Summary of inventory models

### 3.2 Inventory management in practice

The models presented before may seem to be unrealistic for practical purposes. Regarding this, Azadivar and Rangarajan (2008) stated: "One may wonder, given the many simplifications made in developing inventory management models, if the models are of value in practice. The short answer is a resounding "Yes"! ". Although all models are not applicable in all situations, the models presented in the preceding sections have served as a basis for developing models for practical situations with excellent results. Table 3.2 summarizes some examples of inventory management applications in practice.

Most of the inventory models presented earlier may be easily implemented using spreadsheets. The information typically comes from an enterprise resource planning systems (ERP) and companies must be able to develop frameworks that allow proper use of that information when it comes to develop inventory management systems. Additionally, there are some other inventory management (and optimization) software available, independent of the ERP systems. Some of these have been developed by: i2 Technologies, Manhattan Associates, SAP and Oracle.

The preceding sections emphasize the relevance of inventory in supply chain management. However, there are other factors impacting supply chain management not covered in this chapter. For instance, with the advent of global supply chains, the location of facilities and transportation modes can have a significant impact on inventory levels and it is recommended that these factors should be taken into consideration when optimizing

| Reference | Company | Comments |
|---|---|---|
| Lee and Billington (1995) | HP | • Goal: Inventory Management in decentralized SC for HP Printers<br>• Inventory reduction of 10%-30% |
| Lin, Ettl, Buckley, Bagchi, Yao, Naccarato, Allan, Kim and Koening (2000) | IBM | • Goal: Decision support system (DSS) for global SC (inventory) management<br>• Approx. $750 million in inventory and markdown reductions |
| Koschat, Berk, Blatt, Kunz, LePore and Blyakher (2003) | Time Warner | • Goal: Optimize printing orders and distribution of magazines in three stage SC<br>• Solutions based on the newsvendor model<br>• $3.5 million increase in annual profits |
| Kapuscinski, Zhang, Carbonneau, Moore and Reeves (2004) | Dell Inc. | • Goal: Identify inventory drivers in SC for better inventory management at Dell DCs<br>• Expected savings of about $43 million; 67% increase in inventory turns; improved customer service |
| Bangash, Bollapragada, Klein, Raman, Shulman and Smith (2004) | Lucent Technologies | • Goal: DSS tool for inventory management of multiple products<br>• Solution based on (s, S) policies<br>• $55 million in inventory reductions; fill rates increased by 30% |
| Bixby, Downs and Self (2006) | Swift & Co. | • Goal: Production management at beef products facilities; DCC tool for sales<br>• Solution adapts production plans based on inventories and customer orders dynamically<br>• $12.74 million in annual savings; better sales force utilization |

Table 3.2. Examples of inventory management applications (extracted from Azadivar and Rangarajan, 2008)

inventory levels in the SC. For an overview of the issues in transportation and inventory management, see Natarajan (2007) and Mendoza and Ventura (2009). Finally, there is an increasing concern about risks involved in the supply chain. Some of these risks are: disruptions during the transfer of products due to uncontrollable events, uncertain supply yields, uncertain supply lead times, etc. Incorporating these factors is fundamental for companies to be able to develop alternative supply strategies in case of disruptions. Rangarajan and Guide (2006) and Tang (2006) discuss some challenges presented by supply chain disruptions and review the relevant literature in this area.

## 4. Inventory and the value of the firm

The empirical question of whether inventory level decisions should be focused on efficiency (i.e., minimum inventory levels) or on responsiveness (i.e., maximum product availability) remains. High inventory levels increases the responsiveness of the supply chain but

decreases its cost efficiency because of the holding cost. Inversely, if inventory levels are too low, shortages may occur resulting in customer dissatisfaction and potential loss of sales. To explore this problem, in this section we elaborate on the relationship between inventory and the value of firms as measured by financial accounting metrics and stock prices returns.
The accounting value[4] of a firm could be proxy by total Invested Capital at a given point in time. Invested Capital (*IC*) is defined as,

$$IC = E + D - C, \tag{4.1}$$

where *E* is equity, *D* is total debt or liabilities with financial cost, and *C* is cash and short-term investments. *D* minus *C* is known in finance as *net* debt.
Given the basic accounting equation (assets equals liability plus equity), as Figure 4.1. illustrates, *IC* is equivalent to assets *minus* liabilities without cost (suppliers included) *minus* cash and short-term investments. Or simply, *IC* is

$$IC = AR + INV - AP + PP\&E + OA - OL, \tag{4.2}$$

where *AR* is accounts receivable, *INV* is inventories, *AP* is accounts payable, *PP&E* is net[5] property, plant, and equipment, *OA* is other assets, and *OL* is other liabilities without financial cost. Assuming *OA* equals *OL*[6], *IC* is reduced to *AR+INV-AP+PP&E*. *AR+INV-AP* is known as net operating working capital (*NOWC*). Thus, in its simplest expression, *IC,* the book value of a firm equals *NOWC* + *PP&E*.

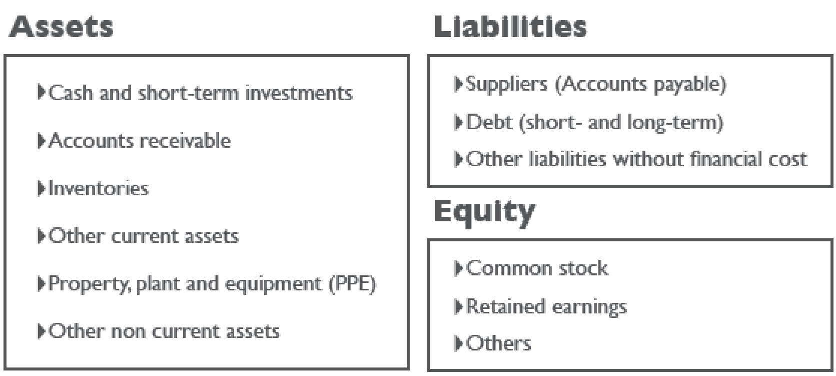


Fig. 4.1. A simplified balance sheet

Table 4.1 provides statistics for *IC* and its main components for American firms in the food sector (i.e., agribusinesses) categorized following a 3-digit SIC code classification as in Trejo-Pech, Weldon and House (2008) and Trejo-Pech, Weldon, House and Gunderson (2009). Table 4.1 comprises 35 years of financial results reported by all US agribusiness firms. This sector weights about 10% of the complete US market in terms of market capitalization, and has been chosen by the authors for two reasons. Inventory levels in agribusinesses could be considered more critical due to the highly perishable nature of food products, and because

[4] Book value and accounting value are term used interchangeably in the research literature and by practitioners
[5] Net of accumulated depreciation
[6] This is not a strong assumption considering that the absolute values of these items in the balance sheet of an average firm are not materially - relevant relative to total assets

the sample includes firms considered as mature (i.e., food processing and beverage firms) as per Jensen (1986). Mature firms are expected to have already fine tuned their inventory level positions. Table 4.1 shows *AR*, *INV*, and *AP*, and their corresponding changes (e.g., *ΔAR* is *AR* in time *t* minus *AR* in *t-1*), all scaled by *IC*. *PP&E* divided by *IC* and the corresponding *ΔPP&E/IC* are also presented in the table. The change in gross *PP&E* is commonly known as *CAPEX* or capital expenditures.

| | Mean | Std. Dev. | CV |
|---|---|---|---|
| AR/IC | 19.15% | 37.82% | 1.97 |
| INV/IC | 30.75% | 46.80% | 1.52 |
| AP/IC | 19.84% | 92.59% | 4.67 |
| ΔAR/IC | 1.33% | 22.07% | 16.62 |
| ΔINV/IC | 2.41% | 24.64% | 10.21 |
| ΔAP/IC | 1.70% | 27.70% | 16.26 |
| PP&Enet/IC | 70.54% | 59.45% | 0.84 |
| CAPEX/IC | 16.23% | 21.09% | 1.30 |

**Notes:** The sample includes all firms listed on the New York stock Exchange, American Stock Exchange, and NASDAQ from **1970 to 2004** with available data in both the Center for Research in Security Prices (CRSP) from the University of Chicago and S&P's Compustat (COMPUSTAT) data bases (total 8,553 agribusiness/year observations). Accounts receivable (*AR*), is COMPUSTAT item 2; Inventories (INV) is COMPUSTAT item 3; Accounts payable (AP) is COMPUSTAT item 70; PP&Enet (net of accumulated depreciation) is COMPUSTAT item 8; CAPEX is COMPUSTAT item 30. All variables are deflated by Invested Capital, defined as in equation 4.1, where debt is long term debt, COMPUSTAT item 9, short-term debt is COMPUSTAT item 34, and cash is COMPUSTAT item 1. The food sector is categorized following a 3-digit SIC code classification. The sector comprises the following industries: bakery (SIC 205); beverages (SIC 208); canned, frozen, and preserved fruits, vegetables (SIC 203); dairy (SIC 202); fats and oils (SIC 207); grain mill (SIC 204); meat (SIC 201); miscellaneous food preparations and kindred (SIC 209); sugar and confectionery (SIC 206); tobacco (SIC 21); food service (SIC 5810 and 5812); retailers (SIC 5400 and 5411); and wholesalers (SIC 5140, 5141, and 5180). **CV** is coefficient of variation.

Table 4.1. Main invested capital components for US food supply chain for the 1970/2004 period

Notice that *NOWC* represents almost one third (30.06%) of *IC* (the value of firms), with inventory being the most important component, 30.75% of *IC* (*AR* and *AP* are practically cancelled out). The remaining 70% is represented by *PP&E.* While *PP&E* represents the highest portion of the book value of agribusiness, its variability, measured by the coefficient of variation (CV), across all agribusiness is the lowest among of all other *IC* components (i.e., 0.84 compared to 1.97, 1.52, and 4.67).

Results in Table 4.1 also show that the change (values on time *t* minus values on *t-1*) of inventory levels is the most relevant among all *NOWC* components, meaning that agribusinesses find more difficult to stabilize their inventories growth in comparison to the growth of *AR* and *AP*. Most importantly, while agribusinesses grow *PP&E* relative to *IC* at a higher rate compared to *NOWC* components (*CAPEX*, 16.23%), *CAPEX* presents very low variability across all agribusinesses in the sample (1.3 CV for *CAPEX* compared to 10.21 for change in inventories).

Thus, inventory is the most important component of *NOWC*, representing one third of the book value of agribusinesses. The other 70% book value of the firm, represented by *PP&E*

has the lowest variability among all *IC* components across agribusinesses. Inventory also changes at the highest rate among all other two *NOWC* components. We will further address the importance of changes in these variables in section 4.1.

*Profitability*

Accounting operating profitability is commonly measured by the financial metric known among practitioners as *NOPAT* (net operating profits after taxes *but before interest*). Some authors call this metric *NOPLAT* (net operating profits less adjusted taxes), and others call it simply *EBIAT* (earnings before interest and after taxes) (Baldwing (2002)). *NOPAT* is estimated as,

$$NOPAT = EBIT \quad x \;\; (1\text{-}Tr), \tag{4.3}$$

where *EBIT* is earning before interest and taxes and *Tr* is the effective income tax rate (i.e., income taxes divided by earnings before income taxes). The exclusion of interest from *NOPAT* allows us to use this proxy as one free of financial costs, or more simply as pure *operating* in nature. How do inventories affect *NOPAT*? At least in two ways: first, the cost of inventories, which might be a function of inventory levels is embedded in the cost of goods sold, and hence, in *EBIT*. Second, obsolete inventory expenses and provisions might also be considered a function of inventory levels and affect *EBIT* as well.

For convenience, *NOPAT* is divided by *IC* to obtain the metric known as Return on Invested Capital (*ROIC*).[7] Thus,

$$ROIC = \frac{NOPAT}{IC}\,. \tag{4.4}$$

*ROIC* provides managers with a metric in percentage terms, on an annual basis, which is very convenient for decision making. *ROIC* measures the operating benefits of a firm relative to the amount of invested capital, with the refinement that *IC* contains only items with financial costs (refer to equations 4.1 and 4.2). This refinement is very important, and makes *ROIC* superior for decision making purposes to other very common profitability metrics such as *ROE* (return on equity), *ROA* (return on total assets), and so on. We elaborate more on this idea below.

The financial cost of a firm, hence of *IC*, comes from two sources, the cost of debt and the cost of equity. It turns out that the financial cost of *IC*, in percentage terms and on an annual basis, is the well known Weighted Average Cost of Capital or better known among financial practitioners as *WACC*, estimated as,

$$WACC = rd \times wd \times (1 - T_r) + re \times we\,, \tag{4.5}$$

where *rd* is the cost of net debt, *wd* is the weight of net debt relative to total net debt plus equity, *re* is the opportunity cost of equity, and *we* is the weight of equity relative to total net debt plus equity. *re* is usually estimated by using an asset pricing model, such as the Capital Asset Pricing Model (CAPM) by Sharpe (1964); the 3-Factors model by Fama and French

[7] Other names for ROIC, commonly used are ROI (return of investment) and ROCE (Return of capital employed)

(1993), and Fama and French (1992); the 4-Factors model incorporating the momentum factor by Carhart (1997), among others. While practitioners commonly use CAPM (Bruner, Eades, Harris and Higgins (1998)), researchers are more comfortable with a multifactor asset pricing model. According to CAPM, the opportunity cost of equity, *re*, depends upon the systematic risk of the firm, which is measured by the "market beta". The market beta is the coefficient of a simple OLS regression of excess firm stock returns (*re*) over a risk free rate security ($r_f$), as the dependent variable, and the excess returns of a diversified portfolio (the market) over $r_f$. Equivalently, the market beta for firm *i* is estimated by dividing the covariance of firm returns ($r_i$) and market returns ($r_m$), $COV_{ri,rm}$, by the variance of market returns, $VAR_{rm}$. Thus,

$$\beta_i = \frac{COV_{ri,rm}}{VAR_{rm}} . \tag{4.6}$$

Then, as the opportunity cost of equity, *re*, depends upon risk expectations captured by $\beta$, CAPM assumes that *re* should be equal to the risk free rate ($r_f$) offered by a security issued by the government plus a market premium, which equals the market return in excess over the risk free security, $r_m$-$r_f$, multiplied for the firm's beta. This is expressed as,

$$r_e = r_f + \beta_i \times (r_m - r_f) . \tag{4.7}$$

Notice that the financial cost of *net* debt [defined as total debt minus cash and short term investment (the two terms at the end of equation 4.1)] equals net interest paid by firms, precisely the item excluded in the estimation of *NOPAT*. The financial cost of equity, on the other hand, is not included on the calculation of profits in the official income statements. Thus, by estimating *NOPAT* managers have an operating performance metric free of financial costs. Further, by equation 4.4, profitability is scaled by *IC*, the same investment base used to estimate *WACC*.

Hence, it then makes sense to compare *ROIC* and *WACC* since one represents the operating benefits and the other represents the cost over the same investment base, *IC*.[8] As long as *ROIC* equals *WACC* in a given period, the value of the firm should remain unchanged since the firm would be generating profits according to expectation of both equity owners and debtors. This comparison could not be done with the other financial accounting metrics referred to above.[9]

In Table 4.2, we present summary statistics related to profitability for US agribusinesses. The operating benefit of a typical US agribusiness has been 9.4% on average during the 35 years period. This number is above the average WACC of a public US American firm. Clarke and De Silva (2003) present a summary of several studies, where *re*, the cost of equity has been between 5 and 6%. The cost of debt, *rd*, is lower than *re* by definition (i.e., residual risk and tax shield in equation 4.5).

[8] ROIC minus WACC is referred to as Economic Value Added (EVA) margin

[9] Financial analysts that emphasize the use of cash flows (e.g., cash flow from operations or free cash flow) over accounting profits (e.g., *NOPAT*) might be tempted to estimate a cash flow metric scaled by *IC*. As cash flows already include changes in working capital and/or CAPEX, the metric estimated by using cash flows should not be compared with WACC for decision making purposes.

| | Mean | Median | CV |
|---|---|---|---|
| IC | 550.333 | 75.892 | 0.14 |
| NOPAT | 79.246 | 275.543 | 3.48 |
| ROIC | 9.4% | 10.4% | 1.11 |

Notes: Data base characteristics explained in notes Table 4.1. *IC* and *NOPAT* are expressed in million USD as of 2004. *NOPAT* is estimated as in equation 4.3. *EBIT* is COMPUSTAT item 178. Details of *IC* estimations are specified in the notes at the bottom of Table 4.1. CV stands for coefficient of variation.

Table 4.2. Summary statistics of selected items for the US food supply chain for the 1970/2004 period

*Market Value of the Firm*

The market value of the firm (FV) captures not only the fundamental or accounting characteristics of the enterprise, but also investors ' expectations. This metric is defined as,

$$FV = MCap + D - C\,, \tag{4.8}$$

where *MCap*, market capitalization, is defined as stock price times the number of shares outstanding. While in *IC* (equation 4.1) equity is assessed at book value, in *FV* this value is "updated" according to what investors believe the firm's equity is worth at market value.[10]
In Table 4.3 we present summary statistics of the book value of equity and its market value for the US food sector.

| | Mean | Median | Std. Dev. | CV |
|---|---|---|---|---|
| Book Value of Equity | 309.304 | 46.809 | 1,052.086 | 3.40 |
| Market Capitalization | 1,127.496 | 62.329 | 6,082.294 | 5.39 |
| Market Firm Value | 1,368.525 | 99.374 | 6,582.137 | 4.81 |
| P/BV | 2.358 | 1.327 | 15.096 | 6.40 |

Note: Data base characteristics explained in notes Table 4.1. Values in million USD as of 2004, expect P/BV, the stock price divided by the book value of shares. Market capitalization is stock price at the end of calendar year, COMPUSTAT item 24 times number of common shares outstanding, COMPUSTAT item 25. The book value of equity is COMPUSTAT item 60.

Table 4.3. Summary statistics of selected items for the US food supply chain for the 1970/2004 period

In the following section we investigate how inventories and other *IC* components affect the market value of firms. To proxy the market value of equity we use stock returns or the changes in stock prices. Annual stock returns are estimated by compounding monthly returns obtained from the CRSP data base. Further, we compare *IC* components in *t* with stock returns in *t+1* to assess the reaction of investors to reported financial metrics.

[10] Debt could also be considered at market value. But since debt securities are not as liquid as equities, it is common to use the book value of debt. In addition, in equation 4.9 financial analysts make an adjustment, especially for firms consolidating results from their subsidiaries. Thus, it is common to multiply the multiple P/BV by Minority Interest (Equity, in the balance sheet).

### 4.1 Regression models

To investigate the impact of *NOWC* components in *t* on stock returns in *t+1* (i.e., how efficiently firms manage operating working capital in *t* and how stock prices react in *t+1*) we run the following OLS regression.

$$R_{i,t+1} = \alpha + \beta_1 \times \Delta INV / IC_{i,t} + \beta_2 \times \Delta AR / IC_{i,t} + \beta_3 \times \Delta AP / IC_{i,t} + \varepsilon_{i,t} \qquad (4.9)$$

where $R_{i,t+1}$ represents stock return of agribusiness *i* one year after the agribusinesses had reported their financial statements. *ΔINV/IC, ΔAR/IC,* and *ΔAP/IC* represent the change in inventories, in accounts receivable, and in accounts payable relative to invested capital, as defined previously.
Results are shown in Table 4.4.

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| $\alpha$ | 0.1580 | 0.0061 | 26.0428 | 0.0000 |
| $\beta_1$ | (0.0969) | 0.0295 | (3.2871) | 0.0010 |
| $\beta_2$ | (0.0549) | 0.0302 | (1.8154) | 0.0695 |
| $\beta_3$ | (0.0003) | 0.0254 | (0.0129) | 0.9897 |

Size of sample: 8,553 firm/year observations. Database as defined in notes of Table 4.1. In model 4.9 stock returns are buy-and-hold returns calculated as $BHR_{i,t} = \Pi^{12}_{j=1} (1+r_{i,j})-1$, where BHRi,t is the buy-and-hold compound annual return for firm *i* in year *t*, and $r_{i,j}$ is CRSP monthly rate of return inclusive of dividends and all other distributions over month *j*. Year refers to fiscal year as defined in Compustat. The return accumulation period starts four months after the end of the agribusiness' fiscal year. Returns used in this model are *t+1*returns following financial statements reported in *t*. Other variables have been defined previously in this chapter.

Table 4.4. Results for regression model (4.9)

As results for regression model (4.9) show, stock price returns in *t+1* are significantly affected by the growth of inventories in *t* at 1% significance level. Further, the sign of the coefficient is negative, implying that a growth in inventory levels negatively affects stock returns. A growth in account receivables also affects negatively stocks returns, but at 10% level of significance, and with a lower coefficient compared to inventories. This is important, since while both, a change in inventories and a change in accounts receivable have a similar impact in terms of cash flow, it seems that investors are more concerned about a change in inventory levels. Finally, according to results in Table 4.4, a change in accounts payable has no significant effect on stock returns.
Our second model tries to investigate how stock returns in *t+1* are affected not only by *NOWC* components, but also by *CAPEX*, a change in sales, and accounting profits. The model has,

$$R_{i,t+1} = \alpha + \beta_1 \times \Delta INV / IC_{i,t} + \beta_2 \times \Delta Sales_{i,t} + \beta_3 \times ROIC_{i,t} + \beta_4 \times CAPEX_{i,t} + \varepsilon_{i,t} \qquad (4.10)$$

where *ΔSales* is growth in sales (from *t-1* to *t*), ROIC is profitability return, as defined before, and *CAPEX* is the growth in gross *PP&E.*
Table 4.5 presents results. First, change in inventories and *CAPEX* relative to *IC* are very significant and negatively affect stock returns in *t+1*. More importantly, while *PP&E*

represents 70% of *IC* compared to inventories representing 30%, a 1% change in inventories has an economic impact similar to a 1% change of *PP&E* (*CAPEX*). This illustrates the economic importance of managing inventories. It might seem surprising that sales growth (from *t-1* to *t*) does not have a significant impact on stock returns in *t+1*. However, profits, as measured by ROIC is significant and positively affects stock returns in *t+1*. Thus, being profits a function of both revenues and expenses, this results should not be surprising, as growth in sales is accompanied by growth in total expenditures.

| Variable | Coefficient | Std. Error | t-Statistic | Prob. |
|---|---|---|---|---|
| $\alpha$ | 0.1767 | 0.0076 | 23.1008 | 0.0000 |
| $\beta_1$ | (0.1123) | 0.0252 | (4.4526) | 0.0000 |
| $\beta_2$ | 0.0007 | 0.0023 | 0.2964 | 0.7669 |
| $\beta_3$ | 0.0174 | 0.0110 | 1.5858 | 0.1128 |
| $\beta_4$ | (0.1276) | 0.0291 | (4.3930) | 0.0000 |

Size of sample: 8,553 firm/year observations. Database as defined in notes of Table 4.1. In model 4.10 stock returns are buy-and-hold returns calculated as $BHR_{i,t} = \Pi^{12}_{j=1} (1+r_{i,j})-1$, where BHRi,t is the buy-and-hold compound annual return for firm *i* in year *t*, and $r_{i,j}$ is CRSP monthly rate of return inclusive of dividends and all other distributions over month *j*. Year refers to fiscal year as defined in Compustat. The return accumulation period starts four months after the end of the agribusiness' fiscal year. Returns used in this model are *t+1*returns following financial statements reported in *t*. Other variables have been defined previously in this document. Variable Sales in model 4.10 is COMPUSTAT item 12. We use the change from *t-1* to *t* of this variable scaled by *IC*.

Table 4.5. Results for regression model (4.10)

## 5. Conclusions

Inventory exists in the supply chain because there is a mismatch between supply and demand. In this chapter, the role of inventory in supply chain management has been highlighted. It has also been shown that inventory models can be useful for implementing inventory policies for the different stages of a supply chain. Section 3 provides a brief discussion of existing inventory models that have been developed to model real systems. Many authors have proposed mathematical models that are easy to implement in practical situations and can be used as a basis for developing inventory policies in real systems. We provide a simple classification of these models based on stocking locations and type of demand.

We also provide an empirical analysis on the relationship among financial metrics, inventory, and the value of firms. We use for this analysis accounting and stock prices from US agribusinesses during the 1970-2004 period. Summary statistics show that inventory is the most important component of Net Operating Working Capital, representing one third of the book value of American agribusinesses. The other 70% book value of the firm, represented by PP&E has the lowest variability among all IC components across agribusinesses. Inventory also changes at the highest rate among all other two IC components.

Using regression analysis we investigate the impact of the growth of *NOWC* components in *t* on stock returns in *t+1* (i.e., how efficiently firms manage operating working capital in *t* and how stock prices react in *t+1*). We find that stock price returns in *t+1* are significantly affected by the growth of inventories in *t* at 1% of significance level. Further, the sign of the coefficient is negative, implying that a growth in inventory levels negatively affects stock returns. A growth in accounts receivable also negatively affects stocks returns, but at 10% level of significance, and with a lower coefficient compared to inventories. This is important, since while both, a change in inventories and a change in accounts receivable have similar impact in terms of cash flow, it seems that investors are more concerned about a change in inventory levels. Results also show that changes in accounts payable have no significant effect on stock returns.

When we incorporate *CAPEX* in the regression analysis, we find that change of inventories and *CAPEX* relative to *IC* are very significant and negatively affect stock returns in *t+1*. More importantly, while *PP&E* represents 70% of *IC* compared to inventories representing 30%, a 1% change in inventories has an economic impact similar to a 1% change of *CAPEX*. This illustrates the economic importance of managing inventories.

From the analysis provided in this chapter it is clear that inventory plays a key role in the market value of firms. Therefore, managing inventories is important as it allows a company to determine the appropriate amount of inventory to hold, so that the firm value is not affected by excess or unnecessary inventory levels in the supply chain. Although the mathematical models presented in section 3 are not applicable in all situations, they serve as a framework for developing models for practical situations.

## 6. References


Axsäter, S., 1996, Using the Deterministic EOQ Formula in Stochastic Inventory Control, *Management Science* 42(6), 830-834.

Azadivar, F. , and A. Rangarajan, 2008, Inventory Control, In Operations Research and the Management Science Handbook in A. Ravindran, ed.: (CRC Press, ).

Baldwing, C., 2002, Fundamental Enterprise Valuation: Earnings, *Harvard Business School Publishing, A Technical Note* 9-801-124.

Bangash, A., R. Bollapragada, R. Klein, N. Raman, H. B. Shulman, and D. R. Smith, 2004, Inventory Requirements Planning at Lucent Technologies, *Interfaces* 34(5), 342-352.

Bixby, A., B. Downs, and M. Self, 2006, A Scheduling and Capable-to-Promise Application for Swift & Company, *Interfaces* 36(1), 69-86.

Bruner, Robert F., Kenneth M. Eades, Robert S. Harris, and Robert C. Higgins, 1998, Best Practices in Estimating the Cost of Capital: Survey and Synthesis, *Financial Practice and Education* Spring / Summer 1998, 13-28.

Carhart, Mark. , 1997, On Persistence on Mutual Funds Performance, *The Journal of Finance* 52, 57-82.

Chen, F. , and Y. Zheng, 1994, Lower Bounds for Multi-Echelon Stochastic Inventory Systems, *Management Science* 40(11), 1426-1443.

Chen, F., and Y. Zheng, 1998, Near-Optimal Echelon-Stock (R,nQ) Policies in Multistage Serial Systems, *Operations Research* 46(4), 592-602.

Chopra, S. , and P. Meindl, 2007. *Supply Chain Management: Strategy, Planning, and Operations* (Prentice Hall Upper Saddle River, NJ, USA).

Chopra, S. , and P. Meindl, 2007. *Supply Chain Management: Strategy, Planning, and Operations* (Prentice Hall Upper Saddle River, NJ, USA).

Clark, A. , and H. Scarf, 1960, Optimal Policies for a Multi-Echelon Inventory Problem, *Management Science* 6(4), 475-490.

Clarke, R., and H. De Silva, 2003, Analytic Investors, *Risk Management Perspectives* April 2003.

DiFillipo, T., 2003, Multi-Criteria Supply Chain Inventory Models with Transportation Costs, (Unpublished Master's thesis, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University).

Fama, Eugene F. , and Kenneth R. . French, 1993, Common Risk Factors in the Returns on Stocks and Bonds, *Journal of Financial Economics* 33, 3-56.

Fama, Eugene F., and Kenneth R. French, 1992, The Cross-Section of Expected Stock Returns, *The Journal of Finance* 47, 427-465.

Federgruen, A., and Y. Zheng, 1995, Efficient Algorithms for Finding Optimal Power-of-Two Policies for Production/Distribution Systems with General Joint Setup Cost, *Operations Research* 43(3), 458-470.

Fisher, M., 1997, What is the Right Supply Chain for Your Product?, *Harvard Business Review* 83-93.

Hadley, G. , and T. Whitin, 1963. *Analysis of Inventory Systems* (Prentice-Hall, Englewood Cliffs, NJ.).

Harris, F., 1990, How many parts to make at once, Operations Research, *(reprint from Factory, The Magazine of Management, 1913, 10 (6), 135–136).* 38(6), 947–950.

Hillier, F. , and G. Lieberman, 2010. *Introduction to Operations Research* (Mc Graw Hill, Boston, MA ).

Jensen, Michael C., 1986, Agency Costs of Free Cash Flow, Corporate Finance, and Takeovers, *American Economic Review* 76, 323-329.

Kapuscinski, R., R. Q. Zhang, P. Carbonneau, R. Moore, and B. Reeves, 2004, Inventory Decisions in Dell´s Supply Chain, *Interfaces* 34(3), 191-205.

Koschat, M. A., G. L. Berk, J. A. Blatt, N. M. Kunz, M. H. LePore, and S. Blyakher, 2003, Newsvendors tackle the Newsvendor Problem, *Interfaces* 33(3), 72-84.

Lee, H. L., and C. Billington, 1995, The Evolution of Supply-Chain-Management Models and Practice at Hewlett-Packard, *Interfaces* 25(5), 42-63.

Lin, G. , M. Ettl, S. Buckley, S. Bagchi, D. D. Yao, B. L. Naccarato, R. Allan, K. Kim, and L. Koening, 2000, Extended-Enterprise Supply-Chain Management at IBM Personal Systems Group and Other Divisions, *Interfaces* 30(1), 7-25.

Liu, C. , and K. Ridgway, 1995, A Computer-Aided Inventory Management System – Part 1: Forecasting, *Integrated Manufacturing Systems* 6(1), 12-21.

Love, S. F. , 1972, A Facilities in Series Inventory Model with Nested Schedules, *Management Science* 18(5), 327-338.

Maxwell, W. , and J. Muckstadt, 1985, Establishing Consistent and Realistic Reorder Intervals in Production-Distribution Systems, *Operations Research* 33(6), 1316-1341.

Mendoza, A. , and J. Ventura, 2010, A Serial Inventory System with Supplier Selection and Order Quantity Allocation, *European Journal of Operational Research* 207 (3) 1304-1315.

Mendoza, A. , and J. A. Ventura, 2009, Estimating Freight Rates in Inventory Replenishment and Supplier Selection Decisions, *Logistics Research* 1(2-3), 185-196.

Muckstadt, J. , and R. Roundy, 1993, Analysis of Multistage Production Systems, in Graves et al., ed.: *In Handbooks in OR & MS* (Elsevier Science Publishers North-Holland, Amsterdam).

Nahmias, S., 2001. Production and Operations Analysis (Irwin, USA).

Natarajan, A., 2007, Multi-Criteria Supply Chain Inventory Models with Transportation Costs, (Unpublished PhD Dissertation, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University.).

Piasecki, D., 2001, Optimizing Economic Order Quantity, IIE Solutions.

Rangarajan, A. , and V. D. R. Guide, 2006, Supply Chain Risk Management: An Overview,, (Working Paper, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University).

Rangarajan, A. , and A. Ravindran, 2005, A Base Period Inventory Policy for Decentralized Supply Chains, Working Paper No. 05-04, Center for Supply Chain Research, Smeal College of Business, The Pennsylvania State University.

Rieksts, B. , Y. Ventura, T. Herer, and S. Daning, 2007, Worst-Case Performance of Power-of-Two Policies for Serial Inventory Systems with Incremental Quantity Discounts, *Naval Research Logistics* 54, 583-587.

Roundy, R., 1986, 98%-Effective Lot-Sizing Rule for a Multi-Product, Multi-Stage Production/Inventory System, *Mathematics of Operations Research* 11(4), 699-727.

Roundy, R., 1985, 98%-Effective Integer-Ratio Lot-Sizing for One-Warehouse Multi-Retailer System, *Management Science* 31(11), 1416-1430.

Schwarz, L. B. , and L. Schrage, 1975, Optimal and System-Myopic Policies for Multi-Echelon Production/Inventory Assembly Systems, *Management Science* 21(11), 1285-1294.

Sharpe, William F., 1964, Capital Asset Prices: A Theory of Market Equilibrium under Conditions of Risk, *Journal of Finance* 19, 425-442.

Silver, E. , D. Pyke, and R. Peterson, 1998. *Inventory Management and Production Planning and Scheduling* (Wiley, USA).

Silver, E. A., D. Pyke, and R. Peterson, 1998. *Inventory Management and Production Planning and Scheduling* (John Wiley & Sons, NJ, USA).

Sun, D., and D. Atkins, 1995, 98%-Effective Lot-Sizing for Assembly Inventory Systems with Backlogging, *Operations Research* 45(2), 940-951.

Tang, C. S., 2006, Perspectives in Supply Chain Risk Management, *International Journal of Production Economics* 103(2), 451-488.

Thirumalai, R., 2001, Multi-Criteria Multi-Decision Maker Inventory Models for Serial Supply Chain Systems, (Unpublished PhD Dissertation, Department of Industrial and Manufacturing Engineering, The Pennsylvania State University).

Trejo-Pech, Carlos J., Richard N. Weldon, and Lisa A. House, 2008, Earnings, Accruals, Cash Flows, and EBITDA for Agribusiness Firms, *Agricultural Finance Review* 68, 301-319.

Trejo-Pech, Carlos, Richard N. Weldon, Lisa A. House, and Michael Gunderson, 2009, The Accrual Anomaly Financial Problem in the Food Supply Chain, *Agribusiness: An International Journal* 25, 520-533.

Zheng, Y., 1992, On Properties of Stochastic Inventory Systems, *Management Science* 38(1), 87-103.

# 11

# Differential Game for Environmental-Regulation in Green Supply Chain

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## 1. Mission

This paper demonstrates that a proper design of environmental-regulation pricing strategies is able to promote Extended Product Responsibility for green supply chain firms in a competitive market. A differential game model comprising Vidale-Wolfe equation has been established in light of sales competition and recycling dynamics as well as regulation related profit function. Analytic solutions of Markovian Nash equilibriums are provided with the necessary condition derived from Hamilton-Jacobi-Bellman equations. We found that governments should opt to gradually raise regulation standards so that rational manufacturers will gradually improve its product recyclability, and, in turn, Extended Product Responsibility will get promoted.

## 2. Background and the importance

Competitive strategies for firms and environmental regulations for governments jointly play an important role in dictating the success of implementing Extended Product Responsibility (EPR) policies (Chen & Sheu, 2009; Reijnders, 2003). At the same time, strategic management has long been considered a significant part of business competitiveness. Most of existing reports, however, concentrate only on the impact of policies *per se*, rather than than on the existence of market interaction. This paper, therefore, shed new light on recycling policy designs under a more realistic market condition by the help a differential game model.
Existing analysis of recycling policy – including Design for Environment (DfE) incentives – are mostly based on a single company model (Chen & Sheu, 2009; Choe & Fraser, 2001; Fullerton & Wu, 1998; Stavins, 2002). From the literature, however, we understand that consequence of incentive behave differently in a multiple companies competition context (Chen & Sheu, 2009; Dockner et al., 2000), and thus the interactive effect of incentive policies and regulations needs to be reviewed. Moreover, product pricing and manufacturing costs mostly determine the profitability of a firm. Manufacturers accrue their profits by setting the right pricing strategies with consideration for competitor responses and product characteristics (Reijnders, 2003). Among the environmental policy literature, however, while tax or subsidy pricing is often discussed, little attention is given to product pricing and environmental friendly design policy. In recent years, EPR has attracted much attention and the notion of EPR has been part of the concept of green supply chain. According to (Barde & Stephen, 1997), EPR is defined as a strategy designed to promote the integration of environmental costs of products throughout

their life cycles into the market distribution mechanism so as to reduce product harm to the environment. A prosperous green supply chain can not be substantiated without the help of proper incentives and public policies (Sheu, 2008). With the implementation of EPR policies in various supply chains, producer responsibilities have been extended from selling products to recycling them, meanwhile pushing waste management issues to upstream manufacturers and even the entire supply chain.

In order to promote the concept of EPR, governments around the globe usually provide financial incentives for manufacturers and encourage them to engage in EPR practices (Palmer & Walls, 1999). Appropriate incentive mechanisms not only internalize externality by changing the cost structure for producers, but they also drive manufacturers to develop more environmentally friendly products. Moreover, although international prominence has shifted to product sustainability, the subject of product design is still seen as one of the top priorities for governments and manufacturers (Chen et al., 2010). When enterprises respond to strict controls regarding their social responsibility, and at the same time begin to take account of competitive pricing and manufacturing costs, it is often considered difficult for them to determine a long-term profit strategy. Existing literature has pointed out that, however, environmentally friendly designs can reduce material use, enhance business competitiveness, and have other benefits, there is no clear suggestions or practical consideration given as to how and to what extent product design can be improved (Chen et al., 2010).

Effect of EPR incentive on green product design reacts differently from a market with competitors. Member firms in a green supply chain, in every dynamic stage of the decision making process, attempt to estimate the actions of their rivals and then identify what corresponding strategies can be used to drive the firm toward a maximized profit situation. Such strategies, however, are expected to coincide with environmentally friendly design from the views of policy makers. To facilitate this process, we use a differential game model to derive optimal design trajectories and to illustrate how manufacturers can adopt optimal product green design and pricing strategies for pursuing maximal profit whilst also complying with social responsibility.

## 3. Literature review and environmental policies

Growing consensus exists that key members of supply and reverse supply chains should be managed in such a manner that their profits are maximized. Policy instrument issues have been investigated extensively in the environmental economics field (Benchekroun & Van Long, 2002; Ulph, 1996; Walls & Palmer, 2001). Along with the growing interest in GSCM by incorporating reverse logistics functionality into an original SCM strategic framework, a comprehensive closed-loop supply chain structure that can address diverse issues is emerging, such as remanufacturing (Mukhopadhyay & Setaputra, 2007; Spicer & Johnson, 2004), product recovery and return (Padmanabhan & Png, 1997), and production-induced waste reprocessing (Tsoulfas et al., 2002).

Moreover, the notion of Design for Environment (DfE) has been suggested (Spicer & Johnson, 2004; Walls, 2003). The DfE possesses broad coverage (Calcott & Walls, 2005) and strives to integrate, in a systematic way, various aspects of environment, health, and safety into the design phase of the production process, while at the same time seeking to satisfy simple and easy disassembling design criteria (Calcott & Walls, 2005; Walls, 2003). Given such broad sentiment, this paper focuses particularly on the recyclability of product green design in the following three areas: ease of disassembly, usage of toxic materials, and reusability of resources (Calcott & Walls, 2005), *i.e.*, design for recycling (Kriwet et al., 1995).

The definition of recycling rate has seen a dispute among literature and across country boarders. Implementation of the recycling vary in countries and therefor the definition remains different. In WEEE Act, the recycling rate amounts to the recycled weight percentage with respect to total disposal. It clearly regulates that: (1) the re-use and recycling rate be up to 75%, and (2) the resource recovery rate be up to 80% of the weight of each recovery (Yamaguchi, 2002). A prevalent definition of recyclability has been known as a rate or percentage of recyclable material in a product composition (Duchin & Lange, 1994). This definition of recyclability is easy in self-checking for individual producer and has been adopted in this paper.

There are various regulatory and financial incentive schemes. Globalized organizations – including Apple, Sony, and Matsushita – invest a large portion of their budgets in DfE activities in order to green their supply chain. The motivation that drives these firms to implement DfE (Walls, 2003) appears to lie in a combination of regulation and production cost (Avila, 2006; Chen et al., 2009; Gottberg et al., 2006; Iliyana, 2006; Palmer & Walls, 1999). In order to compensate for harm caused by the lack of flexibility in command and control, incentive mechanisms can be a complement to maintaining industry growth (Chen et al., 2009; Jaffe et al., 1995). Under these mechanisms, manufacturers are charged differently according to their product's characteristics in ease of handling (Dinan Terry, 1993; Dobbs, 1991; Fullerton & Wu, 1998).

Issues associated with exploiting economic incentives to promote all stages of material recycling have been extensively investigated in the environmental economics field (Benchekroun & Van Long, 2002; Ulph, 1996; Walls & Palmer, 2001). Although efforts to collect, recycle, and smelt large amounts of scrap have been exerted, some materials are left behind, generating an unbalanced closed-loop supply chain.

The price discrimination is expected to regulate manufacturers' environmental responsibility effectively. Among existing incentive designs, product charges or taxes are levied against products that causes environmental pollution prior to production to reflect the externality costs (Barde & Stephen, 1997). We assume that different incentives for firms largely result from differentiated processing fees charged by recycling treatment agencies providing discriminated product recyclability (Duchin & Lange, 1994). In other words, the fee schemes depend on the total amount of scraps as well as the ease of handling in waste treatment and processing.

Comparing to previous literature, we provide a distinctive feature. We extend mixed incentive strategies to a broader view. This paper finds that, for manufacturers in competition, simultaneously offering financial incentives and increasingly stringent regulation is necessary for promoting green product recyclability.

## 4. Competitive differential game model

In attempting to address the effectiveness of EPR instruments in a competitive environment, our model is built on top of a simplified situation in which an integrated financial incentive and regulation standard is imposed. To manifest the dynamic interaction, and for ease of illustration and analysis, we have constructed a differential game model with sales and recycling dynamics. In our model we assume that, for firms to be environmentally conscious, certain regulation standards need to be imposed to reflect current social responsibility (Foulon et al., 2002). Moreover, a certain amount of capital expenditure also needs to be invested in order to comply with government standards (Cohen, 1999; Foulon et al., 2002).

$x_i(t)$ and $\xi_i(t)$ represent the market share and recycling rate of producer $i$ at time $t$, respectively. The incentive is incorporated in recycling treatment fee $u_i(t)$, which is charged

by the treatment agency and depends on the product's recyclability involvement $d_i(t)$, *e.g.*, the extent of ease of disassembly. To implement a simplified financial incentive in our model, a treatment agency directly charges manufacturers processing fees without involving other third party agencies. In the close-to-real situation, there are other agencies as intermediaries, for example, a Producer Responsibility Organization (PRO) charges EEE manufacturers an amount of fees and establishes a fund to operate the system perpetually. These intermediate third part agencies can be incorporated in the future researches.
To study the competitive behavior, *i.e.*, time trajectories, of firms in a market, we denote the opponents' price decisions and market share as

$$p^{-i}(t) = (p_1(t), p_2(t), \dots, p_{i-1}(t), p_{i+1}(t), \dots, p_n(t)),$$
$$x^{-i}(t) = (x_1(t), x_2(t), \dots, x_{i-1}(t), x_{i+1}(t), \dots, x_n(t)).$$

We normalize the market share $x_i(t) \in [0,1]$ such that they sum up to unity at any time instance

$$\sum_{i=1}^{n} x_i(t) = 1.$$

The sales dynamics can be suitably described by a set of differential equations (1) with the form of Vidale-Wolfe (Prasad & Sethi, 2004).

$$\begin{aligned}\dot{x}_i(t) &= f_{x_i}(x_i(t), x^{-i}(t), p(t)) \\ &= \sum_{j\neq i} \rho_j p_j(t)\sqrt{x_i(t)} - \sum_{j\neq i} \rho_i p_i(t)\sqrt{x_j(t)} - \delta(x_i(t) - \sum_{j\neq i} x_i(t))\end{aligned} \quad (1)$$

All firms determine their product prices at very time instance in order to conquer maximal market shares. Pricing decisions are made by responding competitor reactions of prior price and market share changes. Prices differences between products affect customer purchasing preferences, thereby causing sales and market share deviation. Market share change rate $\dot{x}_i$ of firm $i$ in (1) constitutes the influence from its own market share $x_i$ and the market share $x_j$ of other products.
If manufacturers enhance their green product recyclability design, *i.e.*, the percentage of weight in their products been recycled, their product recycling rate will increase proportionately (Choe & Fraser, 2001). However, when reviewing EPR policy literature, we found that the definition of the recycling rate between countries is not limited to a specific context.
To relate to the EPR, the responsibility elasticity to unfulfilled recycles (Jalal & Rogers, 2002) is defined as

$$\alpha = \frac{\frac{\partial M}{M}}{\frac{\partial \tau}{\tau}} \quad (2)$$

where $M = 1 - \sum_{i=1}^{n} \xi_i$ represents unfulfilled recyclables, ignored by all manufacturers, and $\tau$ represents producer responsibility in a country. For example, $\alpha = -2$ means unfulfilled waste will decrease 2% as responsibility increases 1%. Every country may develop different social responsibility levels. This simply reflects the average environmental consciousness and regulation stringency in a particular society.
Let $\xi_i(t)$ and $d_i(t)$ represent the recycling rate of product $i$ and the recyclability involvement of product $i$, respectively. Motivated by diffusion models in marketing and the consequence of new product sales (Dockner & Fruchter, 2004), the recycling dynamics can be suitably

described through (3)

$$\dot{\xi}_i(t) = (\eta + \varepsilon_i d_i(t)/\tau)\sqrt{x_i(t)}(1 - \sum_{i=1}^{n} \xi_i(t)) \tag{3}$$

The influence of the dynamics of the recycling rate constitutes recyclability, the producer responsibility acting on market share and any unfulfilled recycling weight. The resulting behavior follows an S-shape dynamics. At lower rates of recycling, the improvement appears to be slow. When the recycling rate, however, increases to some extent, it starts to rise dramatically. Eventually, as most of the materials are recyclable, it becomes more difficult to improve the recycling rate.

The above two dynamics collectively describe the behavior of a recycling system in a competitive environment. The sales dynamic points out that when manufacturers commence a price war in the market, sales volume rises in consequence. More sales, however, leads to more waste, so that manufacturers need to take heavier responsibility for recycling (Barde & Stephen, 1997). In this case, manufacturers may be more willing to engage in product design recyclability in order to alleviate increasing costs.

In order to provide the conceptualization terse and to simplify consequent derivations, we aggregate all $\xi_i(t)$ to an single $\tau(t)$ (Dockner & Fruchter, 2004). By summing up all $\dot{\xi}_i$ of (3), the recycling dynamics can be easily transformed to

$$\alpha\dot{\tau}(t) = -\eta\tau(t) - \sum_{i=1}^{n} \varepsilon_i d_i(t)\sqrt{x_i(t)} \tag{4}$$

In order to pursue profit maximization, we assume revenue to be solely generated by selling products, while costs are accrued from multiple sources – such as, production cost $w_i(x_i(\cdot))$, production process upgrading cost $h_i(d_i(\cdot))$, recycling fee $u_i(d_i(\cdot))$ paid to the treatment agency, and capital expenditure $n(\tau(\cdot);\zeta(\cdot))$ made to comply with the government regulation standard $-\zeta(\cdot)$ (Jaffe et al., 1995). Upgrading costs includes R&D investment, costs incurred for altering production processes, and costs associated with consuming recyclable materials (Mukhopadhyay & Setaputra, 2007).

In this paper we assume $n$ is linear in $\zeta\tau$, which represents the environmental regulation standard determined by producer responsibility in a society. The net profit amounts to the difference between sales revenue and all accrued costs and can be written as (5) with the notion of NPV, where $r_i$ is the discount rate and assumed to be constant.

$$J_i(p_i(\cdot), d_i(\cdot)) = \int_0^T e^{-rt} F(x_i(t), \tau(t), p_i(t), d_i(t), t)dt \tag{5}$$

where

$$\begin{aligned} &F(x_i(t), \tau(t), p_i(t), d_i(t), t) = \nu_i(x_i(t), p_i(t)) - c_i(x_i(t), \tau(t), d_i(t)) \\ &= \nu_i(x_i(t), p_i(t)) - w_i(x_i(t)) - h_i(d_i(t)) - u_i(x_i(t), d_i(t)) - n_i(\tau(t); \zeta(t)) \end{aligned}$$

To keep the problem explicit, some assumptions are imposed regarding to the behavior of manufacturers:

1. We are dealing with a differential game with simultaneous decision making (Dockner et al., 2000). Every player is rational and seeks to maximize their objective functional.

2. All products are homogeneous but companies are not. Each firm has its own cost structure and ability to attract customers from its competitors.
3. There is only one representative treatment agency and it makes no profit in our system. It offers incentives by charging manufacturers differently according to the level of recyclability.

With the implementation of incentives and regulations, manufacturers constantly ponder how to re-allocate costs more effectively and select suitable recyclability involvement in order to achieve their own profit maximization. With the optimization problem of competing parties, our differential game model solves the Markovian Nash equilibrium. This occurs when a participant in a game speculates the optimal strategy of other participants to find his own optimal strategy. This strategy gives no motivation for all rational participants to deviate from this equilibrium (Dockner et al., 2000).

Let $\phi^i(x_i, \tau, t)$ denote a Markovian strategy of producer $i$. A Markovian Nash equilibrium satisfies the Hamilton-Jacobi-Bellman (HJB) equations (6).

$$r_i V_i = \max_{p_i, d_i}\{\nu_i(x_i, p_i) - c_i(x_i, \tau, d_i) + V_{ix}\dot{x}(x_i, x^{-1}, p_i) + V_{i\tau}\dot{\tau}(x_i, \tau, d_i)\},\ i = 1, 2, \tag{6}$$

where the notation $V_{ix}$ presents the partial derivative of $V_i$ with respect to $x$, *i.e.*, $\partial V_i/\partial x$. Expand the HJB (6) to (7)

$$\begin{aligned} r_i V_i = \max\{&\nu_i(x_i, p_i) - h_i(d_i) - u_i(x_i, d_i) - n_i(\tau; \zeta) + \\ &V_{ix}(\rho_2 p_2 \sqrt{x} - \rho_1 p_1 \sqrt{1-x} - \delta(2x-1)) + \\ &V_{i\tau}\frac{1}{\alpha}(-\eta\tau - \varepsilon_1 d_1 \sqrt{x} - \varepsilon_2 d_2 \sqrt{1-x})\},\ i = 1, 2. \end{aligned} \tag{7}$$

Taking maximization with respect to $p_i$ and $d_i$ on the right-hand side of (7) yields

$$\frac{\partial \nu_i}{\partial p_i} - V_{ix}\rho_i\sqrt{1-x_i} = 0 \tag{8}$$

$$-\frac{\partial h_i}{\partial d_i} - \frac{\partial u_i}{\partial d_i} - V_{i\tau}\frac{\varepsilon_i}{\alpha}\sqrt{x_i} = 0 \tag{9}$$

The resulting Markovian Nash equilibriums of (8) and (9) represent the optimal pricing and design strategies for each firms. We further assume that the revenue function $\nu_i(x_i(\cdot), p_i(\cdot))$ is linear in $x_i(\cdot)$ and quadratic in $p_i(\cdot)$ and the upgrading cost of recyclability design $h_i(d_i(\cdot))$ is quadratic in $d_i(\cdot)$ and the processing fee $u_i(x_i(\cdot), d_i(\cdot))$ is linear in $(1 - d_i(\cdot))\sqrt{x_i(\cdot)}$, and then we have $\frac{\partial h_i}{\partial d_i} = C_{h_i} d_i$ and $\frac{\partial u_i}{\partial d_i} = C_{u_i}\sqrt{x_i}$.

The Markovian Nash equilibriums follow:

$$p_i^* = \frac{\rho_i}{K_{\nu_i}} V_{ix}\sqrt{1-x_i} \tag{10}$$

$$d_i^* = \frac{\frac{\varepsilon_i V_{i\tau}}{\alpha} + C_{u_i}}{C_{h_i}}\sqrt{x_i} \equiv \mathfrak{F}_i\sqrt{x_i} \tag{11}$$

The HJB condition provides a necessary condition for evaluating the Markovian Nash equilibrium trajectories. In order to explore the sufficient condition in the future research,

further restrictions with special structure in the cost function are urged to be imposed (*cf.* Dockner et al. (2000)).
The equilibriums are subgame perfect if they are autonomous (Dockner et al., 2000). From the derivation in the appendix, our solution trajectories are autonomous, that is,

$$p_i^*(t) = \phi_{p_i}^i(x_i(t), \tau(t), t) = \phi_{p_i}^i(x_i(t), \tau(t)), \tag{12}$$

$$d_i^*(t) = \phi_{d_i}^i(x_i(t), \tau(t), t) = \phi_{d_i}^i(x_i(t), \tau(t)). \tag{13}$$

Applying the Markovian Nash equilibrium (10) and (11) into the HJB equations (6), we are then able to solve the Markovian Nash equilibriums with the Hamilton-Jacobi (HJ) equations (14).

$$\begin{aligned} r_i V_i =& \{\nu_i(x_i, \phi_{p_i}^i(x_i, \tau)) - c_i(x_i, \tau, \phi_{d_i}^i(x_i, \tau)) \\ &+ V_{ix}\dot{x}_i(x_i, x^{-1}, \phi_{p_i}^i(x_i, \tau)) + V_{i\tau}\dot{\tau}(x_i, \tau, \phi_{d_i}^i(x_i, \tau))\}, \\ & i = 1, 2. \end{aligned} \tag{14}$$

In a competitive environment, gaining product recyclability is deliberate. A firm often expands its market share by offering prudent price promotion in order not to cause their rivals to fight-back. The small increase in sales gradually costs the manufacture extra fees to process the waste. This excess cost, however, tends to eliminate the benefit of price promotion and give rise to a more conservative promotion strategy. In other words, a producer can choose to sell less in exchange for lower processing fees without engaging in any product design changes, even though an intensive incentive program has been realized in a market.
According to the aforementioned assumption, and for the purpose of illustration, we explicitly set the parameter functions as

$$\nu_1(x, p_1) = C_{\nu_1}x + \frac{1}{2}K_{\nu_1}p_1^2, \tag{15}$$

$$\nu_2(x, p_1) = C_{\nu_2}(1-x) + \frac{1}{2}K_{\nu_2}p_2^2, \tag{16}$$

$$h_1(d_1) = \frac{1}{2}C_{h_1}d_1^2, \tag{17}$$

$$h_2(d_2) = \frac{1}{2}C_{h_2}d_2^2, \tag{18}$$

$$u_1(x, d_1) = C_{u_1}(1-d_1)\sqrt{x}, \tag{19}$$

$$u_2(x, d_2) = C_{u_2}(1-d_2)\sqrt{1-x}, \tag{20}$$

$$n(\tau;\zeta) = E_n\zeta\tau. \tag{21}$$

where production costs $w_1$ and $w_2$ have been merged into the expression of $C_{\nu_1}$ and $C_{\nu_2}$, respectively. Our main problem therefore can be rewritten explicitly as

$$\max_{p_1,d_1} \int_0^\infty e^{-rt}\left[C_{\nu_1}x + \frac{1}{2}K_{\nu_1}p_1^2 - \frac{1}{2}C_{h_1}d_1^2 - C_{u_1}(1-d_1)\sqrt{x} - E_n\zeta\tau\right]dt \tag{22}$$

$$\max_{p_2,d_2} \int_0^\infty e^{-rt}\left[C_{\nu_2}(1-x) + \frac{1}{2}K_{\nu_2}p_2^2 - \frac{1}{2}C_{h_2}d_2^2 - C_{u_2}(1-d_2)\sqrt{1-x} - E_n\zeta\tau\right]dt$$

Subject to

| | $\rho_i$ | $\epsilon_i$ | $\delta$ | $\alpha$ | $\eta$ | $r$ | $C_{v_i}$ | $K_{v_i}$ | $C_{h_i}$ | $C_{u_i}$ | $\zeta$ | $x_0$ | $\tau_0$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0.3 | -2 | -0.8 | 0.08 | | | | | -10 | 0.8 | 0.8 |
| $firm_1$ | 0.3 | 1.1 | | | | | 10 | 0.1 | 36 | 18 | | | |
| $firm_2$ | 0.3 | 1.1 | | | | | 10 | 0.1 | 36 | 18 | | | |

Table 1. Experiment 1: Parameter settings for comparison scenarios.

$$\dot{x} = \rho_2 p_2 \sqrt{x} - \rho_1 p_1 \sqrt{1-x} - \delta(2x-1) \tag{23}$$

$$\alpha\dot{\tau} = -\eta\tau(t) - \varepsilon_1 d_1 \sqrt{x} - \varepsilon_2 d_2 \sqrt{1-x} \tag{24}$$

$$x(0) = x_0 \tag{25}$$

$$\tau(0) = \tau_0 \tag{26}$$

(27)

**Proposition 1.** *For the competition described by (15)–(24), the optimal recyclability in the Markovian Nash equilibrium is a non-decreasing functional of the market share. That is,* $\frac{\partial d_i^*(\cdot)}{\partial x_i(\cdot)} \geq 0$.

(Please refer to appendix for proof.)
Under the Markovian Nash equilibrium, the market share trajectories are not necessarily increasing, instead, it follows the sales dynamics controlled by optimal pricing, so that recyclability cannot be guaranteed to be improved. In the case of a market share trajectory not increasing, the government cannot drive producers to a state of higher recyclability without other effective policy. On the other hand, the government can demand all producers take more product responsibility through making the necessary capital investment – for example, production process reconstruction for total waste reduction. This additional expenditure can change the cost structures of manufacturers and force them to reduce costs in other ways, as there is often no room to raise the sales price in a competitive market. In order to meet government standards and take advantage of available incentive programs, a certain degree of product design change needs to be performed – such as easy-disassembly, or increasing the percentage of recyclable components. Observing the behavior of our model, we conjecture that if the government forces producers to adopt a higher standard of responsibility in recycling waste, producers appear to be more environmentally conscious.

**Proposition 2.** *For the competition described by (15)–(24), the optimal recyclability in Markovian Nash equilibrium is a non-decreasing functional of the regulation stringency (negative of $\zeta$). That is,* $\frac{\partial d_i^*(\cdot)}{\partial \zeta(\cdot)} \leq 0$.

(Please refer to appendix for proof.)
This paper explains the elaborate interaction between market share, pricing and product design. We demonstrate our research findings by two experiments – one comparing the effectiveness of fixed versus increasing policy stringency and the other one showing the performance with various policy stringency. Our propositions can be illustrated and reviewed with the related parameter settings in Table 1.

| Stringent rate $v_\zeta$ | Profit $J_1$ | Profit $J_2$ | Final Recyclability $d_1^*(T)$ | Final Recyclability $d_2^*(T)$ |
|---|---|---|---|---|
| 0.0 | 933 | 931 | 5.96 | 4.21 |
| 0.5 | 892 | 896 | 7.03 | 4.95 |
| 1.0 | 847 | 859 | 8.09 | 5.69 |
| 1.5 | 798 | 821 | 9.16 | 6.43 |
| 2.0 | 744 | 780 | 10.2 | 7.16 |
| 2.5 | 687 | 738 | 11.3 | 7.90 |
| 3.0 | 626 | 693 | 12.3 | 8.64 |
| 3.5 | 561 | 647 | 13.4 | 9.38 |
| 4.0 | 492 | 599 | 14.5 | 10.1 |
| 4.5 | 419 | 549 | 15.5 | 10.8 |

Table 2. Experiment: Profit and recyclability increase with stringent rates increased.

Based on the parameter settings, the optimal state trajectories follows

$$\begin{aligned}
\dot{x} &= -\left(\frac{2\rho_1\mathcal{R}_1\sqrt{\mathcal{T}} + 2\rho_2\mathcal{R}_2\sqrt{\mathcal{T}\mathfrak{X}}}{1+\mathfrak{X}} + 2\delta\right)x + 2\rho_1\mathcal{R}_1\frac{\sqrt{\mathcal{T}}}{1+\mathfrak{X}} + \delta,\\
\alpha\dot{\tau} &= -\eta\tau - (\varepsilon_1\mathcal{F}_1 - \varepsilon_2\mathcal{F}_2)x - \varepsilon_2\mathcal{F}_2,\\
x(0) &= x_0,\\
\tau(0) &= \tau_0.
\end{aligned}$$

In order to manifest the influence of regulation stringency, we conduct an experiment using the parameter set as previous experiment. The Recycling performance changes can be observed by changing the rate of stringency. We let the the regulation standard gradually raised by (28).

$$\zeta = \zeta_0 + v_\zeta(1 - \exp(-t)). \tag{28}$$

The regulation grows with a rate of $v_\zeta$. As shown in Table 2, all parameters remain unchanged in the second experiment and ten levels of rate $v_\zeta$ have been employed in this experiment. In spite of profit decreasing as the regulation becomes more stringent, the recyclability of both firms increases significantly. Under this policy, manufacturers are therefore endowed with motivation to enhance their product design.

## 5. Conclusions

This paper is different from existing works in that it analyzes the interactive effects of financial drivers and environmental policies through a dynamic approach. This paper integrates existing differential game models and establishes a novel dynamics analysis that encourages product recyclability. Taking time and competitors' reactions into consideration, the conditions that drive manufacturers to enhance product recyclability have been identified. This paper makes a contribution on the EPR effectiveness issue in a competitive market. Based on the results of this paper, governments should opt to gradually raise regulation standards so that rational manufacturers will implement the corresponding Markovian strategies, *i.e.*, gradually improve its product recyclability. On the other hand, more incentive benefits nevertheless need to be provided where the regulation standard is fixed, in order to urge businesses to achieve the same level of recyclability as in the case of rising standards.

This conclusion cannot be reached without considering the interactive behavior among competitive firms.
Our results further indicate that governments should consider the effectiveness of environmental policy on the premise that it is nature for business to pursue maximal profits. In order to develop EPR among industries, the first priority of the government should be to enact laws or regulations with rising standards to complement available financial incentive programs. Moreover, to make our differential game model closer to reality, future research can be conducted with other types of treatment agencies, such as Producer Responsibility Organization (PRO), private treatment agencies and the issue of illicit disposal of informal sectors.

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## 7. References

Avila, G. (2006). Product development for RoHs and WEEE compliance, *Printed Circuit Design and Manufacture* 23(5): 28–31.

Barde, J. & Stephen, S. (1997). Do economic instruments help the environment?, *OECD Observer* 204: 22–26.

Benchekroun, H. & Van Long, N. (2002). On the multiplicity of efficiency-inducing tax rules, *Economics Letters* 76(3): 331–336.

Calcott, P. & Walls, M. (2005). Waste, recycling, and design for environmentĄÂŤ: Roles for markets and policy instruments, *Resource and Energy Economics* 27(4): 287–305.

Chen, Y. J. & Sheu, J.-B. (2009). Environmental-regulation pricing strategies for green supply chain, *Transportation Research Part E: Logistics and Transportation Review* 45(5): 667–677.

Chen, Y. J., Wu, D.-H. & Wu, W.-M. (2010). Effective e-waste management: The role of international cooperation and fragmentation, *The 15th International Symposium on Logistics (ISL 2010)*, Kuala Lumpur, Malaysia, pp. 1–1.

Chen, Y. J., Wu, T.-H. & Chen, Y.-L. (2009). The recycling business for sustainability in Taiwan, *European Business Review* 21(5): 403–417.

Choe, C. & Fraser, I. (2001). On the flexibility of optimal policies for green design, *Environmental and Resource Economics* 18(4): 367–371.

Cohen, M. (1999). Monitoring and enforcement of environmental policy, *International Yearbook of Environmental and Resource Economics* 3: 44–106.

Dinan Terry, M. (1993). Economic efficiency effects of alternative policies for reducing waste disposal, *Journal of Environmental Economics and Management* 25(3): 242–256.

Dobbs, I. (1991). Litter and waste management: Disposal taxes versus user charges, *Canadian Journal of Economics* 24(1): 221–227.

Dockner, E. & Fruchter, G. (2004). Dynamic strategic pricing and speed of diffusion, *Journal of Optimization Theory and Applications* 123(2): 331–348.

Dockner, E., Jørgensen, S., Van Long, N. & Sorger, G. (2000). *Differential Games in Economics and Management Science*, Cambridge University Press.

Duchin, F. & Lange, G. (1994). *The Future of the Environment: Ecological Economics and Technological Change*, Oxford University Press, USA.

Foulon, J., Lanoie, P. & Laplante, B. (2002). Incentives for pollution control: Regulation or information?, *Journal of Environmental Economics and Management* 44(1): 169–187.

Fullerton, D. & Wu, W. (1998). Policies for green design, *Journal of Environmental Economics and Management* 36(2): 131–148.

Gottberg, A., Morris, J., Pollard, S., Mark-Herbert, C. & Cook, M. (2006). Producer responsibility, waste minimisation and the WEEE directive: Case studies in eco-design from the European lighting sector, *Science of the Total Environment, The* 359(1-3): 38–56.

Iliyana, H. (2006). RoHs and WEEE-the new European directives: Do they work and why (or why not)? current application and development in the EU and USA, *European Environmental Law Review* 15(3): 62–74.

Jaffe, A., Peterson, S., Portney, P. & Stavins, R. (1995). Environmental regulation and the competitiveness of US manufacturing: What does the evidence tell us?, *Journal of Economic Literature* 33(1): 132–163.

Jalal, K. & Rogers, P. (2002). Measuring environmental performance in Asia, *Ecological Indicators* 2(1-2): 39–59.

Kriwet, A., Zussman, E. & Seliger, G. (1995). Systematic integration of design-for-recycling into product design, *International Journal of Production Economics* 38(1): 15–22.

Mukhopadhyay, S. K. & Setaputra, R. (2007). A dynamic model for optimal design quality and return policies, *European Journal of Operational Research* 18(3): 1144–1154.

Padmanabhan, V. & Png, I. (1997). Manufacturer's returns policies and retail competition, *Marketing Science* 16(1): 81–94.

Palmer, K. & Walls, M. (1999). Extended product responsibility: An economic assessment of alternative policies, *Technical report*, Resources for the Future, Washington, DC.

Prasad, A. & Sethi, S. (2004). Competitive advertising under uncertainty: A stochastic differential game approach, *Journal of Optimization Theory and Applications* 123(1): 163–185.

Reijnders, L. (2003). Policies influencing cleaner production: the role of prices and regulation, *Journal of Cleaner Production* 11(3): 333–338.

Sheu, J. (2008). Green supply chain management, reverse logistics and nuclear power generation, *Transportation Research Part E* 44(1): 19–46.

Spicer, A. & Johnson, M. (2004). Third-party demanufacturing as a solution for extended producer responsibility, *Journal of Cleaner Production* 12(1): 37–45.

Stavins, R. (2002). Experience with market-based environmental policy instruments, *Technical report*, Resources for the Future, Washington, DC.

Tsoulfas, G. T., Pappis, C. P. & Minner, S. (2002). An environmental analysis of the reverse supply chain of SLI batteries, *Resources, Conservation and Recycling* 36(2): 135–154.

Ulph, A. (1996). Environmental policy instruments and imperfectly competitive international trade, *Environmental and Resource Economics* 7(4): 333–355.

Walls, M. (2003). The role of economics in extended producer responsibility: Making policy choices and setting policy goals, *Technical report*, Resources for the Future, Washington, DC.

Walls, M. & Palmer, K. (2001). Upstream Pollution, Downstream Waste Disposal, and the Design of Comprehensive Environmental Policies, *Journal of Environmental Economics and Management* 41(1): 94–108.

Yamaguchi, M. (2002). Extended producer responsibility in Japan, *ECP Newsletter* 10: 1–11.

## A Theorem Proof

*for Proposition 1 in conditions of recyclability.* Given the results of (10), apply the function form (15) to (24), the equations (10) and (11) expand to

$$p_1 = \frac{\rho_1}{K_{\nu_1}} V_{1x}\sqrt{1-x} \tag{29}$$

$$p_2 = \frac{\rho_2}{K_{\nu_2}} V_{2x}\sqrt{x} \tag{30}$$

$$d_1 = \frac{\frac{\varepsilon_1}{\alpha}V_{1\tau} + C_{u_1}}{C_{h_1}}\sqrt{x} \equiv \mathcal{F}_1\sqrt{x} \tag{31}$$

$$d_2 = \frac{\frac{\varepsilon_2}{\alpha}V_{2\tau} + C_{u_2}}{C_{h_2}}\sqrt{1-x} \equiv \mathcal{F}_2\sqrt{1-x} \tag{32}$$

Substitute the Markovian strategies (29) to (32) into (7) and then we have the Hamilton-Jacobi equation

$$\begin{aligned}
rV_1 =& C_{\nu_1}x - \frac{\rho_1^2}{2K_{\nu_1}}V_{1x}^2(1-x) - \frac{1}{2}C_{h_1}\mathcal{F}_1^2 x - C_{u_1}\mathcal{F}_1 x - E_n\zeta\tau \\
&- \frac{\rho_2^2}{K_{\nu_2}}V_{1x}V_{2x}x - V_{1x}\delta(2x-1) - \frac{\eta}{\alpha}V_{1\tau}\tau - \frac{\varepsilon_1}{\alpha}\mathcal{F}_1 V_{1\tau}x - \frac{\varepsilon_2}{\alpha}\mathcal{F}_2 V_{1\tau}(1-x), \\
rV_2 =& C_{\nu_2}(1-x) - \frac{\rho_2^2}{2K_{\nu_2}}V_{2x}^2 x - \frac{1}{2}C_{h_2}\mathcal{F}_2^2 x - C_{u_2}\mathcal{F}_2 x - E_n\zeta\tau \\
&- \frac{\rho_1^2}{K_{\nu_1}}V_{1x}V_{2x}(1-x) - V_{2x}\delta(2x-1) - \frac{\eta}{\alpha}V_{2\tau}\tau - \frac{\varepsilon_1}{\alpha}\mathcal{F}_1 V_{2\tau}x - \frac{\varepsilon_2}{\alpha}\mathcal{F}_2 V_{2\tau}(1-x),
\end{aligned}$$

We conjecture that the value function $V_i$ is linear in the state variables(Prasad & Sethi, 2004).

$$V_1 = \mathfrak{A}_1 + \mathfrak{B}_1 x + \mathfrak{C}_1\tau, \qquad V_2 = \mathfrak{A}_2 + \mathfrak{B}_2(1-x) + \mathfrak{C}_2\tau.$$

Therefore $V_{1x} = \mathfrak{B}_1$, $V_{1\tau} = \mathfrak{C}_1$, $V_{2x} = \mathfrak{B}_2$ and $V_{2\tau} = \mathfrak{C}_2$. The HJ equations expand to

$$\begin{aligned}
r\mathfrak{A}_1 + r\mathfrak{B}_1 x + r\mathfrak{C}_1\tau =& -\frac{\rho_1^2}{2K_{\nu_1}}\mathfrak{B}_1^2 + \delta\mathfrak{B}_1 - \frac{\varepsilon_2}{\alpha}\mathcal{F}_2\mathfrak{C}_1 \\
&+ \left(\frac{\rho_1^2}{2K_{\nu_1}}\mathfrak{B}_1^2 - 2\delta\mathfrak{B}_1 - \frac{\rho_2^2}{K_{\nu_2}}\mathfrak{B}_1\mathfrak{B}_2 - \frac{1}{2}C_{h_1}\mathcal{F}_1^2 - (C_{u_1} + \frac{\varepsilon_1}{\alpha}\mathfrak{C}_1)\mathcal{F}_1 + \frac{\varepsilon_2}{\alpha}\mathcal{F}_2\mathfrak{C}_1 + C_{\nu_1}\right)x \\
&+ \left(-\frac{\eta}{\alpha}\mathfrak{C}_1 - E_n\zeta\right)\tau, \\
r\mathfrak{A}_2 + r\mathfrak{B}_2 x + r\mathfrak{C}_2\tau =& -\frac{\rho_2^2}{2K_{\nu_2}}\mathfrak{B}_2^2 - \delta\mathfrak{B}_2 - \frac{\varepsilon_1}{\alpha}\mathcal{F}_1\mathfrak{C}_2 \\
&+ \left(\frac{\rho_2^2}{2K_{\nu_2}}\mathfrak{B}_2^2 + 2\delta\mathfrak{B}_2 - \frac{\rho_1^2}{K_{\nu_1}}\mathfrak{B}_1\mathfrak{B}_2 - \frac{1}{2}C_{h_2}\mathcal{F}_2^2 - (C_{u_2} + \frac{\varepsilon_2}{\alpha}\mathfrak{C}_2)\mathcal{F}_2 + \frac{\varepsilon_1}{\alpha}\mathcal{F}_1\mathfrak{C}_2 + C_{\nu_2}\right)(1-x) \\
&+ \left(-\frac{\eta}{\alpha}\mathfrak{C}_2 - E_n\zeta\right)\tau.
\end{aligned}$$

Equating powers of $x$ and $\tau$, some of the unknowns can be easily solved as

$$\begin{aligned}\mathfrak{A}_1 &= -\frac{1}{r}(\frac{\rho_1^2}{2K_{\nu_1}}\mathfrak{B}_1^2 - \delta\mathfrak{B}_1 + \frac{\varepsilon_2}{\alpha}\mathcal{F}_2\mathfrak{C}_1),\\ \mathfrak{A}_2 &= -\frac{1}{r}(\frac{\rho_2^2}{2K_{\nu_2}}\mathfrak{B}_2^2 + \delta\mathfrak{B}_2 + \frac{\varepsilon_1}{\alpha}\mathcal{F}_1\mathfrak{C}_2),\\ \mathfrak{C}_1 &= \mathfrak{C}_2 = -\frac{E_n\alpha\zeta}{\alpha r + \eta},\end{aligned}$$

Let

$$\begin{aligned}\mathcal{R}_1 &= \frac{\rho_1^2}{2K_{\nu_1}},\ \mathcal{R}_2 = \frac{\rho_2^2}{2K_{\nu_2}},\\ \mathcal{W} &= r + 2\delta,\\ \mathcal{H}_1 &= \frac{\varepsilon_1\zeta}{\alpha r + \eta},\\ \mathcal{H}_2 &= \frac{\varepsilon_2\zeta}{\alpha r + \eta},\\ \mathcal{Z}_1 &= -\frac{3}{2C_{h_1}}(C_{u_1} - \mathcal{H}_1)^2 - \frac{1}{C_{h_2}}(C_{u_2} - \mathcal{H}_2)\mathcal{H}_2 + C_{\nu_1},\\ \mathcal{Z}_2 &= -\frac{3}{2C_{h_2}}(C_{u_2} - \mathcal{H}_2)^2 - \frac{1}{C_{h_1}}(C_{u_1} - \mathcal{H}_1)\mathcal{H}_1 + C_{\nu_2}.\end{aligned}$$

To solve $\mathfrak{B}_1$ and $\mathfrak{B}_2$,

$$\begin{aligned}\mathcal{R}_1\mathfrak{B}_1^2 - \mathcal{W}\mathfrak{B}_1 - 2\mathcal{R}_2\mathfrak{B}_1\mathfrak{B}_2 + \mathcal{Z}_1 &= 0,\\ -\mathcal{R}_2\mathfrak{B}_2^2 - \mathcal{W}\mathfrak{B}_2 + 2\mathcal{R}_1\mathfrak{B}_1\mathfrak{B}_2 + \mathcal{Z}_2 &= 0,\end{aligned}$$

or

$$\begin{aligned}&\mathcal{W}(\mathfrak{B}_1 + \mathfrak{B}_2)^2 - (\mathcal{Z}_1 + \mathcal{Z}_2)^2 = 0,\\ &\mathcal{R}_1\mathfrak{B}_1^2 + \mathcal{R}_2\mathfrak{B}_2^2 - 2(\mathcal{R}_1 + \mathcal{R}_2)\mathfrak{B}_1\mathfrak{B}_2 + (\mathcal{Z}_1 - \mathcal{Z}_2) = 0.\end{aligned}$$

Let

$$\begin{aligned}\mathfrak{B}_1 &= r\cos\theta,\\ \mathfrak{B}_2 &= r\sin\theta,\end{aligned}$$

Applying the parameterization approach, the system of nonlinear equations transforms to

$$r^2(1 + \sin 2\theta) = ((\mathcal{Z}_1 + \mathcal{Z}_2)/\mathcal{W})^2, \tag{33}$$

$$r^2(1 + \frac{1}{2}\frac{\mathcal{R}_2 - \mathcal{R}_1}{2\mathcal{R}_1 + \mathcal{R}_2}(1 - \cos 2\theta)) = (\mathcal{R}_1 + \mathcal{R}_2)((\mathcal{Z}_1 + \mathcal{Z}_2)/\mathcal{W})^2 - (\mathcal{Z}_1 - \mathcal{Z}_2). \tag{34}$$

Set

$$\mathcal{S} = ((\mathcal{Z}_1 + \mathcal{Z}_2)/\mathcal{W})^2,$$
$$\mathcal{T} = (\mathcal{R}_1 + \mathcal{R}_2)((\mathcal{Z}_1 + \mathcal{Z}_2)/\mathcal{W})^2 - (\mathcal{Z}_1 - \mathcal{Z}_2).$$

Divide 33 by 34 as

$$(\mathcal{T}\frac{2\mathcal{R}_2 + \mathcal{R}_1}{2\mathcal{R}_1 + \mathcal{R}_2} - \mathcal{S}) \tan^2\theta - 2\mathcal{S}\tan\theta + \mathcal{T} - \mathcal{S} = 0.$$

Therefore

$$\tan\theta = \frac{\mathcal{S} \pm \sqrt{\mathcal{S}^2 - (\mathcal{T}\frac{2\mathcal{R}_2+\mathcal{R}_1}{2\mathcal{R}_1+\mathcal{R}_2} - \mathcal{S})(\mathcal{T} - \mathcal{S})}}{\mathcal{T}\frac{2\mathcal{R}_2+\mathcal{R}_1}{2\mathcal{R}_1+\mathcal{R}_2} - \mathcal{S}} \equiv \mathfrak{X}$$

and

$$r = \pm\sqrt{\frac{\mathcal{T}}{1 + \sin 2\tan^{-1}\mathfrak{X}}} = \pm\sqrt{\frac{\mathcal{T}(1 + \mathfrak{X}^2)}{(1 + \mathfrak{X})^2}}$$

Transform back to $\mathfrak{B}_1$ and $\mathfrak{B}_2$,

$$\mathfrak{B}_1 = \pm\frac{\sqrt{\mathcal{T}}}{1 + \mathfrak{X}}, \qquad \mathfrak{B}_2 = \pm\frac{\sqrt{\mathcal{T}\mathfrak{X}}}{1 + \mathfrak{X}},$$

The Markov Nash equilibriums follow

$$p_1^* = \pm 2\mathcal{R}_1\frac{\sqrt{\mathcal{T}}}{1 + \mathfrak{X}}\sqrt{1 - x}, \qquad p_2^* = \pm 2\mathcal{R}_2\frac{\sqrt{\mathcal{T}\mathfrak{X}}}{1 + \mathfrak{X}}\sqrt{x},$$
$$d_1^* = \frac{\frac{E_n\varepsilon_1\zeta}{\alpha r+\eta} + C_{u_1}}{C_{h_1}}\sqrt{x} \equiv \mathcal{F}_1\sqrt{x} \qquad d_2^* = \frac{\frac{E_n\varepsilon_2\zeta}{\alpha r+\eta} + C_{u_2}}{C_{h_2}}\sqrt{1 - x} \equiv \mathcal{F}_2\sqrt{1 - x}.$$

Therefore, the derivative of optimal recyclability $d_i$ with respect to the market share $x$ becomes

$$\frac{\partial d_i^*}{\partial x} = \mathcal{F}_i \geq 0$$

□

□

*for Proposition 2 with respect to stringency.* Follow the results in Proposition 1, the derivative of optimal recyclability $d_i$ with respect to $\zeta$ becomes

$$\frac{\partial d_i^*}{\partial \zeta} = \frac{E_n\varepsilon_i}{\alpha r + \eta} \leq 0,$$

since $\alpha$, $\eta \leq 0$, and $r$, $E_n$, $\epsilon_i \geq 0$.
□ □

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# Logistics Strategies to Facilitate Long-Distance Just-in-Time Supply Chain System

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## 1. Introduction

Just-In-Time (JIT) has become a paradigm in supply chain management since its introduction to the U.S. manufacturing industries in the 1970's (Chopra & Meindl, 2007). Aiming at total logistics cost reduction and customer service enhancement, JIT generates significant impact on the all logistics aspects for the JIT system participants (Daugherty & Spencer, 1990; Gomes & Mentzer, 1991). As international and domestic competitive pressure increases, an increasing number of companies are adopting JIT principles with the anticipation of productivity advancement, waste reduction, and quality breakthroughs. Experts have agreed that JIT strategy has constituted a potent force in improving the U.S. manufacturing competitiveness (Modarress et al., 2000; Wood & Murphy Jr., 2004).

In the present chapter, a long-distance JIT supply chain in a global context is defined as an inter-organizational logistics system which processes physical flows and deliver goods cross across country boundaries at the right time, to the right locations, of the right quantities, and with the right quality (Kreng & Wang, 2005; Wong & Johansen, 2006; Wong et al., 2005). A JIT supply chain entails a highly efficient logistics system as the operational foundation (Bagchi, 1988; Bagchi et al., 1987; Giunipero et al., 2005). Specifically, transportation assumes a much more important role in a JIT system than a conventional multi-echelon supply chain (Schwarz & Weng, 1999). Furthermore, the demand for efficient and integrative distribution centers is drastically higher than the traditional approaches in that shipments entirely rely on distribution centers at each echelon to coordinate and process inbound and outbound flows in a timely manner (Lieb & Millen, 1988). Failure in any particular logistics process could potentially lead to a bottleneck, hindering expected efficiency of JIT systems (Chopra & Meindl, 2007).

Initially established in Japan, the JIT production and purchasing concepts are recognized as a cornerstone of the Japanese manufacturing sector success. The original JIT design is embedded in close and tightly connected distribution networks. The networks are supported by innovative logistics arrangements, such as load-switching and freight consolidation to facilitate inbound and outbound flows (Giunipero et al., 2005). In the last decades, supply chain system has evolved from its original local scale to a multi-national, or even global scope; in the meantime, the demand for JIT operations from global marketplace does not diminish. As a result, manufacturers that attempt to implement extended, long-distance JIT systems will need a substantial modification for the original form of the JIT system (Kreng & Wang, 2005; Wong & Johansen, 2006; Wong et al., 2005).

The thrift development of international logistics and regional economic integration, has led to successes for international operations. U.S. manufacturers establish the well-known Maquiladora between U.S. and Mexico to leverage cost advantages (Wood and Murphy 2004). Dell Computer and HP are lead computer brands utilizing global JIT operations by integrating supply chain partners (Dean & Tam, 2005). In these instances, information technology (IT) utilization and efficient long-distance haulage connecting manufacturing and distribution are key determinants for JIT successes (Bookbinder & Dilts, 1989). Designing an integrated long-distance value chain enabled by synchronized inter-firm information system is thus critical for successful JIT systems (Schniederjans & Cao, 2001).

The foregoing discussion leads to several interesting questions with regard to the emerging global, long-distance JIT system. How can firms configure a global, long-distance supply chain network? How should supply chain partners establish strategies for logistics functions to support a wide-spread value system? In the logistics literature, there is a lesser amount of published work addressing necessary transformation required by global JIT coordination. The present study attempts to develop a systematic approach to establish a global, long-distance JIT system.

This chapter conducts an extensive literature relative to JIT studies and supply chain strategies supporting this strategy. The research integrates multiple research streams and presents a framework utilizing inter-firm IT and consolidation to establish a long-distance JIT system. State-of-the-art communication technologies (e.g. RFID) and logistics strategies (cross-docking) beyond conventional JIT "pillars" are incorporated into the proposed framework. Finally, the main contribution is a roadmap that accounts for long-distance JIT planning and the synthesis of logistics strategies that facilitate the long-distance JIT strategy.

## 2. Logistics strategies in a JIT supply chain

### 2.1 Conventional JIT transportation strategies

JIT system requires consistent transportation service and special handling equipment. Participants of this system should be equipped with higher level of flexibility and adaptability to account for tight coordination in the transportation and distribution network (Harper & Goodner, 1990). The JIT strategy entails a complex and complete rethinking on sourcing decisions and plant and warehouse locations. Broad scale implementation JIT logic of transportation systems result in the following changes (Chapman, 1992; Gomes & Mentzer, 1991): 1. Decreased lead-time requirements necessitating quick transportation; 2. Smaller shipment sizes necessitating more frequent dispatches to contain total transportation costs.

The goal of JIT is a significant reduction of work-in-process inventory by frequent feeding of production inputs. The demand of more frequent, small-size, and premium shipments seem to cause higher transportation cost, and trading off reduced inventory against higher transportation costs become the critical factor for total cost minimization. The systemic JIT approach allows small margin for transportation cycle variation to avoid production disruption. Either delay or early arrival could disrupt production processes. In addition, external factors, e.g. weather, congestion and unexpected accidents, could cause serious delay in JIT and have negative impact on supply chain as a whole.

Highway traffic congestion and JIT manufacturing/inventory management are two rapidly growing, parallel phenomena in today's business scene. Deteriorating traffic congestion has the potential to curtail the gains that supply chain partners pursue through implementation of JIT (Rao & Grenoble, 1991b). In addition, the smaller and more frequent orders, shortened lead-times, and precise scheduling called for by JIT can in turn severely impair the already clogged streets and highways. The smaller size, more frequent delivery transportation has nontrivial negative impacts on the overall transportation infrastructure (Rao & Grenoble, 1991a, 1991b). Both traffic congestion (a social problem) and JIT (a management opportunity) are growing rapidly and are probably on a collision course.

### 2.2 Buyer-supplier proximity paradigm

Common wisdom of JIT implementation suggests that inbound suppliers should be readily located as close as possible to the production centers, as known as the "supplier-buyer plant proximity" paradigm in JIT practices. Schonberger and Gilbert (1983) indicate that JIT purchasing is facilitated by buying from a small number of nearby suppliers – the ideal being single-source purchasing strategy. Nearby suppliers have several advantages. First, JIT material supply with short delivery might reduce total waste of inventory and transport cost. Second, emergency condition such as unexpected material stockout could be rescued by premium delivery. Consequently, configuration of close locations of suppliers and manufacturers with JIT supply chain system reduce the uncertainties. Fig. 1 shows short-distance inbound transportation between suppliers and one manufacturer.

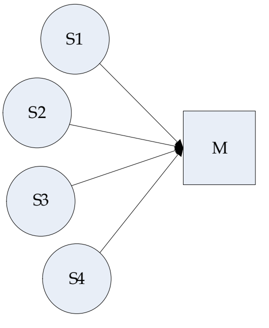


Fig. 1. Short-distance JIT

This proximity paradigm, however, has potential risks. Fast changing market conditions or geographical restrictions may prevent this rigid proximity arrangement from sustaining or even achieving production economies of suppliers and/or buyers. In addition, suppliers follow the proximity paradigm are more likely to incur high site specificity and asset specificity and make the suppliers captive to their manufacturer (Williamson, 1985). Additionally, abrupt termination of the supplier-buyer relationship or potential substitute suppliers brought by industrial incidents, such as technology advancement, could make relation-specific investment obsolescent.

### 2.3 Necessary modifications for long-distance JIT system and deviation from conventional JIT paradigms

Interestingly, JIT researchers have presented contrasting insights into the location arguments between buyers and suppliers. While the prior research stream suggests that JIT partners should locate close to each other for tight coordination, another group of experts suggest otherwise. Anderson and Quinn (1986) indicated that deregulation made longer distance transportation feasible in JIT systems in that the transportation costs can be better controlled than before. Ansari (1986) observed that, in his field study, a majority of U.S. firms (eleven of twenty-one) consider location of suppliers of little or no importance in JIT; in contrast, only two out of twenty-one U.S. companies deem supplier proximity an important factor. Bartholomew (1984) also found that United States auto suppliers are not necessarily close to the assembly plants and that adoption of JIT does not lead suppliers to move plants closer to customers. Finally, Harpter and Goodner (1990) point out that JIT can be implemented in a number of industrial supply chains which overcome geographical challenges by creative design of transportation system.

Accordingly, despite of the wide acceptance of JIT from the U.S. firms (Wood and Murphy, 2004), conventional JIT experiences cannot directly translate into US firms' achievement without any modification. Issues regarding quality, on-time delivery, and fair pricing were more important in the selection of supply chain partners (Ansari, 1986). The global end-to-end supply chain networks of US firms are geographically spread-out, a substantial difference from the original JIT philosophy. In addition, the long-distance supply chain system posts challenges for inter-firm coordination which seemingly contradict to the JIT's original frequent shipping approaches.

Hence, large-scale JIT partner will need to confront the following disadvantages. Firstly, frequent long-distance transportation will certainly cause high transport cost, so efficient and integrative transportation and distribution processes must be arranged to minimize the total costs. Secondly, long-distance transportation results in longer lead-time, and high lead-time variation in turn can cause higher inventory costs. Consistent long-haul modes, therefore, should be utilized to maintain service level. Lastly, JIT participants should be prepared for emergency shortage of material with long-distance supply and distribution line. These disadvantages incur substantially higher logistics costs in the forms of premium delivery or higher level of safety stock. In the next section, multiple approaches are proposed to account for the prior issues. Whereas, the strategies may deviates from the conventional small, frequent shipping activities, the main objective of these strategies is aimed at the consistency of transportation function, inventory minimization, and in the meantime reduces traffic congestion.

## 3. Strategies to overcome long-distance supply chain

In order to overcome the challenges caused by the long-distance supply chain, three "pillars", i.e. B2B IT, consolidation, and inventory classification have been documented in the logistics literature. Whereas these pillars are necessary for global JIT, additional strategies utilizing cutting-edge technologies and logistical arrangements will be required to enable the JIT system. This section first summarizes the three pillars and then proceeds with applications of the latest JIT-enabling communication and logistics innovations that serve as JIT facilitators.

### 3.1 B2B IT for JIT supply chain coordination

Inter-organizational, or B2B, communication technology serves as the foundation for coherent operations (Bookbinder & Dilts, 1989; Lee et al., 1999). In a complex, cross-functional and, possibly, -cultural supply chain, B2B e-commerce could enhance the information sharing between supply chain partners (Malone et al., 1987). As an example, the prevalent EDI system as well as the Internet has been proved to make it possible to track information and trace physical flow among supply chain partners – suppliers, carriers, and buyers are able to obtain accurate data on inventory in transit and in turn better estimate lead-time (Lee et al., 1999).

Extended JIT system can take advantage of integration across the entire value system and reduce the total lead-time by a nontrivial magnitude. Without a IT-enabled network, the bullwhip effects, exasperated by the long-distance transportation and communication, supply chain participants may not substantiate the JIT benefits (Lee et al., 1997). Ultimately, higher level of information sharing among the coordinated processes will translate into timely deliveries and shorter replenishment cycle in JIT system, thus realizing lower inventory levels and better bottom-line performances (Claycomb & Germain, 1999).

### 3.2 Freight consolidation

The efficiencies benefited from better supply chain B2B coordination can also help arrange consolidation (Daugherty et al., 1994; White, 2005). Lately, the regional economic integration, e.g. EU and NAFTA, have removed cross-nation boundaries and help international trading partners to develop large scale consolidation. As such, less-than truckload (LTL) carriers can operate multi-national haulage and move goods to the assigned consolidation center in a JIT fashion. Consolidation of inbound freight involves grouping two or more small shipments from one or more suppliers to form a single large shipment (Bagchi, 1988). Items in temporary storage awaiting consolidation can be combined with outbound shipments for faster, more reliable truckload (TL) transportation (Buffa, 1987).

Fig. 2 shows a manufacturer having long-distance lines without freight consolidation and receiving shipments separately. In contrast, Fig. 3 shows a long-distance inbound transportation system with consolidation, which displayed a relatively simplified freight network. A regional distribution center of this system could assemble loads for multiple suppliers for consolidated shipments to a plant. Inbound small shipments can still operate on a JIT basis, yet the outbound transportation utilizes the more efficient and quicker TL mode.

Consolidating inventory items has been a critical strategy for managing the transportation-inventory trade-off which is targeted at the total logistics cost minimization (White, 2005). Order quantity and order cycle in a consolidation setting are substantially different from those individual, separate orders (Schniederjans & Cao, 2001). Consolidation of items into a single order changes each item's inventory costs regarding ordering, carrying, and expected stockout. Initially, large-scale consolidation may temporarily increase each shipping unit's processing cost and/or inventory carrying cost in the consolidation center. However, consolidation programs combine multi-items into a single order and hence help firms negotiate freight rates (Daugherty & Spencer, 1990).

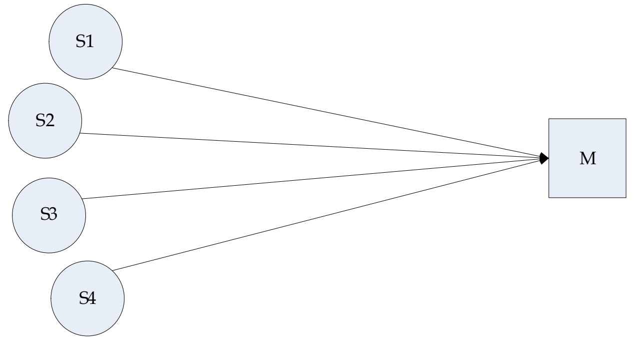


Fig. 2. Long-distance JIT

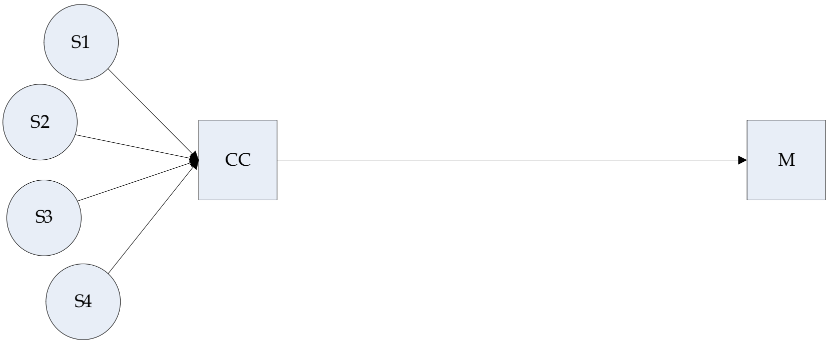


Fig. 3. Long-distance JIT with freight consolidation

By consolidating items for shipping purposes, buyers and shippers can reach increased shipping weight and lower freight rates without substantial increase of the order quantity of content items (Gupta & Bagchi, 1987). Inversely proportional freight rate structure works against the consolidated shipping weight and makes consolidation realize cost minimization. Moreover, decreasing freight rates may eventually offset the cost increase in consolidation and hence serve as the motivation of long-distance JIT due to the existence of strong economies of scale in transportation costs (White, 2005).

### 3.3 Supplier clustering

Supplier clustering and deciding the number and location of consolidation centers are important decisions to long-distance JIT transportation system planning (Wafa & Yasin, 1996). Firms acquire material from not only nearby suppliers but also long-distance suppliers. Consolidation hence may not be justified as a stand-alone system for an individual firm without adequate vendor and/or load concentration in the region serviced by the consolidation center. Shippers' ability to profitably consolidate freight depends on several factors, such as supplier concentration in the region under consideration, line-haul distance between the consolidation center and the destination, and the amount of freight generated in the region (Kelle et al., 2003). As a result, clustering vendors complement consolidation and may help achieve transportation scale economies. Fig. 4 shows consolidating without clustering the shippers.

At higher vendor concentrations, the mean cost per unit freight weight is likely to exhibit a downward trend, implying economies of scale from freight consolidation. These scale economies indicate that consolidation may perhaps be justified in a JIT inventory system with high vendor and/or load concentrations in the area serviced by the consolidation center (Banerjee et al., 2007; Wafa & Yasin, 1996). With an additional consolidation center, percentage of shipments through consolidation could increase and cost per unit could decrease. In cases of insufficient load it may be prudent to locate a consolidator who could arrange consolidation of freight in the same region and thus meet JIT procurement requirements. Fig. 5 shows the clustering and consolidating of the inbound JIT transportation system.

To cite most contrasting examples, compare neighboring origin-destination (OD) pairs versus long-distance OD pairs in supply chains. Consolidation would probably prove uneconomical for small shipments emanating from numerous points scattered over, for instance, Massachusetts and destined for points located in Connecticut. However, it would likely be a superior alternative for shipments from New Jersey to California, with supplier grouping and freight consolidation performed in the northeast area of the U.S.

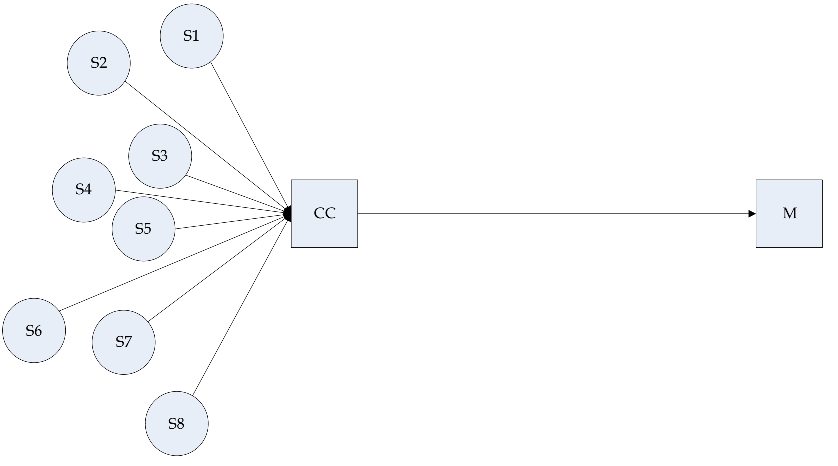


Fig. 4. Long-distance JIT with consolidation but without supplier clustering

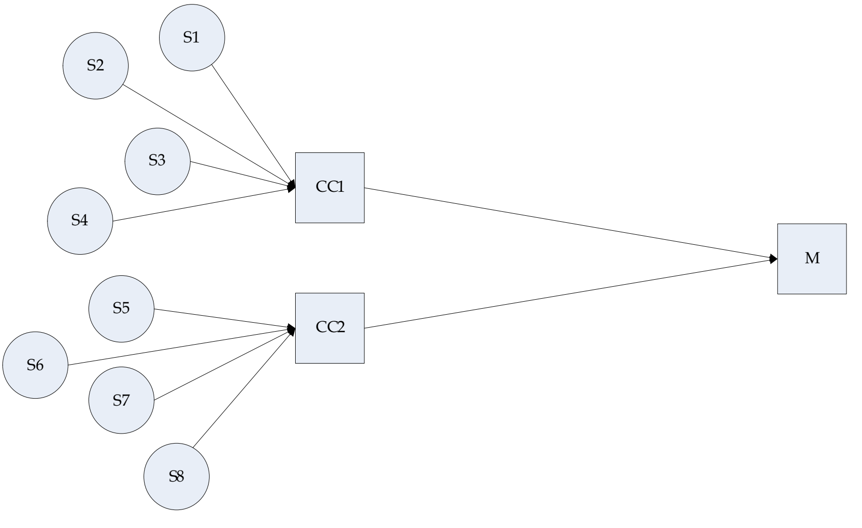


Fig. 5. Long-distance JIT with freight consolidation and supplier clustering

### 3.4 Cost-minimizing transportation mode selection

Because of the potentially high costs resulted from frequent deliveries, carrier selection is crucial for JIT system, especially for long-distance supply chain (Evers, 1999; Schwarz & Weng, 1999). The trend toward deregulation in the transportation industry has created a highly competitive environment in which both freight rates and services are adaptive to innovative shipping strategies. Most certainly, freight consolidation and supplier clustering affect the transportation modal selection. Service levels, i.e. delivery consistency, must thus be thoroughly examined to ensure the minimal transportation-inventory cost trade-off in JIT system.

Trucking is the prominent option for JIT management. Transportation scholars have employed trucking to establish a long-haul JIT model connecting assembly and distribution (Anderson & Quinn, 1986; Gupta & Bagchi, 1987). The long-haul transportation mode in the literature displays features resembling TL, i.e. fast, high-level service line haul from supply sources to the marketplace. The end-to-end TL operations have advantages over LTL operations in long-distance transportation (Lieb & Millen, 1988). TL removes stops in supply chain echelons and thus shortens transportation cycles. In contrast, the multiple terminal connections for LTL increase the likelihood of delays, thus hindering JIT operations. Consequently, if combined with freight consolidation, the distribution of transportation tasks can be as follows: TL should serve the main portion of long-haul transportation, while LTL will be mainly accounted for the feeding operation for cross-docking or the consolidation to take advantage of frequent but small shipments (Gupta & Bagchi, 1987; Lieb & Millen, 1990).

Researchers also propose that rail transportation serves as an alternative for long-haul transportation in the JIT system. While a stream of literature indicates that trucking will replace railroads' role in the JIT setting (Anderson & Quinn, 1986; Hoeffer, 1982; Lieb & Millen, 1988), Higginson and Bookbinder (1990) suggest that railroad industry might outperform competing modes beyond the cost advantages for long-haul. Potential strategies qualified for a rail JIT system include, but are not limited to 1) guaranteed delivery dates, 2) prearranged pickup and delivery, 3) short-term storage, 4) tardiness penalties, 5) regularly scheduled priority trains, 6) bypassing of time-consuming yard functions, 7) close communication with shippers and consignees, and 8) efficient freight consolidation. In short, long-distance JIT system users should incorporate railroads into their transportation choice set in addition to trucking.

Growing air forwarder/consolidator industry now gives firms an additional alternative to move their freight. Air freight integrators, such as Eagle Logistics, provides services by utilizing excess capacities from airlines. Schwarz and Weng (1999) explicitly suggest that, considering the total cost trade-off, firms may offset the high air freight costs through the saving in inventory carrying costs. This trend could mean a higher air freight volume which could drive air transport cost down. Shippers, carriers, and buyers thus should keep an eye on the changing air cargo alternatives and use total cost analysis to estimate the likelihood to use air transport into JIT systems, especially for emergency or express shipments (Gooley, 2000).

### 3.5 Emergence of 3PL partnerships as a global JIT requirements

Extensive 3PL engagement in the global JIT system might be the most distinct feature from the original JIT form. The prominent examples of 3PL integration, perhaps, are displayed in the U.S. computer industry. Dell Computer has followed a strict JIT rule – requiring its suppliers or consolidators (3PL) within 1 hour driving distance to fulfill JIT manufacturing (Magretta, 1998). Furthermore, HP also partners with global 3PL specialists, e.g. FedEx and UPS, to integrate the China-U.S. laptop supply chain (Dean & Tam, 2005). In the era of global supply chain, companies buy parts and components from abroad. Then, those imported parts and components are oftentimes consolidated by 3PLs that are within the driving distance from a manufacturer (Kreng & Wang, 2005). In a foreign manufacturing environment, a cluster is often formed through physical proximity for JIT manufacturing (Wood and Murphy, 2004). Accordingly, the proximity paradigm has never been totally abandoned by successful firms. Rather, they utilize the extended transport networks of global 3PL's in various regions. This partnering with 3PL's streamlines the JIT operations and contributes to lean and agile supply chain (Kreng & Wang, 2005).

### 3.6 Inventory classification to facilitate transportation

An additional fine-tuning strategy to enhance long-distance JIT is the inventory classification. Higginson and Bookbinder (1990) indicate that the well-known ABC classification can be utilized to match distinct transportation modes. For instance, type A, or fast-moving items, should be transported by truck to satisfy time constrains. Type B items can utilize a combination of railroads and short-term storage so firms can reduce freight rates and capitalize on short-term postponement leverage. Type C, slow-moving items, could use modes to meet cost or service considerations. In sum, JIT participants will need to evaluate the trade-off inventory cost against the cost of shipping to determine the best mix of transportation arrangements and, ultimately, the total JIT optimization.

### 3.7 Cross-docking arrangement for seamless physical flow

Utilizing cross-docking to reinforce JIT systems, interestingly, remains unexplored by logistics experts. Cross-docking mechanisms implemented in a consolidation center can allocate and assort large sporadic incoming items into bundles of shipments, which can be specified by the B2B IT system (Gümüş & Bookbinder, 2004; Waller et al., 2006). If combined with freight consolidation, the distribution of transportation tasks can be performed as follows: TL serves as the main portion of long-haul transportation, while LTL will account for the feeding operation for cross-docking or the consolidation to take advantage of frequent but small shipments (Lee et al., 2006). As an example, highly efficient cross-docking operations equipped with Auto ID technologies, e.g. the Wal-Mart automated bar code system, help specify the attributes of shipments and handling directions, and then guide the shipments to loading docks, awaiting outbound transportation. Cross-docking thus helps JIT participants overcome the bottlenecks resulted from complex allocation and assortment processes. Finally, equipped with cross-docking expertise, supply chain partners can have greater agility which substantiates the timely delivery in JIT strategy (Sung & Song, 2003).

### 3.8 Advanced communication JIT enablers

The latest communication technologies have made superior supply chain coordination possible, a determinant for an effective JIT system (Bookbinder & Dilts, 1989). Satellite communication, e.g. global positioning system (GPS), together with the latest radio frequency communication has been proposed to facilitate communication throughout the entire global supply chain system (Giermanksi, 2005). Auto identification (auto-ID) systems, e.g., automated bar code or radio frequency identification (RFID) technologies, can enhance the allocation and assortment functions and control physical flows real-time in distribution centers or terminals (Rutner et al., 2004). In an auto-ID enabled terminal system, multiple shipping entities, e.g. cases, pallets, containers, and shipment contents can be processed

automatically and communicated simultaneously across the entire supply chain (Keskilammi et al., 2003; Penttilä et al., 2006).
The prior technologies can strongly improve the performance at all coordination interfaces. At individual terminals, prolonged, manual operations for freight allocation and assortment are usually considered less productive for multi-echelon logistics systems. Auto ID system can, contrastingly, read attributes on shipment ID tags or bar codes, automatically assigning the shipments to cross-docking for outbound transportation or storage for later processing (Lee & Özer, 2007). Equipped with the latest auto-ID technologies, carriers will be capable of achieving real-time JIT coordination even in a multiple-terminal network.
Finally, advanced IT can assist regulatory institutions businesses to reduce traffic congestion - the major external obstacle for JIT transportation (Rao & Grenoble, 1991b). In the private sector, a number of software packages, such as transportation management system, are now available for improving scheduling and routing of material and goods movements. Such packages can be utilized to explore less congested routings (Rao & Grenoble, 1991a). For transportation administration, long-term policies include investments in 1) logistics facility relocation; 2) satellite operation; 3) changing channel structure and public-private cooperation. In short, endeavor from businesses and transportation regulators in investing supply chain communication and coordination technologies should help alleviate congestion and eventually facilitate the JIT practice.

## 4. A roadmap to simulate and manage long-distance JIT system

From a manufacturer's perspective, transportation in a JIT supply chain can be split into two directions: outbound distribution and inbound supply. Both outbound distribution and inbound supply transport systems need to solve not only short-distance but also long-distance delivery problems. This chapter presents a roadmap as an illustration of managing inbound long-distance JIT system (Fig. 6). While only the inbound section is presented here, the same principle can be applied to outbound section.
With reference to Fig.6, the first step for long-distance JIT operations is to seek the support from top management and to establish consistency with overall business strategy. Operations of the logistical chain are not independent from a firm's and its trading partners' strategies; changes in one business unit (e.g., JIT implementation) need to be assessed in light with strategic impacts along the chain. For a long-distance transportation system, firms participating in JIT systems need to conduct thorough evaluation into how inventory and transportation costs are correlated. The cost trade-off results will direct the subsequent implementation processes.
Supply chain partners should then establish an inter-firm IT system which facilitates terminal processing and freight tracking. The multi-layer terminal network should also be equipped with advanced supply chain technologies and solutions to support cross-docking and consolidation processes. Supply chain optimization programs can be utilized to categorize supply geographical locations and classify inventory items. Equipped with technology and cross-docking expertise, supply chain partners can have greater flexibility to determine transportation modes. Logistics managers should carry out total cost examinations and study alternatives, or various combinations of them: freight consolidation, supplier clustering, and optimal transportation arrangements. Finally, implementation needs continuous managerial effort to monitor the performances.

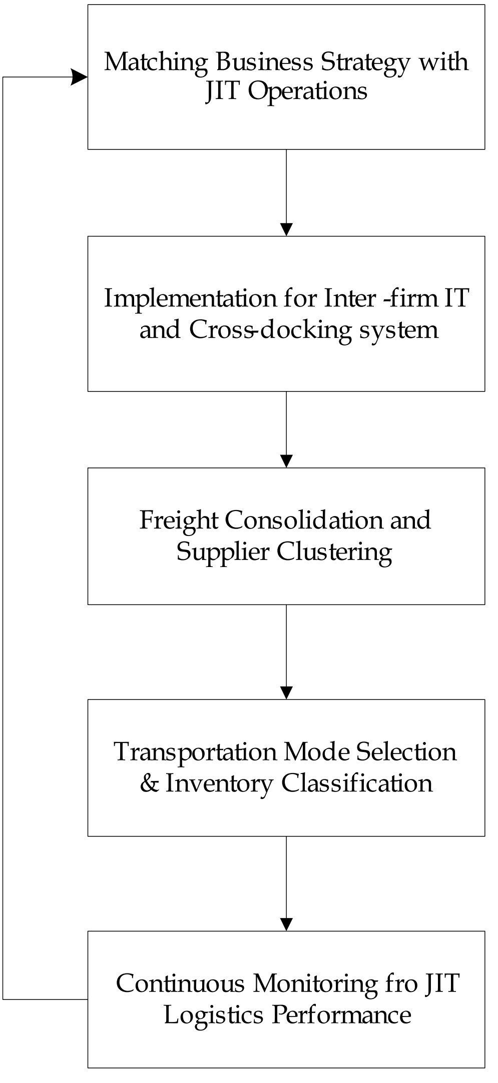


Fig. 6. Roadmap for implementing long-distance JIT system

## 5. Concluding remarks

### 5.1 Discussion and managerial implications

The emerging global supply chain network and increasing outsourcing has drastically extended the geographical span of logistics systems. Furthermore, fierce competition from local and international markets has forced firms to utilize cross-nation, oftentimes global, long-distance JIT for superior customer service level. Equipped with advanced technology and consolidation capabilities supporting conventional JIT operations, supply chain partners may be able to optimize the inventory and transportation cost trade-off in JIT. This chapter thus proposes that by integrating the latest communication technologies (e.g. RFID) and advanced logistics arrangements (e.g. cross-docking), firms could enhance long-distance JIT without sacrificing supply chain profitability and service levels. Finally, this study presents a roadmap to guide decisions of long-distance inbound JIT. The framework is aimed at solving obstacles hindering long-distance JIT, i.e. high transportation costs, long lead-time, traffic congestion, and emergency risks.

Given the complexity of an extended supply chain network, management could utilize the framework to evaluate financial impacts of individual logistics strategies in long JIT systems and the combinations of them. Specifically, supply chain partners will need to jointly monitor rate schedules and service policies incurred by modified freight transportation. They also need to review inventory costs caused by a consolidation strategy. As well, the logistics managers shall carefully evaluate alternatives concerning the supplier clustering, inventory classification, delivery frequency, transport mode of different materials, and risk management for emergencies & response and recovery plans.

Additional accommodations may further facilitate the long haul JIT. The main thrusts of a JIT strategy in production and warehousing should not restrict the method of delivery, as long as that mode can meet JIT service level and overall cost requirement. Rao and Grenoble (1991a, 1991b) suggest short term tactics and long term strategies to deal with traffic congestion problem of JIT system. Off peak deliveries and computer routing support could be the most effective without drastic change in logistics operations. Delivery during non-rush hours can result in more predictable deliveries and less disruption to operations. The cost involved in accommodating off-peak deliveries could be minor if the space and labor is available and the facility already operates around the clock. Other short terms for more efficient transportation infrastructure include improved shipping/receiving facilities, speedy delivery administration, vendor incentives to improve operations, delivery truck design, and unitization/palletization.

### 5.2 Limitations and future research

This chapter is positioned as being a guideline for fine-tuning the original form of JIT. IT utilization, shipment consolidation, and transportation mode selection are the three major components to change the conventional "buyer-seller proximity" paradigm. While the three "pillars" of modified JIT is not new and all these elements are a must regardless of distance in JIT system, these elements only have been separately examined in the literature. Empirical studies as to how these elements individually and collectively contribute to a JIT design success are limited in amount. Currently, there is no empirical research studying the weights and trade-offs of the three JIT pillars, let alone the extended JIT applications in the global contexts. As a result, the following questions remained not fully addressed: among those companies that are practicing successful JIT, how many firms do or do not utilize IT, consolidation (and cross-docking), and/or fast transportation?

Furthermore, the similarities and divergences for domestic and global JIT supply chains in practices are largely unexplored in the empirical research. In-depth field works and extensive empirical studies are therefore in order. Along this line, it is not a secret that U.S. automakers modified Japanese JIT system in seeking competitiveness in the market. Given the highly complex processes and multiple variables in global JIT operations, what would be the system-wide remedial and emergency alternative for JIT failure? As well, extant global

JIT supply chains only focus on particular buyer-supplier pair in the system. Extensive dyadic and triadic method investigating the entire JIT system is thus necessary.

Combinations of the aforementioned solutions and the proposed roadmap paved an avenue for firms to conduct pilot JIT exercise and/or simulation analysis. The high complexity and implementation costs may prevent extensive implementations or experiments for long-distance JIT. Hence, firms or researchers can utilize the prior logistics strategies to simulate scenarios of long-haul JIT on both inbound and outbound sides of a supply chain. Simulation scenarios should reflect long-distance JIT design before and after supporting strategies, e.g. freight consolidation, are implemented. By doing so, supply chain partners may capitalize on low cost simulation exercise to better estimate impacts of the actual decisions pertaining to JIT operations.

## 6. References

Anderson, D.L. and Quinn, R.J. (1986), The Role of Transportation in Long Supply Line Just-in-Time Logistics Channels. *Journal of Business Logistics*, Vol.7, No. 1, pp. 68-88

Ansari, A. (1986), Strategies for the Implementation of JIT Purchasing. *International Journal of Physical Distribution & Materials Management*, Vol.16, No. 7, pp. 5-12

Bagchi, P.K. (1988), Management of Materials under Just-in-Time Inventory System: A New Look. *Journal of Business Logistics*, Vol.9, No. 2, pp. 89-102

Bagchi, P.K., Raghunathan, T.S., and Bardi, E.J. (1987), The Implications of Just-in-Time Inventory Policies on Carr. *Logistics and Transportation Review*, Vol.23, No. 4, pp. 373-384

Banerjee, A., Kim, S.-L., and Burton, J. (2007), Supply Chain Coordination through Effective Multi-Stage Inventory Linkages in a JIT Environment. *International Journal of Production Economics*, Vol.108, No. 1/2, pp. 271-280

Bartholomew, D. (1984), The Vendor-Customer Relationship Today. *Production & Inventory Management*, Vol.25, No. 2, pp. 106-121

Bookbinder, J.H. and Dilts, D.M. (1989), Logistics Information Systems in a Just-in-Time Environment. *Journal of Business Logistics*, Vol.10, No. 1, pp. 50-67

Buffa, F.P. (1987), Transit Time and Cost Factors: Their Effects on Inbound Consolidation. *Transportation Journal*, Vol.27, No. 1, pp. 50-63

Chapman, S.N. (1992), Using Risk-Averse Inventory for JIT Process Improvements. *Production & Inventory Management Journal*, Vol.33, No. 4, pp. 69-74

Chopra, S. and Meindl, P. (2007), *Supply Chain Management : Strategy, Planning, and Operation*, 3rd Ed. Prentice Hall, Upper Saddle River, NJ, USA

Claycomb, C. and Germain, R. (1999), Total System JIT Outcomes: Inventory, Organization and Financial Effects. *International Journal of Physical Distribution & Logistics Management*, Vol.29, No. 9/10, pp. 612-630

Daugherty, P.J., Rogers, D.S., and Spencer, M.S. (1994), Just-in-Time Functional Model. *International Journal of Physical Distribution & Logistics Management*, Vol.24, No. 6, pp. 20

Daugherty, P.J. and Spencer, M.S. (1990), Just-in-Time Concepts: Applicability to Logistics/Transportation. *International Journal of Physical Distribution & Logistics Management*, Vol.20, No. 7, pp. 12-18

Dean, J. and Tam, P.-W. 2005. The Laptop Trail, *Wall Street Journal*: B.1

Evers, P. (1999), The Effect of Lead Times on Safety Stocks. *Production and Inventory Management*, Vol.40, No. 2, pp. 6-10

Giermanksi, J.R. (2005), *The Smart Container: Its Technology, Its Function, and Its Benefit in Securing the Global Supply Chain*, Council of Supply Chain Management Professionals, Oak Brook

Giunipero, L.C., Pillai, K.G., Chapman, S.N., and Clark, R.A. (2005), A Longitudinal Examination of JIT Purchasing Practices. *International Journal of Logistics Management*, Vol.16, No. 1, pp. 51-70

Gomes, R. and Mentzer, J.T. (1991), The Influence of Just-in-Time Systems on Distribution Channel Performance in the Presence of Environmental Uncertainty. *Transportation Journal*, Vol.30, No. 4, pp. 36-48

Gooley, T.B. (2000), Domestic Air Freight Makes a Comeback. *Logistics Management & Distribution Report*, Vol.39, No. 4, pp. 65-69

Gümüş, M. and Bookbinder, J.H. (2004), Cross-Docking and Its Implications in Location-Distribution Systems. *Journal of Business Logistics*, Vol.25, No. 2, pp. 199-228

Gupta, Y.P. and Bagchi, P.K. (1987), Inbound Freight Consolidation under Just-in-Time Procurement: Application of Clearing Models. *Journal of Business Logistics*, Vol.8, No. 2, pp. 74-94

Harper, D.V. and Goodner, K.S. (1990), Just-in-Time and Inbound Transportation. *Transportation Journal*, Vol.30, No. 2, pp. 22-31

Higginson, J.K. and Bookbinder, J.H. (1990), Implications of Just-in-Time Production on Rail Freight Systems. *Transportation Journal*, Vol.29, No. 3, pp. 29-35

Hoeffer, E. (1982), Gm Tries Just-in-Time American Style. *Purchasing*, Vol.19, No.?, pp. 69-?

Kelle, P., Al-Khateeb, F., and Anders-Miller, P. (2003), Partnership and Negotiation Support by Joint Optimal Ordering/Setup Policies for Jit. *International Journal of Production Economics*, Vol.81/82, No. 431-441

Keskilammi, M., Sydänheimo, L., and Kivikoski, M. (2003), Radio Frequency Technology for Automated Manufacturing and Logistics Control. Part 1: Passive RFID Systems and the Effects of Antenna Parameters on Operational Distance. *International Journal of Advanced Manufacturing Technology*, Vol.21, No. 10/11, pp. 769-774

Kreng, V.B. and Wang, I.C. (2005), Economical Delivery Strategies of Products in a JIT System under a Global Supply Chain. *The International Journal of Advanced Manufacturing Technology*, Vol.26, No. 11-12, pp. 1421-1428

Lee, H.G., Clark, T., and Tam, K.Y. (1999), Research Report. Can EDI Benefit Adopters? *Information Systems Research*, Vol.10, No. 2, pp. 186-195

Lee, H.L. and Özer, Ö. (2007), Unlocking the Value of Rfid. *Production & Operations Management*, Vol.16, No. 1, pp. 40-64

Lee, H.L., Padmanabhan, V., and Whang, S. (1997), Information Distortion in a Supply Chain: The Bullwhip Effect. *Management Science*, Vol.43, No. 4, pp. 546-558

Lee, Y.H., Jung, J.W., and Lee, K.M. (2006), Vehicle Routing Scheduling for Cross-Docking in the Supply Chain. *Computers & Industrial Engineering*, Vol.51, No. 2, pp. 247-256

Lieb, R.C. and Millen, R.A. (1988), JIT and Corporate Transportation Requirements. *Transportation Journal*, Vol.27, No. 3, pp. 5-10

Lieb, R.C. and Millen, R.A. (1990), The Responses of General Commodity Motor Carriers to Just-in-Time Manufacturing Programs. *Transportation Journal*, Vol.30, No. 1, pp. 5-11

Magretta, J. (1998), The Power of Virtual Integration: An Interview with Dell Computer's Michael Dell. *Harvard Business Review*, Vol.76, No. 2, pp. 72-84

Malone, T.W., Yates, J., and Benjamin, R.I. (1987), Electronic Markets and Electronic Hierarchies *Communications of the ACM*, Vol.30, No. 6, pp. 484-497

Modarress, B., Ansari, A., and Willis, G. (2000), Controlled Production Planning for Just-in-Time Short-Run Suppliers. *International Journal of Production Research*, Vol.38, No. 5, pp. 1163-1182

Penttilä, K., Keskilammi, M., Sydänheimo, L., and Kivikoski, M. (2006), Radio Frequency Technology for Automated Manufacturing and Logistics Control. Part 2: RFID Antenna Utilisation in Industrial Applications. *International Journal of Advanced Manufacturing Technology*, Vol.31, No. 1/2, pp. 116-124

Rao, K. and Grenoble, W.L. (1991a), Modelling the Effects of Traffic Congestion on Jit. *International Journal of Physical Distribution & Logistics Management*, Vol.21, No. 2, pp. 3-9

Rao, K. and Grenoble, W.L. (1991b), Traffic Congestion and Jit. *Journal of Business Logistics*, Vol.12, No. 1, pp. 105-121

Rutner, S., Waller, M.A., and Mentzer, J.T. (2004), A Practical Look at Rfid. *Supply Chain Management Review*, Vol.8, No. 1, pp. 36-41

Schniederjans, M.J. and Cao, Q. (2001), An Alternative Analysis of Inventory Costs of JIT and EOQ Purchasing. *International Journal of Physical Distribution & Logistics Management*, Vol.31, No. 2, pp. 109-123

Schonberger, R.J. and Gilbert, J.P. (1983), Just-in-Time Purchasing: A Challenge for U.S. Industry. *California Management Review*, Vol.26, No. 1, pp. 54-68

Schwarz, L.B. and Weng, Z.K. (1999), The Design of a JIT Supply Chain: The Effect of Leadtime Uncertainty of Safety Stock. *Journal of Business Logistics*, Vol.20, No. 1, pp. 141-163

Sung, C.S. and Song, S.S. (2003), Integrated Service Network Design for a Cross-Docking Supply Chain Network. *Journal of the Operational Research Society*, Vol.54, No. 12, pp. 1283-1295

Wafa, M.A. and Yasin, M.M. (1996), The Impact of Supplier Proximity on JIT Success: An Informational Perspective. *International Journal of Physical Distribution & Logistics Management*, Vol.26, No. 4, pp. 23-34

Waller, M.A., Cassady, C.R., and Ozment, J. (2006), Impact of Cross-Docking on Inventory in a Decentralized Retail Supply Chain. *Transportation Research: Part E*, Vol.42, No. 5, pp. 359-382

White, S.C. 2005. Special Report: Freight Consolidation. Council of Supply Chain Management Professionals

Williamson, O.E. (1985), *The Economic Institutions of Capitalism*, Free Press, New York

Wong, C.Y. and Johansen, J. (2006), Making JIT Retail a Success: The Coordination Journey. *International Journal of Physical Distribution & Logistics Management*, Vol.36, No. 2, pp. 112-126

Wong, C.Y., Stentoft-Arlbjørn, J., and Johansen, J. (2005), Supply Chain Management Practices in Toy Supply Chains. *Supply Chain Management*, Vol.10, No. 5, pp. 367-378

Wood, D.F. and Murphy Jr., P.R. (2004), *Contemporary Logistics*, 8th Ed. Prentice Hall, NJ. U.S.A.

# 13

# Governance Mode in Reverse Logistics: A Research Framework

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## 1. Introduction

Traditional Supply Chain Management (SCM) is concerned with the flow of raw materials and finished goods (Prahinski & Kocabasoglu, 2006). Today, the scope for SCM in the context of environmental sustainability has extended to include the reverse flow of unsold finished goods, parts and packaging materials from the point of consumption back to the organization or to the rework /refurbishing vendors (Rogers & Tibben-Lembke, 2001). With the rise in environmental awareness, many companies have started to reduce waste, recycle, and refurbish their products for a more sustainable future. Governments in many countries are starting to develop clearer and stricter environmental regulations on issues such as the disposal of chemical waste, clean production, and carbon emissions. For example, firms in Europe are expected to "take-back" the environmentally hazardous products and packaging for recycling or reuse (Kumar & Putnam, 2008).

Today, reverse logistics has been adopted significantly by the automotive and aerospace spare parts markets as well as the electronics and computer hardware markets. The practice of reverse logistics offers several advantages to a company in terms of both tangible and intangible benefits. First, companies are able to retrieve defective equipments and parts which are either salvaged or refurbished and thus reclaim value out of the defective parts. Already, the annual value of commercial returns has exceeded US$100 billion (Stock et al., 2002). Second, the packaging and defective materials are collected and recycled thereby generated scrap value back for the company. Companies have found more economic value in better managing the reverse supply chain (Stock et al., 2006). Third, in the eyes of the customer and society, the organization could gain a good standing and reputation of being a responsible company that takes care of hazardous wastes with effective corporate social responsibility policies. Thus, a supply chain that can differentiate the returned products early and recover timely valuable parts can yield a competitive advantage (Guide et al., 2006).

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In the consumer electronics sector, refurbished computers are sold at cheaper prices by all the leading brands and the demand for such laptops seems to be growing. The spare parts used by the computer manufacturers to service their products on warranty or on sale, include refurbished parts. Many electronic and consumer durable manufacturing companies offer buy back or exchange offer for the old equipment in lieu of the customer purchasing new equipment. However, managing the reverse logistics process is as operations intensive and complex as the forward supply chain, demanding the same focus and can involve multiple logistics partners such as 3PLs. Companies such as IBM, HP, Dell and Xerox have established deep processes and networks of refurbishing centres aligned with spare parts distribution centres. Unlike managing good parts inventory, defective spare parts require more handling and processes at the 3PL end. It has been commonly noticed that while the process demands defective parts to be returned in good condition, both the users and retailers do not pay enough attention to handling defective parts. Statistics suggest that defective parts suffer more damage in transit and handling than good parts.

In the automotive and aerospace industries, reverse logistics is closely linked to spare parts management or service parts logistics. In the automobile industry, the profit margin of the after-sale service is much higher than that of selling new cars, particularly for cars in the low price /high volume segments (Maxton & Wormald, 2004). While manufacturers continue to face constant downward pressure due to the higher costs of materials, lower sales, and stiffer competition, the aftermarket business is able to maintain positive growth because of the consolidation in the market which produces economies of scale, and the fact that people are holding on to cars longer and therefore demand more replacement parts. Further, with the frequent vehicle recalls in recent years, an unfortunate side effect of rapid product innovation, the volume can be even higher than the annual sale as is the case of Toyota in 2010 (Bensinger, 2010).

In the aerospace industry, the extent of outsourcing by manufacturers is as high as 80% (Harney, 2005). Similarly, over 70 percent of a product's total value is created by suppliers in the automotive industry (Leenders et al., 2002). Many spare parts are with the supplier rather than the manufacturer. The management of outsourced supplies in both quality control and chain coordination is a critical issue for both forward and reverse SCM (Youngdahl et al., 2008).

With the growing level of complexity connected to outsourcing, especially offshore outsourcing, many companies have considered and applied the option of outsourcing part of or their entire reverse supply chain to 3PLs. In the aerospace industry, many manufacturers have passed the responsibility of the maintenance, repair and overhaul to an OEM or a third party who specializes in the field. Service technologies have become so specialized that it makes sense to outsource to a specialist like Smart Signal, a company which makes systems that monitor the performance of plane engines to predict probable breakdowns (Harney, 2005). In the automotive industry, 3PLs are also heavily involved in reverse logistics such as shipping returned products. Some manufacturers also outsource the warehousing function of their spare parts to 3PLs as in the case of Embraer in Singapore (Haq, 2007). In general, 38% manufacturers have outsourced reverse logistics according to 2009 14th Annual Third-Party Logistics Study (Langley, 2009).

Some benefits of reverse logistics outsourcing include SCM cost reduction through leveraging on the 3PL's pooled demand as well as its professional expertise and better operational or technology infrastructure for SCM functions. The focal firms can avoid huge capital expenditures in facilities and enjoy the benefits of flexibility afforded by the 3PLs, which release them to focus on their core competencies (Li & Olorunniwo, 2008).

Research to date has not investigated reverse supply chain governance with theoretical rigor. A realistic and rigorous examination on reverse logistics governance is valuable for both academia and practice. What are the advantages and weaknesses of third-party governance? For a manufacturer facing a complex reverse supply chain, should the firm choose outsourcing or invest in supply chain self governance to improve chain coordination? Which aspects of reverse supply chain should be outsourced to reduce cost and which should be kept in-house? How should the firm search for such a 3PL?

This paper views reverse logistics outsourcing as a "buy" decision in SCM, similar to the ordinary outsourcing as a "buy" in the field of firm strategy. The make-or-buy problem is a fundamental issue in strategic management (Rumelt et al., 1994: 564), and various theories such as transaction cost economics (TCE) and resource-based view (RBV) can be applied. We propose a cost-value framework providing a comprehensive account to compare the benefits and costs of the make-or-buy decision in the context of reverse logistics so as to help the manufacturers evaluate the feasibility of reverse logistics outsourcing. This study contributes to the literature by providing a research framework on reverse logistics governance as well as practical suggestions for firms to improve on reverse supply chain collaboration and performance.

The rest of the chapter is organized as follows. We review the outsourcing governance literature as well as some current practices. A research framework that systematically compares the relative benefits and cost of reverse logistics outsourcing versus a self-managed reverse supply chain is then presented. Five sets of propositions are presented for further empirical investigation. The discussions and implications follow thereafter.

## 2. Review on reverse logistics governance & research framework

In a typical supply chain, a focal manufacturer procures from multiple suppliers and sends its products to multiple customers. Under globalization, these suppliers and customers can be located in faraway countries, and the manufacturer needs to find effective ways to manage the flow of goods along a disintegrated and dispersed supply chain. When customers decide to return the products or seek spare parts for repair, the manufacturer normally needs to coordinate with the 3PL(s) to ship the products or spare parts, and may further work with the suppliers if the spare parts are managed in-house. When firms outsource the management of the reverse supply chain, they can choose to outsource the logistics of its supplies or end-products, or the entire reverse supply chain of certain products. For example, UPS and FedEx as 4PLs have helped their clients in the electronics industry to manage their outbound logistics as well as their reverse logistics. Some 3PLs help high-tech manufacturers like Dell manage the inventory and product returns. While this paper discusses the governance of the entire reverse supply chain, it can be applied to part of the chain governance also. The firm can manage the overall reverse chain by itself but outsource the governance of one section to a third party.

The manufacturer needs to consider three fundamental issues when selecting its reverse supply chain partners and the corresponding governance modes, namely, capability, past relationships, and uncertainty according to the management literature (e.g., Folta, 1998; Hoetker, 2005; Vivek et al., 2008). Hereafter, we focus on the impact of the industry and firm characteristics, and exclude the influence of past relationships which is relationship specific.

Various theories have been used to explore these issues. For instance, TCE focuses on the effect of transaction characteristics such as uncertainty and asset specificity on the associated governance costs. It then asks how the make-or-buy decision or another hybrid governance form such as joint ventures magnifies or diminishes that effect (Williamson, 1981; Williamson, 1991). From another lens, RBV looks at the partners' technical capabilities and the potential synergies from combining the partners' resources such as reducing redundant resources and knowledge exchange resulting in new capabilities (Barney, 1991; Madhok, 2002). In addition, scholars have applied real option theory to technology sourcing and identified two types of uncertainty with different implications on governance costs: exogenous uncertainty, i.e., uncertainty largely unaffected by the actions of the partner such as technological uncertainty, and endogenous uncertainty, i.e., uncertainty can be decreased by action of the partner (Folta, 1998). While integration can reduce endogenous uncertainty, external equity collaboration is more effective in controlling exogenous uncertainty (Folta, 1998; Van De Vrande et al., 2009).

TCE is concerned with managing the exchange efficiently to minimize the total transaction cost and is based on the central assumption of firm opportunism (Williamson, 1991; Balakrishnan & Koza, 1993). Exchange attributes such as information asymmetry (Balakrishnan & Koza, 1993), asset specificity (Williamson, 1991), and performance measurement difficulty (Williamson, 1981) would influence the effectiveness of the governance mode, which ranges from a one-off contractual relationship (market), franchises, non-equity alliances, joint ventures, to full integration (hierarchy). An organization can deploy a variety of nonmarket or structural mechanisms, including bureaucratic administration to reduce the transaction cost and contain opportunism (Williamson, 1991). A zero transaction cost environment would lead to perfect market competition in which all exchanges would be executed by contracts while high transaction costs would bring in vertical integration and bureaucratic control.

RBV starts from the heterogeneity of firms and asserts that the firm-specific resource is the primary reason for superior firm performance, which is built through an ongoing learning process (Wernerfelt, 1984; Barney, 1991). Given the resource heterogeneity (resources that differ), imperfect mobility of assets (resources not easily moved between firms), ex post limits on competition, and ex ante limits on competition (limitations exist on competitive resource position and valuation), firms are able to maintain their competitive advantage in an imperfect market (Peteraf, 1993). However, firms operating in an uncertain environment are often difficult to discern which resources are critical for future success. Capability building through learning and experimentation is of paramount concern to them (Madhok, 2002; Gans & Stern, 2003).

Real option theory highlights the exogenous uncertainty beyond the control of firms such as environmental turbulence and technological newness (Van De Vrande et al., 2009). As these uncertainties largely resolve over time, it suggests that firms keep their options open when costs are high. Hybrid governance modes such as alliances can be seen as options for the focal firm to defer the internal development or acquisition of a targeted firm (e.g., Folta, 1998; Hagedoorn & Duysters, 2002). By deferring the full commitment, the firm can limit its exposure to any exogenous uncertainty while keeping a means to capitalize on growth opportunities and potential benefits (Folta, 1998).

There are many studies applying these theoretical lenses to the context of outsourcing, especially supplier outsourcing, and some recent literature have made attempts in incorporating the key concerns of each body of them together. TCE and RBV literature have been integrated in an empirical study on the sourcing decisions of notebook computer manufacturers for innovative flat-panel displays, and it is found that the relative importance of supplier capabilities, past relationships, and being an internal or external supplier, is contingent on the level of uncertainty posed by the desired innovative component (Hoetker, 2005). In a longitudinal study of off-shoring relationships, it is reported that such relationships begin with calculative trust and opportunism, which later leads to resource-based competency building and non-economic trust. It starts from transactional to resource complementarities, and finally to a phase where trust and long-term orientation governs the process (Vivek et al., 2009).

When applying these theoretical perspectives to reverse logistics outsourcing, we use the transaction value approach to synthesize the multiple theories created (Zajac & Olsen, 1993). In contrast to uncertainty or time used before, transaction value is more rigorous and quantitative for general use. It is based on the premise that every governance mode comes with its own cost and value, and the manufacturer should maximize the net transaction value. Pure cost minimization may not be sufficient as the co-evolution of competencies in anticipation of value gains with supply chain partners could be the key for success in some industries (Madhok, 2002). The pursuit of greater joint value from collaboration may require a governance mode that is less cost efficient if the loss of efficiency is more than offset by the value created (Zajac & Olsen, 1993). Similarly, as both endogenous and exogenous uncertainties exist, the manufacturer faces a trade-off between the need for administrative control and the cost of commitment (Folta, 1998). While superior administrative control could minimize opportunistic cost, the associated benefits may be offset by the opportunity cost of committing aggressively to certain reverse logistics technology which may lose value after the change in government regulations. The total cost minimization should thus consider both opportunistic and opportunity cost.

We thus propose following framework to study the governance issue in reverse logistics. On the horizontal level, we examine relative benefits, relative relational cost (cost due to the conflict of interest in the supply chain), and relative external cost (cost due to external uncertainties such as the cost of early commitment). On the vertical level, we examine uncertainty and capabilities, including both stand-alone capabilities and capabilities of value creation from collaboration. We envision that this framework can aid in achieving a better understanding of the preferences of companies in the governance of their reverse logistics.

Notwithstanding the industry and firm characteristics, we can derive the following general observations as bases for further theoretical development.

- When an outsourcer has significant advantage over the manufacturer in the capabilities of managing reverse logistics, the manufacturer can obtain more benefits from outsourcing.
- When there is significant value generated from collaboration with supply chain partners in reverse logistics, the manufacturer can obtain more benefits from self-governing the supply chain as the chain governor would be the owner of these values.
- While high uncertainty may increase conflicts of interest between the manufacturer and the supply chain partners in reverse logistics, increase the relational costs, and make self-governance the better governance mode, external uncertainty may render the commitment of the manufacturer such as facilities obsolete after the change in external environment such as the release of new government regulations. In such cases, outsourcing can reduce the costs of commitment and create more flexibility from the perspective of the manufacturer.

| Transaction Characteristics | Relative capabilities of outsourcer | Capabilities of value creation from collaboration | Uncertainty |
|---|---|---|---|
| Relative benefits | More benefits of outsourcing if outsourcer is more capable | Self-governance can retain more value created | |
| Relative relational costs | | | Self-governance can reduce relational costs when uncertainty is high |
| Relative external costs | | | Outsourcing can reduce external costs when uncertainty is high |

Table 1. Research framework

## 3. Theory & propositions

We now study the governance mode choice in the context of reverse logistics from the perspective of the manufacturer by taking the industry and firm characteristics into consideration. Further elaboration of above framework is necessary for a detailed understanding of particular properties of the preference for self-governance and outsourcing. These topics are discussed in detail, in the following five sub-sections.

### 3.1 Sectoral differences in the preferences for self-governance and outsourcing

The literature on the modes of organization suggests a sector-specific understanding of the association between, on the one hand, the level of technological change in the sectors of industry, and, on the other hand, the form of the organization, be it integration through full ownership or inter-firm linkages through strategic technology alliances (Hagedoorn & Duysters, 2002; Van De Vrande et al., 2009). It is found that environments that induce or require a large degree of learning and flexibility, such as high-tech industries, will see a prevalence for alliances, whereas mergers and acquisitions (M&As) are dominant in the low-tech sectors of industry, where learning and flexibility is less important than in high-tech industries. It is easy to understand as under the conditions of rapid technological change, as is the case of the high-tech industries, learning, organizational change, and quick strategic response ask for flexible organizational forms. More flexible forms of economic organizations, such as strategic alliances, are appropriate as new knowledge expires quickly and timely learning from partners appears more appropriate than control through a formal and hierarchical organization as such. Extending the logic to the governance of reverse logistics, we can similarly expect that the outsourcing of reverse logistics is preferred in high-tech industries. From the above framework, the rationale for outsourcing in high-tech industries include both the higher benefits from a more flexible governance mode which facilitate the value creation in collaboration as well as lower external cost due to the flexibility of outsourcing. In particular, as the time value of a returned high-tech product is relatively high, a reverse supply chain that can get returned products quickly tested for either resale or remanufacture would be valuable. An efficient reverse supply chain governed by a 3PL which can recover the value of returned products significantly would have clear advantage over a self-managed supply chain.

On the other hand, under the conditions of little technological change, as in the low-tech industries, companies demonstrate a preference for formal and well institutionalized modes of organization and control, such as M&As, to be the most appropriate form of external appropriation of innovative capabilities. In the context of reverse logistics, a self-managed supply chain would be preferred as control over relational costs would be more important compared to the benefits from a more flexible supply chain. Hence:

*Proposition 1a: For companies operating in a high-tech sector, the outsourcing of reverse supply chain governance would be relatively preferred as a mechanism for efficiency and flexibility.*

*Proposition 1b: For companies operating in a low-tech sector, the self-governance of a reverse supply chain would be relatively preferred as a mechanism for better control.*

These propositions may explain the prevalence of the engagement of 3PLs in reverse logistics by high-tech firms. Facing high external uncertainty, passing the risky spare parts management to 3PLs would help the high-tech firms focus on their core competencies. Due to fierce competition in the market, manufacturers have to set very liberal return policies which increase the value of return products further (Rogers & Tibben-Lembke, 2001). An efficient return and recycle process would be valuable and professional 3PLs can meet perfectly such needs.

### 3.2 Profitability differences in the preferences for self-governance and outsourcing

In a normal organizational mode choice, firms would prefer M&As for activities in their core business as they would generate the necessary controls (Hagedoorn & Duysters, 2002). In the context of reverse logistics, the core business factor could be translated to the profitability of the reverse supply chain compared to the overall firm profitability. A core business would be the main source of revenue and profit for a company and is thus more important to be protected from the potential loss of capabilities due to the opportunistic behaviour of partners. Here control is more important than flexibility as well as potential benefits from collaboration with external partners. Similarly, a reverse supply chain should be controlled by the manufacturer if it is the main source of profit. Leaving the management to externals would be highly risky and dangerous. Applying our framework, the relational costs of outsourcing a highly profitable supply chain would be extremely high. Self-management would be more appropriate. However, for a reverse supply chain with little profit or even losing money, it is natural for the manufacturer to pass the governance duty to external parties. Hence:

*Proposition 2a: For companies whose profits are largely from reverse logistics, the self-governance of a reverse supply chain is preferred as a mechanism for better control.*

*Proposition 2b: For companies whose profits from reverse logistics are little compared to other sources, the outsourcing of a reverse supply chain is preferred as a mechanism for better efficiency.*

These propositions may explain the significant differences in reverse logistics governance between the automotive and aerospace industries while both industries are similar in product characteristics, supply chain structure, and have high demand for spare parts management. Both products are complex and require high engineering and manufacturing capabilities, and both can easily be broken down into major modules and systems. Both supply chains have a large base of suppliers organized in several tiers (part manufacturers, system integrators to sub-assembly suppliers) who supply to relatively few manufacturers. Both product lives are relatively long with strong demand for maintenance and spare parts and the service quality of reverse logistics is essential for the manufacturers (A.T. Kearney, 2003).

While the outsourcing of reverse logistics is common in the aerospace industry (Harney, 2005), car manufacturers largely operate spare parts management by themselves. A key difference between the two industries is the profit margin of reverse logistics. Automotive manufacturers face steep competition, low growth, and a saturated mass market. The profit margin is very low, (the profit from selling new cars is typically less than 5%). On the other hand, the spare parts market enjoys a much higher margin and is an important source of profits for manufacturers. Though the task of managing thousands of different parts across hundreds of car models is challenging, the profit motivation is strong enough for manufacturers to invest and manage the reverse supply chain themselves. On the contrary, the manufacturers of aircrafts are still enjoying high profit from the limited competition and the technological advantage of incumbents like Boeing and Airbus is not likely to lose in the near future. According to the clockspeed theory, the aerospace industry is one of the slowest industries in industrial environment change (Fine, 1998). Hence, it is logical for these manufacturers to pass the spare parts management to capable 3PLs.

### 3.3 Knowledge & service capabilities in the preferences for self-governance and outsourcing

The knowledge needed for the management of reverse logistics affects the choice of governance mode significantly. It affects both the benefits and costs. On the benefits side, a manufacturer with sufficient knowledge of reverse logistics would prefer to self-manage the chain to save the trouble of searching for a capable 3PL governor as well as future negotiation costs. On the costs side, the less the knowledge base of the manufacturer on reverse logistics, the longer it will take to resolve the external costs amidst much uncertainty, making a higher level of commitment less attractive. Instead, it is prudent to first build familiarity through collaboration with more experienced partners such as the 3PLs, through which the manufacturer creates an option while learning about the opportunity ahead (Folta, 1998). When the knowledge increases, direct involvement becomes more attractive. In other words, firms that are not yet familiar with reverse SCM will first have to learn from its partners before being able to accumulate the knowledge. Therefore, when the partnering firms have dissimilar knowledge bases, the need for learning and flexibility prevails over the need for administrative control (Van De Vrande et al., 2009). Moreover, the use of less integrated governance modes enables those same firms to reverse their commitments at lower sunk costs at any point in time.

Besides the knowledge issue, service capabilities are important for the governance of reverse logistics, which would affect the relative benefits in the governance mode choice. The on-site inspection and maintenance as well as the on-time provision of spare parts are often important in reverse logistics. A manufacturer who is far away from the customer would naturally prefer to find local partners to help in after-sale services and reverse SCM. It may explain the reason for Embraer, an aircraft manufacturer based in Brazil, to engage a 3PL in Singapore to serve its customers in the Asia Pacific. Hence:

*Proposition 3a: For companies who are knowledgeable about reverse logistics, the self-governance of the reverse supply chain is preferred compared to companies not familiar with reverse logistics.*

*Proposition 3b: For companies who are more capable of serving customers effectively, the self-governance of the reverse supply chain is preferred compared to companies less capable in serving customers.*

These propositions may yet be another reason for reverse logistics outsourcing in the high-tech industry. Firms in high-tech industry normally specialized in developing commercially viable innovative products, and supply chain management is not their expertise. It is therefore logical for them to pass the duty of chain governance to a 3PL.

### 3.4 Pooling ability

Reverse logistics is less standardized compared to the forward supply chain. Goods are less likely to be shipped in high volumes, and demand is more difficult to predict. Thus, the cost of managing reverse logistics is often higher than that of the forward supply chain. The pooling ability of the chain governor would be one important aspect of its capabilities and affect supply chain cost significantly. It can increase relative benefits in the transaction value analysis framework.

In the governance of a forward supply chain, Li & Fung is a typical supply chain governor. It is a Hong Kong-based company which serves private label apparel firms in Europe and North America, and is known to operate as a "smokeless" factory by maintaining a large network of suppliers even though it does not own any factory. By using its buying power and trust developed with its supply base, Li & Fung is able to considerably shrink the delivery cycle of time sensitive products (Fung et al., 2008). The pooling effect is important in the supply chain management of Li & Fung, which keeps a rule of having at least 30% but not more than 70% business from a specific supplier to ensure sufficient leverage for supplier compliance but still keep its independence (Fung et al., 2008). However, different from leveraging as power in the forward supply chain, pooling in reverse logistics is more cost centred as it could significantly lower the supply chain cost. 3PLs thus often enjoy advantage over manufacturers as they are able to consolidate shipping orders from multiple manufacturers. Hence:

*Proposition 4: The stronger the pooling ability held by the third party over the manufacturer in reverse logistics, the more suitable it is for the third party to manage the reverse supply chain.*

A corollary from Proposition 4 is that small manufacturers are more likely to engage 3PLs (or large firms but having a small customer base in a region) while large firms would prefer to self manage the reverse supply chain.

### 3.5 Regulatory uncertainty

In contrast to a forward supply chain where the market force is the main external factor, the hands of governmental regulation are much more visible in reverse logistics. With increasing environmental awareness, governments, particularly those in developed countries, are pressing manufacturers and distributors to reduce the production of environmentally hazardous products and packages (Kumar & Putnam, 2008). For example, regulations on End-of-life Vehicles (ELV) Directive adopted by the European Union (EU) in 2000 have motivated manufacturers like Volvo, Saab, and BMW to redesign their cars so that their components can be dismantled more efficiently (Kumar & Putnam, 2008).

New government regulations can change the rule of the game significantly, and manufacturers have to comply to participate in the marketplace and often need to redesign their products and packaging to meet these requirements. Both forward and reverse supply chains could be affected and reverse supply chains tend to be exposed to greater regulatory uncertainty. Thus, the manufacturer must take the potential governmental intervention into consideration in the choice between self-governance and outsourcing. According to our framework, high external costs would lead to a preference for outsourcing. Hence:

*Proposition 5: The stronger the regulatory uncertainty in the industry within a region, the more suitable it is for a third party to manage the reverse supply chain.*

Regions such as the EU where governments tend to be global leaders for new environmental regulation face greater regulatory uncertainty. According to Proposition 5, manufacturers in industries with significant outputs of environmentally hazardous materials should outsource their reverse logistics in such regions. Table 2 summarizes the above propositions.

| Propositions (assumes the external governor is capable) | Whether the firm is in high-tech industries | Whether reverse logistics is an important profit source | Firm's knowledge about reverse logistics | Serving capabilities of the focal firm | Pooling capabilities advantage of the third party | Regulatory uncertainty |
|---|---|---|---|---|---|---|
| Relative benefits | If high-tech industry, more value from the third- party governance | If main profit source, more value preserved by self-governance | If knowledge-able, more value in self-governance | If capable, more value in self-governance | If significant, more value in third-party governance | |
| Relative relational costs | | If main profit source, lower relational costs by self-governance | If knowledge-able, lower relational costs in self-governance | If capable, lower relational costs in self-governance | | |
| Relative external costs | If high-tech industry, lower external costs in third-party governance | | If knowledge-able, lower external cost in self-governance | | | If high, lower external costs in third-party governance |
| Overall conclusion | If high-tech industry, external third-party preferred; else, self-governance preferred | If main profit source, self-governance preferred; else, third party preferred | If knowledge-able, self-governance preferred; else, third party preferred | If capable, self-governance preferred; else, third party preferred | If the third-party has pooling advantage, third party preferred; else, self-governance preferred | If regulatory uncertainty is high, third-party preferred; else, self-governance preferred |

Table 2. Summary of Propositions

## 4. Concluding remarks

This chapter proposes a framework to examine the governance modes of reverse logistics. Drawing on perspectives from multiple organizational theories, we develop a general framework on the governance mode choice considering net transaction value which reflects relative benefits, relational costs and external costs. Applying the framework to the context of reverse logistics, we have generated five sets of propositions. External third-party governance is preferred when the industry is high-tech and when reverse logistics is not a main profit source. When the manufacturer is knowledgeable or able to serve end-customers well, self-governance is preferred. When the third-party has significant pooling advantages over the manufacturer in reverse logistics, or when the regulatory uncertainty is high, third-party governance is preferred. These propositions can explain some phenomena observed in various practices, and can be further investigated empirically.

While the findings in this paper are preliminary, it suggests that the most appropriate governance mode for a reverse supply chain depends on the context of that chain. Practically, for the potential candidates of third-party governors such as 3PLs, they have to identify suitable reverse supply chains to involve and develop their capabilities accordingly. They should also manage their business carefully to consolidate sufficient pooling advantage over the manufacturers, such as having multiple customers in one industry and /or region.

A manufacturer, with a complex reverse supply chain, has to analyze the chain characteristics to know if it is possible for an external third party to govern. If the chain is suitable, it needs to further identify a capable and trustful third-party governor to do so. However, if the reverse supply chain is unsuitable for third-party governance, either the manufacturer or a strong member in the chain should assume the role of the coordinator, improve its capabilities and closely collaborate with the other chain members to improve chain efficiency.

## 5. References


A.T. Kearney, I. (2003). Restructing the global aerospace industry. Retrieved from http://www.seaonline.org/docs/Restruct_aerospa-B5929.pdf

Balakrishnan, S.& Koza, M. P. (1993). Information asymmetry, adverse selection and joint-ventures. *Journal of Economic Behavior and Organization,* 20, 99–117.

Barney, J. B. (1991). Firm resources and sustainable competitive advantage. *Journal of Management,* 17(1), 99-120.

Bensinger, K. (2010). Toyota dealers to start fixing defective gas pedals. *Los Angels Times*.

Fine, C. (1998). Clockspeed: Winning Industry Control in the Age of Temporary Advantage. Perseus Books, Reading, MA.

Folta, T. B. (1998). Governance and uncertainty: the trade-off between administrative control and commitment. *Strategic Management Journal,* 19(11), 1007–1028.

Fung, V., Fung, W.& Wind, Y. (2008). *Competing in a flat world: Building enterprises for a borderless world*. Wharton School Pub, Upper Saddle River, NJ.

Gans, J.& Stern, S. (2003). The product market and the market for “ideas”: commercialization strategies for technology entrepreneurs. *Research Policy,* 32(2), 333-350.

Guide, V. D. R. J., Souza, G. C., van Wassenhove, L. N.& Blackburn, J. D. (2006). Time value of commercial product returns. *Management Science,* 52(8), 1200-1214.

Hagedoorn, J.& Duysters, G. M. (2002). External sources of innovative capabilities: the preference for strategic alliances or mergers and acquisitions. *Journal of Management Studies,* 39(2), 167–188.

Haq, R. (2007). Embraer outsources Singapore logistics hub. *Arabian Business.Com*. Retrieved from http://www.arabianbusiness.com/10598-embraer-outsources-singapore-logistics-hub

Harney, J. (2005). Suppliers fly up the value chain for airplane manufacturers. *Outsourcing Journal*. Retrieved from http://www.outsourcing-journal.com/jun2005b-manufacturing.html

Hoetker, G. (2005). How much you know versus how well I know you: Selecting a supplier for a technically innovative component. *Strategic Management Journal* 26, 75-96.

Kumar, S.& Putnam, V. (2008). Cradle to cradle: Reverse logistics strategies and opportunities across three industry sectors. *International Journal of Production Economics,* 115(2), 305-315.

Langley, J. (2009). The State of Logistics Outsourcing: 2009 third-party logistics: Georgia Institute of Technology.

Leenders, M. R., Fearon, H. E., Flynn, A. E.& Johnson, P. F. (2002). *Purchasing and Supply Management*. McGraw-Hill, New York.

Li, X.& Olorunniwo, F. (2008). An exploration of reverse logistics practices in three companies. *Supply Chain Management: An International Journal,* 13(5), 381 - 386.

Madhok, A. (2002). Reassessing the fundamentals and beyond: Ronald Coase, the transaction cost and resource-based theories of the firm and the institutional structure of production. *Strategic Management Journal,* 23, 535-550.

Maxton, G.& Wormald, J. (2004). *Time for a Model Change: Re-engineering the Global Automotive Industry*. Cambridge University Press, Cambridge, UK.

Peteraf, M. A. (1993). The cornerstones of competitive advantage: A resource-based view. *Strategic Management Journal,* 14(3), 179–191.

Prahinski, C.& Kocabasoglu, C. (2006). Empirical research opportunities in reverse supply chains. *Omega,* 34(6), 519-532.

Rogers, D. S.& Tibben-Lembke, R. S. (2001). An examination of reverse logistics practices. *Journal of Business Logistics,* 22(2), 129-148.

Rumelt, R., Schendel, D.& Teece, D. (Eds.). (1994). *Fundamental issues in strategy*. Boston, MA: Harvard Business School Press.

Stock, J., Speh, T.& Shear, H. (2002). Many happy (product) returns. *Harvard Business Review,* 80(7), 16-17.

Stock, J., Speh, T.& Shear, H. (2006). Managing product returns for competitive advantage. *MIT Sloan Management Review,* 48(1), 57-62.

van de Vrande, V., Vanhaverbeke, W.& Duysters, G. (2009). External technology sourcing: The effect of uncertainty on governance mode choice. *Journal of Business Venturing,* 24, 62-80.

Vivek, S. D., Banwet, D.& Shankar, R. (2008). Analysis of interactions among core, transaction and relationship-specific investments: The case of offshoring. *Journal of Operations Management,* 26(2), 180-197.

Vivek, S. D., Richey, G. J.& Dalela, V. (2009). A longitudinal examination of partnership governance in offshoring: A moving target. *Journal of World Business,* 44(1), 16-30.

Wernerfelt, B. (1984). A resource-based view of the firm. *Strategic Management Journal,* 5(2), 171-180.

Williamson, O. E. (1981). The economics of organization: The transaction-cost approach. *American Journal of Sociology,* 87, 548-577.

Williamson, O. E. (1991). Comparative economic organization: The analysis of discrete structural alternatives. *Administrative Science Quarterly,* 36(2), 269–296.

Youngdahl, W., Ramaswamy, K.& Verma, R. (2008). Exploring new research frontiers in offshoring knowledge and service processes. *Journal of Operations Management,* 26(2), 135–140.

Zajac, E.& Olsen, C. (1993). From transaction cost to transaction value analysis: Implications for the study of interorganizational strategies. *Journal of Management Studies,* 30(1), 131-145.

# 14

# Supply Chain Management and Automatic Identification Management Convergence: Experiences in the Pharmaceutical Scenario

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## 1. Introduction

The past few years have seen an explosion of interest in the main auto-identification technologies in many heterogeneous scenarios. The ability to identify and trace individual objects is essential in many business processes, such as manufacturing, logistics, ticketing, and anti-counterfeiting. These contribute substantially to validate the concept of the 'Internet of Things' (IoT), although there are many ways to describe an IoT. It can be defined as a world-wide network of uniquely addressable interconnected objects, based on standard communication protocols (1). The core idea of the concept of the IoT is to collect any useful information about the objects of the physical world and to use this information in various applications during the objects' life cycle. This feature can help organizations to improve existing internal and external business processes and also to create new ones. In many application scenarios, the two key elements that are making this revolution possible are: radio frequency identification (RFID) technology (Wikipedia Foundation) and the EPCglobal international standard (epcglobal). RFID is a rapidly developing technology that uses RF signals for automatic identification of objects. Among the different types (i.e. passive, semi-passive, and active) of RFID transponders, often called 'tags', the passive ones are used in most track and trace systems due to their higher range and very low cost, since they require no battery to operate. A typical passive RFID tag consists of an antenna and an integrated circuit chip in ASIC technology. In a passive RFID system, the reader transmits a modulated RF signal, which is received by the tag antenna. The RF voltage generated on the antenna is converted into DC (Direct Current). This voltage powers up the chip, which sends back the information that it contains.

RFID is a very interesting wireless technology able to trace and track individual objects on the whole supply chain. This autoidentification technology has recently seen growing interest from a wide range of application sectors such as retail, logistics, localization, healthcare, and pharmaceutical (2) (3). Among these, the pharmaceutical supply chain is a very interesting scenario, in which an item-level traceability is crucial to guarantee transparency and safety in the drug flow. The fragmentation of the supply chain, caused by the overwhelming growth of intermediate wholesalers and retailers involved in drug flow, is resulting in a decrease of transparency and an increase of difficulty to track and trace drugs. Furthermore, the growing counterfeiting problem raises a significant threat within the supply chain system. RFID technology is fundamental but not sufficient to develop an efficient supply chain management (SCM) system. It is most important to adopt international standards for goods traceability in the supply chain. Another crucial aspect is related to e-business message interchange in the supply chain. Each information flow between different actors in the pharmaceutical supply chain should be performed in automatic mode. Currently, there are still some technical and economic barriers that limit the large-scale deployment of these technologies in the pharmaceutical supply chain. Some initiatives are addressing these challenges and obtaining substantial successes. The asserting of some international standards related to goods traceability, such as EPCglobal (4), GS1 (Global Standard 1) and ebXML (electronic business using eXtensible Markup Language), are some interesting examples. Even if there are already several research studies coping with the hardware and software issue of an RFID enabled tracking system, an important issue, which still remains ill analysed, at least in the particular pharmaceutical supply chain, is related to the evaluation of the impacts that these new technologies could have on the main processes of the supply chain. Therefore this chapter presents an innovative framework that tries to find a convergence point among RFID technology, EPC standards and interoperability best practices for B2B interchange. This chapter evaluates this impact in terms of certain key performance indicators (KPIs) of the proposed framework: for example in (5), the authors identify and validate key performance indicators (KPIs) that are useful to trace the impacts of RFID technology in each individual organization and in the SC as a whole even if they don't focus on a particular supply chain. By contrast, this work reports practical experiences, gained with a recent pilot project named TRUE (6), focussed on the development and validation of an open source framework able to guarantee both traceability and data interchange on the whole pharmaceutical supply chain. In this chapter the KPIs are defined both for the wholesaler and for the pharmacy retailer. The defined KPIs are based on the 'critical success factor' (CSF) of the two stakeholders. In this first step, the analysis will be qualitative, and will be aimed at identifying the best indicators for measuring the potential improvements of the proposed framework once it will be really implemented in the pharmaceutical supply chain.

## 2. The pharmaceutical supply chain: The AS-IS model

The first step of this work will be the analysis of the pharmaceutical applicative domain, in order to obtain a realistic picture of the actors involved and how they interact. This kind of AS-IS analysis has been carried out with the support of important actors representative of the pharmaceutical supply chain; for example, the Merck Serono company has collaborated to define the process requirements for the manufacturer. In this early phase the authors do not pretend to be exhaustive, as the specific aim was not to be complete, but, instead, to empathize the benefits obtainable by adopting innovative technologies (e.g. RFID) both for supply chain management and for tracing and tracking. The pharmaceutical supply chain, shown in Fig. 1, is a very complex scenario, with millions of medicine packs moving around the world each year. It is made up of four main stakeholders:

- Manufacturer;
- Wholesaler;
- Pharmacy Retailer;
- Disposal Service.

This supply chain, much more than others, is affected by the need for law of a strict traceability of every drug that is manufactured, distributed and consumed. Moreover, because

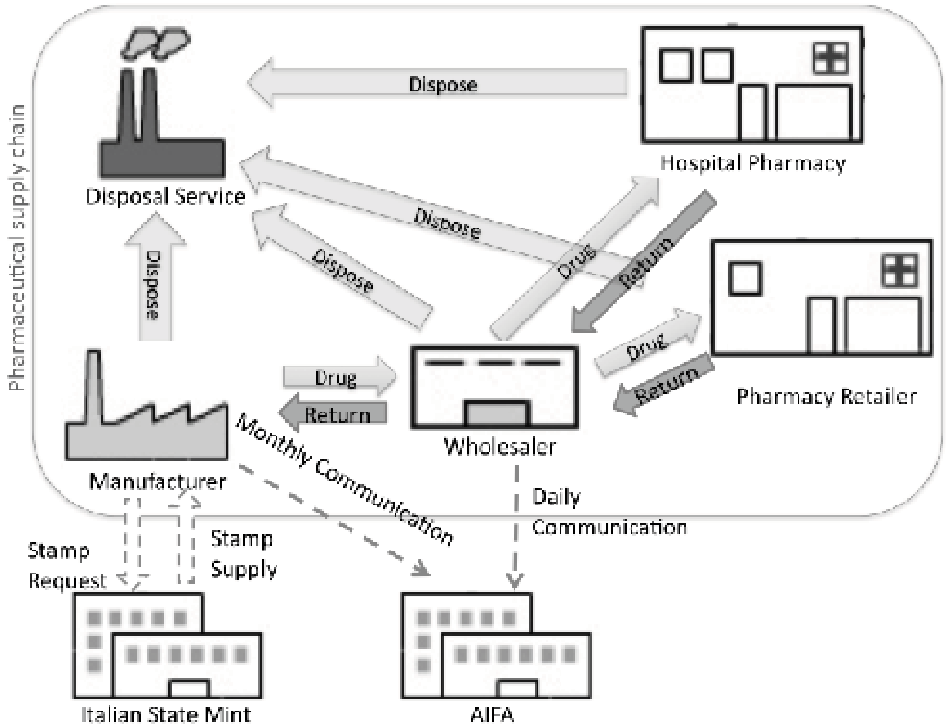


Fig. 1. Pharmaceutical Supply Chain

of the quick responsivity that the whole supply chain must guarantee in order to quickly supply drugs to each pharmacy retailer (it happens also 3 times per day), all the actors involved have the need to exchange business messages (purchase order, order confirmation, etc.) in a quick and reliable way. This vision introduces the need to understand how the traceability is strongly connected and correlated to the ones related to B2B. Currently, the main auto-identification solutions used in the pharmaceutical sector are based on optical technology such as linear or bi-dimensional (i.e. DataMatrix) bar codes.

Unfortunately, these solutions are not effective for tracing systems in the supply chain because they require line-of-sight (LOS) communication, cannot be written or read in bulk, can be easily counterfeited, limit the speed of packaging line operations, are subject to label deterioration due to humidity, etc. The item-level traceability of drugs starts just after the packages are filled during the manufacturing process. In this step, each tagged product is scanned individually on the conveyor belt and then cased to be sent to the wholesalers. The wholesalers separate the products according to their identifiers and place them onto the shelves. Wholesalers receive orders from retailers. These orders often consist of small quantities of different products; they may contain a large number of items. The products in the orders of the retailers are picked and put into some large envelope bags that are scanned and confirmed before their distribution. Upon receipt, the retail pharmacy scans the contents of each bag opening it. Some of the steps described previously go also with the exchange of business messages between actors. For example orders of the pharmacies to the wholesalers are often made electronically as well as those from wholesalers to manufacturers. Anyway there is not a loose integration between the traceability and the messages interchange system. The wholesaler has, therefore, a wide variety of drugs that can come from different manufacturers and has as their main goal to distribute them according to the incoming requests from pharmacy retailers. Among the main characteristics of the pharmaceutical supply chain, derived from this AS-IS analysis, the most important was about the item monitoring: cases arriving at a wholesaler are opened and only one item from each case is inspected. This is done to speed up the entry check, but obviously does not guarantee that there are not missing or misplaced items inside the case. Moreover there is a constant monitoring by the Italian Department of Health (AIFA), who must be continually informed about the drug flow. In particular, the manufacturer must send monthly data about the drugs produced while the wholesaler must send information each 24 hours. Finally, The Italian State Mint ('*Zecca dello Stato*') provides a State Stationery Office stamp on the items. These stamps are applied only for drugs distributed in Italy and provided by the National Health Service. The stamp must quote the following information: the authorization code of the drug item, a drug description, the authorization owner, and a code that identifies the progressive numbering of the item. The last piece of information, the progressive numbering, is used only within the Pharmaceutical House; the other involved stakeholders have no reading system for this information and hence they discard it. This paragraph is aimed at giving the reader a quick but significant view of the Italian pharmaceutical sector, for this reason the level of detail has not been kept too high, while giving enough information to understand what kind of problems affect this supply chain.

## 3. Business-to-Business standards

The previous paragraph has shown how the pharmaceutical supply chain is characterized. It is made up of variegated actors that have different needs and different informative systems. Thus, one of the main problems is to guarantee interoperability among them, providing a flexible strategy able to support communication among the actors. B2B standards can give, sometimes, an answer to this problem. Therefore the pharmaceutical supply chain can be considered similarly to the B2B supply chain where the interoperability between companies is very important for the growth of the business. Companies need to exchange useful information in order to safeguard their economic and commercial transactions for the successful completion of their own business processes. The advent of XML has allowed the exchange of data through the internet by means of 'simple' structured text files but companies, in the course of time, have used XML to define legacy languages very often understood only within their own supply chain. For this reason, the methodological and technological efforts of the companies could not be used by other companies belonging to different supply chains or by new companies in the same supply chain. Therefore, there is a need for a standardization that can provide a common interchange possibly based on XML. The notations describing a business process, the interchange format and technologies that are spread out, are helpful and solve problems related to the B2B interoperability and integration for the specific supply chain. It would be particularly useful, therefore, to provide a solution that helps the user through the whole lifecycle that begins from the definition of the business process and goes up to the use of the specific message on the selected technological infrastructure. It is important, therefore, to link together different levels of analysis: at the high analysis level, it is important to identify a methodology and useful tools not only to define the business process but also to refine business processes in order to reach a detailed level according to implementation needs. At the intermediate level, it is necessary to identify a language conforming to the standards. It is necessary, therefore, to identify a mapping among the high-level messages

defined by the companies and the standard formats of message interchange defined from a B2B perspective. It is important, finally, to use the message defined according to the standard on a specific technological infrastructure. Many technological and methodological solutions are available for solving B2B problems but, to the authors' knowledge, there is no overall solution to the methodological and technological problems that, at the same time, allows maintaining the separation of concerns between methodological and technological levels. According to the authors, although it is important to link different levels of analysis, it is not useful to add complexity to what has been already designed and implemented. One needs to go towards a simplification of the use of standards, notation and technologies in order to support interoperability among companies. The authors will explain the standard methodologies, e-business vocabulary, and technologies that they have analysed.
From the business process perspective, the most important business process design notations used in both scientific and commercial circles are IDEF (7), UML (8) and BPMN (9). Among these notations, BPMN seems to be the best way to represent a company's business process and the interaction between actors inside the companies and outside the companies. With regards to the e-business vocabulary, there was an attempt by OASIS to introduce a generic vocabulary/standard useful to each supply chain partner. The standard is ebXML (10), which belongs to the ebXML framework and the main goal is to define the components that will define a specific business message. There has not been, up to the present moment, a methodology to represent neutral core components in e-business vocabulary (11). For this reason, the ebXML core component is not used by companies because each company must define its own vocabulary (using core components) and share it with other companies of the supply chain. This problem gave birth to UBL (Universal Business Language), an OASIS initiative that defines in its 2.0 version 31 business documents for different areas (12) such as sourcing, ordering, invoice and fulfilment. Finally, with regard to the architectural solutions oriented to the enterprises, the authors consider SOA (service oriented architecture). A simple SOA definition can be: a loosely-coupled architecture designed to meet the business needs of the organization (13). The reference model provided by OASIS (14) for SOA underlines some fundamental concepts that any implementation is based on (15). The SCA (service component architecture) architectural style was created in accordance with the SOA reference model. Moreover, web services was created, taking into account the concepts expressed by the SOA reference model, as a possible SOA implementation. Finally came REST, an architectural style that takes into account on the one hand the concept expressed by the SOA reference model and on the other, the most widespread technology: the Web. The REST architecture, created by Roy Fielding, seems to be very promising because it takes into account experiences acquired over the years in B2B electronic exchange and the strong points of the HTTP protocol that has made it the world's most used protocol.

## 4. Challenges and improvements in the B2B

The notation for business process analysis, business vocabularies, and these architectural solutions, answer to several problems that companies may face in their daily activities but does not provide a complete and integrated solution for business-driven integration problems (16).
The main problems are not only to define methodological and architectural solutions for the exchange of business messages but to link together the methodological and technological approaches in order to provide a solution that answers the needs of all the business partners: i.e., that the business partners may share a common language in order to have

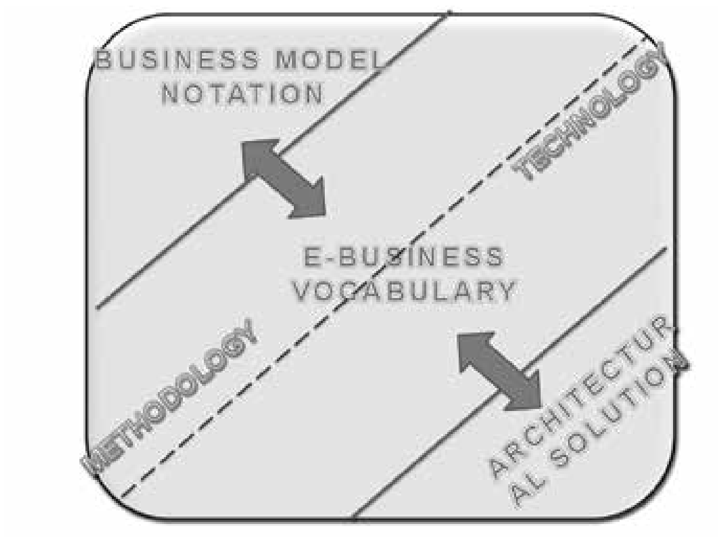


Fig. 2. Representation of the methodological and technological gaps

a communication helpful for the business. In order to identify a conceptual framework, it is important to provide a way to define business messages that, on the one hand, are not very complex for the final user, and, on the other, able to guarantee a business message representation that is easy to understand for the company's information system. There are three main open issues in the definition of the solution for these integration issues. The first is the selection of the notation for the business process design. The business messages come from the more or less complex business process of the company. The business messages may be input or output tasks for execution in the company but, very often, they are not accurately defined in the business process design and its source/target is not well identified. It would appear that BPMN is the best way to represent business messages: it has the modelling primitives useful to define the presence of a message but it does not provide the possibility to define in a formal way the exchanged message. It is easy to understand that the formal definition of a business process is not a task for the business expert but, at the same time, the definition of the process, made up by the designer, must also include the definition of the business message. The second problem is to define a language for a formal definition of a business message but it is difficult to adapt these vocabularies to the different application domains from which they are extracted. Business vocabularies may be very complex, so it is very hard to customise the language, or else it will be very generic compared with the specific application context, so the customisation task may be very difficult. The third problem is that the software architecture can manage the business process exchange efficiently but without thinking (as is right) of the message complexity or the different ways of representing the message. From these open issues, it appears that a double gap (methodological and technological) has to be bridged in order to obtain a solution for business-driven integration (Fig. 2). The e-business vocabulary covers the methodological gap between the definition of the business process and the definition of the business messages. The e-business vocabularies provide inflexible solutions for non-expert users and, very often, it is very hard to link together the business process analysis and the specific e-business vocabulary. Another aspect is the technological gap owing to the need to use a specific business language for the selected

architectural solution. This gap is because of the several technological solutions proposed in the e-business systems that are each based on a specific protocol and on complex rules (for example, ebMS vs AS2).
In several B2B research projects, the notations describing a business process, the interchange format, and technologies are helpful and solve problems related to B2B interoperability and integration for the specific supply chain. According to the authors, it is not useful to add complexity to what has been already designed and implemented. It is instead necessary to move towards a simplification of the use of standards, notation, and technologies in order to support interoperability among firms. Thus, the proposed structured conceptual approach is based on the following goals:

– to provide a high degree of freedom in the business process design and in the formalization of the specific business message;
– to suggest to the companies the use of only one technology of interchange that is flexible and easy to integrate with the company's information system.

For these reasons, the authors propose an approach (Fig. 3) based on a business-driven integration solution that takes into account three different aspects:

– the identification of a proper notation for the business process design (conceptual model);
– the identification of a proper e-business dictionary based on established standards (logical model);
– the selection of a quite simple and reliable technology for business message exchange (physical model).

This structured conceptual approach aims to individualize a possible integration among the various levels that makes the solution feasible, operational, and efficient in comparison with other solutions. The integration among the various levels can be obtained using an ontological approach based on the definition of a meta-model: starting from this meta-model, it will be possible to obtain the specific model (within the specific application context).
This model can be used in the chosen specific technological infrastructure as reference to the underlying level. In the specific case, by selecting the business process notation to use and selecting the business message interchange dictionary, it is possible to define the ontology in which there will be, with proper semantics, both the representation of the notation and the

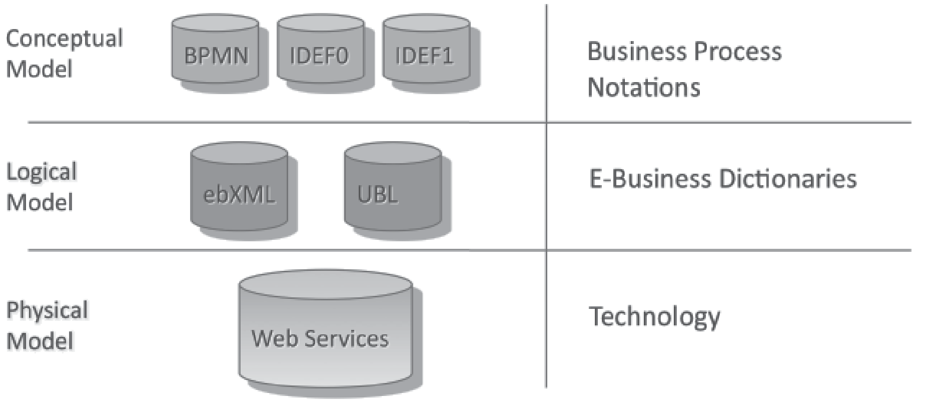


Fig. 3. Conceptual approach

representation of the specific dictionary to be used for the definition of the business messages. The obtained model can use a well defined technological infrastructure that allows business message interchange. According to the authors' experiences, it can be useful to choose a well-defined technological infrastructure that also takes into account the specific partners' needs (within the supply chains).

## 5. EPCglobal network architecture

B2B interoperability is not the only aspect that must be taken into account when speaking about pharmaceutical supply chain. Another important aspect is related to product traceability and identification. The drugs must be constantly checked during transport and stocking. The EPCglobal consortium, mainly represented by the GS1 (Global Standards 1) organization (gs1), defines the standards for developing a universal identification system and an open architecture able to guarantee interoperability and data sharing in a complex multi-vendor scenario. In particular, it proposes the EPCglobal network architecture, whose main feature is the use of the Electronic Product Code (EPC), a code able to univocally identify each item. This architecture comprises a set of standards for hardware devices (e.g. reader), software systems, network services, and data interfaces that allow the EPCglobal network to play a very important role in traceability systems. The EPCglobal architecture is able to guarantee effectiveness, flexibility, and scalability. Furthermore, it is important to observe that this architecture was designed to exploit all the advantages of RFID technology, but it continues to be valid also in the presence of other automatic identification solutions. In fact, it is able to provide most network services even if a linear or two-dimensional barcode is used.
Fig. 4 shows the current status of the standardization process of the EPCglobal architecture framework. The protocol stack can be divided into three parts: identity, capture and exchange. The identity portion contains the standards for the identification of tags and the translation of tag data. The capture portion contains the standards for filtering and collecting the tag data. The exchange portion contains the standards for storing and sharing collected and filtered EPC product data. Let us observe that the Discovery Service standard is in grey because it is not yet an official EPCglobal standard.
The rest of this section reports more details about the most important EPCglobal standards. In particular, the authors focus on portions that are fundamental for a traceability system: Tag Data, Low Level Reader Protocol (LLRP), Application Level Events (ALE), EPC Information Services (EPCIS), and Object Name Services (ONS).

### 5.1 Tag data

In the EPCglobal network the identification is based on the EPC standard that specifies a format of the EPC (epcglobal) code whose length is equal to 96 bits. The EPC code can identify 268 million companies and each company has 16 million product categories available.
Any EPC code has the following information: specification, manufacturer and price. In the Header of an EPC packet (Fig. 5), an encoding schema can be specified. The Filter and Partition Value provides a reliable reading of the EPC tag through a definition of different levels of wrapping and packing while the Domain Identifier identifies the company, the service, the stock keeping unit until pallet and package. Let us observe that the EPC standard supports all GS1 encoding schemas. This is a very important aspect that assures high scalability and flexibility. Some examples of these schemas are: General Identifier (GID), Global Trade Item Number (GTIN), Serialized GTIN (SGTIN), Serial Shipping Container Code (SSCC), etc. In particular, the SGTIN encoding schema is very useful for application scenarios

such as a pharmaceutical supply chain, in which item-level tracing is required. The SGTIN code allows of overcoming GTIN code limits through the association of a serial number to the previous GTIN.

### 5.2 LLRP

The LLRP layer was designed to provide an interface between the RFID reader and the middleware system. It guarantees interoperability among heterogeneous reader systems. LLRP includes several procedures that allow us to control physical parameters of both the antenna and the reader (e.g. AntennaID and RF settings). Furthermore, LLRP implements an 'anti-collisions' protocol to manage access to the wireless channel. The communication between reader and client takes place through messages. They allow us to obtain and to modify the reader configuration and to manage tag access. LLRP communication is based on the following steps:

- features discovery;
- device configuration;
- access and stock list operations setup;
- execution of stock list cycles;
- RF detection operations;
- client report returns.

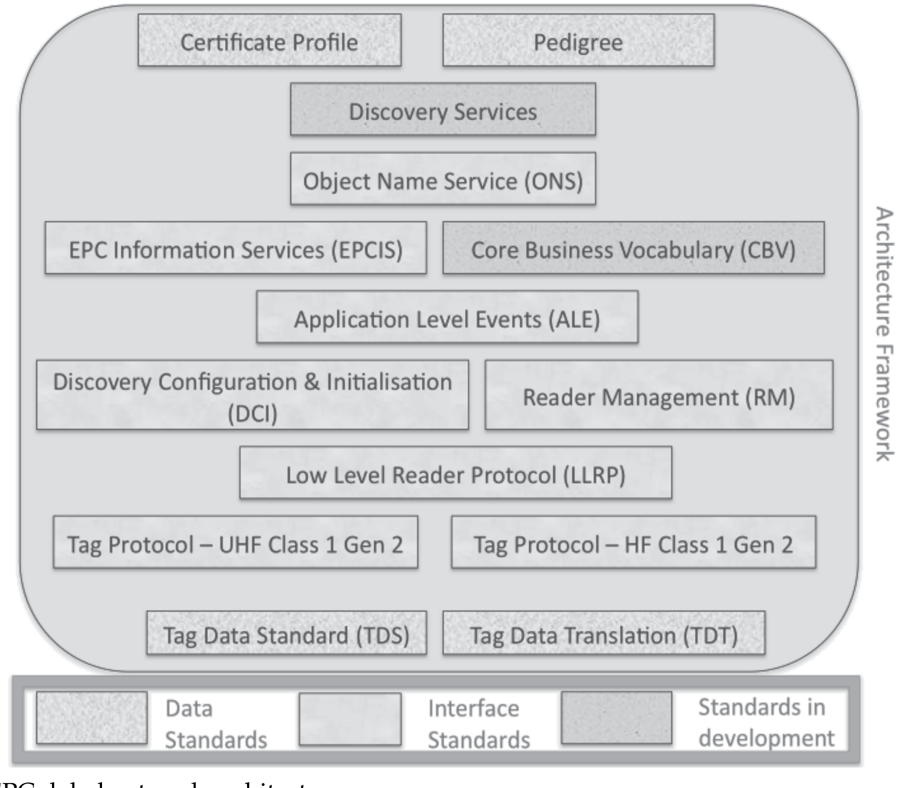


Fig. 4. EPCglobal network architecture

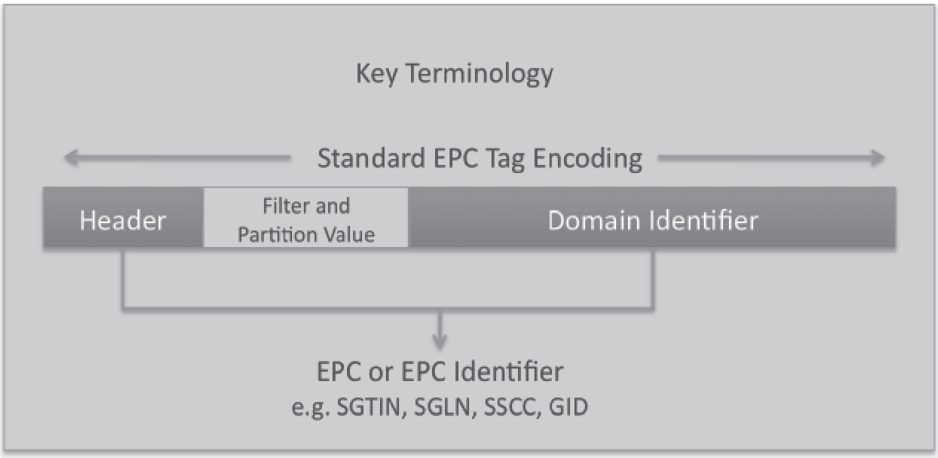


Fig. 5. EPC Code Structure

### 5.3 ALE

The role of the ALE interface within the EPCglobal network architecture is to provide independence between the infrastructure components that acquire the raw EPC data, the architectural components that filter and count that data, and the applications that use the data. This de-coupling is able to offer cost and flexibility advantages to technology providers and end-users. ALE, provided by EPCglobal architecture, does not depend on the data source such as RFID, linear code, data-matrix, etc. In fact, it defines the concept of a 'logical reader' layer. ALE defines a standardized format for reporting accumulated and filtered data in order to facilitate the upper layers processing. Furthermore, it enables business applications to use abstracted means to specify what, when and where particular observations have to be performed and processed by lower layers.

### 5.4 EPCIS

The main role of EPCIS in the EPCglobal network is to provide a repository for EPC events in order to facilitate the sharing and exchanging of traceability data among different business processes of a supply chain. EPCIS defines a standard interface to enable EPC-related data to be captured and queried using a defined set of service operations and associated EPC-related data standards, all combined with appropriate security mechanisms that satisfy the needs of user companies. EPCIS represents the core of the EPCglobal network architecture and differs from lower layers for some key aspects, such as the ability to interpret the current observations using historical data and incorporating semantic information related to the business process in which EPC data is collected. In contrast, the lower layers, such as ALE, manage just raw observations oriented exclusively towards real-time processing of EPC data. In more detail, EPCIS provides two interfaces: one for query request and the other one for capture operations. The query interface allows the trading partner to query information about any event data stored in the EPCIS-repository together with business context. Generally, each partner of a whole supply chain manages its own EPCIS server on one or more databases. However for such a decentralized architecture, since the complete information about an individual object, identified by a specific EPC, may be fragmented across multiple organizations, there is the need of lookup services for locating the providers of all these fragments that constitute the complete lifecycle history of the object. This aspect contributes to make research on Discovery Service a very interesting challenge.

### 5.5 ONS

ONS is a mechanism that leverages Domain Name System (DNS) to discover information about a product and related services from the EPC. In more detail, it is able to provide pointers to authoritative information services of the manufacturer of the object identified by a given EPC. ONS is a sub-part, characterized by namespace onsepc.com (17), of DNS. In particular, as the DNS converts the domain address (i.e. URL) to the IP address, similarly, the ONS converts the EPC to the Uniform Resource Identifier (URI) of an EPCIS.

## 6. Description of the proposed software architecture

The adopted approach aims to define a technological infrastructure able to satisfy both SCM and traceability requirements. Two important choices for the proposed framework have been: ebXML as the proper standard to guarantee interoperability among the different firms, and EPCglobal as the proper standard to guarantee the identification and traceability of products and goods. The separation of concerns is a key aspect of the authors' approach, so they have defined an architecture that can separate, in a clear manner, competences and features from a technological perspective. This architecture is shown in Fig. 6. The data interchange system is based on ebXML and uses an application layer to guarantee an e-business messages exchanging service according to the UBL standard. Furthermore, it exploits an UDDI Discovery Service/ebXML Registry Service to find companies for e-business negotiation and agreement. The main layers of the traceability protocol stack, compliant with EPCglobal standards, are ONS, EPC-IS, ALE and LLRP. Unfortunately, the standardization of Discovery Services by EPCglobal is still pending, and therefore the current available implementation of the EPC protocol stack does not include the Discovery Service. The defined software architecture has been designed by merging the two main previous components: EPCglobal protocol stack and the ebXML for messaging services. In this way, the overall system is able to answer requests from the factory users by sending reports and information about a specific product, marked by an EPC code, or providing the possibility to perform messaging operations such as, for example, sending an order.
The overall system is based on two open-source implementations provided by the scientific community:

– The e-business message exchange sub-system is modelled by the freebXML project (http://www.freebxml.org/), which provides an open-source implementation of the ebXML standard.
– The identification and traceability sub-system is modelled by the Fosstrak framework (fosstrak), which provides an open-source RFID software platform that respects exactly the current standards provided by EPCglobal.

The overall system, thanks to the two open-source projects, is flexible and reliable, guaranteeing the separation of concerns. Furthermore, this choice allows of implementing the Discovery Service as an extension of the FossTrak open framework. The implementation of and experimenting with a Discovery Service mechanism integrated with a network architecture conforming to EPCglobal represent, of course, innovative and interesting features of this work. The authors' contribution in the field of supply chain management research is the definition of the overall architecture for the generic supply chain, the implementation

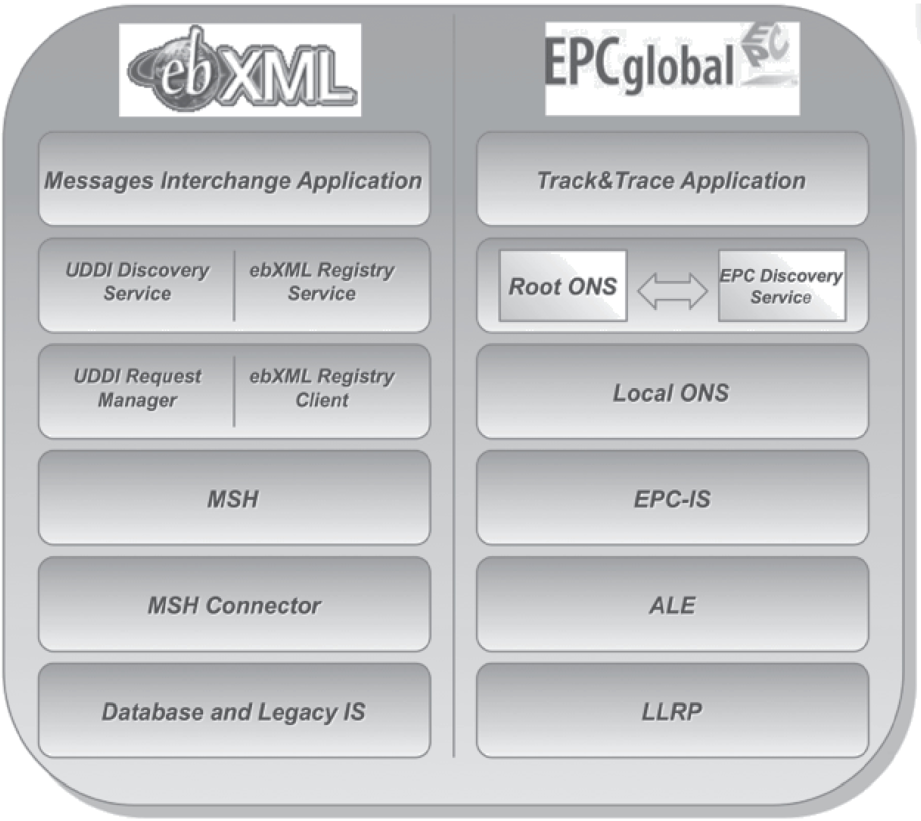


Fig. 6. Defined Software Architecture for traceability and SCM

of middleware able to obtain the proper interoperability between the two open-source implementations (freebXML and Fosstrak), and, finally, the experimentation with real-use cases taking into account the related issues of the pharmaceutical sector.

## 7. Discovery service implementation

Currently, the Discovery Service is not yet an official EPCglobal standard. It is recognized by the Internet Engineering Task Force (IETF) with the name of Extensible Supply-chain Discovery Service (ESDS) (18). ESDS is a protocol for infrastructure that enables track and trace applications as well as product lifecycle information systems to find multiple sources of information.

Many reasons lead to the standardization of this protocol. First of all, it is useful to allow different organizations to collect and store information relating to a particular product, to control the stored information and to decide how many and what information to make available to other organizations. This also takes into account the key principle of information sharing within a community according to which data ownership must be respected. This means that each organization can collect information within their own systems and is not required to route that information to any other organizations. In short, the ESDS allows

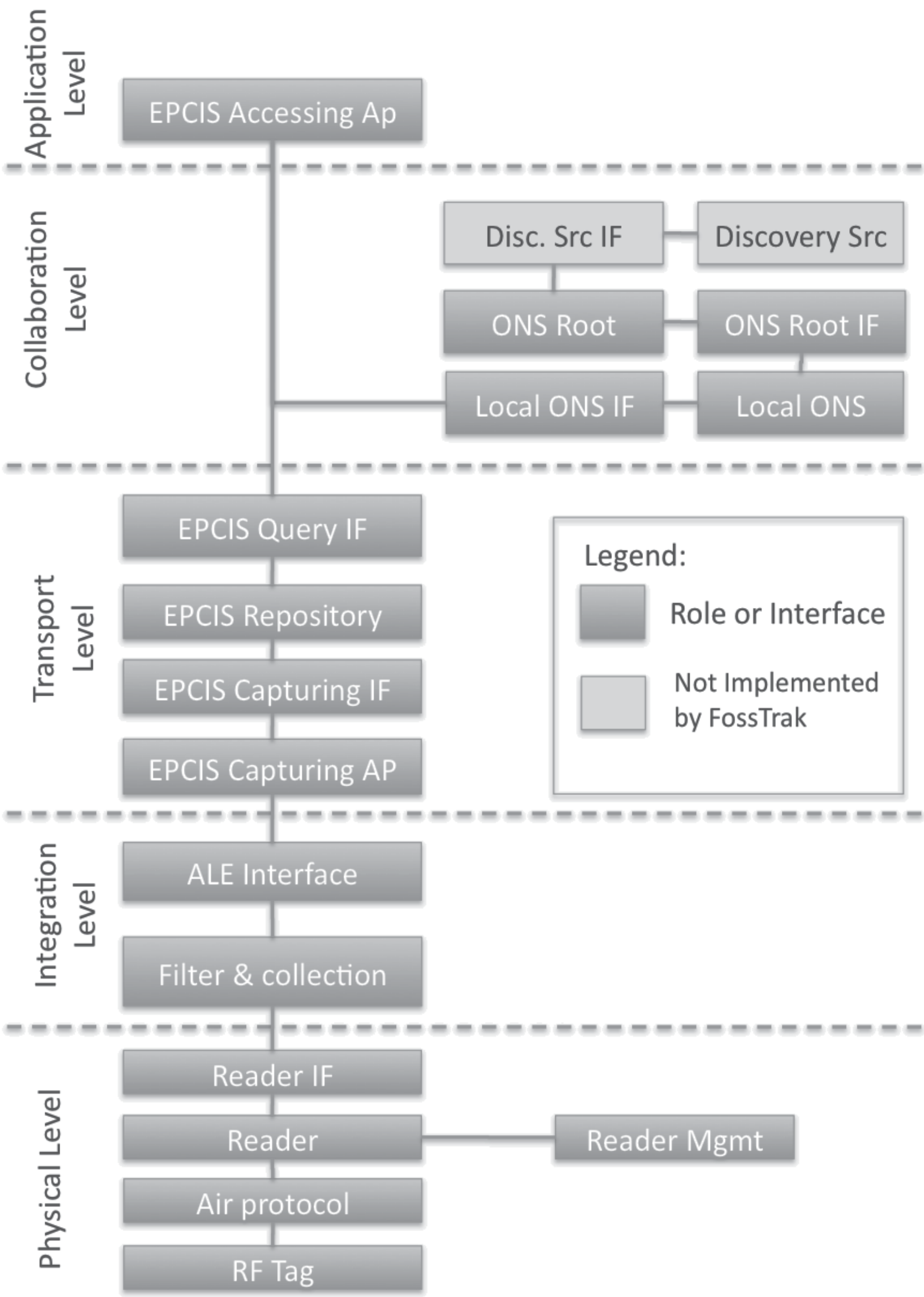


Fig. 7. FossTrak framework layered architecture.

different applications to identify various information resources and to gain a global view of information about a particular product. At a conceptual level, Discovery Services can be regarded as being somewhat analogous to a bottom-up 'search engine' for an IoT. However, there are some fundamental differences from the paradigm of public web search engines. First of all, each information provider will be able to voluntarily publish a record or registration for a particular common identifier, in order to be identified as a potential provider of information. Furthermore, the serial-level information will usually be protected and will only be made available to authorized organizations, with whom the information provider has an established trust relationship. Therefore, there may be only little information provided to non-authenticated users or directly to the general public without authentication. This approach enables the distributed management of the collected information and allows each organization to restrict who can access the data: they can specify an access control policy (which is enforced by a Discovery Service) to limit visibility of the 'link' information and additionally, they can specify and enforce an access control policy within their own information resource that holds the more detailed information. If the use of the Discovery Service is not provided, alternative solutions should be implemented to enable information sharing between trading partners. For example, the solution adopted by FossTrak enforces all members of a supply chain to store their information in a unique EPCIS server. Obviously, the ESDS should not act as an aggregator of detailed information, but should only help a customer to find the sources containing such information. In the literature, several works aim to implement a solution for the Discovery Service. In (19), the authors showed a simple, scalable discovery platform, called the Product Trace Service Platform, which is based on the EPCglobal Network and ONS specification. It is a lightweight proposal whose purpose is to allow the enterprise to develop a Discovery Service easily and quickly, and provide an effective environment to connect supply-chain applications to EPCglobal network. This platform is easy to use and easily extensible owing to the combination with ONS and the use of eXtensible Markup Language (XML), and is seamless in its response to the related EPC queries since it is based on Web Services. Reference (20) focusses on providing a first implementation of a simple, scalable infrastructure for building Discovery Services. Discovery Services are composed of a database and a set of web service interfaces. The developed application tracks the freshness of avocados across a food supply chain and allows the rerouting of products that are unsatisfactory. There is also a European project, BRIDGE (Building Radio Frequency IDentification for the Global Environment) that is focussing on an implementation of the Discovery Service. The BRIDGE project is a European Union funded 3-year Integrated Project addressing ways to resolve barriers to the implementation of RFID in Europe, based upon GS1 and EPCglobal standards. BRIDGE has several WP (work packages), among which WP2 is assigned to research the Discovery Service (21), (22). BRIDGE WP2 suggests two models. The first is the same as ESDS and provides the URL of EPCISs that holds data relevant to a specific EPC. The second is a query-relay model. It relays the EPCIS query to several EPCISs and gives a unification of the results from each EPCIS. It is a large extension of the ESDS and is convenient when results of a query from several EPCISs are needed. Observe that, unlike other works, in order to validate the proposed implementation of the Discovery Service, the authors decided to use a controlled simulation environment that is able to simulate all the most important steps of a supply chain, from the reading of a tag on the production line to its distribution to a retailer. Moreover, to further comply the proposed solution with EPCglobal standards, the authors decided to incorporate it into the FossTrak framework, which is recommended by the EPCglobal group itself, since it implements the entire protocol

stack.
The implementation and experimentation of a Discovery Service mechanism integrated with a network architecture conforming to EPCglobal have been developped as an extension of the framework FossTrak. This is an open framework that implements all interfaces and protocols defined in the EPCglobal specifications. This framework respects exactly the current standards provided by EPCglobal. Let us observe that the Discovery Service is still not implemented in the FossTrak framework because it is not yet an official EPCglobal standard. FossTrak, as shown in Fig. 7, implements the following levels of the EPCglobal network architecture:

1. Physical level: it includes all functions defined in lower layers of the EPCglobal stack. In more detail, it is responsible for the interaction with the reading and encoding procedures. This level covers standards such as Tag Data, Tag UHF Protocol and LLRP.
2. Integration level: it implements the standardized procedures to manage and control the reading devices. This level covers the standards ALE and Reader Protocol.
3. Transport level: it is the core of the architecture implementing the procedures to guarantee sharing and exchanging of traceability data. This level represents the EPCIS.
4. Collaboration level: currently, it implements only the ONS service.
5. Application level: it provides the application interfaces (API) to access or query EPCIS services.

The presented work aims at extending the FossTrak framework by adding a Discovery Service module that follows the guidelines indicated by IETF with the name of ESDS (18). It is able to overcome the restriction in the FossTrak framework of tracing systems characterized by a single organization domain (i.e. unique EPCIS server per supply chain). The purpose of the Discovery Service is to provide the references to every data source related to a specific EPC code in a supply chain composed of many partners. In the EPCglobal architecture, the privileged data source will be, obviously, the EPCIS. Different organizations can manage an object in different phases of its lifecycle, and each of them can collect and store information related to it. Similar objects, created in the same batch, could follow, during their lifecycle, different paths inside different organizations. Each organization should be able to control the information that has collected and stored and should be able to decide which information to make available to other organizations. This goal can be reached through the requesting of client authentication and the specification of access control policies for every data. To implement such a requirement, according to the ESDS, the following minimum set of commands is needed:

1. Hello: this command works as 'ping' and returns the state of the ESDS server (up or down). This method allows also the knowing of the server local time.
2. userLogin: this command allows user authentication. A session identifier keeps up the session.
3. eventCreate: this command creates a new ESDS event. This event includes the EPC code, the references to the services available and all the essential information, for example, the timestamp, the user that created or deleted an event, the supply chain to which the object belongs, and the partner who generated it.
4. eventLookup: this command allows knowing all the events associated to a specific tag, also including the services external to the Discovery Service itself.

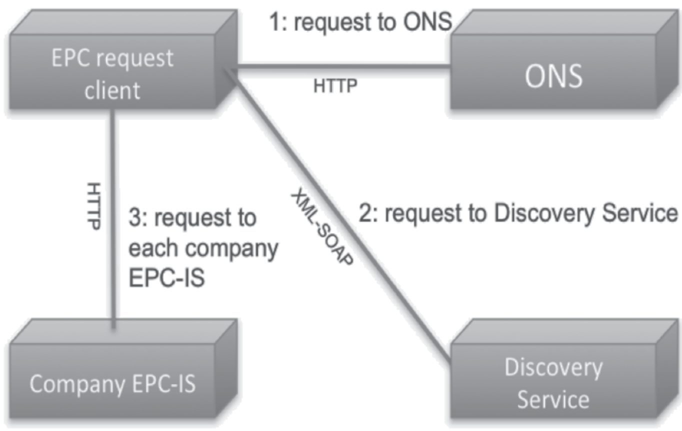


Fig. 8. Logical architecture of Discovery Platform in the large.

This implementation of the Discovery Service has been based on the WSDL (Web Service Description Language) file provided by the IETF draft and has the form of a JAX-WS (Java API for XML Web Services) web service. All the data about ESDS events is stored in a MySQL database that provides the persistence layer to the discovery platform, assuring security, stability, and robustness above all by a massive use of the stored procedure. In the extended EPC network architecture, the ONS server has been implemented by a free Windows based DNS server that supports NAPTR (Naming Authority Pointer) records (code 35). Fig. 8 shows the logic architecture implemented. It is mainly composed of the following modules:

1. ONS server for the startup phase of the Discovery Service.
2. One or more EPCIS for each organization domain.
3. An EPCIS client to insert data inside the organization EPCIS.
4. A client application to insert events inside ESDS.

As can be seen in Fig. 8, the EPC client provides three main operations:

1. Code conversion of the SGTIN tag from urn:epc:id:sgtin:manufacturerID.ObjectID.SerialID to ObjectID.manufacturerID.sgtin.id.onsepc.com form. Then a request to the ONS server will return the references to the URLs of the Discovery Service URL and of the manufacturer EPCIS.
2. EPC-Client will perform a request to the Discovery Service, asking for all the events having as ObjectID a given EPC code, correlating it with the URLs of the authoritative EPCIS. This request has a security check; only users with the right role and credentials can perform this kind of request.
3. EPC-Client will query every EPCIS server whose reference is provided by the Discovery Service, and will receive all and only the events they are authorized to read. The client will show the information retrieved.

## 8. Test bed for the pharmaceutical case

In order to appreciate the main benefits that the overall system implemented is able to provide to all actors of the pharmaceutical supply chain, a use case has been defined and used to carry out an experimental validation in a controlled test environment. It has been developed with the aim of simulating the main steps of the pharmaceutical supply chain. Let us observe that an item-level tracing system of drugs starts just after the packages are filled during the manufacturing process. In this step, each tagged product is scanned individually on the conveyor belt and then cased to be sent to the wholesalers. The wholesalers separate the products according to their identifiers and place them onto the shelves. Wholesalers receive orders from retailers. These orders often consist of small quantities of different products; they may contain a large number of items. The products in the orders of the retailers are picked and put into some large envelope bags that are scanned and confirmed before their distribution. Upon receipt, the retail pharmacy scans the contents of each bag without opening it. The test bed has been defined mainly in order to validate the capability to provide a data interchange and traceability system proper to every actor of the supply chain (i.e. manufacturer, wholesaler, and pharmacy retailer). In order to simulate the pharmaceutical scenario, a controlled laboratory environment, shown in Fig. 9, has been created. It is equipped with an 'items line', a 'cases line', and a 'border gate'. The main software and hardware components used are:

1. three UHF RFID readers, the Impinj Speedway;
2. two Near Field UHF reader antennas by Impinj MiniGuardrail for the item-line;
3. four Near Field UHF reader antennas by Impinj Brickyard for the cases-line;
4. four Far Field UHF reader antennas for the border-gate;
5. two conveyor belts whose speed can be tuned in the range from 0 to 0.66 m/s;
6. HTTP Server Apache Web Server v. 2.2
7. Servlet Container Apache Tomcat v. 6.018 (Servlet, JSP, JSF)
8. DBMS MySQL v. 5.0
9. Development Framework Java 2 Enterprise Edition (Java v. 1.6).
10. Several types of passive UHF RFID tags (e.g. Thinpropeller, Cube2, Paperclip), both near field and far field, have been used in the tests.

After a preliminary setting of the test environment, the use case has been carried out. In order to test the overall system, and so both the traceability module and the interchange of business messages one, this use case can be analysed considering two separate components. For the traceability component, the use case has been defined writing unique EPC code (by using the SGTIN code) and applying RFID tag on each item. Then the transmission of EPC code to the EPCIS server is executed by the FOSSTRAK capture application. The client (the manufacturer) uses SOAPUI (Simple Object Access Protocol User Interface) libraries to insert an XML event into the Discovery Service through the web service. The ONS configuration deals with specifying the Discovery Service link and information about the company's EPCIS that first associated the EPC code with object (manufacturer). It is also necessary to set the zone and to declare local ONS IP addresses to the authority. When the wholesaler receives a tagged object, it retrieves and updates the Discovery Service information, adding its own EPCIS link to the EPC code associated to the object. The query phase is performed by any actor of the supply chain and is based on three main operations. In the ONS service operation, the client (manufacturer, wholesaler, or pharmacy retailer) retrieves the Discovery Service associated to the EPC code and the company's EPCIS (manufacturer) that first associated the EPC code. In the Discovery Service operation, the client retrieves all EPCIS links involved in the EPC code management. Finally, in the EPCIS service operation, the client retrieves the EPCIS information of all organizations that have characterized the lifecycle of the particular tagged object. Instead, the following steps have been carried out to test the business messages interchange component:

– The pharmacy retailer sends an order request for a number of different medicines to the wholesaler.
– The wholesaler sends an order request to the manufacturer, specifying a part of the drugs requested previously from retailers, for a number of pallets for its supplies.
– The manufacturer prepares pallets, using the traceability sub-system to keep track of any package information, and the exchange sub-system to send an order response message to the distributor.
– The wholesaler receives the order response message and pallets, and verifies the correct correspondence between the received message information and the received products.
– The wholesaler prepares the drugs previously requested from the pharmacy retailer and uses the exchange subsystem to send an order response message to the retailer.
– The pharmacy retailer receives the order response message and packages, and verifies the correspondence between the received message information and the received products.

## 9. Methodology based on KPI

A key performance indicator (KPI) is a measure of performance very useful for evaluating the current status of an organization or for foreseeing the possible benefits obtainable by adopting an innovation in the system. KPIs are quantifiable measurements and depend on the particular organization. In order to evaluate the benefits provided by the proposed

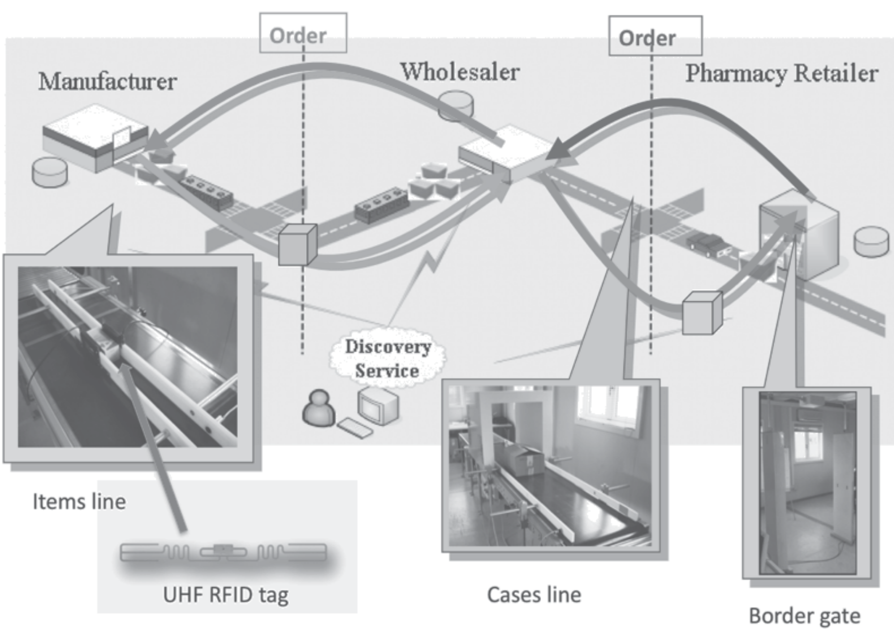


Fig. 9. Controlled test environment.

framework to each actor of the pharmaceutical supply chain, it is strategic to identify the main KPIs for the reference sector. Taking into account the considerable complexity of the pharmaceutical supply chain, this work focussed only on two stakeholders (wholesaler and pharmacy retailer). For these, the main KPIs have been identified and measured. An analysis based on KPIs is carried out by a comparison between AS-IS and TO-BE models. When the authors are not able to measure the KPI on the TO-BE model because the innovation is not yet introduced in the organization, a possible approach consists in identifying some key points where the KPI will be enhanced. This type of analysis is possible thinking about the intersection between the CSFs (critical success factors) and the KPIs both in the wholesaler and in the pharmacy. One of the original contribututions of this work is to identify the main KPIs for a complex business organization such as the pharmaceutical supply chain. The authors have defined not only KPIs but also the CSFs for the pharmaceutical supply chain. The analysis will provide a global vision of the performance and will cover both efficiency and effectiveness of the framework. A study of this type provides a final result not related to the real value of the product for the final user but it provides information about the quality of the final product and the speed and correctness of the business process. Before to define the KPI, it is important to locate the critical situation for each stakeholder of the business process. Focussing attention on the wholesaler, three different types of problems can be highlighted:

– IT problems: it is possible to automate several activities of the AS-IS that, until now, have been manual. For example when the drugs come to the wholesaler, the wholesaler states that all the items in the package are correct and the same wholesaler chooses the correct wholesaler for storing the drugs. It is clear that these and other manual activities do not provide any warrantee about the correctness of the actions.
– Supervision problems: in the AS-IS, the process is not supervised. The only check is by sending information to the AIFA but this check is not in real time and so business process problems are not immediately found.
– Flow problems: several tasks have no value for the business process. For example, when the package comes to the wholesaler, the operator state that all items in the case are undamaged and respect the order done. This task does not provide any value but it brings to an error. The business process, not presented here, is not linear: both manual and automatic efforts are involved in this phase. These features increase the difficulty of monitoring the process flow.

Instead, the main problems of the pharmacy retailer are as follows:

– IT problems: the check of the order is manual but it should be possible to check the order automatically.
– Check problem: in the AS-IS model the process is not supervised. The only check is made by sending information to the AIFA but it is not in real time and so business process problems are not immediately found.
– Flow problem: the flow in the pharmacy is not critical.

## 10. Evaluation of KPI

Taking into account the previous types of problem, the main CSF have been identified for the wholesaler and the pharmacy retailer. The CSFs for the wholesaler are presented in Table I. Table II contains the main CSFs identified for the pharmacy retailer.

| Number | CSF | Metrics | Comment |
|---|---|---|---|
| 1 | Punctuality of the delivery | Time between order and delivery | Influence the Service Level Agreement |
| 2 | Timeliness | Errors/total delivered products | Influence the Service Level Agreement |
| 3 | Correctness of the return | Errors/number of returns | It is desirable that the wholesaler does not have products that come into the pharmacy from other wholesalers |
| 4 | Abatement of product losses | Number of outgoing products/ Number of incoming products | The wholesaler wants to reduce the number of lost products. |
| 5 | Correctness of the escape order | Number of products that come back/total number of orders | A correct order does not generate returned products |

Table 1. CSFs for the wholesaler

Starting from the CSF analysis, it is possible to define the performance indicator for measuring system performance. The same indicators would be measured for both models (i.e. AS-IS and TO-BE). The indicators, both for the wholesaler and for the pharmacy retailer, are of three types: Quality, Service and Cost. The main KPIs identified for the wholesaler are reported in Table III.
Table IV reports the main KPIs identified for the pharmacy retailer. In order to evaluate the main indicators for the TO-BE model, a useful approach is to perform a combined analysis. In particular, connecting together KPIs and CSFs, it is possible to highlight that, for the

Pharmacy Retailer

| Number | CSF | Metrics | Comment |
|---|---|---|---|
| 1 | Punctuality of the delivery | Waiting time for the customer | The client must have the product as soon as possible |
| 2 | Timeliness | Number of requests in stand by due to unavailability of the product | |
| 3 | Time to acquire the request | Time to dismember order | |
| 4 | Correspondence between member of product and information system | Number of orders for products already at the wholesaler's | It is possible to order product already in the wholesaler |

Table 2. CSFs for the Pharmacy Retailer

wholesaler, the quality indicators are strictly related to the CSFs 'Punctuality of the delivery', 'Timeliness' and 'Correctness of the escape order' and the Service indicators are strictly related to the 'Punctuality of the delivery'; finally, the Cost indicator is strictly related to the other defined CSFs. In the same way, for the pharmacy retailer, the impact of the indicator on the punctuality of the delivery is very important, while the impact of the indicator to the other CSF is less important.
The analysis carried out on the pharmaceutical supply chain allowed us to identify the more significant KPIs and CSFs for the wholesaler and pharmacy retailer through a continuous monitoring and reporting of the main business processes for a period lasting 3 months. The measurements of these indicators, performed on the AS-IS model, have highlighted the critical points in the current management of the drug flow. The results of this analysis are not reported in this chapter because the main goal of this work was to identify the best indicators

| | Indicators | | |
|---|---|---|---|
| Number | Quality | Service | Cost |
| 1 | Time to escape order | Punctuality of the delivery | Average cost of order composition (cost of operator + cost of facilities) |
| 2 | Availability of the products | Number of wrong orders | Cost of order preparation |
| 3 | Accuracy in order preparation | Correctness of the order | Number of returned products of the own-company/Number of returned total products Cost of products lost |
| 4 | Number of items in input/output | Number of returned products out of date | Cost to acquire order (includes the cost of delivery) |
| 5 | Number of total escape orders | Number of products lost | Time to compose order |
| 6 | Number of total escape orders for operator | Number of come back orders/Total number of orders | Time to check order |
| 7 | Number of products simply to keep | Punctuality of the first delivery | |
| 8 | Number of products in the wholesaler | Punctuality of the second delivery | |
| 9 | Number of hours for trailer truck | Time to prepare order | |
| 10 | Number of total work hours | Number of completed orders/ Number of work areas | |
| 11 | | Number of orders to manually check | |

Table 3. KPIs for the Wholesaler

| | Indicators | | |
|---|---|---|---|
| Number | Quality | Service | Cost |
| 1 | Availability of the products | Number of orders to dismember/day | Average cost of order composition (cost of operator + cost of facilities) |
| 2 | Number of available products/type of product | Number of orders to make/day | Cost of order preparation |
| 3 | Average time to have the product | Number of incorrect orders | Cost for products lost |
| 4 | | | Cost to acquire order (includes the cost of delivery) |
| 5 | | | Time to compose order |
| 6 | | | Time to check order |

Table 4. KPIs for the pharmacy retailer

to be used to measure the potential improvements of the proposed framework once it will be really implemented in the pharmaceutical supply chain. In order to best appreciate how the proposed framework may be able to solve some of the mentioned problems in the SCM system, the values of some indicators for wholesaler and pharmacy retailer, estimated by the measurements carried out for three months, are reported briefly as follows in Table V.

| KPI | Wholesaler | Pharmacy Retailer |
|---|---|---|
| Number of wrong orders | 50 | 3 |
| Correctness of the order | 7 items wrong | |
| Time to escape order | Average: 90 min Min:1min Max:14h | |
| Number of drugs lost | 178 | |

Table 5. Measurement of some indicators for the AS-IS model

These significant values allow us to assert that the use of the proposed framework will be able to solve several problems mainly because the innovations will minimize manual activities and thus minimize human errors. It is clear that the possibility of tracing at item-level every drug on the whole supply chain allows of obtaining the best flow control process, something not guaranteed in the current management system. The authors foresee that the real impact of the framework is in the quality and service indicators. It is clear that the improvement of service is immediately visible in the costs. For example the introduction of this framework reduces the time of delivery of the order (by eliminating manual checks, which are expensive both in time and in costs). The system improves the service indicators both for the pharmacy retailer and for the wholesaler. From the point of view of the pharmacy retailer, the number of orders per day will be reduced, while the wholesaler will have only to manage a minor number of incorrect orders and drugs lost.

## 11. Open issues

The practical experience gained from developing and testing the described research activity on the item-level traceability in the pharmaceutical supply chain has allowed us to appreciate the enormous advantages related to the use of passive UHF RFID technology and to merging the two chosen standards, EPCglobal and ebXML, into a single software architecture. The test bed has still shown some critical aspects that sometimes can degrade the performance of the overall system: in particular, operating conditions. They have crated the possibility to open a very interesting discussion with a large-scale scientific community about several areas of improvement opportunities for the future. The main issues related to the adoption of these technologies for item-level tracing systems of drugs are:

– Improving the UHF tags' performance in the presence of liquids and metals: the main features of passive UHF tags lead to the assertion that these represent the ideal choice for identification and tracing systems at item-level. Unfortunately, UHF tags could occasionally encounter problems, causing performance degradation, in the presence of materials such as liquids and metals that absorb RF energy. Some recent works (18) have demonstrated that the design of particular UHF tags is able to resolve such performance problems, obtaining optimal performance in each step of the supply chain and even in the presence of metals and liquids.

– Scalability of the EPC network: the use, on a large scale, of the EPC network for tracing systems at item-level could cause a collapse of the Discovery Service. Some proposals aim to use particular load balancing mechanisms or to define and implement a Discovery Service mechanism based on a peer-to-peer paradigm, e.g. exploiting a Distributed Hash Table (DHT), in order to improve scalability and effectiveness.

– Choice of the best standard for the business messages interchanges: there are various standard initiatives addressing the standardization of communication in exchanging information in different domains, such as RosettaNet in the electronic component industry, OAGIS in the automotive industry, CIDX in the chemical industry, and GS1 eCOM in the retail industry. At the moment, however, no document standard is sufficient for all purposes because the requirements significantly differ across businesses, industries and geo-political regions. On the other hand, the ultimate aim of business document interoperability is to exchange business data among partners without any prior agreements related to document syntax and semantics. Therefore, an important characteristic of a document standard is its ability to adapt to different contexts, its extensibility and customization. The UN/CEFACT Core Component Technical Specification (CCTS) is an important landmark in this direction, providing a methodology to identify a set of reusable building blocks, called core components, to create electronic documents. UBL was the first implementation of the CCTS methodology. Some earlier horizontal standards such as Global Standard One (GS1) XML and Open Applications Group Integration Specification (OAGIS), and some vertical industry standards such as CIDX and RosettaNet have also taken up CCTS.

– Evaluation of potential effects of the RFID on the drugs: Before having a large diffusion of RFID technologies in the pharmaceutical sector, it will be necessary to provide all guarantees to exclude every possible effect of electromagnetic waves produced by a UHF RFID system on drugs. Particular attention is focussed on the evaluation effects of tracing RFID systems on the molecular structure of biological drugs. (23). Some recent works (27) have focussed on this topic, exploiting diagnostic techniques such as high pressure liquid chromatography (HPLC) and nuclear magnetic resonance (NMR) spectroscopy. Also the authors have a specific research activity on the topic (28)(29)(30).

– Integration and interoperability of EPC network services with the information systems of organizations: EPC network architecture tries to standardize components and interfaces to serve as a basis for RFID-driven business. Currently, only the local components specified in the EPC network architecture are being used (24). Inter-organizational collaborations on RFID-data exist, but they focus on small closed-loop applications. In order to exchange data on the network, organizations are forced to use proprietary software that connects their local EPC network stacks and thereby their businesses. The lack of standardization and high costs for developing common components over again each time is a major hindering factor for the adoption of RFID (25).

– Improvements of the security mechanisms: as soon as RFID technology becomes pervasive, the resolution of privacy and security problems will assume a crucial role. The possibility of having, especially with UHF systems, read ranges of several meters stimulates the activities of attackers. Different works (26) have been focussed on privacy protection and integrity assurance in RFID systems in order to destroy this technical barrier. Furthermore, the tag-to-reader couple does not represent the only vulnerable area. The main services of the EPC network are based on the Internet (e.g. ONS, Discovery Service, etc.), and so these tracing systems have to adopt all possible mechanisms designed to guarantee confidentiality and integrity in the data transactions through the Internet.

## 12. References


[1] European Commission & EPoSS working group RFID (2008). Internet of things 2020. A roadmap for the future. In Workshop: *Beyond RFID - The Internet Of Things*, 5 September 2008.

[2] Dilek, D.; XXXXXREPLACE et al. HERE BY THE TRUE LIST; SIMILARLY EVERY SECOND TIME IT OCCURS. (2008). Evaluation of RFID Performance for a Pharmaceutical Distribution Chain: HF vs. UHF, *Proc. of the 2008 IEEE International Conference on RFID*, Las Vegas, Nevada, USA, April 16–17, 2008.

[3] De Blasi, M.; et al. (2009). Performance Evaluation of UHF RFID tags in the Pharmaceutical Supply Chain, *Proc. of the 20th Tyrrhenian International Workshop on Digital Communications*, a CNIT Conference - Pula, Sardinia, Italy, September 2–4, 2009.

[4] Thiesse, F.; et al. (2009). Technology, standards, and real-world deployments of the EPC network. *IEEE Internet Computing*, vol. 13, no. 2, Mar./Apr. 2009, pp. 36–43.

[5] Bendavid, E.; et al. (2009). Key performance indicators for the evaluation of RFID-enabled B-to-B e-commerce applications: the case of a five-layer supply chain. *Inf Syst E-Bus Manage*, 2009, 7:1–20 DOI 10.1007/s10257-008-0092-2.

[6] Barchetti, U.; et al. (2010). RFID, EPC and B2B convergence towards an item-level traceability in the pharmaceutical supply chain, *Proc. of the 2010 IEEE International Conference on RFID-Technology and Appliction*, IEEE RFID-TA 2010, Guangzhou, China, June 17-19, 2010, ISBN:978-1-4244-6699-3.

[7] Draft Federal Information Processing Standards Publication. Integration definition for function modeling (IDEF0), 1993.

[8] Eriksson, H. & Penker, M. (2000). *Business Modeling with UML: Patterns at work*, Wiley, New York.

[9] OMG. Business Process Modeling Notation Specification (BPMN), 2006.

[10] OMG. The framework for eBusiness, 2007.
[11] Hofreiter, B. & Huemer, C. (2002). B2B Integration - Aligning ebXML and Ontology Approaches. *Proc. of the First EurAsian Conference on Information and Communication Technology*, pp. 339–349, October 29–31, 2002.
[12] OASIS. Universal Business Language, 2009.
[13] Microsoft SOA electronic book. Service Oriented Architecture (SOA) in the Real World, 2007.
[14] OASIS Service Component Architecture / Assembly (SCA-Assembly) TC. Service Component Architecture Assembly Specification Version 1.0, 2007.
[15] OASIS SOA Reference Model TC. OASIS Reference Model for Service Oriented Architecture, 2008.
[16] Dorn, J.; et al. (2007). A Survey of B2B Methodologies and Technologies: From Business Models towards Deployment Artifacts. *Proc. of the 40th Annual Hawaii International Conference on System Sciences*, January 3–6, 2007.
[17] Mealling, M. (2008). A uniform resource name namespace for the EPCglobal electronic product code (EPC) and related standards. *IETF RFC 5134*, Internet Society, January 2008.
[18] Young, M. (2008). Extensible supply-chain discovery service concepts. *Internet Draft, IETF*, August 29, 2008.
[19] Yingping, C.; et al. (2007). PTSP: a lightweight EPCDS platform to deploy traceable services between supply-chain applications. *Proc. of the 1st Annual RFID Eurasia*, Sept. 5–6, 2007, pp. 1–5, 2007.
[20] Beier, S.; et al. (2006). Discovery services - enabling RFID traceability in EPCglobal networks. *Proc. of the International Conference on Management of Data*, COMAD 2006, Delhi, India, December 14–16, 2006.
[21] University of Cambridge et al. (2007). High level design for discovery services. *Technical Report of the BRIDGE project*, August 15, 2007.
[22] Guijarro, M.; et al. (2008). Working prototype of serial-level lookup service. *Technical Report of the BRIDGE project*, February 2008.
[23] Bassen, H.; et al. (2007). An Exposure System for evaluating possible effects of RFID on various formulations of drug products. *Proc. of the 2007 IEEE International Conference on RFID*, Grapevine, TX, USA. March 26–28, 2007.
[24] Acierno, R.; et al. (2010). Effects Evaluation of UHF RFID systems on the molecular structure of biological drugs. *Proc. of the 4th International Conference on Bioinformatics and Biomedical Engineering*, (iCBBE 2010), June 18–20, Chengdu, China, 2010.
[25] Wamba, S.; et al. (2006). Enabling intelligent B-to-B eCommerce supply chain management using RFID and the EPC network: a case study in the retail industry. *Proc. of the 8th international conference on Electronic commerce*, ICEC '06, Fredericton, NB, Canada, ACM Press, New York, pp. 281–288, 2006.
[26] Staake, T.; et al. (2005). Extending the EPC network: the potential of RFID in anti-counterfeiting. *Proc. of the 2005 ACM symposium on Applied computing*, ACM Press, New York, pp. 1607–1612, 2005.
[27] Mirowski, L.; et al. (2009). An RFID Attacker Behavior Taxonomy. *IEEE Pervasive Computing Magazine*, Oct.–Dec. 2009, pp. 79–84.
[28] Acierno, R.; et al. (2011). RFID-based Tracing Systems for Drugs: Technological Aspects and Potential Exposure Risks. *Proc. of the 1st Annual IEEE Topical Conference on Biomedical Wireless Technologies, Networks, and Sensing Systems*, BioWireleSS 2011, Phoenix, AZ,

USA, Jan. 16–20, 2011.

[29] Mainetti, L.; et al. (2010). Exposure to Electromagnetic Fields in UHF Band of an Insulin Preparation: Biological Effects. *Proc. of the IEEE Biomedical Circuits and Systems Conference*, BIOCAS 2010, Paphos, Cyprus, Nov. 3–5, 2010.

[30] Carata, E.; et al. (2010). Effects Evaluation of UHF RFID Systems on the Molecular Structure of Biological Drugs. *Proc. of the 4th International Conference on Bioinformatics and Biomedical Engineering*, Chengdu, China, Jun 18–20, 2010, pp. 1–4, ISBN: 978-1-4244-4713-8.

[Wikipedia Foundation] Wikipedia description. Radio frequency identification. http://en.wikipedia.org/wiki/RFID.

[epcglobal] GS. EPCglobal framework. http://www.epcglobalinc.org/home.

[gs1] GS1 organization. http://www.gs1.org/.

[fosstrak] FossTrak: open source RFID software platform. http://www.fosstrak.org/.

# Part 2

## Coordination

# 15

# Strategic Fit in Supply Chain Management: A Coordination Perspective

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## 1. Introduction

A supply chain (SC) consists of all companies involved in the procurement, production, distribution and delivery of a product to a customer. Because different economic entities participate in the SC, it is significantly more complicated to manage than a single organization. Decision making in SCs is difficult due to differences between the objective functions of different SC members. Locally optimal decisions made by individual members are not necessarily optimal for the SC as a whole. In today's market, competition between individual companies is being supplemented and supplanted by rivalries between SCs. Obtaining a larger market share means winning the competition. When a SC is not able to satisfy customer's needs, its market share will be lost to competitors. Supply Chain Management (SCM) as a field of study intends to organize, coordinate and control the activities toward the ultimate goal of winning this competition.

One of the critical issues in the SCM is the consistency between "what the supply chain performs" and "what the customer expects". The survival of supply chains in a competitive business environment depends on the consistency between "Customer expectation" and "SC performance", which forms the concept of "Strategic Fit". To examine the concept of strategic fit, we first describe its elements in detail. There are two main elements that constitute strategic fit: (1) the customer's expectation, which is the main building block of the "competitive strategy" of a SC and (2) the SC's performance, which is associated with the "SC strategy" in responding to the established competitive strategy.

The customer's expectation is defined by the target customers that the company intends to serve. A company's "competitive strategy" is its basic method of satisfying more of the customer's expectations than its competitors. Indeed, the competitive strategy of a company includes its target customers and their specific needs, such as the product type, orders, information, special services, and so on. Porter (1979) introduces the following five competitive forces that shape the strategy: bargaining power of buyers, threats of new entrants, bargaining power of suppliers, threats of substitute products or services, and rivalry among existing competitors. The strongest competitive force can be considered as the basis for the strategy formulation (Porter, 2008). Based on Porter's model, the competitive advantage of a company can be based on product differentiation or lower prices (Porter, 1985). Porter's generic competitive strategies model (Porter, 1980) introduces three main competitive strategies, including product differentiation, cost leadership and focus (market segmentation). Applying the appropriate strategy depends on the targeted market scope (broad or narrow) and the customer's expectations (lower cost or product differentiation). According to Porter's generic competitive strategies model, if the customers are cost-conscious or price-sensitive and the company targets a broad industry market, then cost leadership is the right strategy. In cost leadership, the company sets out to become the lowest cost producer in its industry using solutions like economies of scale, preferential access to raw materials, economical distribution channels, proprietary technology, and so on. If the company targets a broad industry market and the customers expect products with unique characteristics, then the product differentiation strategy will be appropriate. Differentiation involves offering a product that is perceived throughout the industry as unique. The uniqueness of a product or service may be associated with the special features of the product, including innovative technology, unique design, size and shape. When the company competes in a focused market segment with a narrow scope, it can exploit from both differentiation and cost leadership strategies in the targeted segment, which is called a focus strategy.

Although the customer expectation is the basis for defining the competitive strategy, it is obvious that the business environment (including, customers, suppliers, competitors, and governmental regulatory agencies) plays a key role in defining a company's competitive strategy. Defining the competitive strategy of an organization requires identifying or predicting the behavior of its customers, suppliers, and competitors. However, if there is little information about the business environment, then the predictability is impaired and the environmental uncertainties increase. Because the strategy is concerned with the future, the strategy planning process always faces some degree of uncertainty. The first step in formulating the competitive strategy is known as identifying the sources of uncertainties. Four sources of uncertainties are identified for an independent company: (1) Demand structure, (2) Supply structure, (3) Competitors, and (4) Externalities (Wernerfelt and Karnani, 1987). A recent study has identified three sources of uncertainties in SC: demand, supply, and process uncertainties (Peidro et al., 2009).

In addition, the defined competitive strategy can move the company toward business environments with low or high degrees of environmental uncertainty. It all depends on "how the company intends to compete." Although the uncertainties make the future more ambiguous, higher levels of uncertainty also provide some opportunities (alongside the risks) for the company (Courtney et al., 1997).

Environmental uncertainties for various businesses differ in kind as well as in degree. Four levels of uncertainty are distinguished for business environments: (1) A clear enough future, (2) Alternative futures, (3) A range of futures, and (4) True ambiguity. Suitable strategies for each level of uncertainty have been presented in the literature (Courtney et al., 1997).

So far, we have discussed the relation between the customer expectations, business environment uncertainties, and competitive strategy. Based on these topics, it follows that the competitive strategy chosen by a SC depends on how much uncertainty the SC faces. Now, we will discuss the required activities and decisions within the SC supplementing the chosen competitive strategy. Indeed, by setting its competitive strategy, the company decides to compete in a business environment with specific types and degrees of uncertainties. Success in this environment requires an appropriate match between the SC strategy and the uncertainties.

There is a close relationship between customer's expectations and "customer satisfaction". If the company meets the customer's expectations more accurately and better than its competitors, it will have satisfied customers. "SC performance" reflects the SC's ability to provide the product or service to the customers that satisfies them. The nature of operations within the SC, including procurements of raw material, manufacturing, transportation, and delivery of goods (i.e., SC performance) forms the "Supply Chain Strategy (SCS)". Because the SC includes all stages in fulfilling a customer request, the SCS includes all activities and decisions associated with the flow of goods and information across the SC. The SCS is about planning and decision making about questions such as network design, sourcing, purchasing, manufacturing, pricing, inventory decisions, transportation, new product development programs, marketing, advertisement, finance, and customer relationship management programs. Chopra and Meindl (2001) introduce the logistical and cross-functional drivers representing the SCS as the facilities, inventory, transportation, information, sourcing, and pricing. The first three drivers are the logistical, and the last three are the cross-functional drivers. Supplementing the above categories, another classification proposes five areas of decision making in SC: production, inventory, location, transportation, and information (Hugos, 2003). A SCS may rely on responsiveness or efficiency (Chopra and Meindl, 2001; Hugos, 2003). Because responsiveness and efficiency are the two ends of a spectrum, the SC manager must resolve the trade-off between responsiveness and efficiency in each of the above categories. Table 1 illustrates the responsiveness-efficiency trade-offs in the five SC drivers according to Hugo.

| Decision making area | Definition | Meaning of efficiency in this area | Meaning of responsiveness in this area |
|---|---|---|---|
| **Production** | Capacity of factories and warehouses across the SC to make and store the products respectively | No excess capacity | Creating a lot of excess capacity |
| **Inventory** | All goods held by the manufacturers, distributors, and retailers throughout the SC | Cost of inventory should be kept as low as possible by holding low amounts of inventories | Holding large amounts of inventory |
| **Location** | Geographical sites of SC facilities | Centralizing activities in fewer locations to gain economies of scale | Decentralizing activities in many locations close to customers and suppliers for fast responses |
| **Transportation** | Movement of goods between different facilities in SC | Slow and low cost modes of transportation | Fast and costly modes of transportation |
| **Information** | Connections among the various activities and stages in the SC | Short term: Collect less information about fewer activities<br>Long term: collect and share informative data generated by the other four drivers | Collecting and sharing accurate and timely data generated by the operations of the other four drivers |

Table 1. The five SC drivers and the responsiveness-efficiency trade-off

Generally speaking, efficiency in performing a task means that the costs are as low as reasonably possible. In a strategy based on efficiency throughout the SC, the customers receive low prices. On the other hand, they cannot always quickly and easily obtain their desired product.

In contrast, in a SC strategy based on responsiveness, the customers receive high availability of products, low lead times, and highly innovative products. However, the customers cannot expect such low prices. In this case, the customers can obtain the desired product more quickly and easily but at higher costs.

Alignment between competitive and SC strategies, known as "strategic fit," can be achieved by adjustments between the SC drivers and environmental uncertainties. The strategic fit is known to be the most important issue associated with the SCM in competitive environments (Hogus 2003, Chopra and Meindl, 2006). Achieving strategic fit is difficult from both the theoretical and practical points of view. Although many prior researchers have studied ways to achieve strategic fit, it still requires more practical solutions. The previous studies have focused on explaining various aspects of the concept of strategic fit, but their models are limited to the problem as they are defined from the macro-strategic perspective.

In this chapter, we discuss how strategic fit can be achieved by coordinated decision making on some decision variables throughout the SC. This chapter, supplementing previous studies, provides a more practical solution for aligning the strategies throughout the SC based on the concept of coordination. Coordination plays a unique and central role in SC management. Hugo (2003) has defined the SCM as the "coordination of production, inventory, location, and transportation among the participants in a supply chain to achieve the best mix of responsiveness and efficiency for the market being served". In the traditional decision making process, each SC member makes its authorized decisions individually. Each SC member aims to maximize its own profit regardless of the other participants. Nevertheless, most of its decisions affect the other members. For example a retailer's decision on the order size affects the production batch size, setup costs and inventory holding costs of the producer. Therefore, we can conclude that the individual optimization of decision variables in the SC results in a local optimization that is not necessarily globally optimal. To address these deficiencies, coordination models have been developed by field researchers. A coordination model in a SC can be defined as an operational plan that aligns the decisions of different SC members toward the globally optimal decision. Coordination mechanisms have an operational plan for finding the globally optimal decisions. If the SC has a decentralized structure, i.e., if independent economic entities participate in the SC, then the globally optimal solution is not always acceptable to all SC participants. Although the globally optimal decisions increase the total SC profitability, they often decrease the profits of some members in the decentralized SC structure. An economic entity accepts a decision if its profit increases by accepting the decision. For example, consider the case in which making a decision increases the total profit (the sum of all SC members' profits) of a two-stage SC (including one retailer and one manufacturer) by $100; now, if the retailer's profit increases by $110 while the manufacturer loses $10, then the manufacturer refuses to implement the decision. In such cases, it is necessary to establish an incentive scheme to induce the lost member to accept and implement the globally optimal decisions. By establishing the incentive scheme, the surplus is shared between members fairly to ensure their participation. If a decision variable X is under the authority of one SC member but affects other members' profitability, then coordinated decision making on the decision variable X increases the overall SC profit. However, applying the coordinated value of the decision variable X decreases the profit of the decision maker. Therefore, coordinated decision making requires appropriate incentive schemes to convince the members to participate. Return policies, discount models, pricing schemes, and delays in payments are some of the incentive schemes in the field of SC coordination. In this chapter, we demonstrate that strategic fit can be achieved in a SC through coordinated decision making.

## 2. Literature review

Fisher (1997) has introduced a structure for determining the right supply chain strategy. According to Fisher's model, the SC strategy is established based on the product type (Fisher, 1997). For functional products, where demand is predictable and stable over time, an efficient supply chain is suitable, while for innovative products where the product lifecycle is short and demand is unpredictable, a responsive supply chain is more appropriate. Fisher's model considers the differences between the products as the main factor in establishing the right SC strategy. Because the product type affects the uncertainties from the customers' side, Fisher's model considers the demand uncertainties as the only effective parameter in establishing the SC strategy. The demand for functional products is mainly predictable, while innovative products have an unpredictable demand. The uncertain demand for innovative products can creates high and frequent shortages in satisfying the customers' demand. The average stock-out rate for functional products is 1% to 2% while this rate is 10% to 40% for innovative products (Fisher, 1997). Based on Fisher's model, there are two main strategies to manage the supply chain: efficiency and responsiveness. The primary purpose of an efficient supply chain is to provide the lowest price to the customers, while a market-responsive SC aims to respond quickly to the customers' demand. Suppose that efficiency is the right strategy for a SC; what must its members do to create an efficient SC? Based on Fisher's model, in this case the manufacturer should maintain a high utilization rate, the inventory should be minimized throughout the SC, and the suppliers should be selected based on their cost and quality. In contrast, to create a market-responsive SC, the manufacturer should deploy excess capacity, a high level of inventory should be held throughout the SC, and the suppliers should be selected based on their flexibility, speed, and quality.

Subsequently, Lee (2002) introduced a framework for establishing a strategy based on supply and demand uncertainties. In Lee's model, in addition to the demand uncertainty, the supply uncertainty has been taken into account. Like the customer demand, the supply process may include uncertainties. If the supply process is well established, it is called a "stable" supply process. The stable supply process has characteristics including high numbers of supply sources, reliable suppliers, dependable lead times, few break downs, and high flexibility. Compared with the stable supply process, if the supply process is in the early development phase, it is called an "evolving" supply process. The evolving supply process has characteristics including limited supply sources, unreliable suppliers, variable lead times, vulnerability to breakdowns, and inflexibility. Although the product type often affects the supply uncertainty in addition to the demand uncertainty, this is not always the case. The product type always defines the demand uncertainty, but it is possible for a product with low demand uncertainty to have higher supply uncertainty. In other words, functional or innovative products can have certain or uncertain supply processes. Therefore, there are four possible combinations of supply-demand uncertainties in Lee's model: functional product-low supply uncertainty, functional product-high supply uncertainty, innovative product-low supply uncertainty, and innovative product-high supply uncertainty. Lee's model provides a framework to establish the appropriate SC strategy for each of these combinations. Lee's model, supplementing Fisher's model, introduces four strategies based on the product type and supply uncertainties for the SC. Table 2 shows Lee's model. As shown in table 2, Lee's model encapsulates the uncertainties as the demand and supply uncertainties and introduces four strategies to manage a SC: efficiency, risk-hedging, responsiveness, and agile strategies.

| Strategy | Demand uncertainty | Supply uncertainty |
|---|---|---|
| Efficient | Low | Low |
| Risk-Hedging | Low | High |
| Responsive | High | Low |
| Agile | High | High |

Table 2. Supply chain strategies based on Lee's model (Lee, 2002)

The efficiency strategy denotes lowering costs as much as possible by eliminating non-value added activities and exploiting economies of scale, high utilization rate, cost-effective transportation, etc. In the risk-hedging strategy, members share and pool the resources to create alternative supply sources and reduce the supply uncertainty risks. The responsiveness strategy is associated with quick responses to the uncertain customer demand. According to Lee's model, when both demand and supply are uncertain, then the agile strategy is appropriate. Agility means responding quickly to the uncertain customer demand while sharing and pooling the sources to evade the supply uncertainty. Indeed, the agile strategy can be viewed as a combination of the risk-hedging and responsiveness strategies (Lee, 2002).

Agility is defined as "using market knowledge to create more value and profit in a rapidly changing market" (Naylor et al., 1999). In contrast, lean thinking is about eliminating all waste throughout the system, including cost and time wastes (Womack and Jones, 1994). Essentially, the agile strategy is implemented where demand is volatile, and the lean strategy is suitable when demand is stable. The agile or lean strategies considered in isolation do not necessarily result in the best strategy (Mason-jones et al., 2000). Agility and leanness can be combined within one supply chain to meet customer demand, which is called "Leagility" (Naylor et al., 1999). Leagility is defined as the combination of lean and agile strategies within a supply chain by determining a decoupling point. The decoupling point defines where the chain must be agile and where it must be lean. Members of the SC upstream of the decoupling point should focus on leanness, while the downstream members should be agile. Figure 1 demonstrates the leagile strategy in a simple SC.

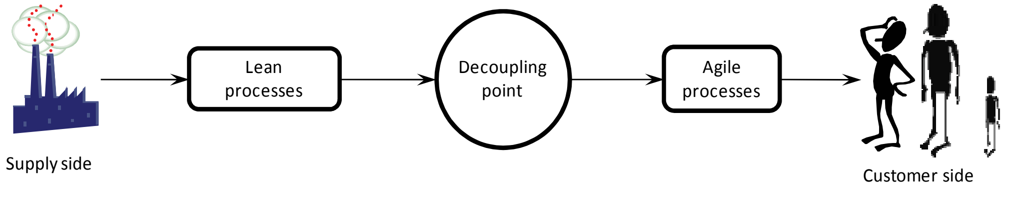


Fig. 1. Leagile strategy (Naylor et al., 1999) and decoupling point in a generic SC structure

According to the basic leagile strategy, by determining the decoupling point, the downstream members must focus on agility while the upstream members must focus on leanness. Because the abilities of members may conflict with their imposed roles (lean or agile), it seems that the basic leagile strategy may fail to achieve the maximum SC profit.
Chopra and Meindl, (2006) consider two main strategies for the SC (efficiency and responsiveness) and introduce a three-step procedure for achieving strategic fit. In the first step, competitive strategy of the SC is established, and as a result, the uncertainty level that SC must face is measured. In the next step, the SC strategy is recognized, and in the last step, the competitive and supply chain strategies are matched to the strategic fit zone (see Figure 2). Chopra and Meindl, (2006) show that there is a direct relation between the competitive strategy and the supply chain strategy in achieving strategic fit, i.e., whenever the competitive strategy targets market segments with higher uncertainties, the supply chain strategy must be shifted toward responsiveness. Figure 2 shows the direct relation between competitive and supply chain strategies in achieving strategic fit. As shown in Figure 2, when increasing the uncertainties, the SC strategy must also increase its responsiveness to avoid the harmful effects of high uncertainty on the customer service level. If the SC intends to focus on efficiency in a highly turbulent business environment, then customers will be lost due to the low service level, low product availability, long lead times, and low responsiveness. The uncertainty causes the overall SC service level to decrease. In an uncertain environment, if the SC does not make any efforts to maintain its service on a reasonable level, then the service level decreases, and the customers abandon it in favor of its more responsive competitors. In contrast, in a certain business environment, all things are predictable, and therefore the customers need low prices in addition to the presumed high responsiveness. Here the competition is based on cost efficiency. In other words, in a certain environment, the responsiveness level of the chain is not damaged and can be fixed at a reasonable level. In this situation, all the competitors can provide the customers with the desired level of responsiveness; therefore, the challenge is to provide them with low prices.

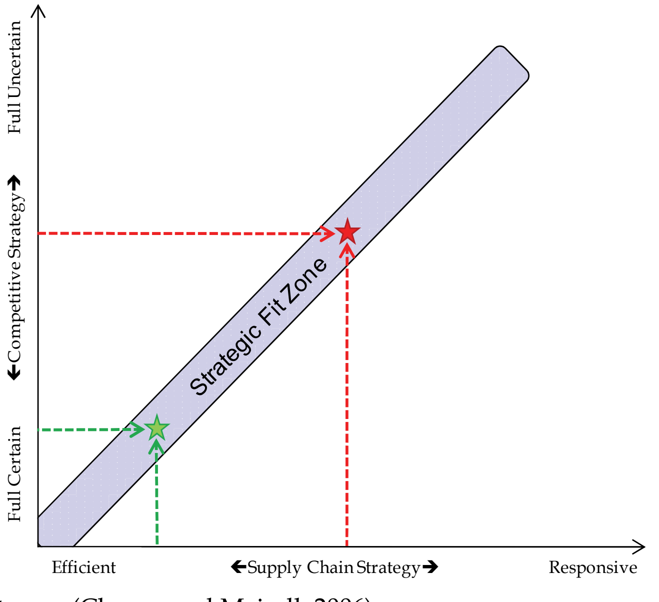


Fig. 2. Strategic Fit zone (Chopra and Meindl, 2006)

In achieving the strategic fit, it is important to know that the desired level of responsiveness can be achieved by assigning different levels of responsiveness to each SC member. If one member has the ability to provide a desired level of responsiveness at a reasonable cost, then it allows other members to be more cost-efficient. Indeed, we can assign different roles to the different members. In contrast to the leagile strategy, the roles of individual members in achieving a given level of responsiveness are not fixed. Each member's role depends on its ability. One critical issue, which is the main concern of this chapter, is that "each SC member uses its potential ability if and only if using the ability creates benefit to itself in addition to the others". Therefore if a costly role is assigned to one member, that member must be compensated and acknowledged by other members to guarantee its participation.

## 3. Achieving strategic fit

The proposed model for achieving strategic fit in SC is based on the Chopra and Meindl model and extends their model by providing more practical insights using the concept of coordination. According to the Chopra and Meindl model, as the SC establishes its competitive strategy against its competitors, the uncertainty level that it must face will become clear. Afterwards, there are two main steps to achieving strategic fit:

1. Establishing the supply chain strategy based on the implied uncertainties
2. Specifying the specific role of each SC member in achieving the established SC strategy.

In this chapter, by merging the concepts of SC coordination and strategic fit, the solutions for the both aforementioned problems are proposed.

### 3.1 SC competitive strategies and uncertainties

We consider a generic four-level SC including retailers, distributor, manufacturers, and suppliers. As the competitive strategy of the SC is defined, each member faces some uncertainty. Four main types of uncertainties are considered in this study: demand uncertainty, transportation time uncertainty, capacity uncertainty, and procurement time uncertainty. The four uncertainty types considered are the most common types of uncertainty in business environments. Table 3 shows the types of uncertainties, their definitions and their sources.

As shown in Table 3, the uncertainties considered include customer demand, transportation time, the reliability of the manufacturing process, and supplier lead times. There are several reasons for investigating these four uncertainties. First, these four uncertainty types are common uncertainties in the business environments that have been studied by the various researchers in the operations management field. Second, by investigating the above mentioned uncertainties, the pairwise relations between all SC members are considered, so the study covers all the SC relations from the customers' side to the suppliers' side. Third, by investigating this set of uncertainties, all the main sources of uncertainty, including customer demand, externalities, process, and supply, are taken into account.

### 3.2 Supply chain strategies

Supply chain strategies are associated with decisions made by the SC members. There are two viewpoints on categorizing SC strategies: (1) based on the decision domain and (2) based on the decision maker. SC drivers, introduced by Chopra and Meindl, (2001) categorize the SC strategies based on the decision domain into six classes: facilities,

| Uncertainty | Definition | Source of uncertainty | Uncertainty affects the relation between … |
|---|---|---|---|
| Customers' demand rate | Retailers receive unpredictable levels of demand from the customers in each period. | Customer demand | Retailers-Customers |
| Transportation time | Various factors, such as weather conditions, customs clearance delays, and traffic congestion, cause the transportation time to be unpredictable. | Externalities | Distributor-Retailers And/or Manufacturers-Distributor |
| Reliability (on capacity) | Unpredictable constraints on the volume of production are caused by factors such as power cuts, machinery break down, workers strike, etc. These constraints prevent distributor orders being met on time. | Process | Manufacturers-Distributor |
| Supplier Lead times | Variable delays from the suppliers in delivery of raw materials to the manufacturers. | Supply | Suppliers-Manufacturers |

Table 3. Four considered uncertainties types

inventory, transportation, information, sourcing, and pricing decisions. From the other point of view, strategies and decisions are implemented by the SC members. Therefore, it is possible to categorize SC strategies based on the decision makers instead of the decision domains. According to the generic model SC with four tiers, the SC strategies based on the decision makers are categorized into the four classes: supplier, manufacturer, distributor, and retailer.

To investigate the effect of each member's strategies and decisions on SC performance, it is more informative to categorize SC strategies based on decision makers instead of decision domains. By categorizing the areas of decision making based on the SC tiers (retailer, distributor, manufacturer, and supplier) we narrow down toward the strategies for coping with four types of uncertainties, each of which is associated with a specific tier of the SC.

In the next step, possible strategies must be defined for each member to deal with the corresponding uncertainties. Table 4 provides a structure for formulating the strategies for each SC member in facing these uncertainties.

As shown in Table 4, each SC tier has some options in coping with uncertainties. Some strategies cause the member to be more responsive, while other strategies cause the member to be more efficient. We do not claim that the suggested general strategies in Table 4 are the all possible strategies, but they are the most common and applicable strategies. It is possible to add more strategies based on the specific conditions of each SC into Table 4.

Some suggested strategies interact with each other. For example, consider the basic responsiveness strategies of a retailer. We designate quick response, high product availability, and high inventory level as the retailer's responsiveness strategies. Nevertheless, in most cases, a quick response strategy and high product availability are created through holding high inventory levels. Therefore, each retailer's responsiveness strategies influence other strategies.

| Tier | Associated Uncertainty | Basic efficiency strategies | Basic responsiveness strategies |
|---|---|---|---|
| Supplier | Supplier Lead times | - Placing the main focus on low costs instead of low and fixed supply times<br>- Supplying only fixed size batches<br>- Investing in advanced systems and facilities as little as possible | - Providing short and fixed delivery times at higher cost<br>- Ability to deliver various batch sizes quickly<br>- High investment in advanced organizational systems and facilities |
| Manufacturer | Reliability (on capacity) | - Single facility located in a low cost area<br>- Inflexibility on production process<br>- Low levels of finished product inventory<br>- Focusing on production of common products<br>- Only in-house production at low cost<br>- Low investment in production facilities | - Multiple facilities located near the markets<br>- Investing in expediting production process<br>- High level of finished product inventory<br>- Focusing on production of innovative products<br>- Outsourcing in emergency cases at higher costs<br>- High investment in production facilities |
| Distributor | Transportation time | - Slow and cheap modes of transportation<br>- Low levels of inventory in the warehouses<br>- Limited number of central warehouses<br>- Low-cost full truckload shipments<br>- Fixed number of trucks | - Fast and expensive modes of transportation<br>- High inventory levels in warehouses<br>- Many warehouses near the markets<br>- Higher-cost less than truckload quick shipments<br>- Flexibility in the number and types of trucks |
| Retailer | Customers' demand rate | - Limited number of Central stores<br>- Focus on providing low price to customers with a tolerable product availability rate<br>- Low inventory levels | - Many stores in the vicinity of customers<br>- Quick response to the customers' orders<br>- High product availability<br>- High inventory levels |

Table 4. Strategies of SC members in facing the uncertainties

Furthermore, some strategies of different tiers of the SC interact with each other. In other words, to create a responsive (efficient) SC, it is not necessary to force all members to focus on responsiveness (efficiency) strategies. When a SC member implement a strategy based on responsiveness (respectively, efficiency), other members can make more efforts on efficiency (responsiveness) to satisfy the customers. In this situation, responsive members, by absorbing the uncertainties, create a definite environment for other members to be more efficient. Here is one critical question: "Who is responsible for absorbing the uncertainties?" One might think that each member that encounters uncertainty is responsible for being more responsive (e.g., a distributor is responsible for transportation time uncertainties). Although this answer is feasible, it is not always the best answer. In the next section, using the "coordinated decision making" concept, we provide and discuss other possibly better solutions to this question.

### 3.3 Coordination in aligning strategies

As we have already discussed, alignment between competitive and SC strategies can be viewed as fitting between SC uncertainties and SC capabilities. According to Table 4, we suggest several generic strategies to cope with uncertainty. Finding the best strategy in each case requires economic analysis. Note that the best strategy in each case is context dependent. An applicable strategy that has the minimum cost is the best choice. There are two criterions in selecting the strategy: "applicability" and "minimum cost". Most of the strategies mentioned in Table 4 are not always totally applicable. For example, distributors are interested in "low-cost full truckload shipments", but when the customers' demand is uncertain, one of the coping strategies is "higher-cost less than truckload quick shipments" at higher costs. If applying this strategy does not offer reasonable gain to the distributor, it is not implemented. Therefore, this strategy is applicable if its implementation brings the distributor more profit.

Because responsiveness strategies are costly, none of the members is interested in being responsive. However, the strategic fit model reveals that in an uncertain environment it is vital that the SC strategy be planned based on responsiveness. Although the responsiveness of the SC does not require all SC members to be responsive, at least one member must be responsible for absorbing the uncertainties and creating the desired level of responsiveness. Coordinated decision making, along with incentive schemes, can resolves this problem. Depending to the types of uncertainties, as discussed above, the features of the coordination models and mechanisms to solve the efficiency-responsiveness trade-off will be different.

#### 3.3.1 Customer's demand rate uncertainty

If the SC competitive strategy targets customers with highly uncertain demand, then to maintain the service level at a reasonable level, the SCS must involve responsiveness. In this situation, the quantity of orders received by the retailers is the uncertain parameter. In this situation, the size of orders for the next period can be estimated only up to some errors. Therefore, shortages may occur in the store. A shortage in the store causes the customers to look to buy the products from the competitors. Therefore, the competitive nature of the market creates a lost sales inventory system. Losing one customer harms the upstream members in addition to the retailer.

Holding more inventory on the part of the retailer is a common method of coping with demand uncertainty. To avoid losing customers, the retailer increases its inventory level at a cost. Holding more inventory as safety stocks at the retailer site decreases the probability of shortages and therefore prevents the loss of customers. By decreasing the shortages, the SC sales volume increases, so all the SC members benefit. The other side of the coin is the risk of excess inventory costs to the retailers.

When a retailer decides independently, only considering its own benefits and costs, increasing the SC sales volume has additional benefits for the other SC members. Therefore, coordinated decision making is more beneficial for the whole SC. At the same time, increasing the retailer's inventory level causes a loss to the retailer with respect to its local optimum decision due to its excess inventory costs. Coordinated decision making is applicable if and only if the retailer receives a certain share of the extra benefits earned by other members.

In general, coordinated decision making about the downstream inventory level in the lost sales inventory systems with uncertain demand increases the retailer inventory (especially its safety stock). In the non-coordinated model, the retailer considers only its own costs in resolving the trade-off between overstocking and shortages, while in fact, losing the customers is costly for all the SC members. Since the cost of the shortage is more than the retailer's cost alone, coordinated decision making recommends decreasing the prevalence of costly shortages by having the retailers hold more inventory. Therefore, encouraging the retailer to hold more inventories will be economical for other members.

It is not rational for an economic entity like a retailer to increase its cost to benefit others. Other members must propose incentives to encourage the retailer to be committed to the coordinated decision about its inventory level. In this case, there is a decision variable (i.e., the retailer's inventory) under the authority of one SC member (i.e., the retailer) that affects other members' profitability through increasing the sales volume. Therefore, coordinated decision making on this variable, accompanied by an appropriate incentive scheme, can create more profit for all members. To convince the retailers, they can be offered incentive schemes, including discounts, profit sharing, pricing. Note that after applying the coordination model, the extra profit must be shared between members in such a way that all members' profits are greater than before applying it. In this way, the retailers accept the responsibility for absorbing uncertainties, and other members can operate in an efficient manner.

Another strategy for coping with demand uncertainty is for the distributor to provide shorter lead times. Because shortages occur due to exhaustion of the retailer stock and replenishing the retailer stock depends on the lead time (time between each retailer's placing an order and receiving the order) provided by the distributor, the shortages will be reduced if the distributor is able to provide shorter lead times. Hence, another strategy for facing the customer demand uncertainty is for the uncertainty to be passed through the retailer and absorbed by the distributor. In this case, instead of holding more inventory at the retailer's site, the retailers' inventory replenishing is expedited. In this new strategy, the distributor is responsible for absorbing the uncertainties. As in the case of the retailer, the distributor absorbing the uncertainties increases its costs. In the previous case, the retailers incurred more costs by increasing their inventory level, while in the current case, instead of the retailers, the distributor suffers more costs by shortening the lead times. Incentive schemes are needed to compensate the distributor for its excess costs and guarantee its acceptance.

Selecting between the two suggested strategies (increasing the retailer's inventory level versus shortening the distributor lead times) requires economic analysis. The strategy with the lower cost is selected as the responsiveness strategy against demand uncertainty. Note that the best strategy is context dependent and therefore may vary from one case to another.

### 3.3.2 Transportation time uncertainty

Transportation time uncertainty means a variance in the shipment time between an origin and a destination. There are several reasons for varying transportation time, including weather conditions, clearance delay, terrorism. If the SC competitive strategy targets market areas that have the above conditions, then the transportation time will be uncertain. In this state, even given a fixed and known demand, the response to the customers will be disturbed due to irregular receipt of batches by the retailers. Therefore, transportation time uncertainty can significantly affect the SC's responsiveness. In turn, low responsiveness in the competitive market causes customer loss and degrades the SC's profitability. According to the strategic fit model, in the presence of increasing uncertainties, the SCS must maintain responsiveness.

The distributor's uncertain transportation time is considered as the supply time uncertainty from the retailer viewpoint. Previous studies have shown that increasing the lead time variance has more serious effects on SC performance than increasing lead time mean (Chaharsooghi and Heydari, 2010). Increasing the average lead time does not create an uncertain parameter, and therefore can be resolved at a certain cost by adjusting the inventory parameters. In contrast, increasing the lead time uncertainty raises the probability of under-stocking at the retailers' sites. Depending on whether the uncertainty in transportation is between manufacturers' sites and warehouses or between warehouses and the retailers' sites, the appropriate strategies will be different.

Figure 3 shows the two types of transportation time uncertainty, including manufacturers' site-warehouses and warehouses-retailers' site transportation time uncertainty. The warehouses are assumed to be under the authority of a distributor.

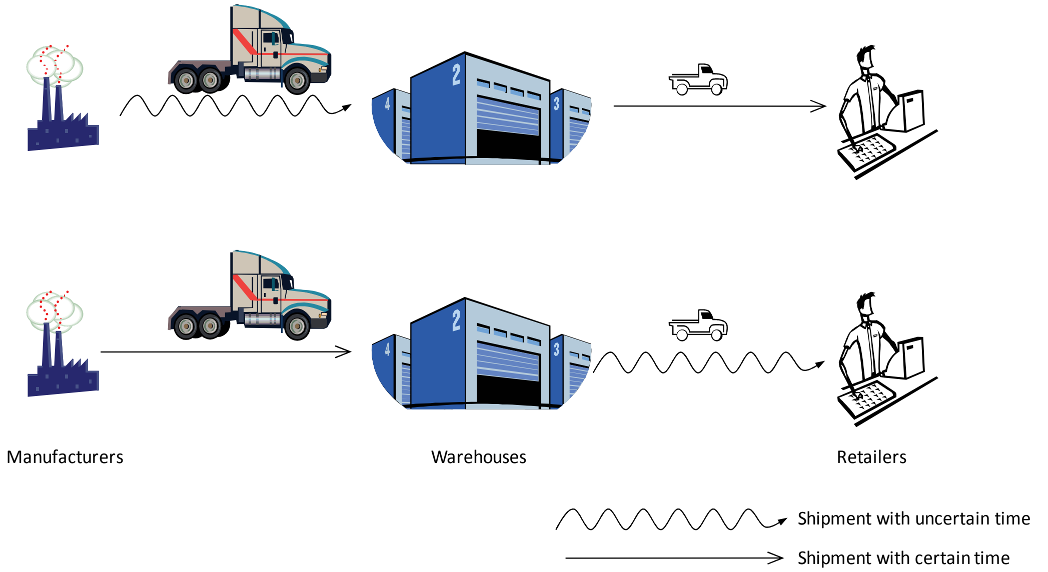


Fig. 3. Manufacturers' site-warehouses (top) versus warehouses –retailers' site (down) transportation time uncertainty

**3.3.2.1 Manufacturers' site-warehouses transportation time uncertainty**

There are two main strategies to prevent the decline of SC responsiveness in case of uncertain shipment times between the manufacturers' sites and the warehouses:

1. Use of more reliable transportation modes with higher costs and lower uncertainty (Note that these alternative modes are not always available)

2. Storage of a higher volume of product in warehouses
3. Combined solution

If expensive modes of transportation are used to deal with the uncertainty, then the distributor must pay more. Moreover, holding more inventory in the distributor warehouses causes investment depreciation and increasing inventory holding costs. By storing more inventory in the warehouses, the effect of late shipments is neutralized by shipping the retailers' orders from the stocks. In addition, a combination of these two strategies (using alternative transportation modes and holding more inventories in the warehouses) can be implemented to provide faster and more reliable transportation toward the retailers.

Apart from the selected strategy, decreasing the lead time uncertainty imposes some extra costs, but it can be seen as an investment (Bookbinder and Çakanyildirim, 1999; Ryu and Lee, 2003). Allowing the distributor to decide on one of the above strategies alone leads to a locally optimum solution. When the distributor selects the transportation mode, the main factor is the cost of each transportation mode. Therefore, the distributor selects a mode at a price as low as reasonably possible. If offering faster response times to the retailers imposes extra costs on the distributor, then the distributor will not choose this option. In this case, the distributor optimizing the transportation time based on its own costs affects the SC responsiveness level. Reducing the SC responsiveness (as a result of an inappropriate transportation strategy) also affects the profitability of all SC members. Because implementing each of the abovementioned strategies imposes costs on the distributor, when there are not adequate incentives the distributor does not change its mind toward coordinated decision making.

When the distributor is committed to the coordinated decisions, the transportation time is globally optimized and the maximum profit is achieved. At this stage, the earned profit is not shared between members fairly. The distributor, by implementing the expensive strategies, has provided these extra profits to the other SC members, while the other members do not pay much for them. To create a win-win situation, the extra benefits gained by the other members as a result of the distributor's coordinated decisions must be fairly shared. Otherwise, the distributor returns to its local decision, and the SC's responsiveness decreases, and all SC members incur losses. Selection between the three mentioned strategies to cope with the transportation uncertainties requires an economic analysis.

#### 3.3.2.2 Warehouses –retailers' site transportation time uncertainty

Another transportation time uncertainty occurs when the retailer places an order to the distributor, the distributor has enough inventory in its warehouse, but the time between placing the retailer's order and receiving the order is uncertain. Reasons such as delay in order processing time, traffic congestion, and traffic restrictions in city can cause this type of uncertainty. In contrast with the manufacturer's site-warehouses transportation, which involves long paths, in this case the paths are mainly includes the urban and suburban streets. Two common strategies to face this type of transportation time uncertainty are as follows:

1. Flexible and quick transportation at higher costs, including:
   a. Using more trucks and re-routing
   b. Less than truckload quick shipments
   c. Network re-design with more nodes (warehouses) close to the retail centers
2. Holding more inventories by the retailers to decrease the probability of under-stocking due to delays.

In the first strategy, the distributor absorbs the uncertainties and allows the retailer to be more efficient. On the other hand, in the second strategy, the distributor passes on the uncertainties, and therefore, the retailer must respond to the lead time uncertainties by holding more inventories. For example, consider a retailer with its own warehouses with free capacity. In this situation, the retailer has the ability to hold more inventory and the second strategy is possible. Often, however, retailers are located in urban areas where this option is less feasible due to the lack of warehouse space and the high rental rate. Therefore, the choice between these two options is not so open, and there are some limitations that make only one option feasible. These limitations are present in all the strategies we have discussed in this chapter.

The distributor's use of flexible and quick transportation modes increases its cost. If the distributor's higher costs are not compensated, then the distributor refuses to implement this strategy. Implementing this strategy by the distributor in an uncertain environment makes the SC more responsive and, according to the strategic fit model, increases the profitability of the whole SC. It is more beneficial for all the SC members to convince the distributor to implement the strategy. The distributor, as an economic entity, implements the strategy that maximizes its own profitability. Determining parameters of the distributor's optimal transportation strategy requires the coordinated decision making. Coordinated decision making on a distributor transportation strategy must be followed by an adequate incentive scheme to guarantee a win-win situation.

Where the first strategy introduced is not applicable, the second alternative strategy can be applied to neutralize the transportation time uncertainty. When the retailers have enough storage space and the inventory holding costs are low, then the second strategy may be more profitable than the first strategy. In this situation, despite the retailers' irregular and delayed replenishments, the shortages are kept under control by holding more inventory in the retailers' sites. Received orders are filled from the retailers' stock. In this case, the retailers, by responding to the lead time uncertainty, allow the distributor to be more efficient. Using incentive schemes such as discounts and delays in payments can encourage the retailer to be committed to the coordinated decisions. Analytical models must be developed to determine the parameters of the coordination model and the relative incentive schemes.

### 3.3.3 Manufacturer's capacity uncertainty

One type of uncertainty that is often studied in the SC literature is the uncertainty associated with the production process. Most of the previous studies in this field consider the capacity constraints of the manufacturer. Uncertain constraints on production capacity where the manufacturer faces unpredictable capacity reduction (UCR), is the main concern of this section. A variety of reasons, such as random power cuts, machinery breakdowns, can cause the UCR in the manufacturers' site. Occurrences of UCR in successive periods disturb the product flow through the SC. This type of uncertainty mainly disturbs the relations between the manufacturers and distributor. The procurement process of the distributor can be seriously disordered due to the inability of manufacturer to satisfy the distributor's orders in a timely manner. The variance of the units per time unit during a certain period can be defined as a quantitative measure of the UCR. One or more manufacturers can experience UCR in their production lines simultaneously. If fluctuations in capacity occur in several manufacturers' sites concurrently, then their harmful effects will be reinforced.

As the capacity uncertainty is associated with the manufacturers, it is possible for each manufacturer to stop the propagation of uncertainty toward the downstream members by implementing the appropriate strategies. On the other hand, it is possible for each manufacturer to pass on the uncertainty by taking no action. In this situation, to maintain the SC responsiveness at a reasonable level, the downstream members (distributor or retailers) must neutralize the uncertainty. In other words, the customers should not sense the uncertainties; therefore, the imposed uncertainty must be neutralized either at the point of creation or by the downstream members. In this case, the manufacturers' sites are the points of creation, so the manufacturers, distributor, and retailers are possible options for neutralizing the uncertainty effect. Several strategies can be implemented facing this uncertainty to maintain the SC responsiveness at a reasonable level:

1. Founding additional manufacturing sites
2. Investment in excess capacity in the current manufacturers' sites
3. Outsourcing some part of the production process by the manufacturers
4. Holding more finished product at the manufacturers' sites
5. Holding more inventory in the distributor's sites
6. Holding more inventory in the retailers' sites

Depending on the uncertainty level and the SC conditions, one or more of the above options can be implemented. If the first four options are selected, then the uncertainty is neutralized at the point of creation by the manufacturer. If the last two options are selected, then the manufacturers pass on the uncertainty and the distributor or retailers have the responsibility of absorbing the uncertainties.

In the first strategy, increasing the numbers of manufacturers' sites can neutralize the impact of UCR. In this situation, if one site faces UCR, then other reserved manufacturing sites can compensate for the lack of capacity at the affected site by slightly increasing their production rates. The second strategy emphasizes providing more capacity to overcome the possible UCR occurrences. In this case, the utilization rate in the normal periods decrease, but in the UCR periods, the lower capacity is replaced by extra capacity. According to the third strategy, a part of the production line that experiences much of the UCR is outsourced to the third parties during the critical periods, often at higher costs. The fourth strategy neutralizes the impact of uncertainty by holding more finished goods at the manufacturers' sites. In this case, despite the output reduction in the production line at critical periods, the distributor's orders are met directly from the stock; therefore, the uncertainty propagation is stopped. Although implementing each of the first four strategies increases the SC responsiveness and the sales volume, it imposes more costs on the manufacturers. The manufacturers, by implementing the above strategies (at a cost), can increase the profitability of the whole SC. The manufacturers' participation depends on improving their profitability. Hence, to guarantee the manufacturers' participation, the other members should share the extra benefits resulting from the coordinated decision making with the manufacturers to create a win-win situation.

On the other hand, the distributor and retailers are responsible for implementing the fifth and sixth strategies, respectively. In implementing the fifth strategy, the manufacturer allows the uncertainty to pass and the distributor is responsible for absorbing the uncertainty. In this situation, the distributor receives its orders with an uncertain delay due to the UCR in the manufacturers' site, but the distributor meets the retailers' orders on time from its stock. In other words, the distributor absorbs the uncertainties by keeping more inventories and thus allows the manufacturer and retailers to operate efficiently.

If the sixth strategy is implemented, then both the manufacturer and distributor allow the uncertainty to pass downstream to the retail level. Because passing uncertainty on to customers causes serious damage to the SC's responsiveness level, the retailers must protect the customers from experiencing the uncertainty. In this case, the retailers meet the customers' orders on time from their own held inventory. The retailer's inventory serves as a buffer to absorb the uncertainty. In the fifth and sixth cases, the distributor and retailers incur more costs, respectively. The commitment of both the distributor and retailers to the coordinated strategy depends on their receiving sufficient incentives from the other SC members.

In the real world cases, mathematical modeling of each of the abovementioned six strategies is used to show which is most suitable for a particular application.

### 3.3.4 Suppliers' lead time uncertainty

Supplier lead time uncertainty can be defined as the unpredictable delays in delivery of raw material from the suppliers to the manufacturers. When a manufacturer places an order, the ordered batches will be delivered after an uncertain time period. Delays in procurement in the manufacturers' sites can cause the production line to shut down temporarily. In turn, shutting down the production line causes disturbances in the timely shipments to the distributor warehouses, damages the retailer's inventory system, and finally decreases the customer service level. We propose two simple strategies in the case of supplier lead time uncertainty:

1. Holding more volumes of raw materials at the manufacturers' sites
2. Shared Suppliers Between Manufacturers (SSBM)

If there is only one supplier and its lead time is uncertain, then there is no choice except to hold more raw materials at the manufacturers' sites to evade the production line downtime. Another option, especially in the case of high inventory holding costs, is multiple sourcing. In this case, to mitigate the risk of supplier delays, the structure of the SC is modified. Each manufacturer must have multiple sources of raw materials to avoid the risk of procurements delays. In the real world, however, the existence of multiple suppliers decreases the manufacturer's order volumes from each supplier. In this situation, the manufacturer is not a privileged customer for the suppliers. Therefore, despite contracting with multiple suppliers, delays frequently occur. On the other hand, contracting with only one supplier increases the probability of production line shutting down due to supply uncertainty. In addition, contracting with only one supplier also destroys the competitiveness between suppliers, which causes the supplier performance to decline over time. We propose the SSBM structure as an appropriate strategy. The SSBM structure is a supply strategy that is not subject to these problems. According to the SSBM strategy, each manufacturer has only one primary supplier, but in the case of delays from the primary supplier, its order can be supplied from one of the other manufacturers' primary suppliers. Figure 4 shows the SSBM structure. Because each manufacturer usually is located near its own supplier, receiving the orders from another supplier imposes more shipment costs in the SSBM structure, but the shortages will be decreased. The manufacturer is charged for the additional shipment costs. The SSBM structure has the following benefits:

1. Preserving the competitiveness between suppliers
2. Each manufacturer is a highly privileged customer of its supplier
3. Decreasing the risk of the production line shutting down
4. Smoothing the flow of materials throughout the SC

As in the previous cases, in this situation also one member (manufacturer) responds to the uncertainty at a cost. Other members should compensate the manufacturers to create a win-win situation. Coordinated decision making in supplying the raw materials with appropriate incentive schemes creates more benefits for all SC members.

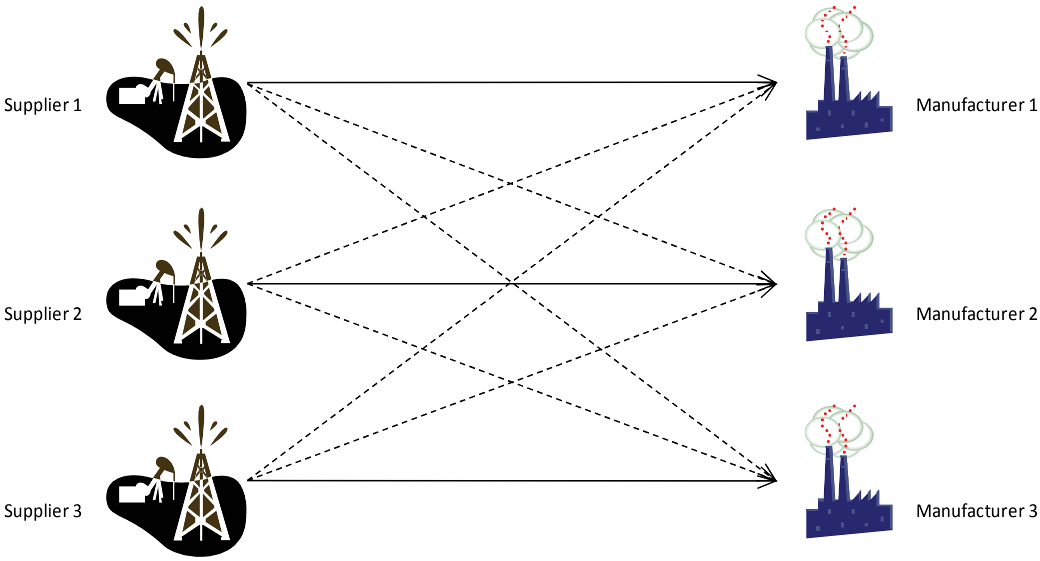


Fig. 4. Proposed SSBM structure

## 4. Conclusions

In this chapter, we have discussed the concept of strategic fit in supply chain management. We have seen that alignment between competitive and SC strategies can be achieved by coordinated decision making. Four major types of uncertainties that result from the chosen competitive strategy were investigated, including customer demand uncertainty, transportation time uncertainty, manufacturers' capacity uncertainty, and supplier lead time uncertainty. According to the strategic fit model, in highly turbulent environments with high level of uncertainty it is essential for the SC to focus on responsiveness to avoid losing customers. When the environment is uncertain, the responsiveness level of the SC decreases and the customers are attracted by the competitors. Therefore, the sales volume of the chain decreases, and all the SC members incur loses.

Appropriate strategies countering each type of uncertainty were examined. Depending on the member of the supply chain that encounters the uncertainty and the uncertainty type, the coping strategies have different characteristics. All of the strategies introduced in this chapter have some points of similarity:

1. All of the strategies require coordinated decision making
2. All of the strategies require an incentive scheme for the member who implements the strategy
3. Implementing each of the strategies means absorbing the uncertainty
4. Most of the uncertainties can be absorbed at the point of creation or with the assistance of downstream members.

In this way, we discussed the fact that achieving strategic fit requires coordinated decision making along with adequate incentive schemes. Incentive schemes guarantee the SC members' commitment to coordinated decisions. Finally, this chapter provides a conceptual framework for achieving better fit between strategies under various conditions. Developing the mathematical models is left as a topic for future study.

## 5. References


Bookbinder, J.H., & Çakanyildirim, M. (1999). Random lead times and expedited orders in (Q,r) inventory systems. *European Journal of Operational Research*, 115 (2), 300–313.

Chaharsooghi, S.K. & Heydari, J. (2010). LT variance or LT mean reduction in supply chain management: Which one has a higher impact on SC performance? *International Journal of Production Economics*. 124(2) , 475–481

Chopra, S.; & Meindl, P. (2001). *Supply Chain Management: Strategy, Planning, and Operations*, Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Chopra, S.; & Meindl, P. (2006). *Supply Chain Management: Strategy, Planning, and Operations*, Prentice-Hall, Inc., Upper Saddle River, New Jersey.

Courtney, H.G., Kirkland, I. & Viguerie, S.P. (1997). Strategy under uncertainty, *Harvard Business Review*, 75(6), 66-79

Fisher, M. (1997). What Is the Right Supply Chain for Your Product? *Harvard Business Review*, 75(2), 105-116.

Hugos, M. (2003). *Essentials of supply chain management*. Wiley, ISBN: 0471235172 , New York

Lee, H. L. (2002). Aligning Supply Chain Strategies with Product Uncertainties. *California Management Review*, 44(3), 105-119.

Mason-Jones, R., Naylor, B. & Towill, D.R. (2000). Lean, agile or leagile? Matching your supply chain to the marketplace, *International Journal of Production Research*, 38(17), 4061–4070.

Naylor, J.B., Naim, M.M. & Berry, D. (1999). Leagility: Integrating the lean and agile manufacturing paradigms in the total supply chain, International Journal of Production Economics, 62, 107-118

Peidro, D., Mula, J., Poler, R. & Lario, F.C., (2009). Quantitative models for supply chain planning under uncertainty: a review, *International Journal of Advanced Manufacturing Technology*, 43(3-4), 400–420.

Porter, M.E. (1979).How Competitive Forces Shape Strategy, Harvard Business Review, 57(2), 137-145

Porter, M. E. (1980), *Competitive Strategy*, The Free Press, New York.

Porter, M. E. (1985), *Competitive Advantage*, The Free Press, New York.

Porter, M.E. (2008). The Five Competitive Forces That Shape Strategy. *Harvard Business Review*, 86(1), 78-93.

Ryu, S.W. & Lee, K.K. (2003). A stochastic inventory model of dual sourced supply chain with lead-time reduction. *International Journal of Production Economics*. 81-82, 513–524.

Wernerfelt B. & Karnani, A. (1987). Competitive strategy under uncertainty, *Strategic Management Journal*, 8(2), 187-194.

Womack, J.P. & Jones, D.T. (1994). From lean production to the lean enterprise. *Harvard Business Review*, 72 (March-April), 93-103.

# 16

# Towards Improving Supply Chain Coordination through Business Process Reengineering

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## 1. Introduction

Global marketplaces, higher levels of product variety, shorter product life cycles, and demand for premium customer services are all things which cause pressure for one supply chain to be more efficient, more time compressed and more cost effective. This has become even more critical in recent years because the advancement in information technology has enabled companies to improve their supply chain strategies and explore new models for management of supply chain activity. Among others, important research area in the supply chain management literature is the coordination of the supply chain. Actually, the understanding and practicing of supply chain coordination has become an essential prerequisite for staying competitive in the global race and for enhancing profitability. Hence, supply chain management needs to be defined to explicitly recognise the strategic nature of coordination and information sharing between trading partners and to explain the dual purpose of supply chain management: to improve the performance of an individual organisation an to improve the performance of the whole supply chain. In this context, we present the business process reengineering as a tool for achievinging effective supply chain management, and illustrate through a case study how business process modelling can help in achieving successful improvements in sharing information and the coordination of supply chain processes.

It is well recognised that advances in information technologies have driven much change through supply chain and logistics management services. Traditionally, the management of information has been somewhat neglected. The method of information transferring carried out by memebers of the supply chain has consisted of placing orders with the member directly above them. This caused many problems in the supply chain including: excessive inventory holding, longer lead times and reduced service levels in addition to increased demand variability or the 'Bullwhip Effect'. Thus, as supply chain management progresses, supply chain managers are realising the need to utilise improved information sharing throughout the supply chain in order to have coordinated supply chain and to remain competitive. However, coordination is not just a mere information sharing. Information can be shared but there may not be any alignment in terms of incentives, objectives and decisions (Lee et al., 1997b). Coordination involves alignments of decisions, objectives and incentives and this can be done only through new reengineered business process models, which need to follow the information sharing. Appropriate business processes are a prerequisite for the strategic utilisation of information sharing, because the simple use of information technology applications to improve information transfers between supply chain members is not in itself enough to realise the benefits of information sharing. A mere increase in information transfers does not mean that information distortions (Bullwhip Effect) will be avoided and the efficiency of logistics processes will be improved. The business models of existing processes have to be changed so as to facilitate the better use of the information transferred (Trkman et al., 2007). In this chapter, by using business process modelling and simulation we show how achieving only successful business process changes can contribute to the full utilisation of improved information sharing, and so to the full coordination of the supply chain. In accordance with the above, the main goals of this chapter are:

- To develop strategic connection between information sharing and supply chain coordination through business process reengineering;
- To present how only full coordinated supply chains can increase supply chain performances as costs and value of Bullwhip Effect;
- To promote value of Bullwhip Effect as a universal performance for supply chain coordination;
- To connect existing theoretical studies with a real-life complex case study, in an attempt to provide people in the working world with the expected performance improvements discussed in this chapter.

In order to achieve these goals, this chapter analyse a two-level supply chain with a single supplier who supplies products to a retailer who, in turn, faces demands from the end customer. In addition, a discrete events simulation model of the presented supply chain has been developed.

The organisation of the rest of this chapter is as follows: The next two sections briefly review related literature about the key concepts of the chosen topic. Section 4 formulates the case study and outlines business process models for the current and proposed state for the company under consideration. Section 5 details a simulation study with experimentation concerning information sharing, business process models and a type of inventory control, while Section 6 discusses the results and concludes.

## 2. Supply chain coordination

### 2.1 Background

A supply chain is the set of business processes and resources that transforms a product from raw materials into finished goods and delivers those goods into the hands of the customer. Supply chain management has been defined as 'the management of upstream and downstream relationship with suppliers, distributors and customers to achieve greater customer value-added at less total cost' (Wilding, 2003). The objective of supply chain management is to provide a high velocity flow of high quality, relevant information that enables suppliers to provide for the uninterrupted and precisely timed flow of materials to customers. Supply chain excellence requires standardised business processes supported by a comprehensive data foundation, advanced information technology support and highly capable personnel. It needs to ensure that all supply chain practitioners' actions are directed at extracting maximum value. According to (Simchi-Levi et al., 2003), supply chain management represents the process of planning, implementing and controlling the efficient, cost-effective flow and storage of raw materials, in-process inventory, finished goods, and related information from the point of origin to the point of consumption for the purpose of meeting customers' requirements. The concept of supply chain management has received increasing attention from academicians, consultants and business managers alike (Tan et al., 2002; Feldmann et al., 2003; Croom et al., 2000; Maslaric, 2008). Many organisations have begun to recognise that supply chain management is the key to building sustainable competitive edge for their products and/or services in an increasingly crowded marketplace (Jones, 1998). However, effective supply chain management requires the execution of a precise set of actions. Unfortunately, those actions are not always in the best interest of the members in the supply chain, i.e. the supply chain members are primarily concerned with optimising their own objectives, and that self serving focus often results in poor performance. Hence, optimal performance and efficient supply chain management can be achieved if the members of supply chain are coordinated such that each member's objective becomes aligned with the supply chain's objective.

According to (Merriam-Webster, 2003), coordination is a process to bring into a common action, movement or condition, or to act together in a smooth concerted way. Coordination is studied in many fields: computer science, organisation theory, management science, operations research, economics, linguistic, psychology, etc. In all of those fields, 'coordination' deal with similar problems and some of that knowledge might be utilised in the research of supply chain coordination. Coordination issues in supply chain are discussed in the literature in various ways including supply chain coordination (Lee et al., 1997a), channel integration (Towill et al., 2002), strategic alliance and collaboration (Bowersox, 1990; Kanter, 1994), information sharing and supply chain coordination (Lee et al., 1997a; Lee et al., 1997b; Chen et al., 2000), collaborative planning, forecast and replenishment (Holmstrom et al., 2002), and vendor-managed inventory (Waller et al., 1999). In general, supply chain coordination can be accomplished through centralisation of information and/or decision-making, information sharing and incentive alignments. Various analyses on different coordination mechanisms have been carried out to develop optimal solutions for coordinating supply chain system decisions and objectives. Most literature addresses coordination problems in the following three situations (Sahin & Robinson, 2002): (1) decentralised or centralised decision-making; (2) full, partial, or no information sharing; (3) coordination or no coordination. For the purpose of the present chapter, we will review situations belonging to the second category, information sharing.

### 2.2 Information sharing

Coordination between the different companies is vital for success of the global optimisation of the supply chain, and it is only possible if supply chain partners share their information. In traditional supply chains, members of the chain make their own decision based on their demand forecast and their cost structure. So, many supply chain related problems such as Bullwhip Effect can be attributed to a lack of information sharing among various members in the supply chain. Sharing information has been recognised as an effective approach to reducing demand distortion and improving supply chain performance (Lee et al., 1997a). Accordingly, the primary benefit of sharing demand and inventory information is a reduction in the Bullwhip Effect and, hence, a reduction in inventory holding and shortage costs within supply chain. The value of information sharing within a supply chain has been extensively analysed by researches. Various studies have used a simulation to evaluate the value of information sharing in the supply chains (Towill et al., 1992; Bourland et al., 1996; Chen, 1998; Gavirneni et al., 1999; Dejonckheere et al., 2004; Ferguson & Ketzenberg, 2006). Detailed information about the amount and type of information sharing can be found in (Li et al., 2005).

The existing literature has investigated the value of information sharing as a consequence of implementing modern information technology. However, the formation of a business model and utilisation of information is also crucial. Information should be readily available to all companies in supply chains and the business processes should be structured so as to allow the full use of this information (Trkman et al., 2007). One of the objectives of this chapter is to offer insights into how the value of information sharing within a two-level supply chain is affected when two different models of business process reengineering are applied. Moreover, the literature shows that, although numerous studies have been carried out to determine the value of information sharing, little has been published on real systems. The results in this chapter have been obtained through a study of a real-life supply chain case study using simulation.

### 2.3 Bullwhip effect

Behind the objectives regarded to developing strategic connection between information sharing and supply chain coordination through business process reengineering and connecting existing theoretical studies with a real-life case study, this chapter has two more objectives. First, to examine the impact of information sharing with combinations of different inventory control policies on Bullwhip Effect and inventory holding costs, and second, to promote value of Bullwhip Effect as a common performance for supply chain coordination.

The Bullwhip Effect is a well-known phenomenon in supply chain management. In a single-item two-echelon supply chain, it means that the variability of the orders received by the manufacturer is greater than the demand variability observed by the retailer. This phenomenon was first popularised by Jay Forrester (1958), who did not coin the term bullwhip, but used industrial dynamic approaches to demonstrate the amplification in demand variance. At that time, Forrester referred to this phenomenon as 'Demand Amplification'. Forrester's work has inspired many researchers to quantify the Bullwhip Effect, to identify possible causes and consequences, and to suggest various countermeasures to tame or reduce the Bullwhip Effect (Boute & Lambrecht, 2007). One of those researchers is Lee (Lee et al., 1997a; Lee et al., 1997b) who named this phenomenon as 'Bullwhip Effect' and who identified the main causes of the Bullwhip Effect and offered solutions to manage it. They logically and mathematically proved that the key causes of the Bullwhip Effect are: (1) demand forecasting updating; (2) order batching; (3) price fluctuation; and (4) shortage gaming. According to this researcher, the key to managing the Bullwhip Effect is to share information with the other members of the supply chain. In these papers, they also highlighted the key techniques to manage the Bullwhip Effect.

A number of researchers designed games to illustrate the Bullwhip Effect. The most famous game is the 'Beer Distribution Game'. This game has a rich history: growing out of the industrial dynamics work of Forrester and others at MIT, it is later on developed by Sterman in 1989. The Beer Game is by far the most popular simulation and the most widely used games in many business schools, supply chain electives and executive seminars. Simchi-Levi et al., (1998) developed a computerized version of the Beer Game, and several versions of the Beer Game are nowadays available, ranging from manual to computerized and even web-based versions (Jacobs, 2000).

We can measure the Bullwhip Effect in different ways, but for the purpose of this research we accepted the measures applied in (Fransoo & Wouters, 2000). We measure the Bullwhip Effect as the quotient of the coefficient of variation of demand generated by one echelon(s) and the coefficient of variation of demand received by this echelon:

$$w = \frac{c_{out}}{c_{in}} \tag{1}$$

where:

$$c_{out} = \frac{\sigma\left(D_{out}\left(t, t+T\right)\right)}{\mu\left(D_{out}\left(t, t+T\right)\right)} \tag{2}$$

and:

$$c_{in} = \frac{\sigma\left(D_{in}\left(t, t+T\right)\right)}{\mu\left(D_{in}\left(t, t+T\right)\right)} \tag{3}$$

$D_{out}(t,t+T)$ and $D_{in}(t,t+T)$ are the demands during time interval $(t,t+T)$. For detailed information about measurement issues, see (Fransoo & Wouters, 2000).

## 3. Business process reengineering

### 3.1 Background

The key to supply chain coordination is not 'copy-pasting' best practice, which assume implementation of new information technology, from one company to another. Given the unique context in which each supply chain operates, the key to full coordination lies in the application of a context specific solution which is mostly regarded to business processes of the company.

The business process is a set of related activities which make some value by transforming some inputs into valuable outputs. In reengineering theories, organisational structures are redesign by focusing on business processes and their outcome. Business process reengineering may be seen as an initiative of the 1990s, which was of interest to many companies. The initial drive for reengineering came from the desire to maximize the benefits of the introduction of information technology and its potential for creating improved cross-functional integration in companies (Davenport & Short, 1990). Business redesign was also identified as an opportunity for better IT integration both within a company and across collaborating business units in a study in the late 1980s conducted at MIT. The initiative was rapidly adopted and extended by a number of consultancy companies and 'gurus' (Hammer, 1990). In business process reengineering, a business process is seen as a horizontal flow of activities while most organisations are formed into vertical functional groupings sometimes referred to in the literature as 'functional silos'. Business process reengineering by definition radically departs from other popular business practices like total quality management, lean production, downsizing, or continuous improvement. Business process reengineering is based on efficient use of information technology, hence companies need to invest large amount of money the achieve information technology enabled supply chain. Implemenation of new information technology is necessary, but no means sufficient condition for enable efficient and cheap information transfers. Business process reengineering is concerned with fundamentally rethinking and redesigning business processes to obtain dramatic and sustaining improvements in quality, costs, services, lead times, outcomes, flexibility and innovation. In support of this, technological change through the implementation of simulation modelling is being used to improve the efficiency and consequently is playing a major role in business process reengineering (Cheung & Bal, 1998).

### 3.2 Business process modelling

A business process model is an abstraction of business that shows how business components are related to each other and how they operate. Its ultimate purpose is to provide a clear picture of the enterprise's current state and to determine its vision for the future. Modelling a complex business requires the application of multiple views. Each view is a simplified description (an abstraction) of a business from a particular perspective or vantage point, covering particular concerns and omitting entities not relevant to this perspective. To describe a specific business view process mapping is used. It consists of tools that enable us to document, analyse, improve, streamline, and redesign the way the company performs its work. Process mapping provides a critical assessment of what really happens inside a given company. The usual goal is to define two process state: AS-IS and TO-BE. The AS-IS state defines how a company's work is currently being performed. The TO-BE state defines the optimal performance level of 'AS-IS'. In other words, to streamline the existing process and remove all rework, delay, bottlenecks and assignable causes of variation, there is a need to achieve the TO-BE state. Business process modelling and the evaluation of different alternative scenarios (TO-BE models) for improvement by simulation are usually the driving factors of the business renovation process (Bosilj-Vuksic et al., 2002). In the next section a detailed case study is presented.

## 4. A case experience of business process reengineering

The case study is a Serbian oil downstream company. Its sales and distribution cover the full range of petroleum products for the domestic market: petrol stations, retail and industries. The enterprise supply chain comprises fuel depot-terminal (or distribution centre), petrol stations and final customers. The products are distributed using tank tracks. The majority of deliveries is accomplished with own trucks, and a small percentage of these trucks is hired. The region for distribution is northern Serbia. It is covered by two distribution centres and many petrol stations at different locations. In line with the aim of the chapter only a fragment, namely the procurement process, will be shown in the next section. Presented model was already used in (Groznik & Maslaric, 2010), and a broader description of the case study can be found in (Maslaric, 2008).

From the supply chain point of view, the oil industry is a specific business, and for many reason it is still generally based on the traditional model. The product is manufactured, marketed, sold and distributed to customers. In other industries, advanced supply chain operation is becoming increasingly driven by demand-pull requirements from the customer. There is a strong vertically integrated nature of oil companies and that may be a potential advantage. In other industries, much attention is focused on value chain integration across multiple manufacturers, suppliers and customers. In the oil industry, more links in the chain are 'in house', suggesting simpler integration. In practice, there is still a long way to go to achieve full integration in the oil supply chain.

### 4.1 AS-IS model development

The next section covers the modelling of the existing situation (AS-IS) in the procurement process of the observed downstream supply chain case study. The objective was to map out in a structured way the distribution processes of the oil company. The modelling tools used in this case study come from the Igrafx Process. These modelling tools were applied in order to identify the sequence of distribution activities, as well as the decisions to be taken in various steps of the distribution process. The AS-IS model was initially designed so that the personnel involved in the distribution processes could review them, and after that the final model shown in Figure 1 was developed.

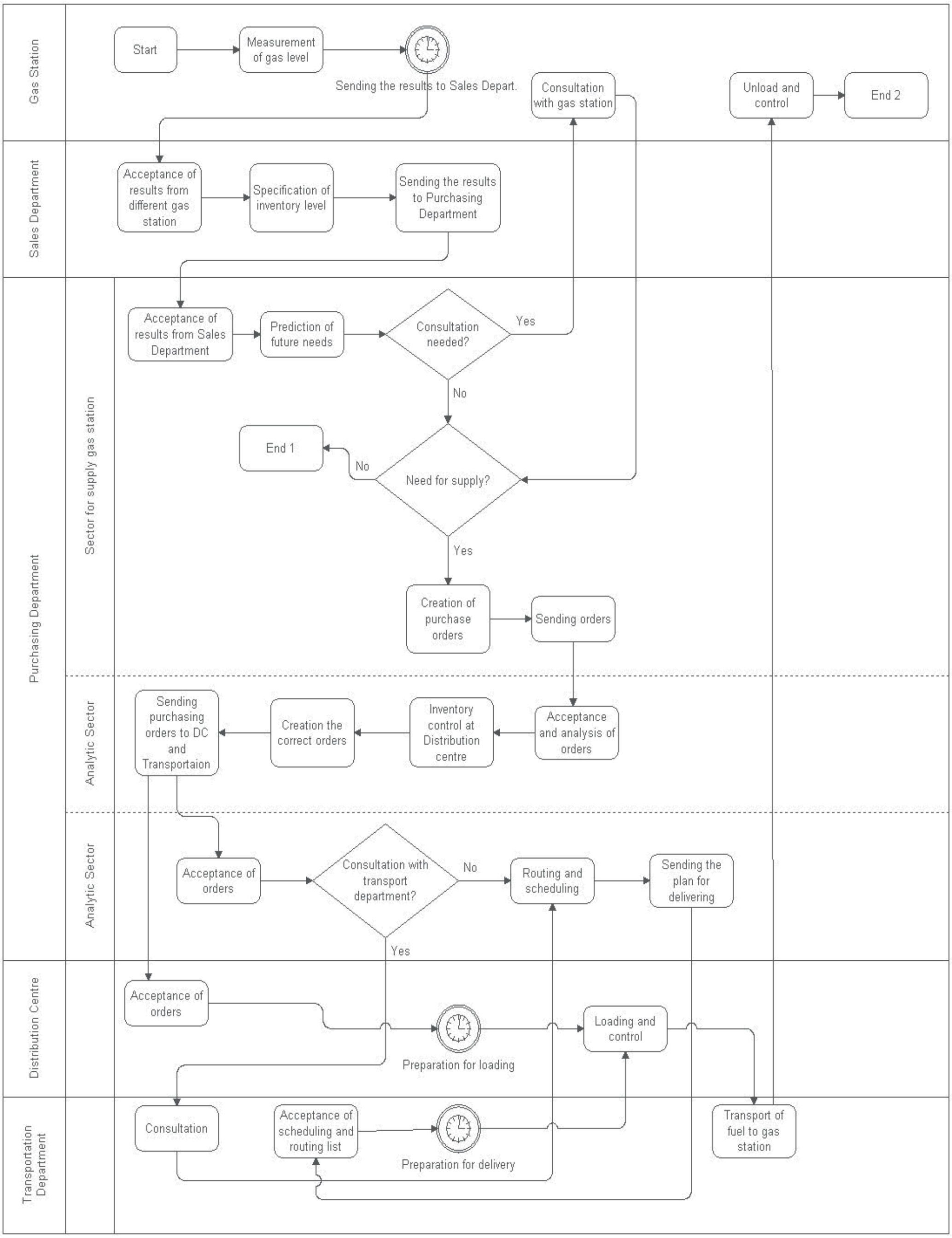


Fig. 1. AS-IS model of the process

The core objective of supply chains is to deliver the right product at the right time, at the right price and safely. In a highly competitive market, each aims to carry this out more effectively, more efficiently and more profitably than the competitors. Because both the prices and quality of petrol in Europe are regulated, the main quality indicator in oil supply chains is the number of stock-outs. The main cost drivers are therefore: number of stock-outs, stock level at the petrol station and process execution costs. Lead time is defined as the time between the start (measurement of the stock level) and the end (either the arrival at a petrol station or the decision not to place an order) of the process (Trkman et al., 2007).
The main problems identified when analysing the AS-IS model relate to the company's performance according to local optimisation instead of global optimisation. The silo mentality is identified as a prime constraint in the observed case study. Other problems are in inefficient and costly information transfer mainly due to the application of poor information technology. There is no optimisation of the performance of the supply chain as a whole. Purchasing, transport and shipping are all run by people managing local, individual operations. They have targets, incentives and local operational pressures. Everything was being done at the level of the functional silo despite the definition that local optimisation leads to global deterioration. The full list of problems identified on tactical and strategic levels are identical to those in (Trkman et al., 2007), so for greater detail see that paper. Based on the mentioned problems, some improvements are proposed. The main changes lie in improved integration of whole parts of the supply chain and centralised distribution process management.

### 4.2 TO-BE models development

The emphasis in business process reengineering is put on changing how information transfers are achieved. A necessary, but no means sufficient condition for this is to implement new information technologies which enable efficient and cheap information transfers. Hence, information technology support is not enough as deep structural and organisational changes are needed to fully realise the potential benefits of applying new information technology. In this case study we develop two different propositions for business process reengineering (two TO-BE models) to show how implementation of new information technology without business process renovation and the related organisational changes does not mean the full optimisation of supply chain performance.
The first renewed business model (TO-BE 1) is shown in Figure 2 and represents the case of implementing information technology without structural changes to business processes. In the TO-BE 2 model, there is no integrated and coordinated activity through the supply chain. Inventory management at the petrol stations and distribution centre is still not coordinated.
The TO-BE 2 model assumes that the processes in the whole downstream oil supply chain are full integrated and the distribution centre takes responsibility for the whole procurement process. The TO-BE 2 business model is shown in Figure 3. The main idea is that a new organisational unit within the distribution centre takes on a strategic role in coordinating inventory management and in providing a sufficient inventory level at the petrol stations and distribution centre to fulfil the demand of the end customer. It takes all the important decisions regarding orders in order to realise this goal. Other changes proposed in the TO-BE 2 model are the automatic measurement of petrol levels at petrol stations and the automatic transfer of such data to the central unit responsible for petrol replenishment; the predicting of future demand by using progressive tools; and using operations research methods to optimise the transportation paths and times. The role of information technology in all of these suggestions is crucial.

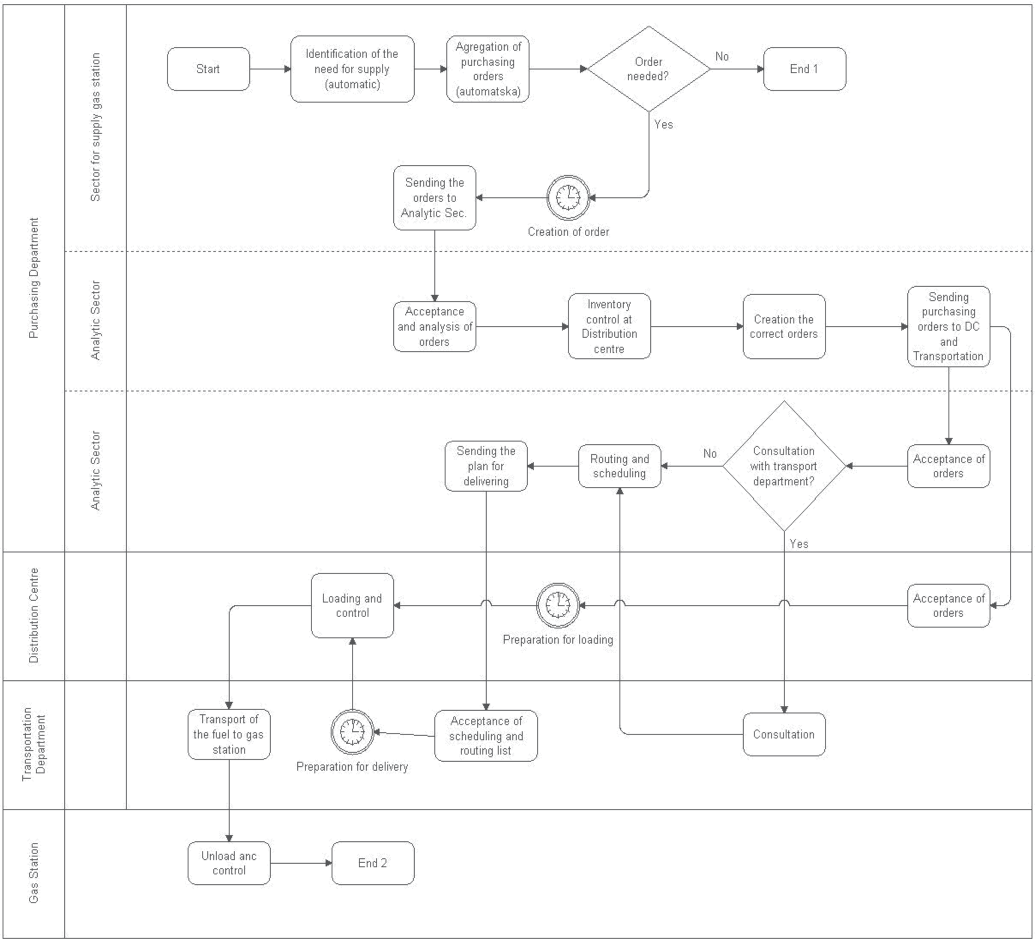


Fig. 2. TO-BE 1 model of the process

### 4.3 Measuring the effect of reengineering

The effect of the changes can be estimated through simulations. Because our study has two kinds of objective, we have two kind of simulations. In our first example we simulated business processes to investigate the impact of business process reengineering on the information sharing value, measured by lead times and transactional costs. The second simulation, which partly uses the results of the first simulation, represents an object-oriented simulation which helps define the impact of information sharing and appropriate inventory control on the Bullwhip Effect and inventory holding costs in the oil downstream supply chain under consideration. Both simulations are especially important as they enable us to estimate the consequence of possible experiments.

In the first simulation we estimated changes in process execution costs and lead times. First a three-month simulation of the AS-IS and of both the TO-BE models was run. In the AS-IS model a new transaction is generated daily (the level of petrol is checked once a day), and in the TO-BE it is generated on an hourly basis (the level of stock is checked automatically every hour). The convincing results are summarised in Table 1. The label ‘Yes’ refers to

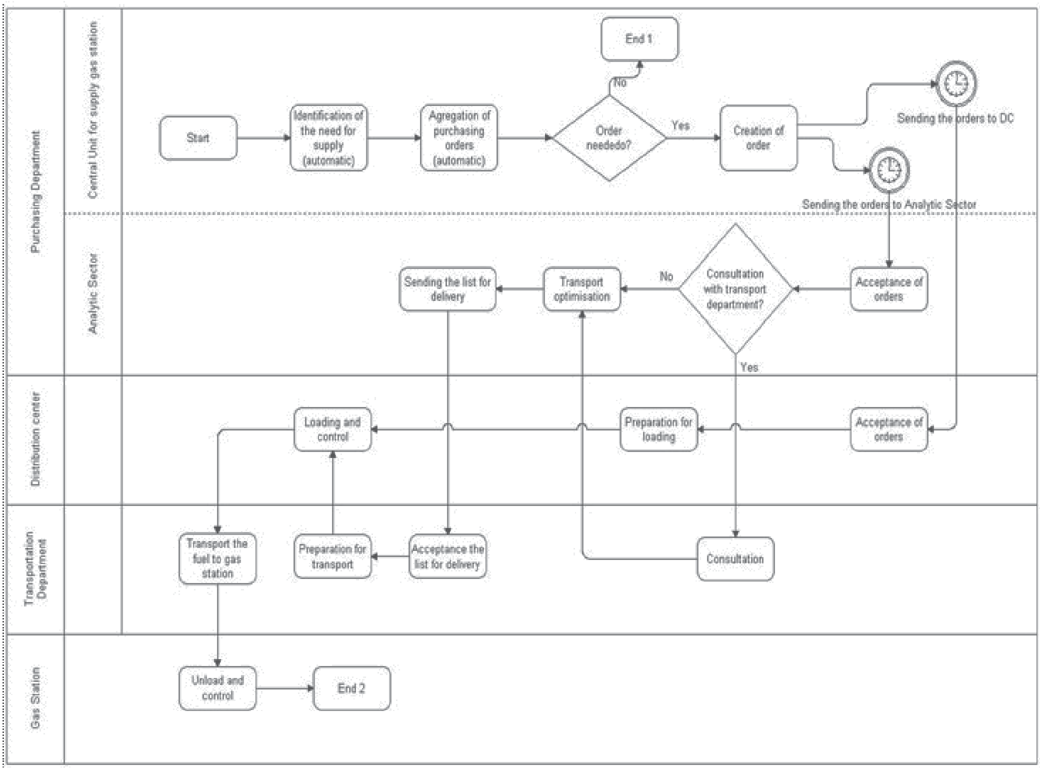


Fig. 3. TO-BE 2 model of the process

those transactions that lead to the order and delivery of petrol, while the label 'No' means a transaction where an order was not made since the petrol level was sufficient. The average process costs are reduced by almost 50%, while the average lead time is cut by 62% in the case of the TO-BE 2 business model. From this it is clear that this renovation project is justifialbe from the cost and time perspectives. The results in Table 1 show that a full improvement in supply chain performances is only possible in the case of implementing both new information technology which enables efficient information sharing, and the redesign of business processes. The mere implementing of information technologies without structural and organisational changes in business processes would not contribute to realising the full benefit.

| Transaction | No. | Av. lead-time (hrs) | Av. work (hrs) | Av. wait (hrs) | Average costs (€) |
|---|---|---|---|---|---|
| Yes (AS-IS) | 46 | 33.60 | 11.67 | 21.93 | 60.10 |
| No (AS-IS) | 17 | 8.43 | 2.40 | 6.03 | 8.47 |
| Yes (TO-BE 1) | 46 | 27.12 | 10.26 | 16.86 | 56.74 |
| No (TO-BE 1) | 1489 | 0.00 | 0.00 | 0.00 | 0.00 |
| Yes (TO-BE 2) | 46 | 12.85 | 4.88 | 7.98 | 32.54 |
| No (TO-BE 2) | 1489 | 0.00 | 0.00 | 0.00 | 0.00 |

Table 1. Comparasion of simulation results for the AS-IS and TO-BE models

The results of the previous simulation (lead time) were used as an input for the next simulation so as to help us find the impact of information sharing on the Bullwhip Effect and inventory holding costs in the observed supply chain.

## 5. Inventory control simulation

In this section we employed an object-oriented simulation to quantify the benefit of information sharing in the case study. The system in our case study is a discrete one since supply chain activities, such as order fulfilment, inventory replenishment and product delivery, are triggered by customers' orders. These activities can therefore be viewed as discrete events. A three-month simulation of the level of stock at a petrol station that is open 24 hours per day was run.

In order to provide results for the observed supply chain performance, the following parameters are set:

- *Demand pattern*: Historical demand from the end customer to petrol stations and from petrol stations to distribution centres was studied. From this historical demand, a probability distribution was created.
- *Forecasting models*: The exponential smoothing method was used to forecast future demand.
- *Information sharing*: Two different types of information sharing were considered: (1) No IS-no information sharing (AS-IS model); and (2) IS-full information sharing (TO-BE models).
- *Lead time*: Lead time from the previous simulation business process was used.
- *Inventory control*: Three types of inventory replenishment policy were used: (1) No inventory policy based on logistical principles. There was a current state in the viewed supply chain (AS-IS model); (2) The petrol station and distribution centre implement the (s, S) inventory policy according to demand information from the end customer, but the distribution centre was not responsible for the petrol station's replenishment policy – no VMI policy (TO-BE 1 model); and (3) VMI – full information sharing is adopted and the distribution centre is in charge of the inventory control of the petrol station. The one central unit for inventory control determines the time for replenishment as well as the quantities of replenishment (TO-BE 2 model).
- *Inventory cost*: This is the cost of holding stocks for one period.
- *Bullwhip Effect*: The value of the Bullwhip Effect is measured from equations (1), (2) and (3).

When we talk about inventory control, regular inventories with additional safety stock are considered. These are the inventories necessary to meet the average demand during the time between successive replenishment and safety stock inventories are created as a hedge against the variability in demand for the inventory and in replenishment lead time. The graphical representation of the above mentioned inventory control method is depicted in Figure 4 (Groznik & Maslaric, 2009; Petuhova & Merkuryev, 2006).

The inventory level to which inventory is allowed to drop before a replacement order is placed (reorder point level) is found by a formula:

$$s = E(X) * LT + STD(X) * \sqrt{LT} * z \qquad (4)$$

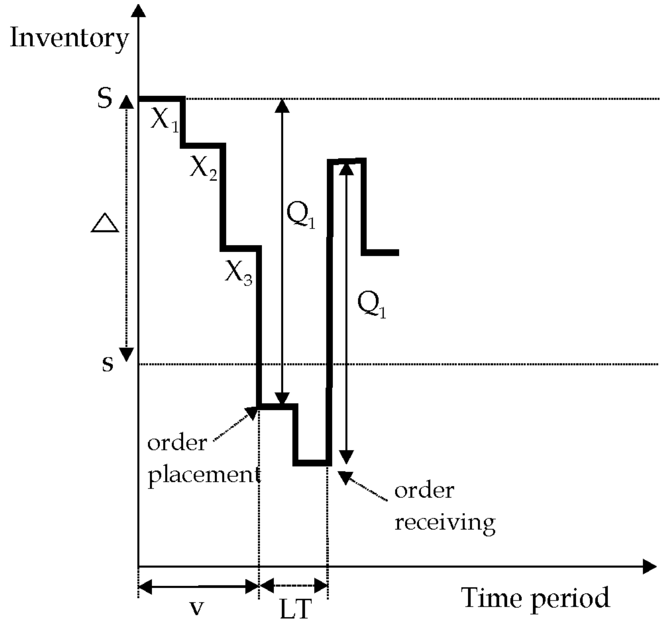


Fig. 4. Inventory control method

where:
*LT* – lead time between replenishment;
$STD(X) = \sqrt{D(X)}$ - standard deviation of the mean demand;
*z* – the safety stock factor, based on a defined in-stock probability during the lead time.
The total requirements for the stock amount or order level S is calculated as a sum of the reorder point level and a demand during the lead time quantity:

$$S = s + E(X)*LT \tag{5}$$

The order quantity $Q_i$ is demanded when the on-hand inventory drops below the reorder point and is equal to the sum of the demand quantities between the order placements:

$$Q_i = X_1 + X_i + ... + X_v \tag{6}$$

Where v is random variable, and represents a number of periods when an order is placed.
While the demand *X* is uncertain and implementing such a type of inventory control method, placed order quantity Q is expected to be a random *variable* that depends on the demand quantities.
To investigate the effect of information sharing upon supply chain performance (Bullwhip Effect and inventory costs), three scenarios are designed with respect to the above parameters:

- *Scenario 1*: No IS, no defined inventory control, (AS-IS model);
- *Scenario 2*: IS, no VMI, (TO-BE 1) model; and
- *Scenario 3*: IS, VMI, (TO-BE 2) model.

The simulation was run using GoldSim Pro 9.0. The performance measures derived from the simulation results are summarised in Figure 5 and Figure 6. The results from Figure 5 show that the value of the Bullwhip Effect is smallest for Scenario 3, which assumed full information sharing with appropriate structural changes of business processes, and full coordination in inventory control across the supply chain. These results also show that fully utilising the benefit of implementing information technology and inventory management based on logistical principles can decrease the value of Bullwhip Effect by 28% in the observed case study.

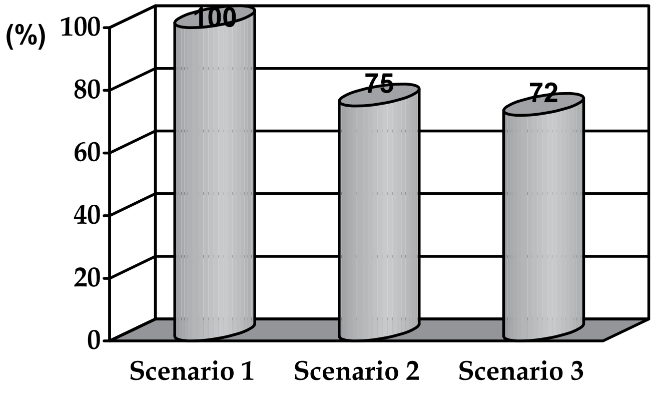


Fig. 5. Bullwhip effect value comparasion of three scenarios

In Figure 6 a comparison of inventory costs with regard to the scenarios is shown. The minimum inventory holding costs are seen in Scenario 3, like in the first case. The result from Figure 5 show that benefits from the application of new information technology, business process reengineering and coordinated inventory policy, expressed by decreasing inventory holding costs, could be 20%.

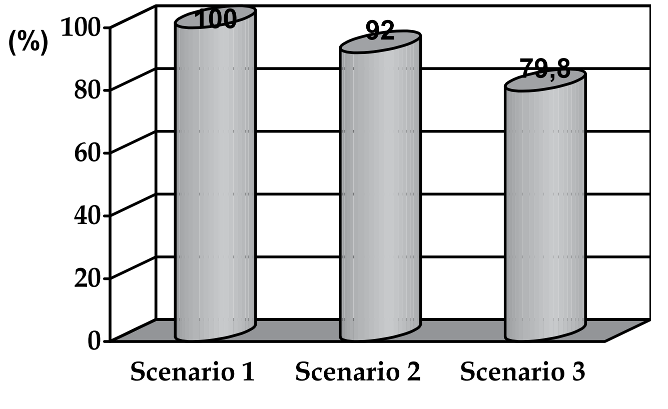


Fig. 6. Inventory costs comparasion of three scenarios

## 6. Conclusion

Supply chain management has become a powerful tool for facing up to the challenge of global business competition because supply chain management can significantly improve supply chain performance. This chapter explores how achieving only successful business process changes can contribute to the full utilisation of improved sharing, and so to the full coordination of the supply chain. The conclusions of the simulation experiments are: information sharing can enhance the performance of the supply chain. In addition, business process reengineering and coordination are also important mechanisms in the supply chain to improve performance. Coordination can reduce the influence of the Bullwhip Effect and improve cost efficiency. In the previous literature there were not many connections between theoretical studies and a real-life complex case study. This chapter is hence one of the few attempts in this direction. This research represents a part of the project financed by the Ministry of Serbia.

## 7. References

Bosilj-Vuksic, V.; Indihar-Stemberger, M.; Jaklic, J. & Kovacic, A. (2002). Assessment of E-Business Transformation using Simulation Modelling. *Simulation*, Vol. 78, No. 12, pp. 731-744, ISSN: 0037-5497

Bourland, K.; Powell, S. & Pyke, D. (1996). Exploring Timely Demand Information to Reduce Inventories. *European Journal of Operational Research*, Vol. 44, No. 2, pp. 239-253, ISSN: 0377-2217

Boute, R.N. & Lambrecht, M.R. (2007). Exploring the Bullwhip Effect by Means of Spreadsheet Simulation. *Vlerick Leuven Gent Working Paper Series*, Vol. 4, pp. 1-33, Vlerick Leuven Gent Management School, Leuven

Bowersox, D.J. (1990). The Strategic Benefits of Logistics Alliances. *Harvard Business Review*, Vol. 68, No. 4, pp. 36-45, ISSN: 0017-8012

Chen, F. (1998). Echelon Reorder Point, Installation Reorder Points, and the Value of Centralized Demand Information. *Management Science*, Vol. 44, No. 12, pp. 221-234, ISSN: 0025-1909

Chen, F.; Drezner, Z.; Ryan, J.K. & Simchi-Levi, D. (2000). Quantifying the Bullwhip Effect in a Simple Supply Chain: the Impact of Forecasting, Lead Times, and Information. *Management Science*, Vol. 46, No. 3, pp. 436-443, ISSN: 0025-1909

Cheung, Y. & Bal, J. (1998). Process Analysis Techniques and Tools for Business Improvement. *Business Process Management Journal*, Vol. 4, No. 4, pp. 274-290, ISSN: 1463-7154

Croom, S.; Romano, P. & Giannakis, M. (2000). Supply Chain Management: An Analytical Framework for Critical Literature Review. *European Journal of Purchasing and Supply Management*, Vol. 6, No. 1, pp. 67-83, ISSN: 0969-7012

Davenport, T.H. & Short, J. (1990). The New Industrial Engineering: Information Technology and Business Process Redesign. *Sloan Management Review*, Vol. 34, No. 4, pp. 11-27, ISSN: 0019-848X

Dejonckheere, J.; Disney, S.M.; Lambrecht, M.R. & Towill, D.R. (2004). The Impact of Information Enrichment on the Bullwhip Effect in Supply Chains: a Control Theoretic Approach. *European Journal of Operational Research*, Vol. 153, No. 3, pp. 727-750, ISSN: 0377-2217

Feldman, M. & Miler, S. (2003). An Incentive Scheme for True Information Providing in Supply Chains. *Omega*, Vol. 31, No. 2, pp. 63-73, ISSN: 0305-0483

Ferguson, M. & Ketzenberg, M.E. (2006). Information Sharing to Improve Retail Product Freshness of Perishables. *Production and Operations Management*, Vol. 15, No. 1, pp. 57-73, ISSN: 1937-5956

Fransoo, J.C. & Wouters, M.J.F. (2000). Measuring the Bullwhip Effect in the Supply Chain. *Supply Chain Management: An International Journal*, Vol. 5, No. 2, pp. 78-89, ISSN: 1359-8546

Gavirneni, S.; Kapuscinski, R. & Tayur, S. (1999). Value of Information in Capacitated Supply Chains. *Management Science*, Vol. 45, No. 1, pp. 16-24, ISSN: 0025-1909

Groznik, A. & Maslaric, M. (2009). Investigating the Impact of Information Sharing in a Two-Level Supply Chain Using Business Process Modelling and Simulation: A Case Study, *Proceedings of 23rd European Conference on Modelling and Simulation*, pp. 39-45, ISBN: 0-9553018-8-2, Madrid, June 2009, European Council for Modelling and Simulation, Madrid

Groznik, A. & Maslaric, M. (2010). Achieving Competitive Supply Chain Through Business Process Re-engineering: A Case from Developing Country. African Journal of Business Management, Vol. 4, No. 2, pp. 140-148, ISSN: 1990-3839

Hammer, M. (1990). Reengineering Work: Don't automate obliterate. *Harvard Business Review*, Vol. 64, No. 4, pp. 104-112, ISSN: 0017-8012

Holmstrom, J.; Hameri, A.P.; Nielsen, N.H.; Pankakoshi, J. & Slotte, J. (1997). Examples of Production Dynamics Control for Cost Efficiency. *International Journal of Production Economics*, Vol. 48, No. 2, pp. 109-119, ISSN: 0925-5273

Jacobs, F.R. (2000). Playing the Beer Distribution Game over the Internet. *Production and Operations Management*, Vol. 9. No. 1, pp. 31-39, ISSN: 1937-5956

Jones, C. (1998). Moving Beyond ERP: Making the Missing Link. *Logistics Focus*, Vol. 6, No. 7, pp. 187-192, ISSN: 1350-6293

Kanter, R.M. (1994). Collaborative Advantage: the Art of Alliances, *Harvard Business Review*, Vol. 72, No. 4, pp. 96-112, ISSN: 0017-8012

Lee, H.L.; Padmanabhan, P. & Whang, S. (1997a). The Bullwhip Effect in Supply Chain. *Sloan Management Review*, Vol. 38, No. 3, pp. 93-102, ISSN: 0019-848X

Lee, H.L.; Padmanabhan, P. & Whang, S. (1997b). Information Distortion in a Supply Chain: the Bullwhip Effect. *Management Science*, Vol. 43, No. 4, pp. 546-558, ISSN: 0025-1909

Li, J.; Sikora, R.; Shaw, M.J. & Tan, G.W. (2005). A Strategic Analysis of Inter-organizational Information Sharing. *Decision Support Systems*, Vol. 42, pp. 251-266, ISSN: 0167-9236

Maslaric, M. (2008). An Approach to Investigating the Impact of Information Charasteristic on Logistic Processes Planning and Coordination in Supply Chains. Master Thesis. University of Novi Sad, Serbia

Merriam-Webster. (2003). Merriam-Webster Collegiate Dictionary, 11th ed., Merriam-Webster

Petuhova, J. & Merkuryev, Y. (2006). Combining Analytical and Simulation Approaches to Quantification of the Bullwhip Effect. *International Journal of Simulation*, Vol. 8, No. 1, pp. 16-24, ISSN: 1473-8031

Sahin, F. & Robinson, E.P. (2002). Flow Coordination and Information Sharing in Supply Chains: Review, Implications, and Directions for Future Research. *Decision Science*, Vol. 33, No. 4, pp. 505-536, ISSN: 0011-7315

Simchi-Levi, D.; Kaminsky, P. & Simchi-Levi, E. (1998). *Designing and Managing the Supply Chain*. Irwin/McGraw-Hill Professional. ISBN: 0-07-284553-8, New York, USA

Simchi-Levi, D.; Kaminsky, P. & Simchi-Levi, E. (2003). *Managing the Supply Chain: The Definitive Guide for the Business Professional*. McGraw-Hill Professional. ISBN: 0-07-141031-7, New York, USA

Tan, K.C.; Lyman, S.B. & Wisner, J.D. (2002). Supply Chain Management: a Strategic Perspective. *International Journal of Operations and Production Management*, Vol. 22, No. 6, pp. 614-631, ISSN: 0144-3577

Towill, D.R.; Naim, N.M. & Wikner, J. (1992). Industrial Dynamics Simulation Models in the Design of Supply Chains. *International Journal of Physical Distribution and Logistics Management*, Vol. 22. No. 5, pp. 3-13, ISSN: 0960-0035

Towill, D.R.; Childerhouse, P. & Disney, S.M. (2002). Integrating the Automotive Supply Chain: Where are We Now? *International Journal of Physical Distribution & Logistics Management*, Vol. 32, No. 2, pp. 79-95, ISSN: 0960-0035

Trkman, P.; Stemberger, M.I.; Jaklic, J. & Groznik, A. (2007). Process Approach to Supply Chain Integration. *Supply Chain Management: An International Journal*, Vol. 12, No. 2, pp. 116-128, ISSN: 1359-8546

Waller, M.; Johnson, M.E. & Davis, T. (1999). Vendor-Managed Inventory in the Retail Supply Chain. *Journal of Business Logistics*, Vol. 20, No. 1, pp. 183-204, ISSN: 0735-3766

Wilding, R. (2003). The 3Ts of Highly Effective Supply Chains. *Supply Chain Practice*, Vol. 5, No. 3, pp. 30-39, ISSN: 1466-0091

# 17

# Integrated Revenue Sharing Contracts to Coordinate a Multi-Period Three-Echelon Supply Chain

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## 1. Introduction

A supply chain can be defined as a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. Different entities in a supply chain operate subject to different sets of constraints and objectives under different industrial environments. Each member of a decentralized supply chain has its own decision rights to optimize its costs or benefits. Recently, the topic of decentralized supply chain modelling and analysis has been of great interest. Most of the studies on decentralized supply chain modelling have focused on designing a mechanism to fully integrate these individualistic decisions in order to ensure that the decision outcome of an individual member of the supply chain is in accordance with the decision outcome of the entire supply chain (Cachon & Lariviere, 2001; Moinzadeh and Bassok, 1998; Tsay et al., 1999).

Perfect coordination mechanisms allow the decentralized supply chain to perform as well as a centralized one, in which all decisions are made by a single entity to maximize supply-chain-wide profits. Several types of contractual agreements which may determine incentive mechanisms to integrate a decentralized supply chain, inclunding profit sharing (Atkinson, 1979; Jeuland and Shugan, 1983), consignment (Kandel, 1996), buy-backs (Pasternack, 1985; Emmons & Gilbert, 1987), quantity-flexibility (Tsay & Lovejoy, 1999), revenue sharing (Giannoccaro & Pontrandolfo, 2004; Cachon & Lariviere, 2005; Chang & Hsueh, 2006, 2007), revenue allocation rules (Shah et al., 2001), and quantity discounts (Dolan, 1987), etc.

One of these contractual agreements, revenue sharing is a mechanism that is gaining popularity in practice and in research. Shah et al. (2001) have adopted Nash's game theory to formulate a model which explores a fair revenue allocation mechanism among the members of a multi-tier supply chain. The model provides a compromise solution of maximized revenue for each individual member of the supply chain under the inventory and production constraints. Giannoccaro & Pontrandolfo (2004) have extended the revenue sharing contract of two-tier to a three-tier supply chain model. Cachon & Lariviere (2005) have presented the revenue sharing contract concept and discussed its influence on supply chain performances. The revenue sharing contract can be described by two parameters, retail price and retailers' revenue retention ratio. Chang & Hsueh (2006, 2007) extended Giannoccaro & Pontrandolfo (2004) to explore a three-tier supply chain integration problem with the time-varying multi-period demand and the constant price elasticity demand function. Multiple objective programming techniques are applied to determine the revenue sharing contract parameters, the purchasing price and revenue sharing ratios among the members of the supply chain. In order to heighten the incentive cooperation, equilibrium behaviors for decentralized supply chains are included and regarded as compromise benchmarks for supply chain integration.

The remainder of this chapter is organized as follows. In Section 2, two multi-period three-tier supply chain network models are presented. A equilibrium model of decentralized supply chain network is introduced first. Herein the optimality conditions of the various decision-makers are derived and formulated as a finite-dimensional variational inequality model. A multi-objectives programming model to determine the revenue sharing constract parameters is given next. In Section 3, a well-known solution algorithm, diagonalization method, is presented to solve the variation inequility model of supply chain networkequilibrium. In Section 4, a supply chain network example is provided for the demonstration. Conclusions are given in the end.

## 2. Model formulation

The supply chain network is composed of $m$ manufacturers, $n$ distributors, and $o$ retailers. The other assumptions about the members of the supply chain network are summarized as follows:

1. To accommodate changes in demand, the product inventory within this supply chain network is stored at the manufacturers' warehouses so that the manufacturers will have sufficient inventory or production capacity to satisfy the distributors' demand in the current time period.
2. The total costs of the manufacturers have to bear are production cost, inventory cost and transportation cost. The distributors are only responsible for the product handling and purchasing costs. The retailers are directly associated with the market demand and responsible for transportation costs and purchasing cost. All the cost functions for the manufacturers, distributors, and retailers are continuous, convex, and nonlinear functions.
3. The demand function is a known function which can describe the relationship between the market demand and market price.

### 2.1 Notations

$d_k(t)$ : The product demand of retailer $k$ at time period $t$

$f_i(e)$ : The production cost of manufacturer $i$ at time period $e$

$\overline{f}_i(e)$ : The average production cost of manufacturer $i$ at time period $e$

$h_i(t)$ : The inventory cost of manufacturer $i$ at time period $t$

$\overline{h}_i(t)$ : The average inventory cost of manufacturer $i$ at time period $t$

$I_i(t)$ : The inventory level of manufacturer $i$ at time period $t$

$L_j(t)$ : The product quantity of distributor $j$ at time period $t$

$m_j(t)$ : The product handling cost of distributor $j$ at time period $t$

$\overline{m}_j(t)$ : The average product handling cost of distributor $j$ at time period $t$

| | |
|---|---|
| $q_i(e)$ : | The production quantity of manufacturer $i$ at time period $e$ |
| $q_{ij}(t)$ : | The product quantity delivered from manufacturer $i$ to distributor $j$ at time period $t$ |
| $q_{ijt}(e)$ : | The product quantity produced by manufacturer $i$ at time period $e$ and delivered to distributor $j$ at time period $t$ |
| $q_{jk}(t)$ : | The product quantity delivered from distributor $j$ to retailer $k$ at time period $t$ |
| $s_{ij}(t)$ : | The transportation cost from manufacturer $i$ to distributor $j$ at time period $t$ |
| $\bar{s}_{ij}(t)$ : | The average transportation cost from manufacturer $i$ to distributor $j$ at time period $t$ |
| $s_{jk}(t)$ : | The transportation cost from distributor $j$ to retailer $k$ at time period $t$ |
| $\bar{s}_{jk}(t)$ : | The average transportation cost from distributor $j$ to retailer $k$ at time period $t$ |
| $T_{ij}$ : | The leading time between manufacturer $i$ and distributor $j$ |
| $T_{jk}$ : | The leading time between distributor $j$ and retailer $k$ |
| $z_i, z_j, z_k$ : | The profit for manufacturers, distributors, and retailers |
| $z_i^*, z_j^*, z_k^*$ : | The maximum profit for manufacturers, distributors, and retailers |
| $z_i^E, z_j^E, z_k^E$ : | The equilibrium profit for manufacturers, distributors, and retailers |
| $\phi_k^3$ : | The ratio of the retail revenues retained by retailer $k$ |
| $\phi_{jk}^2$ : | The ratio of the wholesale revenue retained by distributor $j$, which is resulted from the transaction between distributor $j$ and retailer $k$ |
| $\rho_{ij}^1(t)$ : | The selling price of manufacturer $i$ to distributor $j$ at time period $t$ |
| $\rho_j^2(t)$ : | The selling price of distributor $j$ at time period $t$ |
| $\rho_k^3(t)$ : | The selling price of retailer $k$ at time period $t$ |

### 2.2 Market equilibrium model

Chang & Hsueh (2006) first focus on decision behaviours of manufacturers and then turn to decision behaviours of distributors and retailers, subsequently. A complete equilibrium model is finally constructed.

#### 2.2.1 The manufacturers' optimality conditions

Each manufacturer's behaviour of seeking profit maximization can be expressed as follows.

$$\max \quad \pi_i = \sum_{jt} \rho_{\mathrm{ij}}^1(t) q_{ij}(t) - \sum_e f_i(e) - \sum_t h_i(t) - \sum_{jt} s_{ij}(t) \tag{1}$$

subject to

$$q_i(e) = \sum_{jt} q_{ijt}(e) \qquad \forall e \tag{2}$$

$$I_i(t) = \sum_{j,e<t} q_{ijt}(e) \qquad \forall t \tag{3}$$

$$q_{ij}(t) = \sum_{e \le t\text{-}T_{ij}} q_{ij(t\text{-}T_{ij})}(e) \qquad \forall j,t \tag{4}$$

$$q_{ijt}(e) \ge 0 \qquad \forall j,t,e \tag{5}$$

$$\rho_{ij}^{1}(t) \ge 0 \qquad \forall j,t \tag{6}$$

Eq. (1) designates that the profit of a manufacturer is the difference in total revenues and total costs. Eq. (2) defines that the entire volume of production of manufacturer $i$ at time period $e$ is equal to the sum of the quantities shipped from this manufacturer to all distributors after time period $e$. Eq. (3) defines that the entire volume of inventory at time period $t$ is equal to the sum of the quantities produced by the manufacturer $i$ before time period $t$. Eq. (4) defines that the volume of transaction between manufacturer $i$ and distributor $j$ at time period $t$ is equal to the sum of the product quantity produced by manufacturer $i$ for distributor $j$ before time period $t - T_{ij}$. Note that the production cost $f_i(e)$ depends upon the entire volume of production at time period $e$. The inventory cost $h_i(t)$ depends upon the entire volume of inventory at time period $t$. The shared transaction cost depends upon the volume of transaction at time period $t$. Eqs. (5) and (6) are nonnegative constraints.

The manufacturers compete in a noncooperative fashion following Nash (1950, 1951). Each manufacturer will determine this optimal production quantity, inventory quantity, distribution quantity at each time period. The optimality conditions for all manufacturers simultaneously expressed as Eq. (7).

$$\frac{\partial f_i^*(e)}{\partial q_{ijt}^*(e)} + \frac{\partial h_i^*(t)}{\partial q_{ijt}^*(e)} + \frac{\partial s_{ij}^*(t)}{\partial q_{ijt}^*(e)} \begin{cases} = \rho_{ij}^{1*}(t) \ , \text{ if } q_{ijt}^*(e) > 0 \\ \ge \rho_{ij}^{1*}(t) \ , \text{ if } q_{ijt}^*(e) = 0 \end{cases} \qquad \forall i,j,t,e \tag{7}$$

### 2.2.2 The distributors' optimality conditions

Herein, each distributor's behavior of seeking profit maximization can be expressed as follows.

$$\max \quad \pi_j = \sum_t \rho_j^2(t) \sum_k \bar{q}_{jk}(t) - \sum_{it} \rho_{ij}^1(t - T_{ij}) q_{ij}(t - T_{ij}) - \sum_t m_j(t) \tag{8}$$

subject to

$$L_j(t) = \sum_i q_{ij}(t - T_{ij}) \qquad \forall t \tag{9}$$

$$\sum_i q_{ij}(t - T_{ij}) = \sum_k q_{jk}(t) \qquad \forall t \tag{10}$$

$$q_{ij}(t) \ge 0 \qquad \forall i,t \tag{11}$$

$$q_{jk}(t) \ge 0 \qquad \forall k,t \tag{12}$$

$$\rho_j^2(t) \geq 0 \qquad \forall t \tag{13}$$

Eq. (8) designates that the profit of a distributor is the difference in total revenues and total costs. Eq. (9) defines that the entire product quantity of distributor *j* at period *t* is equal to the sum of purchase quantity from all manufacturers at the corresponding time period $t\text{-}T_{ij}$. The handling cost $m_j(t)$ depends upon the entire product quantity at period *t*. Eq. (10) ensures that the received total product quantity of the distributor *j* from all manufacturers departing at time period $t\text{-}T_{ij}$ must be greater than or equal to the product quantity of the distributor *j* which can be distributed to all retailers at time period *t*. Eqs. (11) ~ (13) are nonnegative constraints.

Congenially, the distributors compete in a noncooperative manner, too. At each time period, each distributor will determine the optimal order quantity with each manufacturer as well as distribution quantity for each retailer. The optimality conditions for all distributors satisfy Eqs. (14)~(16).

$$\rho_{ij}^{1*}(t-T_{ij}) + \frac{\partial m_j^*(t)}{q_{ij}^*(t-T_{ij})} \begin{cases} = \gamma_j^*(t) \ , \ \text{if } q_{ij}^*(t-T_{ij}) > 0 \\ \geq \gamma_j^*(t) \ , \ \text{if } q_{ij}^*(t-T_{ij}) = 0 \end{cases} \qquad \forall i,j,t \tag{14}$$

$$\gamma_j^*(t) \begin{cases} = \rho_j^{2*}(t) \ , \ \text{if } q_{jk}^*(t) > 0 \\ \geq \rho_j^{2*}(t) \ , \ \text{if } q_{jk}^*(t) = 0 \end{cases} \qquad \forall j,k,t \tag{15}$$

$$\gamma_j(t) \geq 0 \qquad \forall j,t \tag{16}$$

Note that $\gamma_j(t)$ is the Lagrange multiplier associated with constraint (10) for distributor *j* at time period *t*.

### 2.2.3 The retailers' optimality conditions

On the analogy of the well-known spatial price equilibrium conditions, the equilibrium conditions for each retailer at each time period can be stated as follows:

$$\rho_j^*(t-T_{jk}) + s_{jk}^*(t) \begin{cases} = \rho_k^{3*}(t) \ , \ \text{if } q_{jk}^*(t) > 0 \\ \geq \rho_k^{3*}(t) \ , \ \text{if } q_{jk}^*(t) = 0 \end{cases} \qquad \forall j,k,t \tag{17}$$

$$d_k^*(t) \begin{cases} = \sum_j q_{jk}^*(t-T_{jk}) \ , \ \text{if } \rho_k^{3*}(t) > 0 \\ \leq \sum_j q_{jk}^*(t-T_{jk}) \ , \ \text{if } \rho_k^{3*}(t) = 0 \end{cases} \qquad \forall k,t \tag{18}$$

Eq. (17) ensures that the product will be distributed to the retailer *k* from distributor *j* at time period *t*, if the price charged by the distributor *j* for the product at time period $t - T_{jk}$ plus the transportation cost faced by retailer *k* at time period *t* doesn't exceed the price that consumers of retailer *k* are willing to pay for the product at time period *t*. Eq. (18) states that the total product quantity distributed to the retailer *k* from all distributors at time period

$t-T_{jk}$ is equal to the customers' demands of retailer *k* at time period *t*, if the price the consumers of retailer *k* are willing to pay for the product at time period *t* is positive.

### 2.2.4 Equilibrium condition of the supply chain

The equilibrium state of the multi-period supply chain is one where the time-space flows between the tiers of the supply chain network coincide and the product shipments and prices simultaneously satisfy the all optimality conditions, i.e., Eqs. (7) and (14)~(18). Furthermore, they can also be expressed as a variational inequality problem.

$$\begin{aligned}
&\sum_{ijte}\left[\frac{\partial f_i^*(e)}{\partial q_{ijt}^*(e)}+\frac{\partial h_i^*(t)}{\partial q_{ijt}^*(e)}+\frac{\partial s_{ij}^*(t)}{\partial q_{ijt}^*(e)}-\rho_{ij}^*(t)\right]\left[q_{ijt}(e)-q_{ijt}^*(e)\right]+\\
&\sum_{ijt}\left[\rho_{ij}^*(t-T_{ij})+\frac{\partial m_j^*(t)}{\partial q_{ij}^*(t-T_{ij})}-\gamma_j^*(t)\right]\left[q_{ij}(t-T_{ij})-q_{ij}^*(t-T_{ij})\right]+\\
&\sum_{jkt}\left[\gamma_j^*(t)-\rho_j^*(t)\right]\left[q_{jk}(t)-q_{jk}^*(t)\right]+\sum_{jt}\left[\sum_i q_{ij}^*(t-T_{ij})-\sum_k q_{jk}^*(t)\right]\left[\gamma_j(t)-\gamma_j^*(t)\right]+\\
&\sum_{jkt}\left[\rho_j^*(t-T_{jk})+s_{jk}^*(t)-\rho_k^*(t)\right]\left[q_{jk}(t)-q_{jk}^*(t)\right]+\sum_{kt}\left[\sum_j q_{jk}^*(t-T_{jk})-d_k^*(t)\right]\left[\rho_k(t)-\rho_k^*(t)\right]\geq 0
\end{aligned} \tag{19}$$

The equilibrium state of the multi-period supply chain is one where the time-space flows between the tiers of the supply chain network coincide and the product shipments and prices simultaneously satisfy the all optimality conditions, i.e., Eqs. (7), and (14)~(18). Since the amount of products must follow the flow conservation constraints, each product received by a retailer must come from some manufacturer by way of some distributor. Therefore, Chang & Hsueh (2007) define such a product flow as a time-dependent path flow $q_{pk}(e,t)$ where a path p is composed of a link $(i,j)$ and a link $(j,k)$. It means that the products are produced by manufacturer *i* at time period *e*, and then are delivered to distributor *j* and retailer *k* at time period *t*, sequentially. The equilibrium conditions of whole supply chain network can then be simplified as Eq. (18) and the following:

$$\frac{\partial f_i^*(e)+h_i^*(t)}{\partial q_{ij}(e,t)}+\frac{\partial s_{ij}^*(t)+m_j^*(t+T_{ij})}{\partial q_{ij}(t)}+s_{jk}^*(t+T_{ij})\begin{cases}=\rho_k^{3*}(t+T_{ij}+T_{jk})\ ,\ \text{if } q_{pk}^*(e,t)>0\\ \geq\rho_k^{3*}(t+T_{ij}+T_{jk})\ ,\ \text{if } q_{pk}^*(e,t)=0\end{cases}\quad\forall p,k,t,e \tag{20}$$

Let Eq. (21) stands. Equilibrium conditions (18) and (20) can be transformed into the following variational inequality formulation (22) with the constraint set Ω, i.e., (2)~(6), (9)~(13).

$$\hat{c}_{pk}(e,t)=\frac{\partial f_i(e)+h_i(t)}{\partial q_{ij}(e,t)}+\frac{\partial s_{ij}(t)+m_j(t+T_{ij})}{\partial q_{ij}(t)}+s_{jk}(t+T_{ij}) \tag{21}$$

$$\sum_{pket}\left[\hat{c}_{pk}^*(e,t)-\rho_k^{3*}(t+T_{ij}+T_{jk})\right]\left[q_{pk}(e,t)-q_{pk}^*(e,t)\right]+\sum_{kt}\left[\sum_j q_{jk}^*(t-T_{jk})-d_k^*(t)\right]\left[\rho_k(t)-\rho_k^*(t)\right]\geq 0 \tag{22}$$

The first term of Eq. (22) is a path-based variational inequiality formulation and can be equivalently transformed into a link-based VI one (Chen, 1999). Therefore, the variational inequiality model for a decentralized supply chain network can then be established as follows (Chang & Hsueh, 2007).

$$\sum_{ijet}\left[\frac{\partial f_i^*(e)+h_i^*(t)}{\partial q_{ij}(e,t)}\right]\left[q_{ij}(e,t)-q_{ij}^*(e,t)\right]+\sum_{ijt}\frac{\partial s_{ij}^*(t)+m_j^*(t+T_{ij})}{\partial q_{ij}(t)}\left[q_{ij}(t)-q_{ij}^*(t)\right]$$
$$+\sum_{jkt}s_{jk}^*(t)\left[q_{jk}(t)-q_{jk}^*(t)\right]+\sum_{kt}\left[\sum_j q_{jk}^*(t-T_{jk})-d_k^*(t)\right]\left[\rho_k^3(t)-\rho_k^{3*}(t)\right]\geq 0 \tag{23}$$

subject to: Eqs. (2)~(6) for all manufacturer *i* and Eqs. (9)~(13) for all distributor *j*.

### 2.3 Revenue sharing model for supply chain integration

The unique feature of revenue sharing contract is that the sellers will provide lower selling price to the buyers and the buyers will share part of the product sales revenue with the sellers. About the revenue sharing rule, Chang & Hsueh (2006) assume that the retail sales revenue can be shared within members of the third tier, second tier, and first tier of the supply chain network and the wholesale sales revenue can be shared within members of the second tier and first tier of supply chain network. In other words, excluding the portion of retail sales retained by each retailer, the remaining retail sales revenue will be returned to the distributors, and the manufacturers will receive their shares of the retail sales revenue after the distributors have retained their portion of retail sales revenue. The distributors retain their portion of wholesale sales revenue, the residual wholesale sales revenue will be returned to the manufacturers. The sales revenue resulted from selling products from manufacturers to distributors are solely retained by the manufacturers. Under such integration stipulation, the retailers' profits and distributors' profits are defined as shown in Eq. (24) and (25), respectively.

$$z_k=\sum_t \phi_k^3\rho_k^3(t)d_k(t)-\sum_{jt}s_{jk}(t)-\sum_{jt}\rho_j^2(t-T_{jk})q_{jk}(t-T_{jk})\ \ \forall k \tag{24}$$

$$z_j=\sum_{kt}\phi_{jk}^2(1-\phi_k^3)\rho_k^3(t)d_k(t)+\sum_{kt}\phi_{jk}^2\rho_j^2(t)q_{jk}(t)-\sum_{it}\rho_{ij}^1(t-T_{ij})q_{ij}(t-T_{ij})-\sum_t m_j(t)\ \ \forall j \tag{25}$$

The manufacturers' profits are defined as follows.

$$z_i=\sum_{jkt}(1-\phi_{jk}^2)(1-\phi_k^3)\rho_k^3(t)d_k(t)+\sum_{jkt}(1-\phi_{jk}^2)\rho_j^2(t)q_{jk}(t)\ +\sum_{jt}\rho_{ij}^1(t)\sum_{e\leq t}q_{ijt}(e)\ -\sum_e f_i(e)$$
$$-\sum_t h_i(t)-\sum_{jt}s_{ij}(t)\ \ \forall i \tag{26}$$

As a result, the profitability of members in the supply chain will differ according to the different buyers' revenue sharing ratio. Since the buyers and sellers' benefits are in conflict with each other and it is almost impossible to maximize the benefits for every member of the supply chain, only a compromised result can be achieved. Therefore, Chang & Hsueh (2006) have applied the compromise programming theory to establish an intertemporal supply chain revenue sharing model as follows:

$$\max \quad \mu = \sum_i \frac{z_i - z_i^E}{z_i^S - z_i^E} + \sum_j \frac{z_j - z_j^E}{z_j^S - z_j^E} + \sum_k \frac{z_k - z_k^E}{z_k^S - z_k^E} \tag{27}$$

subject to:

- flow conservation constraints

(2)~(6) for all *i*

(9)~(13) for all *j*

$$d_k(t) = \sum_j q_{jk}(t - T_{jk}) \quad \forall k, t \tag{28}$$

- definitional constraints

(24)~(26)

- boundary constaints

$$z_i \le z_i^s \quad \forall i \tag{29}$$

$$z_j \le z_j^s \quad \forall j \tag{30}$$

$$z_k \le z_k^s \quad \forall k \tag{31}$$

$$\rho_{ij}^1(t) \le \rho_{ij}^{1^*}(t) \quad \forall i, j, t \tag{32}$$

$$\rho_j^2(t) \le \rho_j^{2^*}(t) \quad \forall j, t \tag{33}$$

$$\rho_{ij}^1(t) \le \rho_j^2(t + T_{ij}) \quad \forall i, j, t \tag{34}$$

$$\rho_j^2(t) \le \rho_k^3(t + T_{jk}) \quad \forall j, k, t \tag{35}$$

- value range constraints

$$\rho_k^3(t) \ge 0 \quad \forall k, t \tag{36}$$

$$0 \le \phi_{jk}^2 \le 1 \quad \forall j, k \tag{37}$$

$$0 \le \phi_k^3 \le 1 \quad \forall k \tag{38}$$

The objective of the compromise programming model is to maximize the sum of relative distance from the negative solution $\left(z_i^E, z_j^E, z_k^E\right)$, as shown in Eq. (27). It is well known that the profit of each individual in the perfect competition market is lowest. Furthermore, in order to avoid the rejection of the revenue sharing contracts due to the fact that the compromised profit solution provide in the revenue sharing contract for each member of the supply chain is less than the profits made at market equilibrium before revenue sharing. We let the negative solution $\left(z_i^E, z_j^E, z_k^E\right)$ of the proposed compromise programming model be the equilibrium profits for manufacturers, distributors, and retailers that are obtained from the variational inequalities, Eq. (23). On the other hand, the share profits for manufacturers, distributors, and retailers are very important parameters in Eq. (27). Based on fairness doctrine, we suggest that the excess profit resulted from the supply chain integration must be shared by all the members in the supply chain.

In addition, the feasible solution is defined by flow conservation constraints, definitional constraints, boundary constraints, and value boudary constriants. Eqs. (2)~(6), (9)~(13), and (28) are flow conservation constrints. Eq. (28) limits the total market demand for retailer $k$ at time $t$, which is equal to the total product quantity delivered from all distributors at time $t-T_{jk}$. Eqs. (24)~(26) define the profits of members in the supply chain.

There are three kinds of boundary constraints in this model. The first one is about the profits limits. Eqs. (29)~(31) require the profits for the manufacturers, distributors, and retailers must be less than the share profits negotiated with each member of the supply chain. They also ensure that each relative distance from the negative solution is between 0 and 1. The second one is about upper limits of selling prices. Eqs. (32)~(33) set the upper limits of selling prices be equal to the corresponding equilibrated prices. The equilibrated manufacturers' and distributors' selling prices can be obtained from the variational inequalities, Eq. (23) and estimated by using Eq. (7) and Eqs. (14), (15) respectively. The third one is to avoid a singular phenomenon, i.e. selling prices are less than prime costs, Eq. (34) requires the distributors' selling prices in each time period $t+T_{ij}$ must be greater than the manufacturers' selling prices in each time period $t$. Eq. (35) requires the retailers' selling price in each time period $t+T_{jk}$ must be greater than the distributors' selling price in each time period $t$.

Value boudary constriants includ Eqs. (36) and (37)~(38). Eq. (36) limits all retailers' selling price to be nonnegative. Eq. (37) and (38) limit each buyer's revenue sharing ratio, regardless the transaction type, to be between 0 and 1.

## 3. Solution algorithm

Chang & Hsueh (2007) adopted a diagonalization method to solve the variation inequility model (23). It is a well-known solution algorithm for solving the VI problem (Chen, 1999). A time-space network representation technique and a two-staged concept are utilized for solving such a problem. They are explained in detail as follows.

First, we utilize the time-space network representation technique to simplify the procedure of solution algorithm. Given a two-manufacturer two-distributor two-retailer network with three time-dependent costumers' demands, and five time periods, the time-space network can be drawn in Fig. 1. At each time period, the static network is reproduced and each manufacturer node is duplicated. In addition, one time-independent dummy origin node $O$ and three time-dependent dummy destination nodes $S3$, $S4$, $S5$ are created. Four types of links are present in this time-space network.

1. The bold broken line that connects dummy origin node $O$ and a duplicated manufacturer node $M_i'$ is a dummy link. Similarly, the bold broken line that connects a retailer node $R_k$ and a dummy destination node $S_t$ is also a dummy link. The costs of

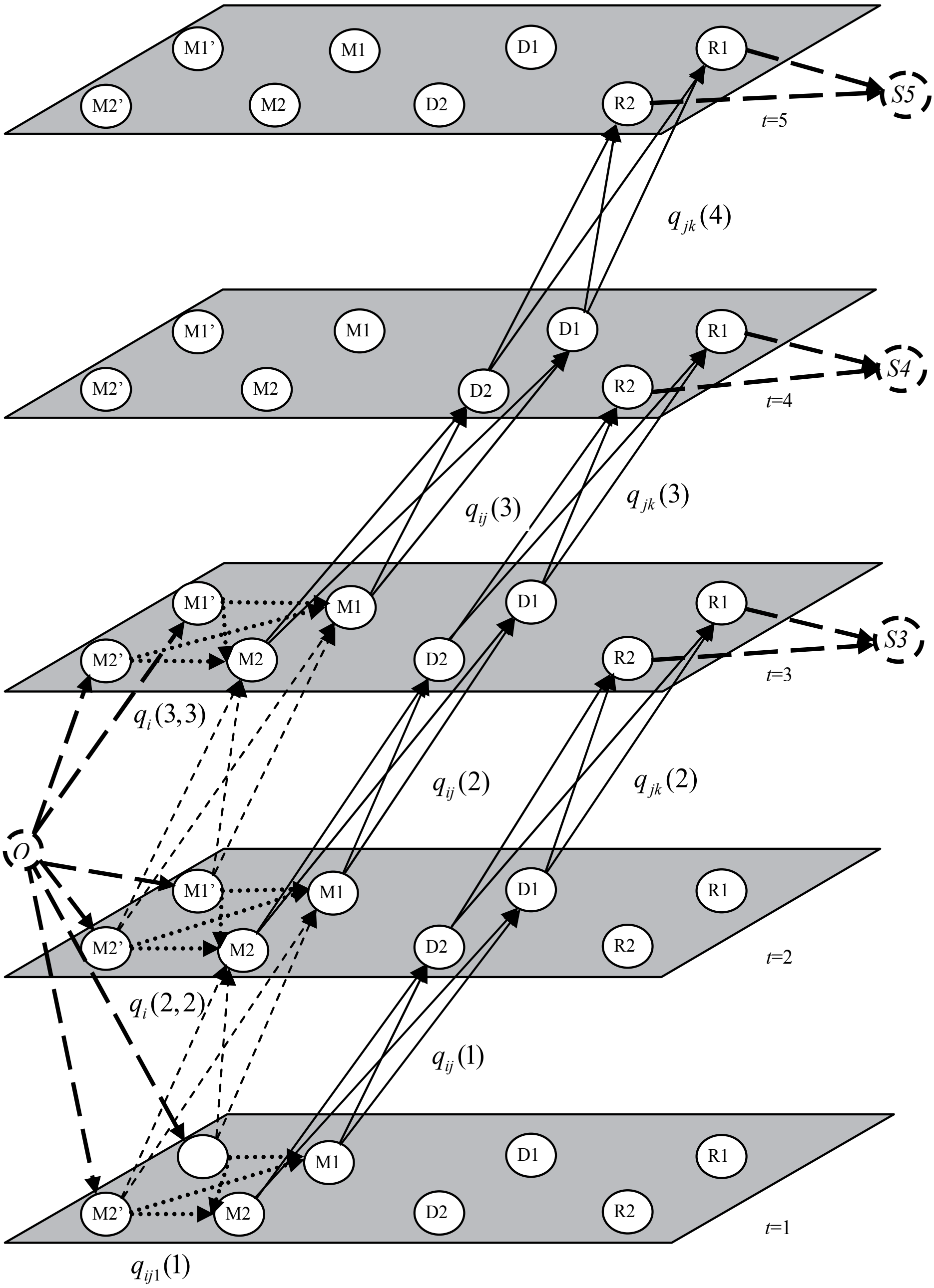


Fig. 1. Time-space network of a three-tier supply chain (Chang & Hsueh, 2007)

these dummy links are equal to zero. Having these dummy nodes and dummy links, the time-dependent costumers' demands are distributed over the supply chain from a dummy origin node to the corresponding dummy destination node.

2. The dotted line that connects a duplicated manufacturer node $M_i'$ and a manufacturer node $M_i$ at the same time period bears the products produced and sent out by manufacturer $i$ at the same time period $e$. The cost of this link is marginal production cost $\partial f_i(e)/\partial q_i(e,e)$ where $q_i(e,e)=\sum_j q_{ij}(e,e)$.
3. The fine broken line that connects a duplicated manufacturer node $M_i'$ and a manufacturer node $M_i$ between diffident time periods bears the products produced by manufacturer $i$ at time period $e$ and sent out at following time period $t$. The cost of this link is marginal production cost $\partial f_i(e)/\partial q_i(e,t)$ and marginal inventory cost $\partial h_i(t)/\partial q_i(e,t)$ where $q_i(e,t)=\sum_j q_{ij}(e,t)$.
4. The solid line that connects a manufacturer node $M_i$ and a distributor node $D_j$ bears the products delivered from manufacturer $i$ to distributor $j$ at time period $t$. The cost of this link is marginal transportation cost $ds_{ij}(t)/dq_{ij}(t)$ and marginal handling cost $\partial m_j(t+T_{ij})/\partial q_{ij}(t)$. Furthermore, the solid line that connects a distributor node $D_j$ and a retailer node $R_k$ bears the product delivered from distributor $j$ to retailer $k$ at time period $t$. The cost of this link is transportation cost $s_{jk}(t)$.

Second, since the decision variables of the proposed variation inequiality model (23) include flow variables $\left\{q_{ijt}(e),q_{ij}(t),q_{jk}(t)\right\}$ and price variables $\rho_k^3(t)$, the flow variables and the price variables are calculate separately. The detailed steps of solution algorithm are stated as follows:

*Step 0: Initialization.*

Step 0.1: Set $l$=0.

Step 0.2: Assign the maximum demand quantity of each retailer at time period $t$ to the empty time-space network in order to find an initial flow solution $\left\{q_{ij}^0(e,t),q_{ij}^0(t),q_{jk}^0(t)\right\}$.

Step 0.3: Calculate the initial price of each retailer by $\rho_k^3(t)^0=\hat{c}_{pk}(e,t)^0$, if $q_{pk}(e,\mathrm{t})^0>0$ according to the initial flow solution.

*Step 1: Diagonalization operation.*

Step 1.1: Set $l$=$l$+1.

Step 1.2: Fix the all retailers' price $\rho_k^3(t)^{l-1}$ and the flows for all time-space links other than on the subject time-space link at the current level, i.e., $\mathbf{q}^{l-1}\setminus q_{ij}(e,t)^{l\text{-}1}$ or $\mathbf{q}^{l-1}\setminus q_{ij}(t)^{l\text{-}1}$. Solve the following VI model (39) or (40) to find a flow solution $\left\{q_{ij}(e,t)^l,q_{ij}(t)^l,q_{jk}(t)^l\right\}$.

$$\sum_{ijet}\hat{f}_{ijet}^*\left(\mathbf{q}^{l-1}\setminus q_{ij}(e,t)^{l\text{-}1},q_{ij}^*(e,t)^l\right)\left[q_{ij}(e,t)-q_{ij}^*(e,t)^l\right]$$
$$+\sum_{ijet}\hat{h}_{ijet}^*\left(\mathbf{q}^{l-1}\setminus q_{ij}\left(e,t\right)^{l\text{-}1},q_{ij}^*\left(e,t\right)^l\right)\left[q_{ij}\left(e,t\right)-q_{ij}^*\left(e,t\right)^l\right]$$

$$+\sum_{ijt}\hat{s}_{ijt}\left(q_{ij}^{*}(t)^{l}\right)\left[q_{ij}(t)-q_{ij}^{*}(t)^{l}\right]+\sum_{ijt}\hat{m}_{j,t+T_{ij}}\left(q_{ij}^{*}(t)^{l}\right)\left[q_{ij}(t)-q_{ij}^{*}(t)^{l}\right] \tag{39}$$

$$+\sum_{jkt}s_{jk}^{*}(t)^{l}\left[q_{jk}(t)-q_{jk}^{*}(t)^{l}\right]\geq 0$$

$$\sum_{ijet}\hat{f}_{ijet}\left(\mathbf{q}^{*l}\right)\left[q_{ij}(e,t)-q_{ij}^{*}(e,t)^{l}\right]+\sum_{ijet}\hat{h}_{ijet}\left(\mathbf{q}^{*l}\right)\left[q_{ij}(e,t)-q_{ij}^{*}(e,t)^{l}\right]$$

$$+\sum_{ijt}\hat{s}_{ijt}\left(q_{ij}^{*}(t)^{l}\right)\left[q_{ij}(t)-q_{ij}^{*}(t)^{l}\right]+\sum_{ijt}\hat{m}_{j,t+T_{ij}}\left(q^{l-1}\setminus q_{ij}(t)^{l-1},q_{ij}^{*}(t)^{l}\right)\left[q_{ij}(t)-q_{ij}^{*}(t)^{l}\right] \tag{40}$$

$$+\sum_{jkt}s_{jk}^{*}(t)^{l}\left[q_{jk}(t)-q_{jk}^{*}(t)^{l}\right]\geq 0$$

Where

$$\hat{f}_{ijet}=\frac{\partial f_i(e)}{\partial q_{ij}(e,t)}\quad \forall i,j,e,t \tag{41}$$

$$\hat{h}_{ijet}=\frac{\partial h_i(t)}{\partial q_{ij}(e,t)}\quad \forall i,j,e,t \tag{42}$$

$$\hat{s}_{ijt}=\frac{\partial s_{ij}(t)}{\partial q_{ij}(e,t)}=\frac{\partial s_{ij}(t)}{\partial q_{ij}(t)}=\frac{ds_{ij}(t)}{dq_{ij}(t)}\quad \forall i,j,t \tag{43}$$

$$\hat{m}_{j,t+T_{ij}}=\frac{\partial m_j(t+T_{ij})}{\partial q_{ij}(t)}\quad \forall j,t \tag{44}$$

Step 1.3: According to the resulted flow solution $\left\{q_{ij}(e,t)^{l},q_{ij}(t)^{l},q_{jk}(t)^{l}\right\}$, calculate the corresponding price of each retailer $\rho_k^3(t)^l$ as follows.

$$\rho_k^3(t)^l=\hat{c}_{pk}(e,t)^l,\ \text{if}\ q_{pk}(e,t)^l>0 \tag{45}$$

*Step 2: Convergence check.*

If $\max_{ijet}\left|q_{ij}(e,t)^{l}-q_{ij}(e,t)^{l-1}\right|\leq\varepsilon$, $\max_{ijt}\left|q_{ij}(t)^{l}-q_{ij}(t)^{l-1}\right|\leq\varepsilon$, $\max_{jkt}\left|q_{jk}(t)^{l}-q_{jk}(t)^{l-1}\right|\leq\varepsilon$, and $\max_{kt}\left|\rho_k^3(t)^l-\rho_k^3(t)^{l-1}\right|\leq\varepsilon$, then stop; otherwise go to Step 1.1.

## 4. Numerical example

### 4.1 Input data

The numerical example of Nagurney and Toyasaki (2003) is modified and extended from one-period problem to multi-period problem. The network consists of two manufacturers, two distributors, ten retailers, and five time periods. Each of the transportation times is one period. The production cost and inventory cost functions for the manufacturers are respectively given by:

$$f_i(e) = 2.5q_i^2(e) + q_1(e)q_2(e) + 2q_i(e) \qquad \forall i; e = 1,2,3 \tag{46}$$

$$h_i(t) = \sum_{e \le t}(t-e)\left[q_{ijt}(e) + q_1(e) + 0.2q_2(e) + 0.4\right]q_{ijt}(e) \qquad \forall i; t = 1 \sim 3 \tag{47}$$

The transportation cost functions faced by the manufacturers and associated with the distributors are given by:

$$s_{ij}(t) = 0.5q_{ij}^2(t) + 3.5q_{ij}(t) \qquad \forall i; j; t = 1,2,3 \tag{48}$$

The handling cost functions of the distributors are given by:

$$m_j(t) = 0.5\left[\sum_{i=1}^{2} q_{ij}(t-1)\right]^2 \qquad \forall j, t = 2,3 \tag{49}$$

The transportation cost functions faced by the retailers and associated with the distributors are given by:

$$s_{jk}(t) = q_{jk}(t-1) + 5 \qquad \forall j; k; t = 3,4,5 \tag{50}$$

The demand functions at the demand markets are:

$$d_k(t) = -2\rho_k^3(3) - \sum_{k' \ne k} 0.1\rho_{k'}^3(t) + \delta_k(t) \tag{51}$$

where $\delta_k(t)$ is a constant of demand function of retailer $k$ at time period $t$. They are listed in Table 1.

| period | retailer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3 | 245 | 187 | 174 | 233 | 155 | 178 | 203 | 237 | 219 | 207 |
| 4 | 326 | 334 | 278 | 346 | 287 | 259 | 290 | 265 | 327 | 322 |
| 5 | 196 | 242 | 261 | 240 | 285 | 253 | 262 | 253 | 267 | 227 |

Table 1. Constants of demand functions

### 4.2 Test results

#### 4.2.1 An equilibrated solution

The proposed diagonalization method was implemented in Visual C++ to solve the proposed network equilibrium of decentralized supply chain network. The yielded equilibrium flow patterns and selling prices are shown in Table 2. The equilibrium profits of members of supply chain network are shown in Table 3. The total profit is 3082.77. Manufacturers have most of them. Retailer 6 is not chosen. Retailer 3, 7, and 10 have negtive profit due to perfect competition.

Furthermore, the rationale of the proposed variational inequalities model and associated solution algorithm can be verified by checking if the resulting total costs of supply path satisfy the network equilibrium conditions, i.e. Eqs. (18) and (20). The check results of equilibrium condition (18) are listed in Table 4. At time period 3, products are only distributed to Retailer 1, 4, and 8. Too lower prices make no product distributed to those retailer markets. The computed equilibrium customers' demand is equal to the product quality delivered from all distributors. For example, the total amount of products is 8.06 which are delivered from distributor 1 and 2, as shown in Table 2.

| time period | | *t*=1 | *t*=2 | *t*=3 | *t*=4 | *t*=5 |
|---|---|---|---|---|---|---|
| product quantity produced by manufacturer *i* at time period *e* and distributed to distributor *j* at time period *t* | 1->1 | *e*=1 3.48 | *e*=1 1.76<br>*e*=2 6.48 | *e*=1 0.00<br>*e*=2 0.00<br>*e*=3 5.38 | - | - |
| | 1->2 | *e*=1 3.48 | *e*=1 1.76<br>*e*=2 6.48 | *e*=1 0.00<br>*e*=2 0.00<br>*e*=3 5.38 | - | - |
| | 2->1 | *e*=1 3.48 | *e*=1 1.76<br>*e*=2 6.48 | *e*=1 0.00<br>*e*=2 0.00<br>*e*=3 5.38 | - | - |
| | 2->2 | *e*=1 3.48 | *e*=1 1.76<br>*e*=2 6.48 | *e*=1 0.00<br>*e*=2 0.00<br>*e*=3 5.38 | - | - |
| product quantity distributed from manufacturer *i* to distributor *j* at time period *t* | 1->1 | 3.48 | 8.24 | 5.38 | - | - |
| | 1->2 | 3.48 | 8.24 | 5.38 | - | - |
| | 2->1 | 3.48 | 8.24 | 5.38 | - | - |
| | 2->2 | 3.48 | 8.24 | 5.38 | - | - |
| product quantity distributed from distributor *j* to retailer *k* at time interval *t* | 1->1 | - | 4.03 | 2.02 | 0.00 | - |
| | 1->2 | - | 0.00 | 4.07 | 0.00 | - |
| | 1->3 | - | 0.00 | 0.00 | 0.70 | - |
| | 1->4 | - | 0.96 | 7.14 | 0.00 | - |
| | 1->5 | - | 0.00 | 0.00 | 6.86 | - |
| | 1->6 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->7 | - | 0.00 | 0.00 | 0.96 | - |
| | 1->8 | - | 1.98 | 0.00 | 0.00 | - |
| | 1->9 | - | 0.00 | 2.27 | 2.24 | - |
| | 1->10 | - | 0.00 | 0.99 | 0.00 | - |
| | 2->1 | - | 4.03 | 2.02 | 0.00 | - |
| | 2->2 | - | 0.00 | 4.07 | 0.00 | - |
| | 2->3 | - | 0.00 | 0.00 | 0.70 | - |
| | 2->4 | - | 0.96 | 7.14 | 0.00 | - |
| | 2->5 | - | 0.00 | 0.00 | 6.86 | - |
| | 2->6 | - | 0.00 | 0.00 | 0.00 | - |
| | 2->7 | - | 0.00 | 0.00 | 0.96 | - |
| | 2->8 | - | 1.98 | 0.00 | 0.00 | - |
| | 2->9 | - | 0.00 | 2.27 | 2.24 | - |
| | 2->10 | - | 0.00 | 0.99 | 0.00 | - |

| time period | | *t*=1 | *t*=2 | *t*=3 | *t*=4 | *t*=5 |
|---|---|---|---|---|---|---|
| product quantity of customers of retailer *k* | 1 | - | - | 8.06 | 0.00 | 0.00 |
| | 2 | - | - | 1.91 | 0.00 | 0.00 |
| | 3 | - | - | 0.00 | 3.96 | 0.00 |
| | 4 | - | - | 0.00 | 4.03 | 8.13 |
| | 5 | - | - | 0.00 | 14.29 | 0.00 |
| | 6 | - | - | 0.00 | 0.00 | 0.00 |
| | 7 | - | - | 4.54 | 1.98 | 0.00 |
| | 8 | - | - | 0.00 | 1.41 | 0.00 |
| | 9 | - | - | 13.72 | 0.00 | 1.92 |
| | 10 | - | - | 0.00 | 4.49 | 0.00 |
| price of manufacturer *i* for distributor *j* | 1->1 | 71.97 | 91.49 | 75.47 | - | - |
| | 1->2 | 71.97 | 91.49 | 75.47 | - | - |
| | 2->1 | 71.97 | 91.49 | 75.47 | - | - |
| | 2->2 | 71.97 | 91.49 | 75.47 | - | - |
| price of distributor *j* | 1 | - | 78.94 | 109.98 | 86.24 | - |
| | 2 | - | 78.94 | 109.98 | 86.24 | - |
| price of retailer *k* | 1 | - | - | 87.97 | 114.99 | 58.47 |
| | 2 | - | - | 61.69 | 117.04 | 82.68 |
| | 3 | - | - | 54.84 | 91.85 | 91.94 |
| | 4 | - | - | 84.89 | 120.12 | 81.63 |
| | 5 | - | - | 44.84 | 96.59 | 98.10 |
| | 6 | - | - | 56.95 | 81.85 | 90.42 |
| | 7 | - | - | 70.11 | 98.17 | 92.20 |
| | 8 | - | - | 85.92 | 85.01 | 88.47 |
| | 9 | - | - | 78.53 | 115.25 | 93.48 |
| | 10 | - | - | 72.21 | 113.97 | 71.63 |

Table 2. Equilibrated solution of supply chain network

| member | equilibrated solution |
|---|---|
| manufacturer *1, 2* | 1094.03 |
| distributor *1, 2* | 218.13 |
| retailer *1* | 69.02 |
| retailer *2* | 55.61 |
| retailer *3* | -3.38 |
| retailer *4* | 148.68 |
| retailer *5* | 138.93 |
| retailer *6* | - |
| retailer *7* | -0.47 |
| retailer *8* | 13.69 |
| retailer *9* | 36.49 |
| retailer *10* | -0.12 |
| total profit | 3082.77 |

Table 3. Profits of members of the supply chain (equilibrated solution)

The check results of equilibrium condition (20) are summarized in Table 5 ~ Table 7. The equilibrated supply path cost is obtained by summing all relative costs along the path. For example, consider supply path *M1'*→*M1*→D1→R4 producing and sending at time period 1, the total cost is 84.89.

$$\hat{c}_{M1'\to M1\to D1\to R4}(1,1)=\frac{\partial f_1(1)}{\partial q_1(1,1)}+\frac{ds_{11}(1)}{dq_{11}(1)}+\frac{\partial m_1(2)}{\partial q_{11}(1)}+s_{14}(2)=64.98+6.98+6.97+5.96=84.89 \quad (52)$$

It is observed that the total costs of each supply path arriving at the same retailer and time period are equal to the corresponding retailer's price. For example, there are four supply paths to Retailer 4 and they arrive at the time period 3. Their total costs are 84.89. There are eight supply paths to Retailer 1 and they arrive at the time period 4. Half of them are manufactured at time period 1, but delivered to distributors till time period 2. Incured inventory costs are counted. Total costs of eight supply paths are the same and equal to the coressponding retailer price, as shown in Table 6.

| retailer | *t* = 3 | | | *t* = 4 | | | *t* = 5 | | |
|---|---|---|---|---|---|---|---|---|---|
| | price | demand | distibuted amount | price | demand | distibuted amount | price | demand | distibuted amount |
| 1 | 87.97(1) | 8.06 | 8.06 | 114.99(4) | 4.03 | 4.03 | 58.47 | 0.00 | 0.00 |
| 2 | 61.69 | 0.00 | 0.00 | 117.04(2) | 8.13 | 8.13 | 82.68 | 0.00 | 0.00 |
| 3 | 54.84 | 0.00 | 0.00 | 91.85 | 0.00 | 0.00 | 91.94(4) | 1.41 | 1.41 |
| 4 | 84.89(3) | 1.91 | 1.91 | 120.12(1) | 14.29 | 14.29 | 81.63 | 0.00 | 0.00 |
| 5 | 44.84 | 0.00 | 0.00 | 96.59 | 0.00 | 0.00 | 98.10(1) | 13.72 | 13.72 |
| 6 | 56.95 | 0.00 | 0.00 | 81.85 | 0.00 | 0.00 | 90.42 | 0.00 | 0.00 |
| 7 | 70.11 | 0.00 | 0.00 | 98.17 | 0.00 | 0.00 | 92.20(3) | 1.92 | 1.92 |
| 8 | 85.92(2) | 3.96 | 3.96 | 85.01 | 0.00 | 0.00 | 88.47 | 0.00 | 0.00 |
| 9 | 78.53 | 0.00 | 0.00 | 115.25(3) | 4.54 | 4.54 | 93.48(2) | 4.49 | 4.49 |
| 10 | 72.21 | 0.00 | 0.00 | 113.97(5) | 1.98 | 1.98 | 71.63 | 0.00 | 0.00 |

Table 4. Check results of equilibrium condition (18)

| path | *e* = 1, *t* = 1 | path | *e* = 1, *t* = 1 | path | *e* = 1, *t* = 1 |
|---|---|---|---|---|---|
| M1-D1-R1 | 87.97 | M1-D1-R4 | 84.89 | M1-D1-R8 | 85.92 |
| M1-D2-R1 | 87.97 | M1-D2-R4 | 84.89 | M1-D2-R8 | 85.92 |
| M2-D1-R1 | 87.97 | M2-D1-R4 | 84.89 | M2-D1-R8 | 85.92 |
| M2-D2-R1 | 87.97 | M2-D2-R4 | 84.89 | M2-D2-R8 | 85.92 |
| price of R1 | 87.97 | price of R4 | 84.89 | price of R8 | 85.92 |

Table 5. Check results of equilibrium condition (20) -- supply path costs (arrival at *t* = 3)

| path | $e$ = 1, $t$ =2 | $e$ = 2, $t$ = 2 | path | $e$ = 1, $t$ =2 | $e$ = 2, $t$ = 2 |
|---|---|---|---|---|---|
| M1-D1-R1 | 114.99 | 114.99 | M1-D1-R2 | 117.04 | 117.04 |
| M1-D2-R1 | 114.99 | 114.99 | M1-D2-R2 | 117.04 | 117.04 |
| M2-D1-R1 | 114.99 | 114.99 | M2-D1-R2 | 117.04 | 117.04 |
| M2-D2-R1 | 114.99 | 114.99 | M2-D2-R2 | 117.04 | 117.04 |
| price of R1 | 114.99 | | price of R2 | 117.04 | |
| path | $e$ = 1, $t$ =2 | $e$ = 2, $t$ = 2 | path | $e$ = 1, $t$ =2 | $e$ = 2, $t$ = 2 |
| M1-D1-R4 | 120.12 | 120.12 | M1-D1-R9 | 115.25 | 115.25 |
| M1-D2-R4 | 120.12 | 120.12 | M1-D2-R9 | 115.25 | 115.25 |
| M2-D1-R4 | 120.12 | 120.12 | M2-D1-R9 | 115.25 | 115.25 |
| M2-D2-R4 | 120.12 | 120.12 | M2-D2-R9 | 115.25 | 115.25 |
| price of R4 | 120.12 | | price of R9 | 115.25 | |
| path | $e$ = 1, $t$ =2 | $e$ = 2, $t$ = 2 | | | |
| M1-D1-R10 | 113.97 | 113.97 | | | |
| M1-D2-R10 | 113.97 | 113.97 | | | |
| M2-D1-R10 | 113.97 | 113.97 | | | |
| M2-D2-R10 | 113.97 | 113.97 | | | |
| price of R10 | 113.97 | | | | |

Table 6. Check results of equilibrium condition (20) -- supply path costs (arrival at $t$ = 4)

| path | $e$ = 3, $t$ =3 | path | $e$ = 3, $t$ =3 |
|---|---|---|---|
| M1-D1-R3 | 91.94 | M1-D1-R5 | 98.10 |
| M1-D2-R3 | 91.94 | M1-D2-R5 | 98.10 |
| M2-D1-R3 | 91.94 | M2-D1-R5 | 98.10 |
| M2-D2-R3 | 91.94 | M2-D2-R5 | 98.10 |
| price of R3 | 91.94 | price of R5 | 98.10 |
| path | $e$ = 3, $t$ =3 | path | $e$ = 3, $t$ =3 |
| M1-D1-R7 | 92.20 | M1-D1-R9 | 93.48 |
| M1-D2-R7 | 92.20 | M1-D2-R9 | 93.48 |
| M2-D1-R7 | 92.20 | M2-D1-R9 | 93.48 |
| M2-D2-R7 | 92.20 | M2-D2-R9 | 93.48 |
| price of R7 | 92.20 | price of R9 | 93.48 |

Table 7. Check results of equilibrium condition (20) -- supply path costs (arrival at $t$ = 5)

### 4.2.2 A compromise solution

Subsequently, the following nonlinear programming model is adopted to determine the maximal total profit of the centralized supply chain network.

$$\max \;\; \pi = \sum_{kt} \rho_k^3(t) d_k(t) - \sum_{jkt} s_{jk}(t) - \sum_{jt} m_j(t) \; - \sum_{ie} f_i(e) - \sum_{it} h_i(t) - \sum_{ijt} s_{ij}(t) \tag{53}$$

subject to: (2)~(5) for all $i$, (9)~(12) for all $j$, (28), and (36).

The LINGO 10.0 package was used to solve this model. The maximum total profit of the centralized supply chain network is 3171.81. Consequently, the increment of total profits is 89.04, compared with equilibrium profits for members of the supply chain network. Let all members of the supply chain network share the increment.

After obtaining the above data, the LINGO 10.0 package was used to solve the proposed revenue sharing compromise model for supply chain integration. Sharing rates of retail revenues for retailer *k* and sharing rates of wholesale revenues for distributor *j* are summarized in Table 8 and Table 9 respectively. The sharing rate of retail revenue for retailer *1* and retailer *10* is 77.44% and 25.12% respectively. Other retailers do not have to share their revenues with and distributors. In addition, the sharing rate of wholesale revenues for distributor *1* transacted with retailer 1 is 100% and the sharing rate of wholesale revenues for distributor *2* transacted with retailer 1 is 76.85%. Other distributors do not have to share their revenues with manufacturers. The compromise flow patterns and selling prices are shown in Table 10.

The solving results of the market equilibrium model and revenue sharing model are compared and the profits for members of the supply chain network between the equilibrium solution and the compromise solution are listed in Table 11. The total profit of the compromise solution is equal to 3171.81; that is the same as the counterpart of the centralized supply chain network.

The comparisons of retail prices and customers' demands are summarized in Table 12. Most of the retail prices of the compromise solution are greater than the counterpart of the equilibrated solution. But the market transaction volume of the compromise solution is less than the market transaction volume under market competition condition but the individual and the aggregate profits will be greater than the profits under market competition model. In other words, such an integration strategy is workable for all members within the supply chain. Parts of customers' surplus are transferred to the members of the supply chain network. Therefore, using the proposed revenue sharing model can indeed create win-win situation for all members within the supply chain.

| retailer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 77.44% | 0.00% | 0.00% | 0.00% | 0.00% | - | 0.00% | 0.00% | 0.00% | 25.12% |

Table 8. Sharing rates of retail revenue for retailers

| distributor | retailer | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | 100.00% | 0.00% | 0.00% | 0.00% | 0.00% | - | 0.00% | 0.00% | 0.00% | 0.00% |
| 2 | 76.85% | 0.00% | 0.00% | 0.00% | 0.00% | - | 0.00% | 0.00% | 0.00% | 0.00% |

Table 9. Sharing rates of wholesale revenue for distributors

| time period | | $t$=1 | $t$=2 | $t$=3 | $t$=4 | $t$=5 |
|---|---|---|---|---|---|---|
| product quantity produced by manufacturer $i$ at time period $e$ and distributed to distributor $j$ at time period $t$ | 1->1 | $e$=1 0.00 | $e$=1 0.00<br>$e$=2 0.00 | $e$=1 0.00<br>$e$=2 0.00<br>$e$=3 13.61 | - | - |
| | 1->2 | $e$=1 0.00 | $e$=1 0.00<br>$e$=2 1.62 | $e$=1 0.00<br>$e$=2 0.00<br>$e$=3 0.51 | - | - |
| | 2->1 | $e$=1 0.00 | $e$=1 0.00<br>$e$=2 0.33 | $e$=1 0.00<br>$e$=2 0.00<br>$e$=3 0.00 | - | - |
| | 2->2 | $e$=1 18.06 | $e$=1 0.00<br>$e$=2 14.09 | $e$=1 0.00<br>$e$=2 0.00<br>$e$=3 1.01 | - | - |
| product quantity distributed from manufacturer $i$ to distributor $j$ at time period $t$ | 1->1 | 0.00 | 0.00 | 13.61 | - | - |
| | 1->2 | 0.00 | 1.62 | 0.51 | - | - |
| | 2->1 | 0.00 | 0.33 | 0.00 | - | - |
| | 2->2 | 18.06 | 14.09 | 1.01 | - | - |
| product quantity distributed from distributor $j$ to retailer $k$ at time interval $t$ | 1->1 | - | 0.00 | 0.33 | 12.96 | - |
| | 1->2 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->3 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->4 | - | 0.00 | 0.00 | 0.09 | - |
| | 1->5 | - | 0.00 | 0.00 | 0.57 | - |
| | 1->6 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->7 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->8 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->9 | - | 0.00 | 0.00 | 0.00 | - |
| | 1->10 | - | 0.00 | 0.00 | 0.00 | - |
| | 2->1 | - | 11.93 | 3.30 | 1.52 | - |
| | 2->2 | - | 1.08 | 0.00 | 0.00 | - |
| | 2->3 | - | 0.00 | 0.00 | 0.00 | - |
| | 2->4 | - | 1.87 | 0.00 | 0.00 | - |
| | 2->5 | - | 2.12 | 0.00 | 0.00 | - |
| | 2->6 | - | 0.00 | 0.00 | 0.00 | - |
| | 2->7 | - | 0.16 | 0.00 | 0.00 | - |
| | 2->8 | - | 0.29 | 0.00 | 0.00 | - |
| | 2->9 | - | 0.61 | 0.00 | 0.00 | - |
| | 2->10 | - | 0.00 | 12.41 | 0.00 | - |
| product quantity of customers of retailer $k$ | 1 | - | - | 11.93 | 3.63 | 14.47 |
| | 2 | - | - | 1.08 | 0.00 | 0.00 |
| | 3 | - | - | 0.00 | 0.00 | 0.09 |
| | 4 | - | - | 1.87 | 0.00 | 0.00 |
| | 5 | - | - | 2.12 | 0.00 | 0.57 |

| time period | | t=1 | t=2 | t=3 | t=4 | t=5 |
|---|---|---|---|---|---|---|
| | 6 | - | - | 0.00 | 0.00 | 0.00 |
| | 7 | - | - | 0.16 | 0.00 | 0.00 |
| | 8 | - | - | 0.29 | 0.00 | 0.00 |
| | 9 | - | - | 0.61 | 0.00 | 0.00 |
| | 10 | - | - | 0.00 | 12.41 | 0.00 |
| price of manufacturer *i* for distributor *j* | 1->1 | 4.71 | 85.78 | 0.00 | - | - |
| | 1->2 | 0.00 | 62.66 | 53.96 | - | - |
| | 2->1 | 45.84 | 86.96 | 0.00 | - | - |
| | 2->2 | 0.00 | 81.23 | 53.96 | - | - |
| price of distributor *j* | 1 | - | 45.84 | 87.61 | 0.00 | - |
| | 2 | - | 0.00 | 81.23 | 53.96 | - |
| price of retailer *k* | 1 | - | - | 88.05 | 117.81 | 53.96 |
| | 2 | - | - | 63.23 | 123.93 | 85.79 |
| | 3 | - | - | 56.96 | 94.46 | 95.74 |
| | 4 | - | - | 87.03 | 130.25 | 84.74 |
| | 5 | - | - | 45.84 | 99.19 | 108.13 |
| | 6 | - | - | - | - | - |
| | 7 | - | - | 72.13 | 100.77 | 96.32 |
| | 8 | - | - | 89.96 | 87.61 | 91.58 |
| | 9 | - | - | 80.32 | 120.25 | 98.95 |
| | 10 | - | - | 74.32 | 111.08 | 74.74 |

Table 10. Compromise solution of supply chain network integration

| member | equilibrated solution | compromise solution | increment |
|---|---|---|---|
| manufacturer *1* | 1094.03 | 1100.88 | 6.85 |
| manufacturer *2* | 1094.03 | 1100.88 | 6.85 |
| distributor *1* | 218.13 | 224.98 | 6.85 |
| distributor *2* | 218.13 | 224.98 | 6.85 |
| retailer *1* | 69.02 | 75.87 | 6.85 |
| retailer *2* | 55.61 | 62.46 | 6.85 |
| retailer *3* | -3.38 | 3.47 | 6.85 |
| retailer *4* | 148.68 | 155.53 | 6.85 |
| retailer *5* | 138.93 | 145.78 | 6.85 |
| retailer *6* | - | - | - |
| retailer *7* | -0.47 | 6.38 | 6.85 |
| retailer *8* | 13.69 | 20.54 | 6.85 |
| retailer *9* | 36.49 | 43.34 | 6.85 |
| retailer *10* | -0.12 | 6.73 | 6.85 |
| total profit | 3082.77 | 3171.81 | 89.04 |

Table 11. Comparisons of profits for members of the supply chain network

It is also found that if the manufacturers and distributors sell their products to the downstream buyers at lower prices, when the distributors share parts of their revenue with the manufacturers and the retailers share parts of their revenue with the distributors, higher profits for the manufacturers, distributors, and retailers can be achieved. For example, at time period 1, distributor 2 gets free products from manufacturer 2. Most of them are sold to retailer 1 at the free price but they are sold to the customer market at the second highest price of the time period 3. Consequently, retailer 1 are asked to share 77.44% of retail revenue to distributor 2, but distributor 2 only can have 23.15% of shared retail revenue and the other 76.85% should be shared to manufacturer 2. In addition, distributor 2 must share 76.85% of wholesale revenue to manufacturer 2.

| time period | retailer | equilibrated solution | | compromise solution | |
|---|---|---|---|---|---|
| | | price | demand | price | demand |
| $t$ = 3 | 1 | 87.97 | 8.06 | 88.05 | 11.93 |
| | 2 | 61.69 | - | 63.23 | 1.08 |
| | 3 | 54.84 | - | 56.96 | - |
| | 4 | 84.89 | 1.91 | 87.03 | 1.87 |
| | 5 | 44.84 | - | 45.84 | 2.12 |
| | 6 | - | - | - | - |
| | 7 | 70.11 | - | 72.13 | 0.16 |
| | 8 | 85.92 | 3.96 | 89.96 | 0.29 |
| | 9 | 78.53 | - | 80.32 | 0.61 |
| | 10 | 72.21 | - | 74.32 | - |
| $t$ = 4 | 1 | 114.99 | 4.03 | 117.81 | 3.63 |
| | 2 | 117.04 | 8.13 | 123.93 | - |
| | 3 | 91.85 | - | 94.46 | - |
| | 4 | 120.12 | 14.29 | 130.25 | - |
| | 5 | 96.59 | - | 99.19 | - |
| | 6 | - | - | - | - |
| | 7 | 98.17 | - | 100.77 | - |
| | 8 | 85.01 | - | 87.61 | - |
| | 9 | 115.25 | 4.54 | 120.25 | - |
| | 10 | 113.97 | 1.98 | 111.08 | 12.41 |
| $t$ = 5 | 1 | 58.47 | - | 53.96 | 14.47 |
| | 2 | 82.68 | - | 85.79 | - |
| | 3 | 91.94 | 1.41 | 95.74 | 0.09 |
| | 4 | 81.63 | - | 84.74 | - |
| | 5 | 98.10 | 13.72 | 108.13 | 0.57 |
| | 6 | - | - | - | - |
| | 7 | 92.20 | 1.92 | 96.32 | - |
| | 8 | 88.47 | - | 91.58 | - |
| | 9 | 93.48 | 4.49 | 98.95 | - |
| | 10 | 71.63 | - | 74.74 | - |
| total | | - | 68.44 | - | 49.22 |

Table 12. Comparisons of retail prices and customers' demands

## 5. Conclusion

The proposed compromise programming model can determine the selling price and revenue sharing ratios among the members of the supply chain and increase the profits for manufacturers, distributors and retailers, simultaneously. The supply chain network is successfully coordinated by adopting the revenue sharing contract. The results of the supply chain network equilibrium model provide the compromise benchmarks for the supply chain network integration. This idea can be applied to explore the issue of supply chain integration by using other other negotiating coordination contracts of supply chain network. Note that developing path-based algorithms is helpful in solving the medium and large size problems, in order to increase the practicability of the proposed variational inequality model.

## 6. References


Atkinson, A. A. (1979). Incentives Uncertainty and Risk in the Newsboy Problem. *Decision Sciences*, Vol. 10, pp. 341-353.

Cachon, G. P. and Lariviere, M. A. (2001). Contracting To Atsure Supply: How to Share Demand Forecasts in a Supply Chain. *Management Science*, Vol. 47, No. 5, pp. 629-646.

Cachon, G. P. and Lariviere, M. A. (2005). Supply Chain Coordination with Revenue-Sharing Contracts: Strengths and Limitations. *Management Science*, Vol. 51, No. 1, pp. 30-44.

Chang, M.-S. and Hsueh, C.-F. (2006). A Multiple-Period Three-Tier Supply Chain Network Integration Based on Revenue Sharing Contract, *The 4th International Conference on Supply Chain Management and Information Systems*, Taichung, Taiwan.

Chang, M.-S. and Hsueh, C.-F. (2007). An Approach for Integration of a Decentralized Supply Chain Network Based on Network Equilibrium Analysis and Multiple Objectives Programming, *The 2007 International Conference and Annual Meeting of Chinese Institute of Transportation*, Taipei, Taiwan.

Chen, H. K. (1999). *Dynamic Travel Choice Models: A Variational Inequality Approach.* Springer-Verlag, Berlin.

Dolan, R. J. (1987). Quantity Discounts: Managerial Issues and Research Opportunities. *Marketing Science*, Vol. 6, pp. 1-27.

Emmons, H. and Gilbert, S. M. (1987). Note: The Role of Returns Policies in Pricing and Inventory Decisions for Catalogue Goods. *Management Science*, Vol. 44, pp. 276-283.

Giannoccaro, I. and Pontrandolfo, P. (2004). Supply Chain Coordination by Revenue Sharing Contracts. *International Journal of Production Economics*, Vol. 89, pp. 131-139.

Jeuland, A. and Shugan, S. (1983). Managing Channel Profits. *Marketing Science*, Vol. 2, pp. 239-272.

Kandel, E. (1996). The Right to Return. *Journal of Law and Economics*, Vol. 39, pp. 329-356.

Moinzadeh, K. and Bassok, Y. (1998). *An Inventory/Distribution Model with Information Sharing between the Buyer and the Supplier*, School of Business Administration, University of Washington.

Nash, J. F. (1950). Equilibrium Points in N-Person Games. *Proceedings of the National Academy of Sciences*, Vol. 36, pp.48-49, USA.

Nash, J. F. (1951). Noncooperative Games. *Annals of Mathematics*, Vol. 54, pp. 286-298.

Pasternack, B. (1985). Optimal Pricing and Returns Policies for Perishable Commodities. *Marketing Science*, Vol. 4, pp. 166-176.

Shah, N., Gjerdrum, J., and Papageorgiou, L. G. (2001). Transfer Prices for Multi-Enterprise Supply Chain Optimization. *Industrial Engineering and Chemistry Research*, Vol. 40, pp. 1650-1660.

Tsay, A. and Lovejoy, W. S. (1999). Quantity Flexibility Contracts and Supply Chain Performances. *Manufacturing and Service Operations Management*, Vol. 1, pp. 89-111.

Tsay, A., Nahmias, S., and Agrawal, N. (1999). Modeling Supply Chain Contracts: A Review. in Tayur, S., Ganeshan, R., Magazine, M. (Eds), *Quantitative Models for Supply Chain Management*, pp. 1339-1358, Kluwer Academic Publishers.

# 18

# The Impact of Demand Information Sharing on the Supply Chain Stability

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## 1. Introduction

Supply chain management (SCM) is defined as a set of approaches utilized to efficiently integrate suppliers, manufacturers, distributors and retailers to make sure that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying customer requirements. As a long-term cooperation strategy among enterprises, supply chain requires stable operations as necessary conditions for optimization and long-term competitive advantage of the whole supply chain. Stability, therefore, becomes an important indicator in supply chain management.

Research on supply chain stability began in early 1960s. Based on system dynamics method, Forrester（1961） proves the presence and the cause of the bullwhip effect. He indicates that bullwhip effect could be weakened by improving decision-making behavior. From then on, the bullwhip effect and supply chain stability have been studied by many researchers. Most of these studies employed an ordering policy known as the APIOBPCS model (John *et al.*, 1994; Disney and Towill, 2003). APIOBPCS policy is optimal in that, the policy minimizes the variance of the inventory levels with a sequence of forecast errors of demand over the lead time given (Vassian, 1954). In discrete time domain, pure time delays are readily handled by the *z*-transform and many results are known about its stability (Disney and Towill, 2002), variance amplification properties (Disney and Towill, 2003; Disney *et al.*, 2004), and dynamic performance (Dejonckheere *et al.*, 2003). Disney et al. (2006) investigate the stability of a generalized OUT (Order Up To) policy for the step response in both discrete and continuous time. Disney *et al.* (2007) prove that discrete and continuous Bullwhip Effect expressions have similar structures and show that the two domains are managerially equivalent and each domain can be used to study a supply chain in practice.

The pure time delay causes complications in the time domain differential/difference equations. In the frequency domain, such equations generate an infinite number of zeros in the transfer function. Certain progress has been made on the stability of such systems by recasting the policy as a Smith Predictor (Warburton *et al.*, 2004; Riddalls and Bennett, 2002). However, little is known about variance amplification issues or other aspects of the model's dynamic performance. The use of Lambert ω function to solve such problems has recently gained some popularity. Several authors have studied the production and inventory control problem using continuous mathematics; and in the solution process the Lambert ω function is used (Warburton, 2004a, b; Warburton et al., 2004).

Nagatani and Helbing (2004) study several conceivable production strategies to stabilize supply chains. They derive linear stability conditions using simulations for different control strategies. The results indicate that the linear stability analysis is a helpful tool for the judgment of the stabilization effect, although unexpected deviations can occur in the non-linear regime. Lalwani and Disney (2006) outline a framework for developing state space representations of production and inventory control policies from their transfer functions. They focus on the discrete time case and derived state space representations that are both controllable and observable. The state space approach is then used to determine the stability boundary of the production ordering system based on the eigenvalues of the state matrices. Saad *et al.* (2006) reveal the effectiveness of the various decision policies to improve stability under different types of disturbances. Their findings demonstrate the ability of the approach to provide a wealth of potential solutions, and confirm the qualitative behavior of a supply chain in response to the different policies. Strozzi *et al.* (2007) studiy the relationships among bullwhip effect, stability of the supply chain and costs-applied divergence-based control strategy to stabilize the supply chain dynamic with a consequent reduction of the total costs and bullwhip effect. Saee (2008) points out that trend forecasting is often observed to increase instability creating the so-called bullwhip effect when used to assess demand. On the other hand, with reliability to increase stability in controller design, a trend of a tracking variable is used to drive correction. Ouyang (2008) analyzes the bullwhip effect in multi-stage supply chains operated with linear and time-invariant inventory management policies and shared supply chain information. Robust analytical conditions are derived based only on inventory management policies, to predict the presence of the bullwhip effect and bound its magnitude.

The concept of BIBO (bounded input, bounded output) stability is adopted in this study which means if a bounded input is given (e.g., step and impulse), the system produces a bounded output. A stable system will respond to any finite input and return to its initial conditions. An unstable system, however, will respond to a finite input with oscillations of ever increasing magnitude (or explode exponentially without bounds). A critically stable system will result in oscillations about the initial conditions of a constant magnitude (Disney, 2005). In contrast, an unstable system will produce infinite fluctuations in response to the input signal. In this paper, supply chain stability is defined as follows: suppose the supply chain system model has a stable initial state, then the system is stable if order, inventory and work-in-process response could recover equilibrium in a finite time after an appropriate demand disturbance. An unstable system will typically oscillate with ever increasing amplitude between positive and negative infinity. Of course, in a practical situation, the amplitude of the oscillations will be limited by the capacity of the plant (the production facility). A system can also be “critically stable” in that, by setting parameters on the boundary of stability, the system is in a perpetual limit cycle. Both critically stable and unstable systems are clearly inefficient and undesirable from a production/inventory control viewpoint, and thus should be avoided.

## 2. Review of the IOBPCS family

The IOBPCS (Inventory and Order Based Production Control System) family of Decision Support Systems is summarized in Table 1 (Sarimveis, 2007). As can be discovered, different members within the IOBPCS family have either some or all of these generic components. IOBPCS is the basic periodic review algorithm for issuing orders into a supply pipeline, in

| Model | Full Name | Target Inventory | Demand policy | Inventory policy | Pipeline policy |
|---|---|---|---|---|---|
| **IBPCS** | Inventory based production control system | Constant | $G_a(z) = 0$ | $G_i(z) = \frac{1}{T_i}$ | $G_w(z) = 0$ |
| **IOBPCS** | Inventory and order based production control system | Constant | $G_a(z) = \frac{\alpha}{1-(1-\alpha)z^{-1}}$ | $G_i(z) = \frac{1}{T_i}$ | $G_w(z) = 0$ |
| **VIOBPCS** | Variable inventory and order based production control system | Multiple of average market demand | $G_a(z) = \frac{\alpha}{1-(1-\alpha)z^{-1}}$ | $G_i(z) = \frac{1}{T_i}$ | $G_w(z) = 0$ |
| **APIOBPCS** | Automatic pipeline, inventory and order based production control system | Constant | $G_a(z) = \frac{\alpha}{1-(1-\alpha)z^{-1}}$ | $G_i(z) = \frac{1}{T_i}$ | $G_w(z) = \frac{1}{T_w}$ <br> $G_w(z) = T_p$ |
| **APVIOBPCS** | Automatic pipeline, variable inventory and order based production control system | Multiple of average market demand | $G_a(z) = \frac{\alpha}{1-(1-\alpha)z^{-1}}$ | $G_i(z) = \frac{1}{T_i}$ | $G_w(z) = \frac{1}{T_w}$ <br> $G_w(z) = T_p$ |

Table 1. The IOBPCS family

this case based on the current inventory deficit and incoming demand from customers. At regular intervals of time the available system "states" are monitored and used to compute the next set of orders. This system is frequently observed in action in many market sectors. Towill (1982) recasts the problem into a control engineering format with emphasis on predicting dynamic recovery, inventory drift, and noise bandwidth (leading importantly to variance estimations). Edghill and Towill (1989) extended the model, and hence the theoretical analysis, by allowing the target inventory to be a function of observed demand. This Variable Inventory OBPCS is representative of that particular industrial practice where it is necessary to update the "inventory cover" over time. Usually the moving target inventory position is estimated from the forecast demand multiplied by a "cover factor". The latter is a function of pipeline lead-time often with an additional safety factor built in. A later paper by John *et al.* (1994) demonstrates that the addition of a further feedback loop based on orders in the pipeline provided the "missing" third control variable. This Automatic Pipeline IOBPCS model was subsequently optimized in terms of dynamic performance via the use of genetic algorithms, Disney *et al.* (2000).

The lead-time simply represents the time between placing an order and receiving the goods into inventory. It also incorporates a nominal "sequence of events" delay needed to ensure the correct order of events.

The forecasting mechanism is a feed-forward loop within the replenishment policy that should be designed to yield two pieces of information; a forecast of the demand over the lead-time and a forecast of the demand in the period after the lead-time. The more accurate this forecast, the less inventory will be required in the supply chain (Hosoda and Disney, 2005).

The inventory feed-back loop is an error correcting mechanism based on the inventory or net stock levels. As is common practice in the design of mechanical, electronic and aeronautical systems, a proportional controller is incorporated into the inventory feedback loop to shape its dynamic response. It is also possible to use a proportional controller within a (WIP) error correcting feedback loop. This has the advantage of further increasing the levers at the disposal of the systems designer for shaping the dynamic response. In particular the WIP feedback loop allows us to decouple the natural frequency and damping ratio of the system.

## 3. DIS-APIOBPCS model

Based on Towill (1996), Dejonckheere *et al.* (2004) and Ouyang (2008), this paper establishes a Demand Information Sharing (DIS) supply chain dynamic model where customer demand data (e.g., EPOS data) is shared throughout the chain. A two-echelon supply chain consisting of a distributor and a manufacturer is considered here for simplicity.

### 3.1 Assumptions

1. The system is linear, thus all lost sales can be backlogged and excess inventory is returned without cost.
2. No ordering delay. Only production and transportation delay are considered in distributor and manufacturer's lead-time.
3. Events take place in such a sequence in each period: distributor's last-period order is realized, customer demand is observed and satisfied; distributor observes the new inventory level and places an order to manufacturer; manufacturer receives the order.
4. Distributor and manufacturer will operate under the same system parameters for the deduction of mathematical complexity.
5. APIOBPCS is chosen to be adapted as the ordering policy here.

### 3.2 DIS-APIOBPCS description

This paper compares a traditional supply chain, where only the first stage observes consumer demand and upstream stages have to make their forecasts with downstream order information, with a DIS supply chain where customer demand data is shared throughout the chain. Their block diagrams are shown in Figs. 1 and 2. The two scenarios are almost identical except that every stage in the DIS supply chain receives not only an order from the downstream member of the chain, but also the consumer demand information.

This paper uses the APIOBPCS structure as analyzed in depth by John *et al.* (1994), which can be expressed as, "Let the production targets be equal to the sum of an exponentially smoothed (over $T_a$ time units) representation of the perceived demand (that is actually a sum of the stock adjustments at the distributor and the actual sales), plus a fraction ($1/T_i$) of the inventory error in stock, plus a fraction ($1/T_w$) of the WIP error." By suitably adjusting parameters, APIOBPCS can be made to mimic a wide range of industrial ordering scenarios including make-to-stock and make-to-order.

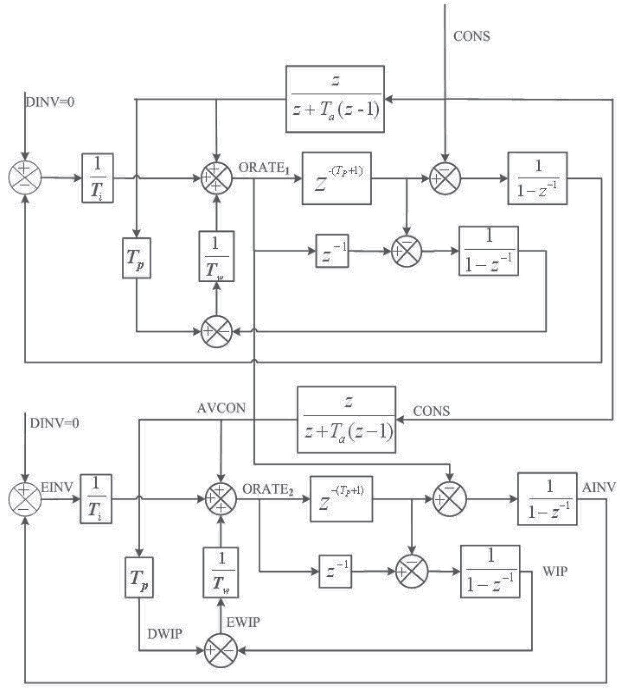



Fig. 1. DIS-APIOBPCS supply chain

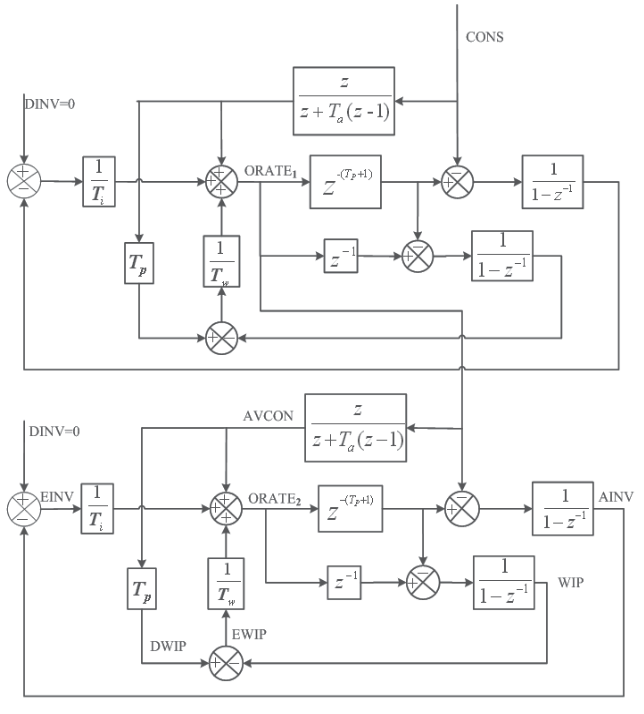



Fig. 2. Traditional supply chain

The following notations are used in this study:
*AINV*: Actual Inventory;
*AVCON*: Average Consumption;
*WIP*: Work in Process;
*COMRATE*: Completion Rate;
*CONS*: Consumption;
*DINV*: Desired Inventory;
*DWIP*: Desired WIP;
*EINV*: Error in Inventory;
*EWIP*: Error in WIP;
*ORATE*: Order Rate.

A demand policy is needed to ensure the production control algorithm to recover inventory levels following changes in demand. In APIOBPCS, this function is realized by smoothing the demand signal with a smoothing constant, $T_a$. The smoothing constant *a* in the *z*-transform can be linked to $T_a$ in the difference equation $\alpha = \frac{1}{1+T_a}$; $T_p$ represents the production delay expressed as a multiple of the sampling interval; $T_w$ is the inverse of *WIP* based production control law gain. The smaller $T_w$ value, the more frequent production rate is adjusted by *WIP* error. $T_i$ is the inverse of inventory based production control law gain. The smaller $T_i$ value, the more frequent production rate is adjusted by *AINV* error. It should be noted that the measurement of parameters should be chosen as the same as the sampling interval. For example, if data are sampled daily, then the production delay should be expressed in days.

### 3.3 Transfer function

In control engineering, the transfer function of a system represents the relationship describing the dynamics of the system under consideration. It algebraically relates a system's output to its input. In this paper, it is defined as the ratio of the z-transform of the output variable to the *z*-transform of the input variable. Since supply chains can be seen as sequential systems with complex interactions among different parts, the transfer function approach can be used to model these interactions. A transfer function can be developed to completely represent the dynamics of any replenishment rule. Input to the system represents the demand pattern and output the corresponding inventory replenishment or production orders.
The transfer functions of DIS-APIOBPCS system for *ORATE/CONS, WIP/CONS* and *AINV/CONS* are shown in Eqs.(1) –(3).

$$\frac{ORATE}{CONS} = \frac{z^{1+T_p}\left[T_i(T_p+T_w)(-1+z)+(z+T_a(z-1))T_w X_1\right]}{\left[T_a(-1+z)+z\right]\left\{T_w+T_i\left[-1+(1+T_w(-1+z))z^{T_p}\right]\right\}} \tag{1}$$

$$X_1 = \frac{z^{1+T_p}\left[-T_aT_w+T_i(T_p+T_w)(-1+z)+(1+T_a)T_w z\right]}{\left[T_a(-1+z)+z\right]\left\{T_w+T_i\left[-1+(1+T_w(-1+z))z^{T_p}\right]\right\}}$$

Here, $X_1$ is the *ORATE/CONS* transfer function of the distributor.

Let $\Omega(z) = \dfrac{ORATE}{CONS}$,

Then,

$$\frac{WIP}{CONS} = \left(\frac{1 - z^{-T_p}}{z - 1}\right) \cdot \Omega(z) \tag{2}$$

$$\frac{AINV}{CONS} = \frac{\Omega(z) \cdot z^{-T_p} - X_1 z}{z - 1} \tag{3}$$

## 4. Stability analysis of DIS-APIOBPCS supply chain

It is particularly important to understand system instability, because in such cases the system response to *any* change in input will result in uncontrollable oscillations with increasing amplitude and apparent chaos in the supply chain. This section establishes a method to determine the limiting condition for stability in terms of the design parameters.

The stability condition for discrete systems is: the root of the system characteristic equation (denominator of closed-loop system transfer function) must be in the unit circle on the $z$ plane. The problem is that the algebraic solutions of these high degree polynomials involve a very complex mathematical expression that typically contains lots of trigonometric functions that need inspection. In such cases, the necessary and sufficient conditions to show whether the roots lie outside the unit circle are not easy to determine. Therefore, the Tustin Transformation is taken to map the $z$-plane problem into the $w$-plane. Then the well-established Routh–Hurwitz stability criterion could be used. The Tustin transform is shown in Eq.(4). This method changes the problem from determining whether the roots lie inside the unit circle to whether they lie on the left-hand side of the $w$-plane.

$$z = \frac{1 + \omega}{1 - \omega} \tag{4}$$

Take $T_a$=2，$T_p$=2 for example, the characteristic equation is showed in Eq.(5) and the $\omega$-plane transfer function now becomes Eq.(6).

$$D(z) = \left[2(z-1) + z\right]\left\{T_w + T_i\left[-1 + (1 + T_w(-1 + z))z^2\right]\right\}^2 = 0 \tag{5}$$

$$T_w\omega^4 + (2T_w + 4T_i + 2T_iT_w)\omega^3 + (16T_i + 14T_iT_w - 12T_w)\omega^2$$

$$+(-20T_i + 14T_w + 22T_iT_w)\omega + (10T_iT_w - 5T_w) = 0 \tag{6}$$

This equation is still not easy to investigate algebraically, but the Routh-Hurwitz stability criterion can now be utilized which does enable a solution in Eq.(7).

When 0.5< $T_i$ <1.618， $\dfrac{T_i(-3 - T_i - \sqrt{9T_i^2 - 2T_i + 1})}{2(T_i^2 - T_i - 1)} < T_w < \dfrac{T_i(-3 - T_i + \sqrt{9T_i^2 - 2T_i + 1})}{2(T_i^2 - T_i - 1)}$

When $T_i$ >1.618, $$T_w > \frac{T_i(-3 - T_i + \sqrt{9T_i^2 - 2T_i + 1})}{2(T_i^2 - T_i - 1)} \tag{7}$$

There is no limit to the value of $T_p$ and $T_a$ for this approach, but these parameters must be given to some certain values for clarity. Thus, the stability conditions of the system under different circumstances are obtained, as shown in Table 2.

| | | |
|---|---|---|
| **$T_a$=1,2** | **$T_p$=1** | $\frac{2T_i}{2T_i+1} < T_w < \frac{-T_i}{T_i-1}$, $0 < T_i < 1$ <br> $T_w > \frac{2T_i}{2T_i+1}$, $T_i > 1$ |
| | **$T_p$=2** | $\frac{T_i(-3-T_i-\sqrt{9T_i^2-2T_i+1})}{2(T_i^2-T_i-1)} < T_w < \frac{T_i(-3-T_i+\sqrt{9T_i^2-2T_i+1})}{2(T_i^2-T_i-1)}$ <br> $0.5 < T_i < 1.618$ <br> $T_w > \frac{T_i(-3-T_i-\sqrt{9T_i^2-2T_i+1})}{2(T_i^2-T_i-1)}$ $T_i > 1.618$ |
| | **$T_p$=3** | $\frac{2T_i}{2T_i+1} < T_w < \frac{T_i(-4T_i-2T^2{}_i+3-\sqrt{8T_i^2-4T_i-16T_i^3+1+16T_i^4})}{2(T_i^3-2T_i^2-T_i+1)}$ <br> $0 < T_i < 2.155$ <br> $T_w > \frac{2T_i}{2T_i+1}$ $T_i > 2.155$ |

Table 2. Stability conditions of the APIOBPCS system

According to control engineering, a system's stability condition only depends on the parameters affecting feedback loop, as Table 2 shows. The stability boundary of DIS-APIOBPCS is determined by $T_p$, $T_i$, and $T_w$, whereas $T_a$ will not change the boundary. It is interesting to note that the D–E line where $T_i = T_w$ (Deziel and Eilon, 1967) always results in a stable system and has other important desirable properties, as also reported in Disney and Towill (2002).

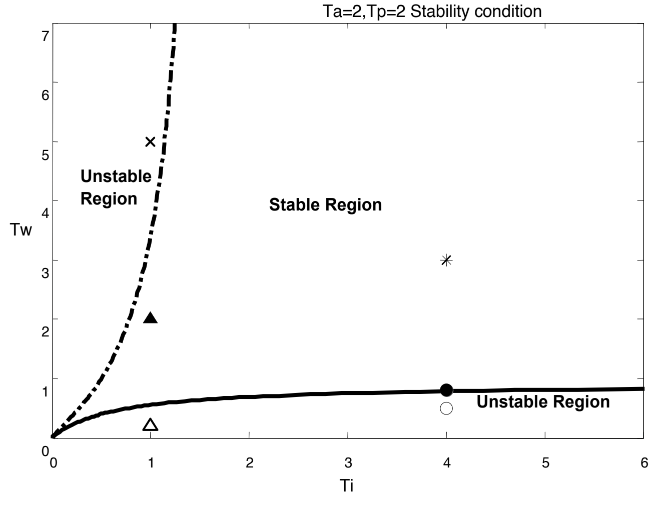
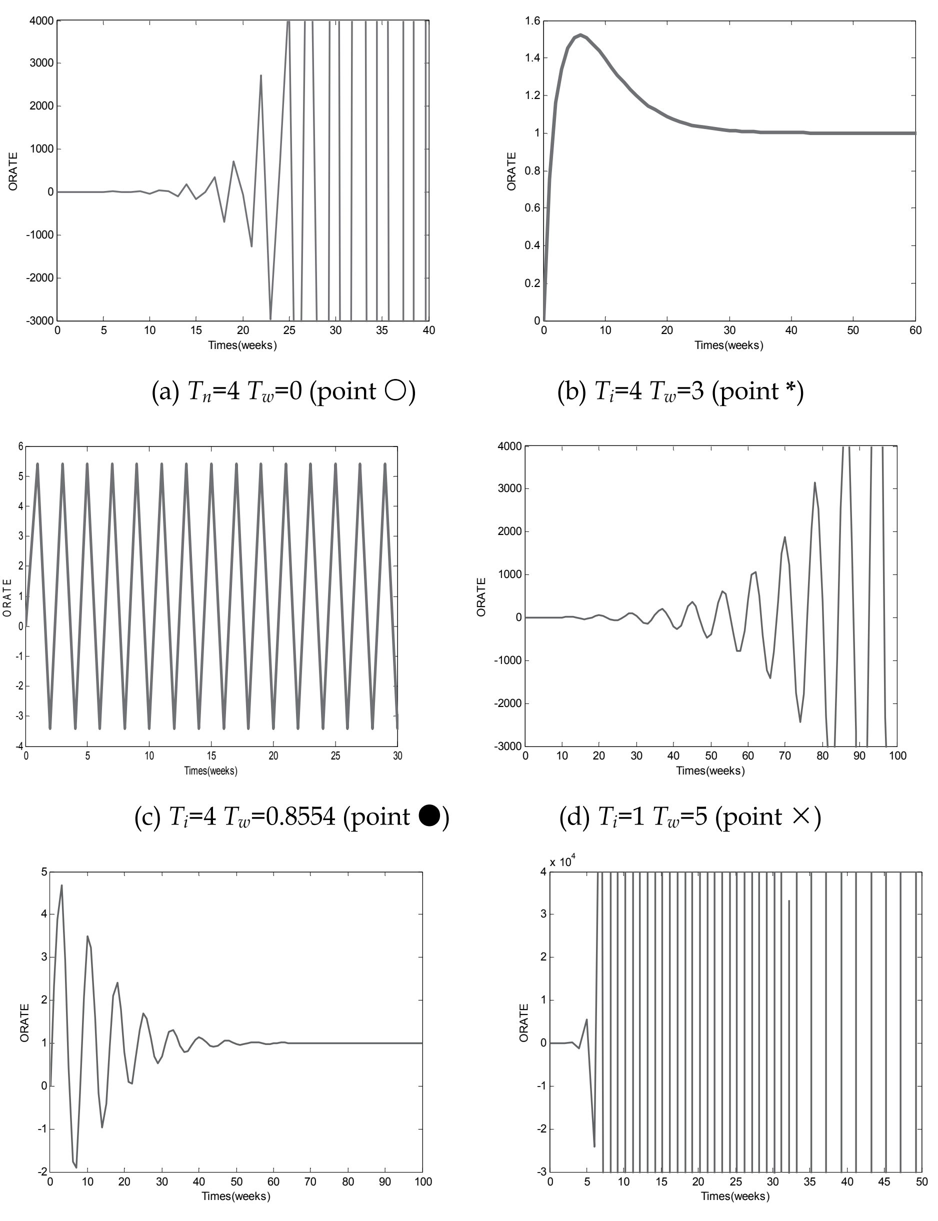



Fig. 3. The stability boundary when $T_a = 2$ and $T_p = 2$

Thus it is important that system designers consider carefully about parameter settings and avoid unstable regions. Given $T_p$=2, the stable region of DIS-APIOBPCS is shown in Figure 3, which also highlights six possible designs to be used as test cases of the stable criteria to a unit step input. For sampled values of $T_w$ and $T_i$, the exact step responses of the DIS-APIOBPCS supply chain are simulated (Fig. 4) for stable; critically stable; and unstable designs.




(a) $T_n$=4 $T_w$=0 (point ○) (b) $T_i$=4 $T_w$=3 (point *)

(c) $T_i$=4 $T_w$=0.8554 (point ●) (d) $T_i$=1 $T_w$=5 (point ×)

(e) $T_i$=1 $T_w$=2 (point ▲) (f) $T_i$=1 $T_w$=0.2 (point △)

Fig. 4. Sampled dynamic responses of DIS-APIOBPCS

These above plots conform the theory by clearly identifying the stable region for DIS-APIOBPCS. The stable region provides supply chain operation a selected range for parameter tuning. In other words, the size of the region reflects the anti-disturbance capability of a supply chain system. As long as $T_i$ and $T_w$ are located in the stability region, the supply chain could ultimately achieve stability regardless the form of the demand information. While the parameters are located outside the stability region however, rather than returning to equilibrium eventually, the system will appear oscillation. In real supply chain systems, this kind of oscillation over production and inventory capacity will inevitably lead system to collapse.

## 5. Dynamic response of DIS-APIOBPCS

Note that having selected stable design parameters, $T_a$, $T_i$, $T_w$ and $T_p$ significantly affect the DIS supply chain response to any particular demand pattern. This section concentrates on the fluctuations of *ORATE*, *AINV* and *WIP* dynamic response. There are various performance measures under different forms of demand information. For demand signals in forms of step and impulse, it is appropriate to use peak value, adjusted time and steady-state error as measures of supply chain dynamic performance. For Gaussian process demand, noise bandwidth will be a better choice. For other forms of demand information, such as cyclical, dramatic and the combinations of the above, which measures should be used still needs further investigation.

### 5.1 Dynamic response of DIS-APIOBPCS under step input

Within supply chain context, the step input to a production/inventory system may be thought of as a genuine change in the mean demand rates (for example, as a result of promotion or price reductions). A system's step response usually provides rich insights when seeking a qualitative understanding of the tradeoffs involved in the ''tuning'' of an ordering policy (Bonney et al., 1994; John et al., 1994; Disney et al., 1997). Such responses provide rich pictures of system behavior. A unit step input is a particularly powerful test signal that control engineers to determine many properties of the system under study. For example, the step is simply the integral of the impulse function, thus understanding the step response automatically allows insight to be gained on the impulse response. This is very useful as all discrete time signals may be decomposed into a series of weighted and delayed impulses.

By simulation, a thorough understanding of the fundamental dynamic properties can be clarified, which characterize the geometry of the step response with the following descriptors.

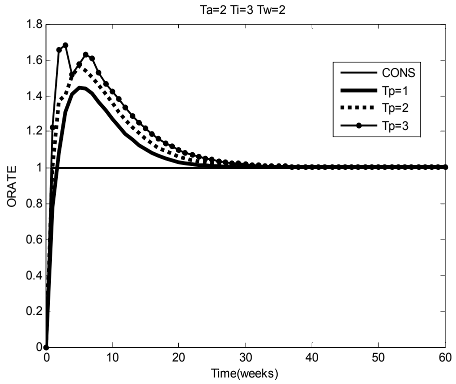
**Peak value:** The maximum response to the unit step demand which reflects response smoothness;

**Adjusted time**: transient time from the introduction of the step input to final value (±5 percent error) which reflect the rapidness of the supply chain response;

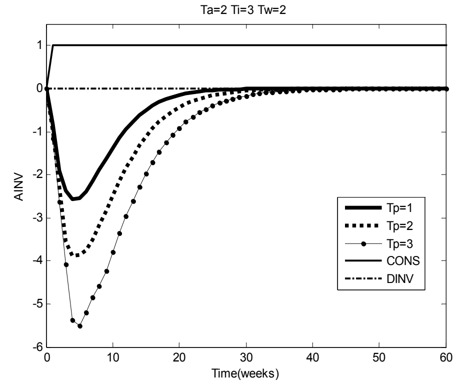
**Steady-state error**: I/O difference after system returns to the equilibrium state, which reflects the accuracy of the supply chain response.

#### 5.1.1 The impact of $T_p$ on DIS-APIOBPCS step response

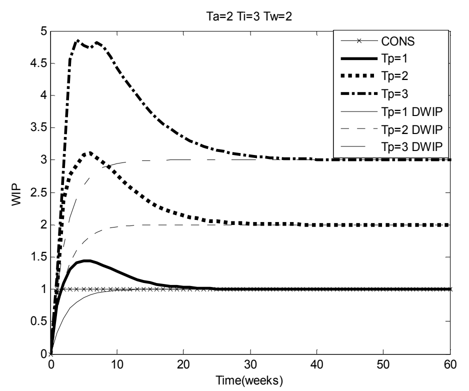
As in real supply chain management environment, $T_p$ is a parameter which is hardly to change frequently and artificially. No matter how $T_p$ is set, the steady-state error of *ORATE*, *AINV* and *WIP* keeps zero. As shown in Figure 5, the smaller $T_p$ value, the smaller peak value and shorter adjusted time. That is to say, when facing an expanding market demand, supply chain members could try to shorten the production lead-time in order to lower required capacity and accelerate response to market changes.




(a) *ORATE*




(b) *AINV*

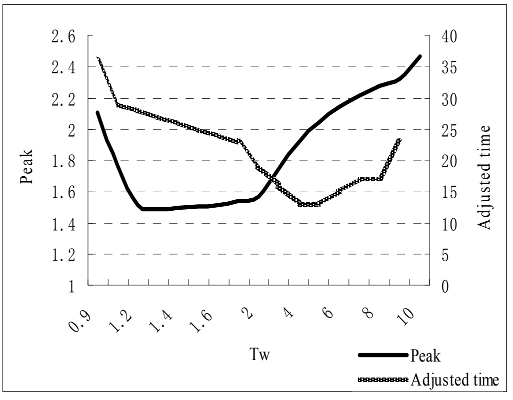



(c) *WIP*

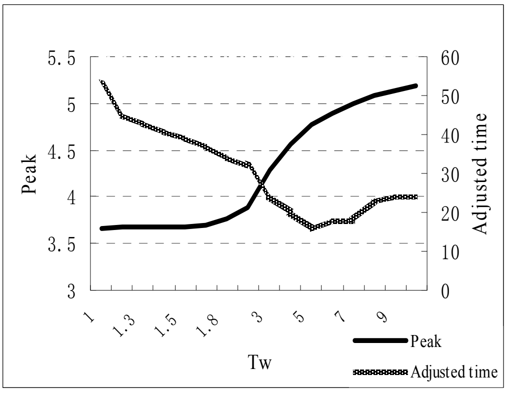
Fig. 5. The impact of $T_p$ on DIS-APIOBPCS step response

#### 5.1.2 The impact of $T_w$ on DIS-APIOBPCS step response

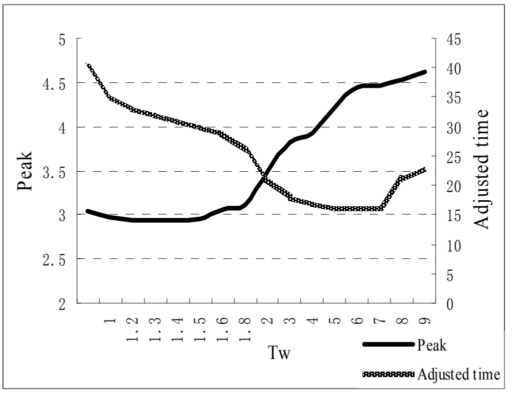
Fig.6 depicts the responses of DIS-APIOBPCS under different $T_w$ settings. It is shown that given other parameters as constant, with $T_w$ increasing, the adjusted time of *ORATE*, *AINV* and *WIP* responses and the peak value of *ORATE* response will first decline and then rise, and the peak value of *AINV* and *WIP* responses will rise, while all the steady-state error will remain zero. This means if the supply chain has a low production or stock capacity, when the market demand is expanded, less proportion of *WIP* should be considered in order quantity determination, to promote the performance and dynamic response of the supply chain.




(a) *ORATE*




(b) *AINV*

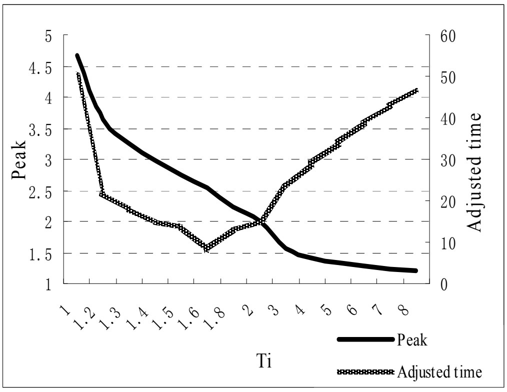



(c) *WIP*

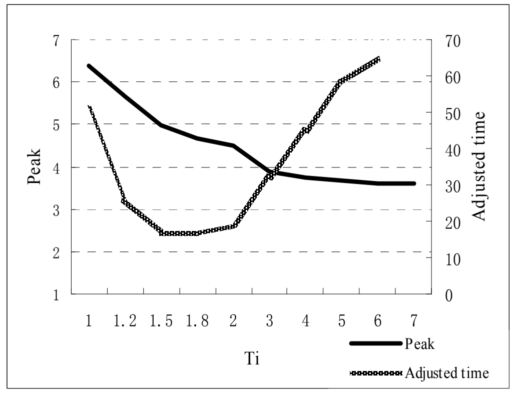
Fig. 6. The impact of $T_w$ on DIS-APIOBPCS step response

### 5.1.3 The impact of $T_i$ on DIS-APIOBPCS step response

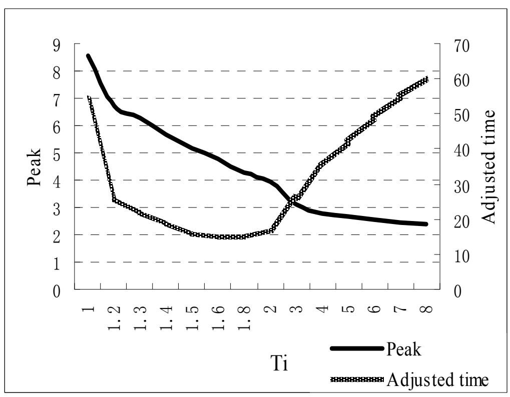
Responses of DIS-APIOBPCS under different $T_i$ settings are shown in Fig.7. With other parameters given, it can be found that the peak value of *ORATE*, *AINV* and *WIP* responses will decline when $T_i$ increase, but the adjusted time follows a U-shaped process, and the steady-state error keeps zero. This phenomenon indicates that when the market demand expands, supply chain members must strike a balance between production, inventory capacity and replenishment capabilities, and make a reasonable decision on inventory adjustment parameter so as to maximize supply chain performance and to maintain long-term and stable capability.




(a) *ORATE*




(b) *AINV*



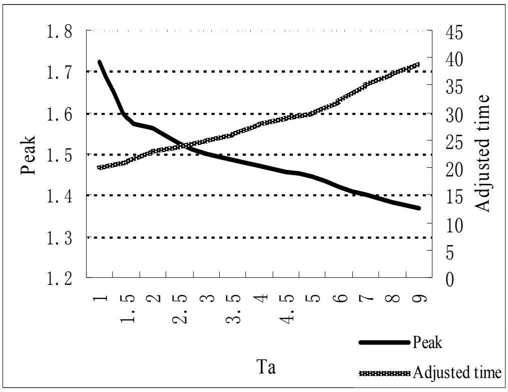

(c) *WIP*

Fig. 7. The impact of $T_i$ on DIS-APIOBPCS step response

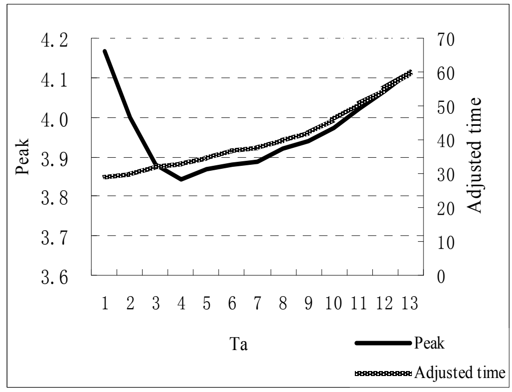
#### 5.1.4 The impact of $T_a$ on DIS-APIOBPCS step response

As shown in Fig.8, increasing $T_a$ is followed by declining peak value of *ORATE* and *WIP* response and rising adjusted time, but the *AINV* peak value will first decline then rise. From the analysis above, it is clear that $T_a$ should be reduced for the purpose of enhancing the rapidness of the supply chain. But if the manager aims at production and inventory smoothness, $T_a$ settings around 3.5 will be a reasonable choice.

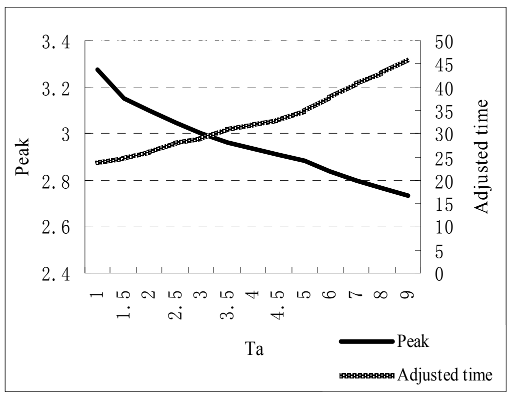
From Section 5.1, it can be concluded that as long as the system parameters are located in the stable region, the steady-state error of dynamic response will keep zero, which means the requirement of response accuracy can always be met, whereas the smoothness and




(a) *ORATE*




(b) *AINV*




(c) *WIP*

Fig. 8. The impact of $T_a$ on DIS-APIOBPCS step response

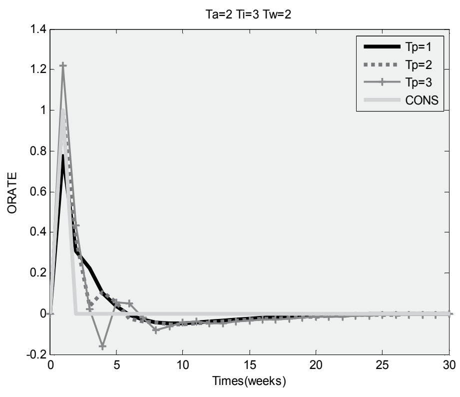
rapidness of dynamic response sometimes have the contradictory requirements on system parameter settings. For instance, the dynamic response of *ORATE*, *AINV* and *WIP* will be all smoother and more rapid by decreasing $T_p$, however, smoothness needs $T_i$ to stay low while rapidness prefers a higher $T_i$ value. The supply chain members should adjust the system parameters integratively for all the objectives of dynamic response so as to improve the overall supply chain performance.

### 5.2 Dynamic response of DIS-APIOBPCS under impulse input

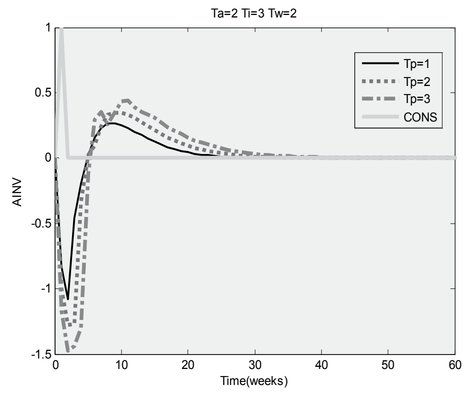
Demand in form of impulse can be seen as a sudden demand in the market. The sudden demand appears frequently because there are a large number of uncertain factors in the market competition environment. Sudden demand will have a serious impact on supply chains, thus enterprises need to restore stability from this sudden change as soon as possible, thereby reducing the volatility of the various negative effects.

#### 5.2.1 The impact of $T_p$ on DIS-APIOBPCS impulse response

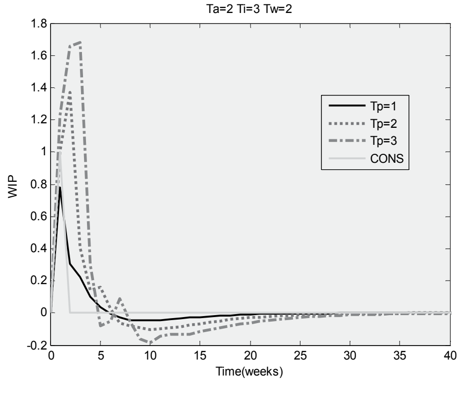
From Fig. 9, it can be seen that no matter how $T_p$ is set, the steady-state error of *ORATE*, *AINV* and *WIP* keep zero. The smaller $T_p$ value, the smaller peak value and shorter adjusted time. That is to say, when facing a sudden market demand, supply chain members could try to shorten the production lead-time in order to restore supply chain stability.




(a) *ORATE*




(b) *AINV*

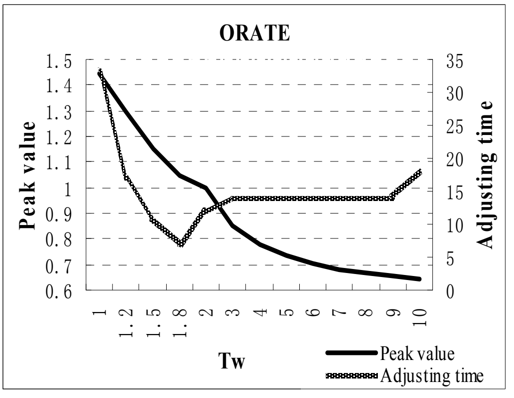



(c) WIP

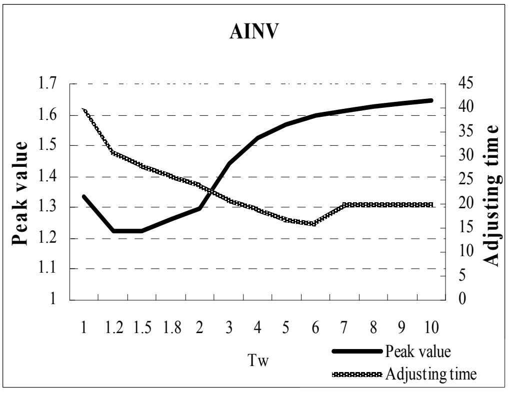
Fig. 9. The impact of $T_p$ on DIS-APIOBPCS impulse response

### 5.2.2 The impact of $T_w$ on DIS-APIOBPCS impulse response

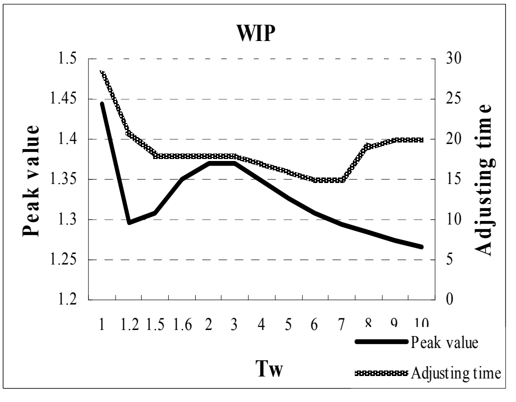
Fig.10 depicts that with other parameters given and the increase of $T_w$, the adjusted time of *ORATE* and *WIP* response will first decline and then rise, the adjusted time of *AINV* response will decline when $T_w$<6 and then rise. The peak value of *ORATE* declines; the peak value of *WIP* will first decline then rise and eventually declines. But with the increase of $T_w$, the peak value of *AINV* response will rise.




(a) *ORATE*




(b) *AINV*

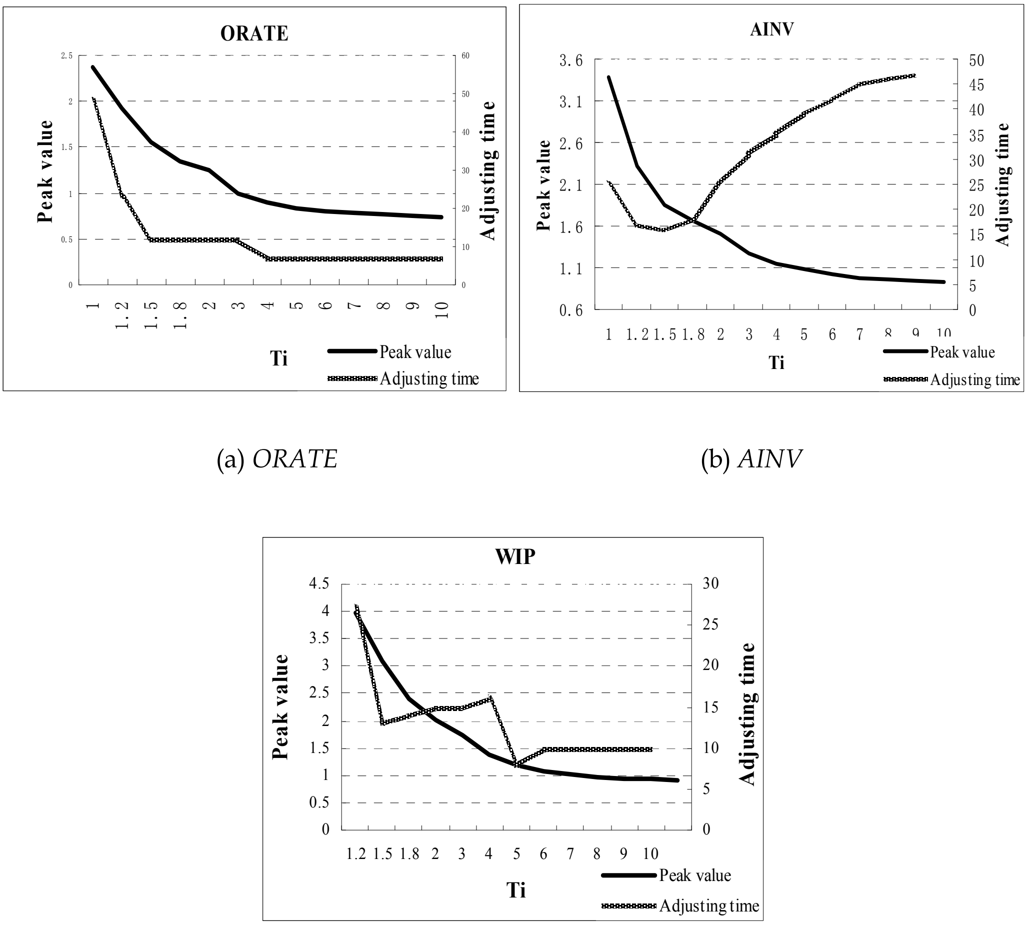



(c) *WIP*

Fig. 10. The impact of $T_w$ on DIS-APIOBPCS impulse response

### 5.2.3 The impact of $T_i$ on DIS-APIOBPCS impulse response

Impulse responses of DIS-APIOBPCS under different $T_i$ are shown in Fig.11. With other parameters given, it can be found that the peak value of *ORATE*, *AINV* and *WIP* response will decline when $T_i$ increases. The adjusted time of *AINV* response follows a process that first decline and then rise; the adjusted time of *ORATE* and *WIP* response will decline. The steady-state error keeps zero. This phenomenon indicates that when the market demand bursts, supply chain members must strike a balance between production, inventory capacity and recovery capabilities, and make a reasonable decision on inventory adjustment parameter so as to maximize supply chain performance and maintain long-term and stable operation.




(a) *ORATE* (b) *AINV*

(c) *WIP*

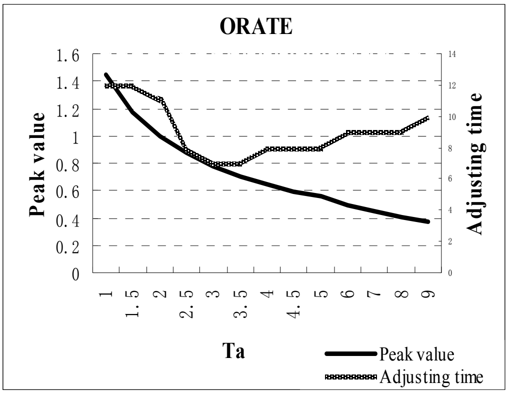
Fig. 11. The impact of $T_i$ on DIS-APIOBPCS impulse response

### 5.2.4 The impact of $T_a$ on DIS-APIOBPCS impulse response

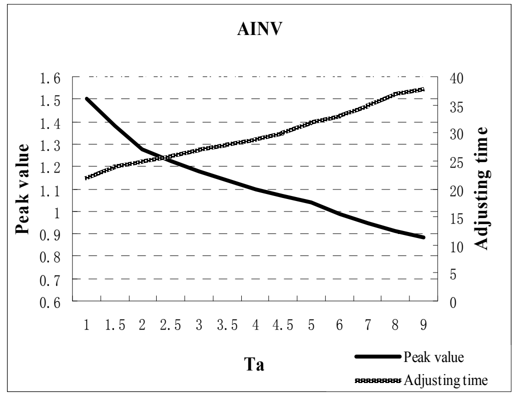
As shown in Fig.12, increasing $T_a$ is followed by declining peak value of *ORATE*, *AINV* and *WIP* response and rising adjusted time. From the analysis above, it is clear that $T_a$ should be reduced for the purpose of enhancing the rapidness of supply chain. But if the manager aims at production and inventory smoothness, $T_a$ settings should be higher.

### 5.3 Dynamic response of the DIS-APIOBPCS under stochastic demand input

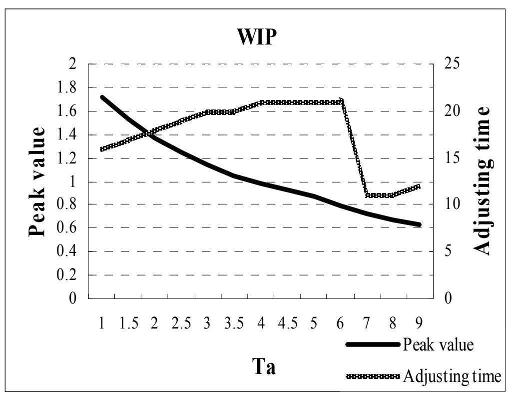
Noise bandwidth ($W_n$) is commonly used in communication engineering system to measure the inherent attributes of the system. It is defined as the area under the squared frequency response of the system, expressed as Eq.(8).




(a) *ORATE*




(b) *AINV*



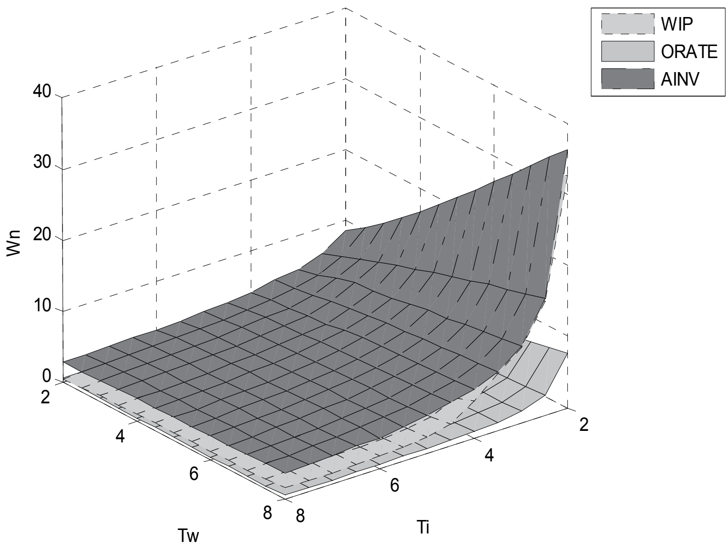

(c)*WIP*

Fig. 12. The impact of $T_a$ on DIS-APIOBPCS impulse response

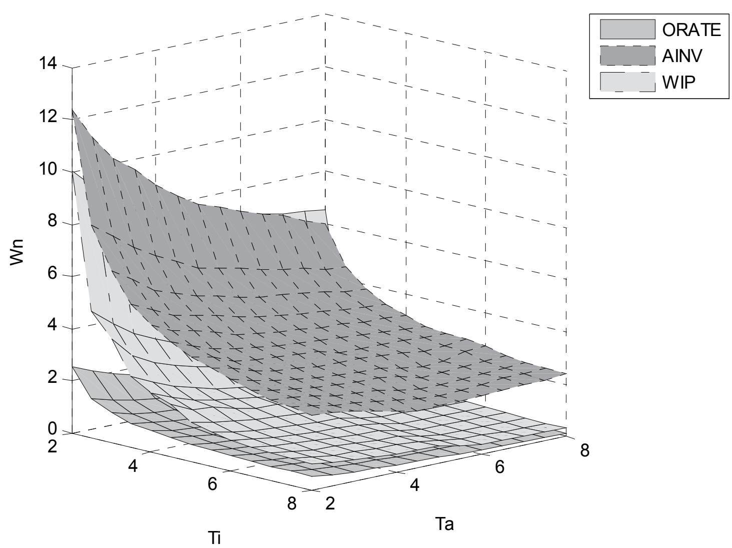
$$W_n = \int_0^{\pi} \left| ORATE_f \right|^2 dw \tag{8}$$

Noise bandwidth is a performance measure that is proportional to the variance of the ORATE response when the demand information consists of pure white noise (constant power density at all frequencies), (Garnell and East, 1977 and Towill, 1999). Pure white noise maybe interpreted as an independently and identically distributed (i.i.d.) normal distribution. Thus, the noise bandwidth may be reasonably considered a surrogate metric for production adaptation costs. These costs may include such factors as hiring/firing, production on-costs, over-time, increased raw material stock holdings, obsolescence, lost capacity etc. So when demand is i.i.d. form, the noise bandwidth can directly measure fluctuations in production.

The relationship between $W_n$ and system parameters $T_a$, $T_i$ and $T_w$ are shown in Fig.13.




(a)




(b)

Fig. 13. The impact of system parameters on dynamic response under stochastic input

The fluctuations of *ORATE*, *AINV*, and *WIP* response caused by demand fluctuations could be reduced by tuning system parameters. From Fig.13, it can be concluded that the *ORATE* and *WIP* fluctuation can be weakened by increasing $T_a$ and decreasing $T_w$. The inventory fluctuation can be weakened by increasing $T_i$ and reducing $T_w$. Moreover, $T_a$ should be increased when $T_i$ is small, otherwise $T_a$ should be reduced. This shows that for members of the supply chains, system fluctuation can be reduced by adjusting the system parameters in feed-forward and feedback loops. However, when the inventory adjustment parameter $T_i$ is a larger value, reducing inventory fluctuations has the opposite requirements on $T_a$.

### 5.4 Dynamic response of the DIS-APIOBPCS under different order intervals

In Sections 5.1-5.3, this paper analyzes how the system parameters impact the system dynamic responses to customer demand in forms of step, impulse, Gaussian Process in DIS-APIOBPCS system. In this part, dynamic response to variant order intervals is studied. In order to filter out the disturbance of random factors in simulation, demand information in form of impulse will be appropriate. According to the step response of peak value and adjusted time in DIS-APIOBPCS system, if $T_w$ takes 2, 3 or 4, the unit impulse response will be more desirable, given $T_a$=2, $T_p$=2, $T_i$=3 as shown in Fig.14. When $T_w$=2, the unit impulse response has a peak value of 1, but in other situations, the response will either has a higher or lower peak value.

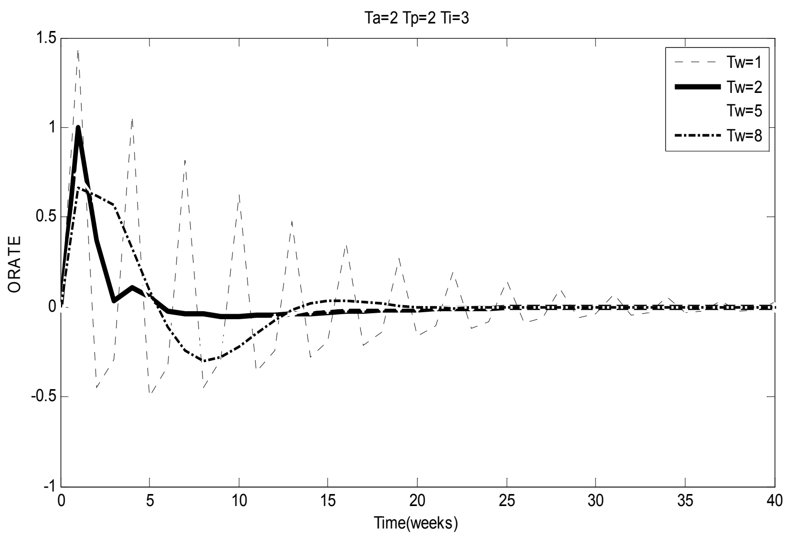
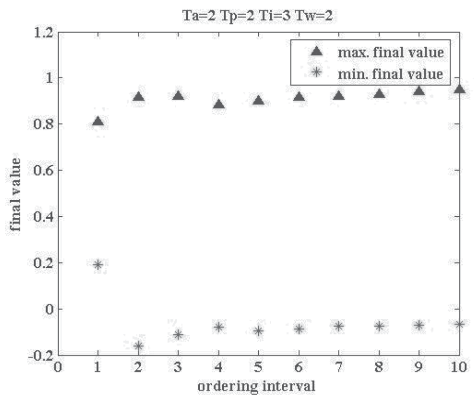
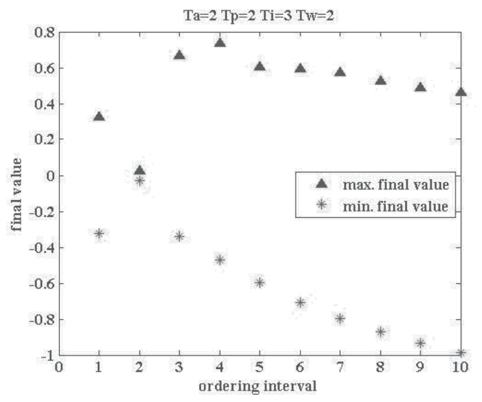



Fig. 14. The impact of $T_w$ on DIS-APIOBPCS impulse response

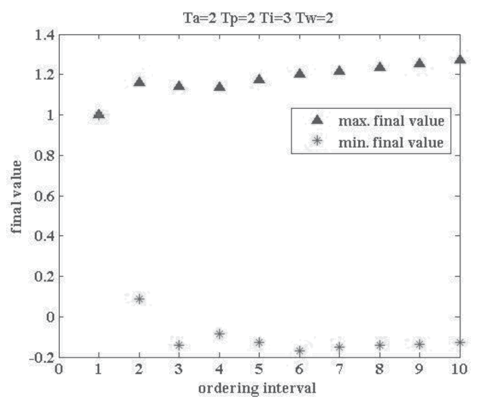
From the simulation experiments under different order intervals from 1 to 10 week, the maximum and minimum value of the response can be seen in Fig.15. When the order interval is 1 week, the *ORATE* response has a minimum oscillation amplitude and the one of *WIP* response is 0. The oscillation amplitude of *AINV* response will be minimal when the order interval is 2 week as shown in Fig.16.




(a) *ORATE*



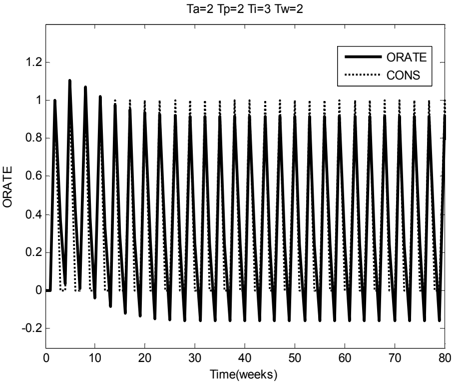

(b) *AINV*



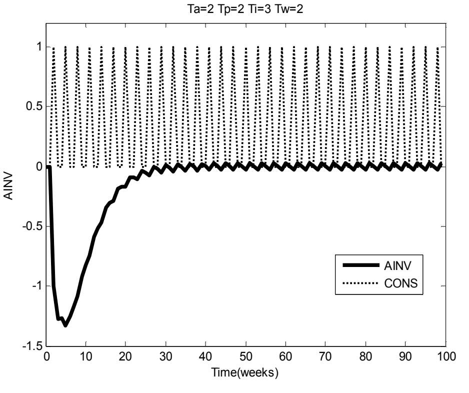

(c) *WIP*

Fig. 15. The maximum and minimum value of response under different order intervals

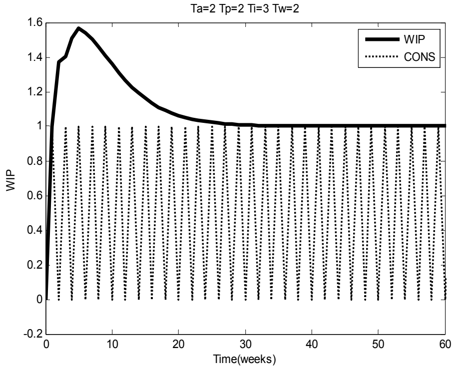
When the order interval of the supply chain is fixed, the system parameter setting will also influence the dynamic response. With other parameters given, the optimal order interval of *ORATE* response is still 1 week whether $T_p$ is increasing. However, the optimal order interval of *AINV* and *WIP* response will increase with $T_p$, and the increase of $T_i$, $T_w$ and $T_a$ have no influence on the optimal order intervals. So it can be concluded that the optimal order intervals will only be decided by the production lead-time no matter how much other parameters are set. Because the page limits, this paper only gives the situation when $T_p$=2 and $T_p$=4, as shown in Figs.17 and 18.




(a) *ORATE*

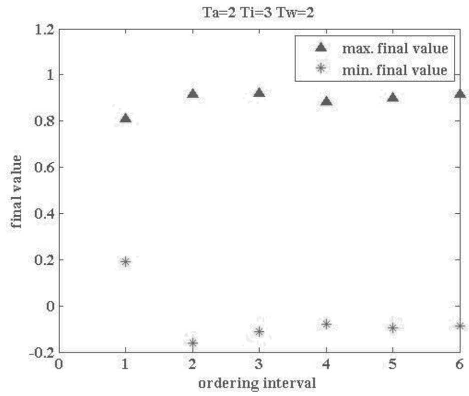



(b) *AINV*

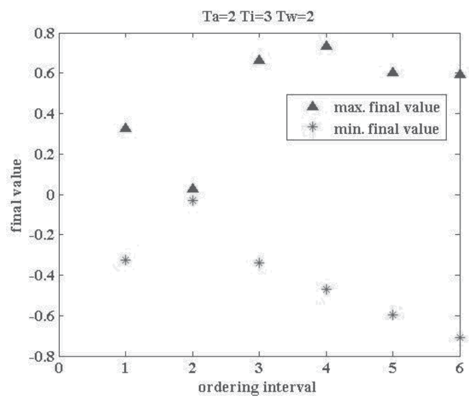



(c) *WIP*

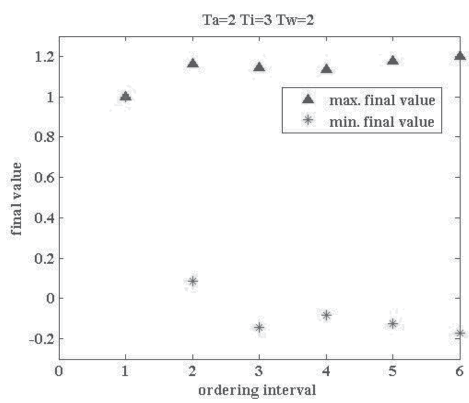
Fig. 16. The dynamic response under optimal order interval




(1) *ORATE*

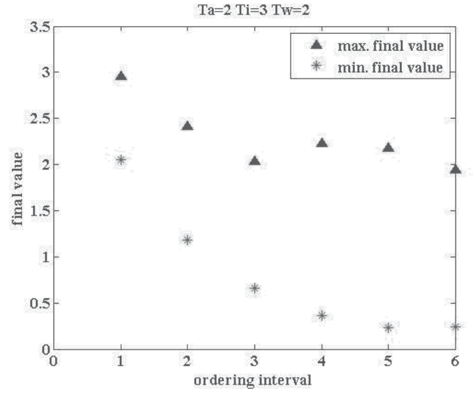



(2) *AINV*

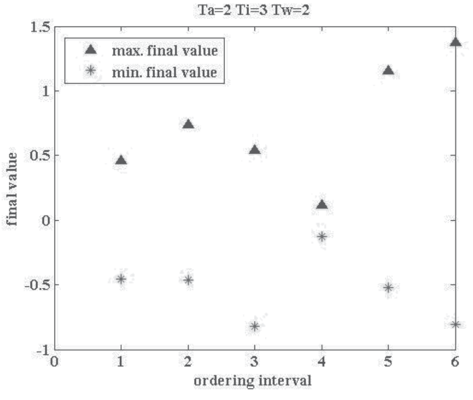



(3) *WIP*

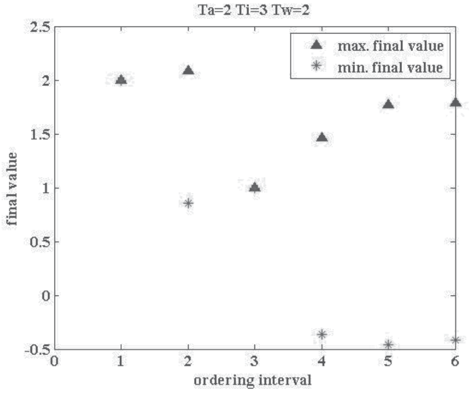
Fig. 17. The impact of order intervals on dynamic response when $T_p$=2




(1) *ORATE*




(2) *AINV*




(3) *WIP*

Fig. 18. The impact of order intervals on dynamic response when $T_p$=4

## 6. Conclusions

Based on APIOBPCS model, this paper analyzes a demand information-sharing two-echelon supply chain system model (DIS-APIOBPCS). The management significance of four key parameters is analyzed and the stability condition under different lead-times is figured out. The stability boundary is verified by simulation. Any parameters' value beyond the stability region will lead to instability of supply chain, thus it could be avoided via tuning parameters of the feedback loops within the supply chain for a specific production lead-time.

Then the system dynamic responses to customer demand in forms of stepwise, impulsive, stochastic distribution and variant order intervals are analyzed. Regarding the step and impulsive demand information input, the smaller the production lead-time, the lower the peak value and the shorter the adjusted time. This means companies can reduce capacity requirements when the market demand expands (and *vice versa*) by decreasing production lead-times. $T_i$ and $T_w$ not only provide a means of ensuring stability, but also drive capacity requirements to satisfy a step increase in demand. Supply chain members must strike a balance between production, inventory capacity and recovery capabilities, and make a reasonable decision on inventory adjustment parameters so as to maximize supply chain performance and maintain long-term and stable operation. Under normally distributed input, the noise bandwidth can directly measure fluctuations in production. The fluctuations of *ORATE*, *AINV*, and *WIP* response caused by demand fluctuations could be reduced by tuning system parameters. The optimal order intervals will only be affected by the production lead-time.

The DIS-APIOBPCS system model could be expanded to any two enterprises in multi-echelon supply chain systems and those using other information sharing strategies. Furthermore, research on stability condition and dynamic response under other demand information forms is an important problem in supply chain management.

## 7. Acknowledgement

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## 8. References

Dejonckheere J., Disney S.M., Lambrecht M.R., Towill D.R. Measuring and avoiding the Bullwhip Effect: a control theoretic approach. European Journal of Operations Research, 2003,147 (3), 567–590.

Dejonckeere J., et al. The impact of information enrichment on the bullwhip effect in supply chains: a control engineering perspective, Euro. J. Operational Res. 2004, 153(3): 727-750.

Disney S.M., Naim M.M., Towill D.R. Genetic algorithm optimization of a class of inventory control systems. International Journal of Production Economics 2000, 68:259–78.

Disney S.M., Towill D.R. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. International Journal of Production Research, 2002, 40 (1), 179–204.

Disney S.M., Towill D.R. On the Bullwhip and inventory variance produced by an ordering policy. The International Journal of Management Science, 2003, 31(3): 157–167.

Disney S.M., Towill D.R., Van de Velde, W. Variance amplification and the golden ratio in production inventory control systems. International Journal of Production Research, 2004, 90 (3), 295–309.

Disney S M. Towill D.R. Eliminating drift in inventory and order based production control systems. International Journal of Production Economics, 2005, 93–94: 331-344.

Disney S.M., Towill D.R., Warburton, R.D.H. On the equivalence of control theoretic, differential, and difference equation approaches to modeling supply chains. International Journal of Production Economics, 2006, 101 (1), 194–208.

Warburton R.D.H., Disney S.M. Order and inventory variance amplification: The equivalence of discrete and continuous time analyses. International Journal of Production Economics, 2007, 110(1-2): 128-137.

Fernanda Strozzi, Carlo Noè, José-Manuel Zaldívar. The Control of Local Stability and the Bullwhip Effect in a Supply Chain. International Journal of Production Economics, 2007, 12:1-11.

Forrester J.W. Industrial Dynamics. MIT Press, Cambridge, MA. 1961

Sarimveis H., et al. Dynamic modeling and control of supply chain systems: A review. Computers and operations research, 2008, 35(11): 3530-3561.

Khalid Saee. Trend forecasting for stability in supply chains. Journal of Business Research, Available online 16 January 2008.

Lalwani C.S., Disney S.M., Towill D.R. Controllable, observable and stable state space representations of Order-up-to policy. International Journal of Production Economics, 2006, 101:172-184

Nordin Saad, Visakan Kadirkamanathan. A DES Approach for the Contextual load modeling of Supply Chain System for Instability Analysis. Simulation Modeling Practice and Theory, 2006, 14:541-563

Riddalls C.E., Bennett S. The stability of supply chains. International Journal of Production Research, 2002, 40 (2), 459–475.

Takashi Nagatani, Dirk Helbing. Stability Analysis and Stabilization Strategies for Linear Supply Chains. Physica A, 2004:633-660.

Towill D.R. Dynamic analysis of an inventory and order based production control system. International Journal of Production Research .1982;20:671–87.

Towill D.R. Industrial dynamics modeling of supply chains. International Journal of Physical Distribution &Logistics Management, 1996,26(2):23~42.

Vassian H.J. Application of discrete variable servo theory to inventory control. Operations Research, 1954. 3, 272–282.

Warburton R.D.H. An analytical investigation of the Bullwhip Effect. Production and Operations Management , 2004a, 13 (1), 150–160.

Warburton R.D.H. An exact solution to the production inventory control system. International Journal of Production Economics, 2004b, 92 (1), 81–96.

Warburton R.D.H., Disney S.M., Towill D.R., Hodgson J.P.E. Further insights into the stability of supply chains. International Journal of Production Research, 2004, 42 (3), 639–648.

Yanfeng Ouyang. The effect of information sharing on supply chain stability and the bullwhip effect. European Journal of Operational Research.2007, 182(3),1107-1121.

# Part 3

## Modeling and Analysis

# 19

# Complexity in Supply Chains: A New Approach to Quantitative Measurement of the Supply-Chain-Complexity

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## 1. Introduction

The increasing globalization of market is forcing hard competition, consequently resulting increased complexity in supply chains. Complexity has many negative effects (consequences) on supply chains such as high operational costs, customer dissatisfaction, time delay in delivery, excess inventory or inventory shortage (stockouts), lack of cooperation, collaboration and integration among supply chain participants etc. A supply chain consists of multiple business partners who work together directly or indirectly which is collaborated by information, material and financial flows. These flows may lead to high complexity due to the lack of information (distorted information) within supply chain participants. Uncertainty variety, diversity, numerousness etc. are some of the factors which lead to the variation between expected (planed, scheduled) and actual flows and this variation called as complexity in this present study. These factors can be originated from exogenous and/or endogenous drivers. Therefore, supply chain complexity (SCC) can be classified into two general types as internal and external from its sources. Supply chain complexity is closely correlated with total supply chain management cost. Any increase in complexity level in a supply chain has a relevant contribution to its total cost. Complexity can be reduced by an effective complexity management that provides costs reduction within supply chains.

In order to manage complexity in supply chains effectively and efficiently, a four stage complexity management model is proposed to use which covers identifying, measuring, analyzing and controlling (reducing and avoiding) of complexity. After defining the complexity clearly, it is recommended to be measured so as to identify it quantitatively so that it can be analyzed, reduced and avoided. Defining the root causes of the complexity is required to improve the system complexity. However, complexity may result excess inventory which can be sometimes useful for the company, if a customer wants to pay for it. Otherwise high complexity is required to be reduced because of its high costs to the company.

With respect to obtaining a quantitative measure, complexity in supply chains is defined as the quantitative variations (deviations) between actual and predicted flows caused by uncertainty and variety through material and information flows. Regarding the definition of complexity in this study, complexity will be measured by using a new proposed entropy measure based on Shannon information entropy (Shannon, 1948) which is a measure of the average uncertainty or information associated with random variable.

Complexity as a concept of manufacturing has been studied by several researchers. For example, Wilding (1998) used a 'supply chain complexity triangle' which includes deterministic chaos, parallel interactions and demand amplification to understand the generation of uncertainty within supply chains. Calinescu et al. (2001) analyzed the manufacturing complexity by categorizing it into three; decision-making complexity, structural complexity and behavioural complexity. Milgate (2001) described uncertainty, technological intricacy and organizational system as dimensions of supply chain complexity so as to manage it. In order to manage complexity in manufacturing effectively and efficiently, understanding and measuring complexity are required. This study focuses on the measurement of the supply chain complexity associated with uncertainty and variety by information and material flows based on a new modified entropy measure.

Entropy is commonly known as a measure of the energy dispersal for a system in thermodynamics (second law of thermodynamics). However, Shannon (1948) and Shannon and Weaver (1949) studied the entropy from a statistical perspective which evaluates uncertainty (associated with random variables) in a system by measuring the information content within this system. His famous approach is called as Shannon´s information entropy in the relevant literature.

The academic survey on entropy measure from its statistical aspect has begun with Yao (1985) who studied the entropy as a measure of flexibility. Later, Deshmukh et al. (1992) presented a static measure of complexity based on entropy method. Ronen and Karp (1994) developed an approach that determines the location of a lot by using entropy measurement. Entropy as a measure of complexity in supply chains was first introduced by Frizelle and Woodcock (1995). Later, Sivadasan et al. (2002), Deshmukh et al. (1998) and Sivadasan et al. (2006) studied their approach with an industry practice done by the Institute for Manufacturing (IFM) at Oxford and Cambridge universities (see website www.ifm.eng.cam.ac.uk/csp/projects/complexschain.html). Their papers present an entropy-based approach in more detail and defined structural (deals with variety (schedule) and operational (deals with uncertainty (deviation from the schedule)) complexity measures by extending Shannon information entropy. In their work, complexity is considered as a random variable with different states and corresponding probabilities for each state. Based on their work Makui and Aryanezhad (2003) presented a new approach which developed a static complexity measure based on entropy. Martinez-Olvera (2008) developed a methodology based on entropy measure to compare different supply chain information sharing by using computer simulation.

Later, Isik (2010) provided their approach and modified the complexity measures. In prior entropy-based works on complexity (Shannon, 1948; Shannon and Weaver, 1949; Frizelle Woodcock, 1995; Sivadasan et al., 2002; Sivadasan et al., 2006), it is argued that complexity (or entropy) is only a function of probabilities of different states. However, Isik (2010) argues that complexity is not only a function of probabilities of different states, but also each state can have different complexity levels of its own that needs to be considered. As a contribution of the new approach, an "expected value" is defined for each state and the deviation from that expected value is measured. This study presents her work with an example given which measures complexity (variations) between actual and scheduled demand levels.

This study is organized as follows. Section 2 presents supply chain complexity, its characteristics and classification of complexity sources in supply chains. Section 3 is considered complexity management in supply chains. Complexity measurement is represented by section 4. Section 5 demonstrates a case study about complexity measurement. Section 6 concludes this study.

## 2. Complexity and supply chain complexity

Manufacturing is becoming more complex than ever in the last decade due to the globalizations and its effect. Increasing complexity of supply chains leads to high operational costs which have to be reduced to be able to manage by an effective collaboration among supply chain partners. The sources of the complexity may occur from external and/or internal drivers. Therefore, understanding and measuring complexity are becoming increasingly important from the managerial side of the organizations to cope with this complexity. Although, complexity is very difficult to define formally, there are some definitions of complexity in the relevant literature. A suitable one of them regarding the present study is as follows:

"Complexity is being marked by an involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with (Webster's Third International Dictionary, Gove 1986)".

In order to measure complexity in supply chains, the data used is required to be quantitative. Regarding the definition above and referring to the goal of this study, complexity can be defined as quantitative differences between predicted and actual states which are associated with uncertainty and/or variety caused by internal and external drivers in a (supply chain) system.

A supply chain consists of many participants which collaborate directly or indirectly to fulfil customer demand along the supply chain. Within each organization in a supply chain, a participant receives demands from the prior downstream stage and places orders with the next upstream stage to be able to supply the downstream customer demands (see figure 1). All these activities are operated by the flows (information, material and financial) in a typical supply chain. Information and/or material flows along the supply chain systems are the main complexity drivers which have to be managed effectively and efficiently. Each participant within a supply chain has its own prediction on demand (forecast) based on the present demand received from its downstream customer so as to supply the required product (or service) to this customer. Figure 1 is illustrated to demonstrate a simple three stage supply chain and its flows. Some forecasting methods used to predict the demand by using historical demand data (moving average, exponential smoothing method, autoregressive integrated moving average models (for example see Montgomery et al., 2008). However, forecasting has always a misleading associated with uncertainty which cause mismatch between planed and actual demand values. This costly mismatch is related

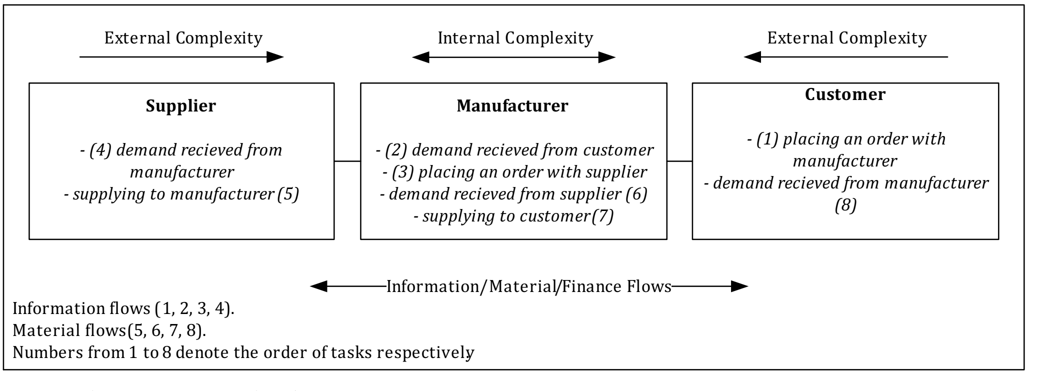


Fig. 1. Flows in a supply chain.

with what planed (predicted or forecasted) and what actually received. These quantitative differences (variations) between actual and predicted values are called as complexity in this study.

Regarding this study, a supply chain complexity can be defined as whole operational, structural and behavioural variations caused by uncertainties and/or varieties which occurs expectedly (predicted) and/or not expectedly (unpredicted) through internal or external drivers along a supply chain system.

### 2.1 Characteristic of the supply chain complexity

A system consists of many parts or elements of various types which are linked each other directly or indirectly. These various elements and their interrelationships are significant for complexity occurring in a system. Furthermore, a supply chain is a complicated system due to the uncertain manufacturing environment, so complexity presented in this study is interpreted as a system complexity. There are some key characteristics (dimensions) of complexity occurring in a supply chain system which need to be discussed to understand the impact of these characteristics on the occurrence of complexity. However, the key dimensions may act on each other or one another. Therefore, the explanations of these dimensions do not only represent the value itself, but also highlight the relationship and interaction between the characteristics of the complexity.

**Numerousness:** This characteristic of the complexity covers the number of components such as items (raw, manufactured or end), products, processes, supply chain participants such as customers or suppliers, relationships, interactions, goals, locations, etc. A high number level of any components contributes increasingly complexity in a supply chain system. In order to deal with this characteristic, it is only required to reduce the level of number. The changeability of number under any consideration is directly related with any change in complexity level.

**Diversity:** Diversity is related with the homogeneity or heterogeneity of a system. A high (or *low*) level of diversity of any components such as customer, product or transport channels along the supply chains leads to system`s heterogeneous (*or homogeneity*) and results a high (*or low*) level of complexity.

**Interdependency**: Interdependence covers the intended or unintended relationship between at least two (or more) states such as items, products, processes, supply chain participants etc. which may cause complexity in a system. Interdependence states cannot be operated without each other or without any influence from each other. Complexity increases in direct proportion to the increase of Interdependence.

**Variability:** Variability refers to a state characteristic of being changeable where an event produces possible different outcomes in a system. A variable system represents rapidly changeable element over time. E.g. consumers change their mind unexpectedly over time which results a change in product specifications. Any increase in variability causes increased complexity in a system. From the supply chain side, variability considers measurable (quantitative) variations between the expected and actual states in a system.

**Variety:** Variety is linked with a state of being various. A variable system consists of elements or components which are different from each other. For example, a product or a process variety in supply chains leads to increase in complexity level over time. Variety represents dynamical behaviour of a system.

**Uncertainty:** Uncertainty represents all difficulties to be able to make a clear picture of a system due to the lack of information or knowledge. Systems` deficits such as indefiniteness,

risks, ambiguities or ambivalences, connectedness lead to high level of uncertainty in a system. Uncertainty and complexity are linked very closely each other. The more uncertainty in a supply chain system is, the more complexity occurs in this system. The most common effect of uncertainty that causes complexity is well known as the "bullwhip effect" in the literature. As a future work, complexity measuring in bullwhip effect will be discussed in more detail.
The complexity characteristics presented above can be closely related to each other, one can effect the others or one can cause the occurring of the others. The each characteristic has not the same effect (more or less) on a supply chain system with or without any interactions or interrelationships between them. For example, a high level of variety may cause variability in a system or high density of diversity may lead to uncertainty. If the level of these characteristics is reduced, complexity will be reduced as well. However, this study only concentrates on the uncertainty, variability and variety with respect to complexity measurement based on entropy so the other complexity characteristics will not discussed in more detail.

### 2.2 Classification of supply chain complexity

Various sources involve complexity in supply chains. Material and information flows represent the main complexity drivers along a supply chain due to the factors such as uncertainty, variability, size, speed, diversity etc. A supply chain consists of exogenous and endogenous interactions and interrelationships which cause increase in complexity, resulting unpredictability in a system. Companies need to cope with this increasing complexity from both internal and external side to compete better in global market. Therefore, supply chain complexity can be classified into two general types from its sources:

- internal supply chain complexity drivers
- external supply chain complexity drivers

Organizations have to reduce and avoid both internal and external complexity, so as to obtain more reliable, more predictable and less complex system. Both internal and external sources may be originated from operational, structural and behavioural uncertainties in a supply chain system.
***Internal SCC drivers***: Internal complexity is associated with material and information flows within single business partner of a supply chain. This type of complexity is related with the structure of this single business partner, which covers such as process, product, production and organizational uncertainties. Some specific examples for internal supply chain complexity are process deficits, material shortfall, machine breakdowns, lack of management, large product variety, etc. Internal drivers can be reduced and avoided by improving information and material flows within the single business partner.
***External SCC drivers***: External complexity driver is related with material and information flows exported by other business partners (customer and supplier) to a single business partner in a supply chain. Globalisation, technological innovation, high competition and customer demand variety are some of the external drivers of the supply chain complexity. External supply chain drivers can be reduced and avoided by more corporations between the partners to get a more reliable system.
However, from the measurement aspect of a supply chain complexity, a measurement of complexity can be considered the whole system which may be called total SCC.

## 3. Complexity management in supply chains

Globalizing supply chains drive complexity which needs to be managed effectively and efficiently to reduce high costs and to improve operating performance in many industries. Complexity is too difficult to eliminate entirely by organizations but they can bring it under control and avoid it in the future by an efficient and effective management system. Supply chain complexity can be effectively managed by four strategies/steps: namely, identifying, measuring, analyzing and controlling (reducing and avoiding). The all strategies are related to each other and have closely interactions and interrelationships. Figure 2 illustrates the complexity management stages in a supply chain.

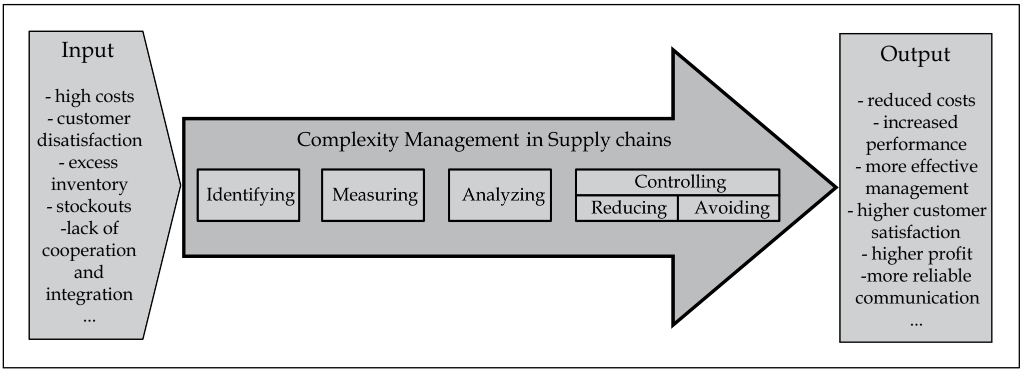


Fig. 2. Steps of a complexity management in supply chains.

**Identifying:** Identifying is the first step to begin in order to manage the complexity in supply chains efficiently and effectively. Therefore, it is first recommended to accept existence of the complexity by managers before coping with this complexity. Complexity is defined as all quantitative variations between planed and actual flows along a supply chain in this study. Bringing the complexity to light help the manager to detect how big the variations between the actual flows and the expected flows which lead to high operational costs.

The complexity sources of all variations and their interdependencies and interrelationships to each other should be clearly defined, resourced and recorded at this stage to be able to prove their solutions later. The sources can be categorized according to potential reasons. For example, external resources can be originated from supplier or from customer; internal factors can be related with such as machine, laboratory, process, people etc.

**Measuring:** After defining the complexity, it is first recommended to measure it, in order to dedicate how the system behaves. Therefore, regarding the definition of the complexity in this study, entropy is used as a measure for complexity. Measuring complexity will be discussed in more detail in section 4.

**Analyzing:** After the measuring step, the results of the complexity measures are needed to be analyzed. Analyzing complexity values is related with the aim of the measuring. A measurement can be analyzed from many perspectives. For example, a complexity measure can be implemented for

- analyzing internal, external and total complexity of a supply chain from its sources,
- comparing the supply chain flows (material and/or information) E.g. same products on different product lines, different products on the same line,
- comparing the performance among various supply chain partners, etc.

In this step the root causes of the complexity and their costs in a supply chain can be analyzed to detect the countermeasures regarding this complexity as well. Some problem solving methods (such as brainstorming, cause and effect analyze, root cause analysis, etc.) can be used for analyzing the root causes of the complexity occurring in a system.

**Controlling:** Controlling is a fundamental step of the management and it is related with taking complexity under control. Complexity is not only needed to be reduced, but also it is required to be avoided so as to prevent against its existence in the future. Therefore, the step controlling consists of two parts: namely, reducing and avoiding. Improving of information sharing within supply chains can mitigate the high complexity and help reducing the costs. Hence, effective and efficient use of IT tools and methods can help the controlling complexity in supply chains. These tools do not only improve information quality, but also they integrate supply chain`s participants.

**Reducing:** Complexity is not always easy to remove completely from the system. Thus, it needs to be considered to reduce as much as possible. Reducing complexity is a cost-based strategy for the realisation of supply chain management. The strategy of reducing supply chain complexity includes the improving material and information flows along the supply chains. Hence, an integrated complexity management is required by standardisation (for example ISO quality assurance standards) and harmonisation of interfaces between information, material and financial flows in order to decrease level of complexity, reduce costs and improve supply chain` efficiency. Therefore, not only the supply chain flows, but also the processes, business partners, product and production planning, logistic activities, services stand etc. are needed to be improved by integrated complexity management. However, a SCOR model (The supply-chain operations reference model) can be used to reduce complexity. A supply chain partner typically operates five basic business processes (plan, source, make, deliver, and return) in this model. These processes will not be discussed in detail in this study. Authors like Lee et al. (1997a) and Lee et al. (1997b) offer some countermeasures to reduce uncertainty in supply chains.

**Avoiding:** The aim of an efficient complexity management in supply chains does not only cover the reduction in complexity level by taking corrective actions, but also it comprises avoiding of the complexity by preventive actions in the future. For example, ISO standardizations, total quality management, six sigma and lean production management can be used to avoid supply chain complexity in the future (for example see Martin, 2007; Hoyle, 2009). Improved communication between partners of supply chains and continuous training of the people can corroborate the preventive actions as well.

Each step is very significant to complexity management in supply chains. Amount of four management's stages, measuring is the key stage to be able to realize the other stages effectively. Therefore, this study present a measurement method based on entropy method and it is presented in the next section.

## 4. Measuring supply chain complexity based on entropy measurement

In order to manage complexity in manufacturing, measurement is required. The aim of the complexity measurement is to be able to obtain a numerical scale to compare the complexity values of a system on different problems. Therefore, an information theoretic measure called *classical entropy measure(s)* in this study according to Calinescu et al. (2000), Sivadasan et al. (2002) and Sivadasan et al. (2006) based on Shannon´s information theory (Shannon 1948) and a *new proposed entropy measure(s)* according to (Isik, 2010) are presented to measure complexity behaviour between two supply chain participants.

#### 4.1 Classical entropy measure

The concept of entropy is known as the second law of thermodynamics and was first introduced by the German physicist Rudolf Julius Emmanuel Clausius (1822-1888). Scientists such as James Clerk Maxwell (1831-1879), Josiah Willard Gibbs (1839-1903), Ludwig Eduard Boltzmann (1844-1906), and Claude Elwood Shannon, (1916-2001) studied entropy from a statistical aspect. Shannon (1948) described the entropy as a measure of information or uncertainty on random variables, which take different probabilities among the states into account. The average uncertainty associated with an outcome is represented by discrete random variable $X$ on a finite set $X=\{x_1,...,x_n\}$ with probability distribution function $p(x_i)$ being in state $i$, $(i=1,...,n)$. The *Shannon's information* entropy $H(X)$ of $X$ is defined as

$$H(X)=-\sum_{i=1}^{n}p(x_i)\log_2 p(x_i) \tag{1}$$

Shannon used logarithm to the base 2 in the entropy formula to give entropy the dimension of a binary digit (bit). The Shannon's entropy represents the following properties (Shannon, 1948; Shannon and Weaver, 1949).

- $p(x_i)=1/n$ , n represents the number of possible outcomes in a system
- Information is a non-negative quantity: $H(X)\geq 0$, since $0\leq p(x_i)\leq 1$.
- The sum of all probabilities equals 1: $\sum_{i=1}^{n}p(x_i)=1$
- If an event has probability 0, then the entropy is also zero.
- Entropy achieves its maximum value ($H(X)=\log_2 n$) when all outcomes occur with the same probability ($p(x_i)=\frac{1}{n}$), (all outcomes are equal likely) so the system is being in most uncertain and unpredictable states.
- Entropy attains its minimum value ($H(X)=0$) when only one outcome occurs with probability 1 ($p(x_i)=1$) which means outcome is known with complete certainty, then there is least information occurrence in a system.

This study focuses on the measurement of complexity in manufacturing based on Shannon's information entropy. Frizelle and Woodcock (1995), Deshmukh et al. (1998), Calinescu et al. (2000), Sivadasan et al. (2002) and Sivadasan et al. (2006) introduced entropic measurement for manufacturing complexity by using Shannon's entropy. Complexity can be divided into two: namely, structural (static) and operational (dynamic).

*Structural (static) complexity* is defined as the expected amount of information required to define the state of a system for a given period. Structural complexity is related with the information in the schedule and it is associated with variety amount of the complexity characteristics (see section 2.1) in a system which can be written as follows (Frizelle and Woodcock 1995; Sivadasan et al. 2002; Deshmukh et al. 1998):

$$H^{I}{}_{(s)}=-\sum_{i=1}^{M}\sum_{j=1}^{N}p_{ij}\log_2 p_{ij} \tag{2}$$

where

$H^I{}_{(s)}$ : Structural complexity

$p_{ij}$ : Probability of resource $i$, $(i = 1,...,M)$ being in state $j$, $(j = 1,...,N)$

$M$ : Number of resources

$N$ : Number of possible states for resource $i$

*Operational (dynamic) complexity* is considered as the expected amount of information required to define deviation from the schedule due to uncertainty characteristic of complexity. Operational complexity is related with the monitoring of planned and unplanned events and it can be defined as (Frizelle and Woodcock 1995; Deshmukh et al. 1998; Sivadasan et al. 2002):

$$H^I{}_{(o)} = -(1-P)\sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}\log_2 p_{ij} \tag{3}$$

where

$H^I{}_{(o)}$ : Operational complexity

$P$ : Probability of the system being "in control (scheduled)" state

$(1-P)$ : Probability of the system being "out of control (unscheduled)" state

### 4.2 New proposed/modified entropy measure

Focus of this study is to present the superiority of the new proposed entropy measures by modifying classical complexity measures based on entropy. The classical measures have some drawbacks to be improved. They indicate that complexity is only a function of different state. Whereas, Isik (2010) proposes, each state can have its own expected outcome value for the state in a system which is needed to be considered. Because each state has different cost level that has to be taken into consideration as well. The costs are not only related with complexity cost to organizations but also its countermeasure`s costs due to the corrective and avoiding actions. According to classical approaches, two different states with the same probabilities of occurrence but with different cost levels can have the same entropy or complexity level. From a point of view of cost effect, the larger distance to the expected outcome value has to produce a greater complexity value because larger distances to the expected outcome value have a larger effect on the system than the smaller distances. Therefore, the classical measures are needed to be expanded to cover a contribution of the expected value as well. The expected outcome value needs to be defined with respect to the problems which will be addressed. Complexity in this paper is defined as a variation between predicted and actual flows. Therefore, the existence of variation between planned and actual demand shows complexity existence. If the variation between demand flows equal zero, then there is no complexity occurring. In manufacturing systems it is expected that there is no variation between predicted and actual flows (ideal case). I.e. there is no deviation from the schedule. Therefore the expected outcome value for this study is zero. However, the expected value can be also some tolerated variation between expected and actual flows in manufacturing system according to the problem structure. The corresponding deviation from that expected value shows the complexity of that particular state (Isik, 2010).

As a contribution of the new complexity approach, an expected outcome value is defined for each state and the deviation $(d_i)$ from that expected value is measured.

The new modified entropy measure can be defined as follows:

$$H^{I} = -\sum_{i=1}^{n}\left[\log_2 p_i\right] p_i d_i \tag{4}$$

The new modified structural complexity can be defined as follows:

$$H^{II}{}_{(s)} = -\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\log_2 p_{ij}\right] d_{ij} p_{ij} \tag{5}$$

The new modified operational complexity can be defined as follows:

$$H^{II}{}_{(o)} = -(1-P)\sum_{i=1}^{M}\sum_{j=1}^{N}\left[\log_2 p_{ij}\right] d_{ij} p_{ij} \tag{6}$$

where $(d_{ij})$ (absolute value of $(d_{ij})$ is considered) is the deviation of outcomes from the expected outcome value for the state.

## 5. A case study

Complexity in supply chains is associated with material and information flows between supply chain partners. In this case study, a single supplier–customer system is considered which is illustrated in figure 3. In this present example, the supplier has its own forecast demand level (expected values of demand) and the customer places order (actual demand values) with its supplier. Therefore, the variations between actual and scheduled demand levels will be analyzed to address how much the scheduling goal on demand of the supplier is achieved. Monthly predicted and actual demand values are created as a simple example to show how to use the entropy-based complexity measure in manufacturing (see table 1).

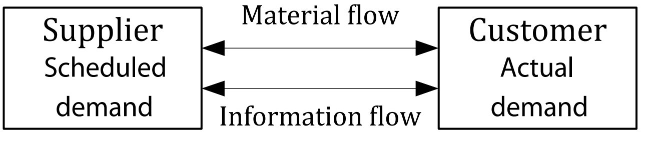


Fig. 3. A single supplier–customer system.

In order to illustrate the variations between actual and expected flows, the curves of actual and scheduled demand values are plotted in figure 4.
The entropic complexity measurement includes three steps below.

*1. Calculation of the variation*

As a first step of the complexity measure the quantitative differences (variations) between actual and scheduled demand values are calculated by subtracting actual values from expected values and seen in variation column in table 1.

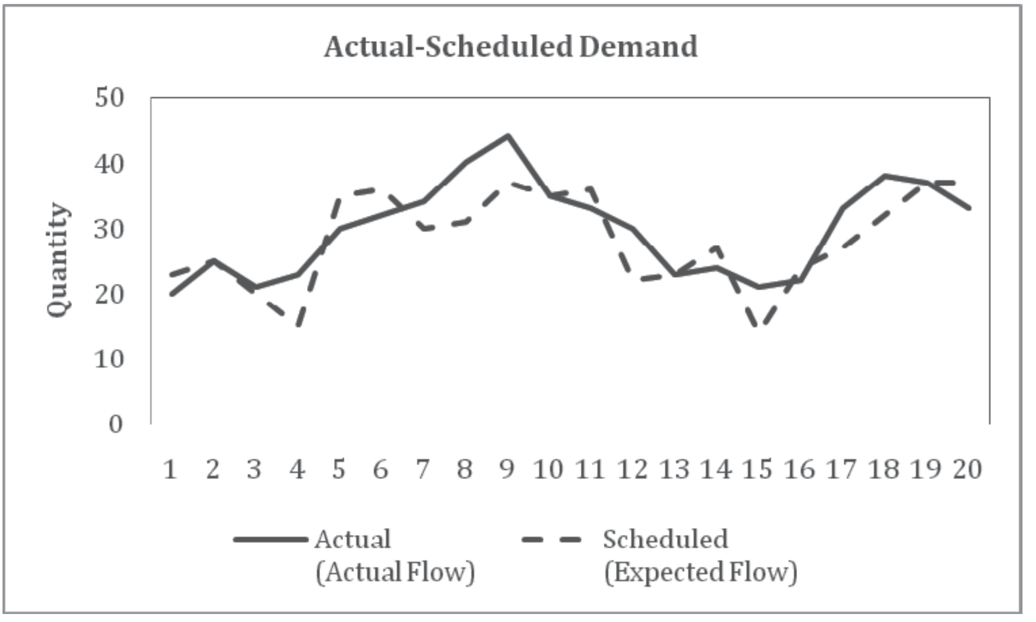


Fig. 4. Actual and scheduled demand values.

| Time/month | Demand level | | Variation (actual-scheduled) |
|---|---|---|---|
| | Actual (actual flow) | Scheduled (expected flow) | |
| 1 | 20 | 23 | -3 |
| 2 | 25 | 25 | 0 |
| 3 | 21 | 20 | 1 |
| 4 | 23 | 15 | 8 |
| 5 | 30 | 35 | -5 |
| 6 | 32 | 36 | -4 |
| 7 | 34 | 30 | 4 |
| 8 | 40 | 31 | 9 |
| 9 | 44 | 37 | 7 |
| 10 | 35 | 35 | 0 |
| 11 | 33 | 36 | -3 |
| 12 | 30 | 22 | 8 |
| 13 | 23 | 23 | 0 |
| 14 | 24 | 27 | -3 |
| 15 | 21 | 14 | 7 |
| 16 | 22 | 24 | -2 |
| 17 | 33 | 27 | 6 |
| 18 | 38 | 32 | 6 |
| 19 | 37 | 37 | 0 |
| 20 | 33 | 37 | -4 |

Table 1. The variations between actual and scheduled demand values.

*2. State definition*

A state is what the system is doing and a system can be in one or more states. For this example the discrete random variables occur in two states: namely, "in control" and "out of control". The "in control" states include planned or scheduled states and the "out of control" states include unplanned or unscheduled states. The system is said to be "in control", if the variations between actual and scheduled values of the demand equal zero and all positive and negative variations indicate "out of control" states. The character "*x*" represents the variation values. The state definitions are illustrated in table 2.

| State Description | Quantitative Differences ($x$) (Actual–Predicted) | Definition |
|---|---|---|
| "In Control State (ICS)"/ scheduled | 0 | No variation between the expected and actual demand values, acceptable. |
| "Out of Control State (OCS)"/ unscheduled | >0 | Positive variations which has to be taken under control, not-acceptable. |
| | <0 | Negative variations which has to be taken under control, not-acceptable. |

Table 2. The state definition.

*3. Creating a probability distribution and data analyze*

In order to calculate complexity based on entropy approach, a probability histogram is created to analyze the measurement results. Therefore, definition of the state´s intervals is necessary. A state interval can be chosen according to structure of the problem which will be analyzed. According to structure of the variation, one in control state (ICS) and four out of control states (OCS) with chosen upper and lower state´s bounds are proposed in this study.

| State interval | State description | Variation manageability | Complexity cost level | Countermeasures |
|---|---|---|---|---|
| 0 | ICS | - | - | - Improving information and material flows<br>- corrective and preventive actions<br>- communication and continuous training |
| $+6 \le x \le +10$ | OCS1 | very difficult to manage with serious consequences | Cost Level 1 | |
| $+1 \le x \le +5$ | OCS2 | manageable by taking certain steps with suitable policy | Cost Level 2 | |
| $-5 \le x \le -1$ | OCS3 | manageable by taking certain steps with suitable policy | Cost Level 3 | |
| $-10 \le x \le -6$ | OCS4 | very difficult to manage with serious consequences | Cost Level 4 | |

Table 3. State categorisations and their effects on complexity management.

The criterion of complexity analyzing is illustrated in table 3. These criterions can be different regarding the structure of problems or organizations. Each state interval has its own complexity cost level according to its manageability to be considered. The states that are very far from 'under control' states have to be more costly than that are nearly 'under control' with respect to complexity management. The more divergence to an expected value of a state, the greater the complexity and its costs. Therefore, cost levels 1 and 4 are the larger than cost levels 2 and 3. According to difficulty in management and cost level, countermeasures are required with respect to aiming to reduce or avoid complexity by corrective and preventive actions, improved communication and continuous training from a point of view of complexity management. The cost value for "in control" state (ICS) is zero (or very near zero) and there is no need to take any corrective action in this case study. However, it can be still improved by some actions to manage better.
Two statements I and II are considered for the complexity measurement. Statement I represents the original frequencies values and statement II represents the exchanged frequencies values to show the superiority of the new proposed complexity measure. Based on the calculation of the corresponding frequencies for each state interval and their probability distributions in the system, classical and new proposed structural complexity are calculated by equations 2 and 5 and operational complexity by equations 3 and 6. The results are seen in table 4. The deviation values $d_{ij}$ are considered mid range of the state intervals in equations 5 and 6.

| **Complexity Results of Actual-Scheduled Demand** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **State** | | **Frequency** | | **Probability** | | **Complexity/ Entropy** | | **Complexity/ Entropy** | |
| **Description** | **Interval** | **(I)** | **(II)** | **(I)** | **(II)** | **(I)** $H^{I}(s) = -\sum_{i=1}^{M}\sum_{j=1}^{N} p_{ij}\log_2 p_{ij}$ | | **(II)** $H^{II}(s) = -\sum_{i=1}^{M}\sum_{j=1}^{N} [\log_2 p_{ij}] d_{ij} p_{ij}$ | |
| | | | | | | **Classical** | **New** | **Classical** | **New** |
| ICS | 0 | 4 | 4 | 0,20 | 0,20 | 0,00 | 0,00 | 0,00 | 0,00 |
| OCS1 | +6 ≤ x ≤+10 | 3 | 3 | 0,15 | 0,15 | 0,41 | 3,28 | 0,41 | 3,28 |
| OCS2 | +1 ≤ x ≤ +5 | 2 | 2 | 0,10 | 0,10 | 0,33 | 1,00 | 0,33 | 1,00 |
| OCS3 | -5 ≤ x ≤ -1 | 7 | 4 | 0,35 | 0,20 | 0,53 | 1,59 | 0,46 | 1,39 |
| OCS4 | -10 ≤ x ≤ -6 | 4 | 7 | 0,20 | 0,35 | 0,46 | 3,72 | 0,53 | 4,24 |
| Structural Complexity | | | | | | 1,74 | 9,59 | 1,74 | 9,91 |
| Operational Complexity | | | | | | 1,39 | 7,67 | 1,39 | 7,93 |

Table 4. Complexity values of actual-scheduled demand.

In order to illustrate the superiority of the new proposed measure, a small change on the data is considered. Therefore, the frequency value, (7) of OCS3 ("-5 ≤ x ≤ -1") is exchanged with the value (4) of OCS4 ("-10 ≤ x ≤ -6") from the data of statement I, (highlighted by italic in statement II) and complexity values for exchanged values (statement II) are calculated again according to classical and new proposed approaches which are shown in table 4.

According to outcome of the results, classical entropy approaches do not indicate any change on results after the frequency exchange. However, the new proposed complexity measures indicate some changes on the results due to the deviation value from the expected value $(d_{ij})$.

Although the classical complexity measures do not take into consideration the deviation value from the expected value, the new proposed approach is considered with deviation value. The same probability values have the same entropy/complexity values thus the entropy is only a function of probability of different states. The new proposed measure discerns the states which are more under control than others. It can be a better indicator for complexity in supply chains. I.e. situations that are very far from being "under control" are evaluated worse as compared with those being not so far from "under control", even if their probabilities are the same. Furthermore, more divergence to an expected value (being under control state) means more difficulty to bring complexity under control and this difficulty leads to higher costs (Isik, 2010). Therefore, it is recommended that the new proposed entropic measurement is better than the classical measurement with respect to analyzing measurement results on manufacturing cost.

## 6. Conclusions

Managing increasing complexity in manufacturing is absolutely necessary to companies to compete better in global market. In order to manage complexity effectively and efficiently, it is recommended that complexity has to be defined, measured, analyzed, reduced and avoided. This study presents all of these management strategies and especially concentrates on measurability of the complexity by using Shannon's information theory. This study proposes a modification of Shannon entropy for measurement of a system complexity and proves that Shannon's entropy measure and its use in manufacturing have a drawback. In their work complexity/entropy is only a function of probability of different states. However, Isik, (2010) proposes that it is not sufficient to analyze complexity, because each state has its own complexity level in a system which has to be considered. Therefore two new complexity measures (structural and operational) are modified to analyze complexity.

## 7. References

Calinescu, A., et al., 2000. Complexity in manufacturing: an information theoretic approach. In: I.P. McCarthy and T. Rakotobe-Joel, eds. Proceedings of the conference on complexity and complex systems in industry, 19–20 September, University of Warwick, Warwick, 30–44.

Calinescu, A., et al. 2001. Classes of complexity in manufacturing. 17th national conference on manufacturing research, 4–6 September, University of Cardiff, Cardiff, 351–356.

Deshmukh, A.V., Talavage, J.J. and Barash, M.M., 1992. Characteristics of part mix complexity measure for manufacturing systems. IEEE international conference on systems, man and cybernetics, 18–21 October, New York, USA, 1384–1389.

Deshmukh, A.V., Talavage, J.J., and Barash, M.M., 1998. Complexity in manufacturing systems. Part 1: analysis of static complexity. IIE Transactions, 30 (7), 645–655.

Frizelle, G. and Woodcock, E., 1995. Measuring complexity as an aid to developing operational strategy. International Journal of Operations and Production Management, 15 (5), 26–39.

Gove, P.B., 1986. Complexity. Webster's third new international dictionary of the English language unabridged. Massachusetts, USA: Merriam-Webster-Verlag.

Hoyle, D., 2009. ISO 9000 Quality Systems Handbook. Butterworth-Heinemann, Oxford, UK.

Isik, F. 2010. An entropy-based approach for measuring complexity in supply chains. International Journal of Production Research, 48 (12), 3681 – 3696.

Lee, H.L., Padmanabhan, V. and Whang, S., 1997a. The bullwhip effect in supply chains. Sloan Management Review, 38 (3), 93-102.

Lee, H.L., Padmanabhan, V. and Whang, S., 1997b. Information distortion in a supply chain: The bullwhip effect. Management Science, 43 (4), 546-558.

Makui A. and Aryanezhad M. B., 2003. A new method for measuring the static complexity in manufacturing, Journal of the Operational Research Society, 54(5), 555-557.

Martin, J. W. (2007). Lean Six Sigma for supply chain management: The 10-step solution process. The McGraw-Hill Companies, Inc. New York, NY.

Martínez-Olvera, C. 2008. Entropy as an assessment tool of supply chain information sharing. European Journal of Operational Research, 185 (1), 405-417.

Milgate, M., 2001. Supply chain complexity and delivery performance: an international exploratory study. Supply Chain Management: An International Journal, 6 (3), 106–118.

Montgomery, C.D., Jennings, C.L., Kulahci, M., 2008. Introduction to Time Series Analysis and Forecasting (Wiley Series in Probability and Statistics). John Wiley & Sons, Inc., Hoboken, NJ, USA.

Ronen, B. and Karp, R., 1994. An information entropy approach to the small-lot concept. IEEE Transactions on Engineering Management, 41 (1), 89–92.

Sivadasan, S., et al., 2002. An information-theoretic methodology for measuring the operational complexity of supplier–customer systems. International Journal of Operations and Production Management, 22 (1), 80–102.

Sivadasan, S., et al., 2006. Advances on measuring the operational complexity of supplier–customer systems. European Journal of Operational Research, 171 (1), 208–226.

Shannon, C.E., 1948. A mathematical theory of communication. Bell System Technical Journal, 27, 379–423.

Shannon, C.E., Weaver, W., 1949. The Mathematical Theory of Communication. University of Illinois Press, Chicago, IL.

Wilding, R., 1998. The supply chain complexity triangle: uncertainty generation in the supply chain. International Journal of Physical Distribution and Logistics Management, 28 (8), 599–616.

Yao, D.D., 1985. Material and information flows in flexible manufacturing systems. Material Flow, 2, 143–149.

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# A Multi-Agent Model for Supply Chain Ordering Management: An Application to the Beer Game

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## 1. Introduction

The American Production and Inventory Control Society Dictionary defines the term supply chain (SC) as "the process from the initial raw materials to the ultimate consumption of the finished product linking across supplier–user companies." Supply chain management (SCM) literature covers wide range of areas such as logistics, production, scheduling, facility location, procurement, inventory management, ordering management, and so on. Due to the increasing competition in today's global market, business enterprises are forced to improve their supply chains to reduce inventory cost and enhance customer service levels (Wang & Shu, 2005; Giannoccaro, 2003).

Supply chain ordering management (SCOM), which is the main concern of this book chapter is an integrated approach to determine the ordering size of each actor of SC to the upstream actor aiming to minimize inventory costs of the whole supply chain. SCOM is focused on the demand of the chain aiming to reduce inventory holding costs, lower slacks, improve customer services, and increase the benefits throughout the entire supply chain (Chaharsooghi et al., 2008).

The observed performance of human beings operating supply chains, whether in the field or in laboratory settings, is usually far from optimal from a system-wide point of view (Lee & Whang, 1999; Petrovic, 2008). This may be due to lack of incentives for information sharing, bounded rationality, or possibly the consequence of individually rational behaviour that works against the interests of the group. In a few cases, the researchers' focus is placed on the coordination and integration of inventory policies between more than three stages (Kimbrough et al., 2002; Mahavedan et al., 1997; Petrovic et al., 1999; Wang & Shu, 2005). When there is no coordination among supply chain partners, each entity makes decision based on its own criteria, which results in local optimization as opposed to global optimum.

So called Beer game (Sterman, 1989) is a well-known example of supply chain which has attracted much attention from practitioners as well as academic researchers. Optimal parameters of the beer game ordering policy, when customers demand increases, have been analyzed in two different situations. It has been shown that minimum cost of the chain (under conditions of the beer game environment) is obtained when the players have different ordering policies rather than a single ordering policy (Strozzi et al., 2007). Indeed, most of previous works on order policy of beer game use genetic algorithms as optimization technique (Kimbrough et al., 2002; Strozzi et al., 2007).

One ordering policy based on genetic algorithm under conditions of the Beer game environment was introduced (Kimbrough et al., 2002); we call that GA-based algorithm in this chapter. GA-based algorithm has some degrees of freedom contrary to 1-1 algorithm; In the GA-based algorithm, each actor of chain can order based on its own rule and learns its own ordering policy in coordination with other members with the aim of minimizing inventory costs of the whole supply chain.

One limitation of the GA-based algorithm is the constraint of fixed ordering rule for each member through the time. An attempt to mitigate the problem of fixed ordering rules was initiated in (Chaharsooghi et al., 2008), in this study a reinforcement learning model is applied for determining beer game ordering policy. The RL model enables agents to have different rules throughout the time. In this book chapter we try to extract multiple rules for each echelon in the supply chain using Genetic Algorithm.

This book chapter can be viewed as a contribution to the understanding of how to design learning agents to discover insights for complicated systems, such as supply chains, which are intractable when using analytic methods. In this chapter, the supply chain is considered as a combination of various multi-agent systems collaborating with each other. Thus, SCOM can be viewed as a multi-agent system, consisting of ordering agents. Each ordering agent tries to make decisions on ordering size of the relevant echelon by considering the entire supply chain. Agents interact and cooperate with each other based on a common goal. For example, in a linear supply chain with four echelons (as considered in this chapter), there are four ordering agents in SCOM system, each of which is responsible for ordering decisions in its particular echelon. The main objective of ordering agents is to minimize long-term system-wide total inventory cost of ordering from immediate supplier. This is a complex task because of the uncertainty embedded in the system parameters (e.g. customer demand and lead-times) and demand amplification effect (Forrester, 1961), known as 'bullwhip effect'(Lee & Wu, 2006; Fazel Zarandi & Avazbeigi ,2008; Fazel Zarandi et al., 2009).

Throughout this study, we use findings from the management science literature to benchmark the performance of our agent-based approach. The purpose of the comparison is to assess the effectiveness of an adaptable or dynamic order policy that is automatically managed by computer programs—artificial agents. Also the results of the proposed model are compared with two other existing methods in the literature (Chaharsooghi et al., 2008; Kimbrough et al., 2002).

The rest of the book chapter is organized as follows. In section 2, the proposed GA for multi-agent supply chain is described in detail. In section 3, the method is applied on different cases and is compared with other models in the literature. Also in this section, the results are discussed. Finally in the last section, conclusions are summarized.

## 2. Genetic algorithm with local search for multi-supply chain

### 2.1 Genetic Algorithm Pseudo Code

Genetic algorithms, originally called genetic plans, were initiated by Holland, his colleagues, and his students at the University of Michigan in the 1970s as stochastic search techniques based on the mechanism of natural selection and natural genetics, have received a great deal of attention regarding their potential as optimization techniques for solving discrete optimization problems or other hard optimization problems (Masatoshi, 2002).

## 2.2 Representation of ordering policies in GA

In the proposed GA, each rules set (ordering policy) is encoded using binary system. In Fig. 2, the encoding schema is demonstrated. Each echelon in the supply chain has *w* rules. All rules are represented in binary system with *NumberOfBytes* cells which *NumberOfBytes* is a parameter of the model. The first cell in each echelon rule, stores the sign of the rule. 1 is for positive and 0 is for negative. These cells are distinguished with grey colour. The next *NumberOfBytes-1* bits represent how much to order.

1. Initialization. A certain number of rules (Ordering Policies) are randomly generated to form generation 0.
2. Pick the first binary rule from the current generation and decode the chosen rule to obtain the decimal ordering rules.
3. Agents play the Beer Game according to their current decimal rules.
4. Repeat step (3), until the game period (say 35 weeks) is finished.
5. Calculate the total cost for the whole team and assign fitness value to the current rule.
6. Pick the next rule from the current generation and repeat steps (3), (4) and (5) until the performance of all the rules in the current generation have been evaluated.
7. Use GA with local search to generate a new generation of rules and repeat steps (2) to (6) until the maximum number of generation is reached

Fig. 1. The pseudo code of the proposed GA

*W* rules –instead of one rule– enable each agent to have a more adaptive and dynamic behaviour. The effect of different *W*'s on system objective function is also studied in next sections.

| ***Window Basis (w)*** | ***Echelon 1 (Agent 1)*** | | | | | ***Echelon 2 (Agent II)*** | | | | | ***Echelon 3 (Agent III)*** | | | | | ***Echelon 4 (Agent IV)*** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rule 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| Rule 2 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| . . . | . . . | | | | | . . . | | | | | . . . | | | | | . . . | | | | |
| Rule w-1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| Rule w | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |

Fig. 2. Encoding Schema

When it is needed to run a supply chain using a specific ordering policy, first it is mandatory that the chromosome of the ordering policy –similar to that shown in Fig. 2– decoded to decimal system. Two examples of decoding procedure are shown in Fig. 3.

| | | | | | | |
|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 1 | 1 | → | +13 |
| 0 | 1 | 1 | 0 | 0 | → | -3 |

Fig. 3. Decoding Example

### 2.3 Objective function

In the MIT Beer Game, each player incurs both inventory holding costs and penalty costs if the player has a backlog. We now derive the total inventory cost function of the whole supply chain. We begin with the needed notation. In the MIT Beer Game:

- $N$ is the number of players and is 4
- $IN_i(t)$ is the net inventory of player $i$ at the beginning of period $t$
- $C_i(t)$ is the cost of player $i$ at period $t$
- $H_i$ is the inventory holding cost of player $i$, per unit per period (e.g., in the MIT Beer Game, US$1 per case per week)
- $P_i$ is the penalty/backorder cost of player $i$, per unit per period (e.g., in the MIT Beer Game, US$2 per case per week)
- $S_i(t)$ is the new shipment player $i$ received in period $t$
- $D_i(t)$ is the demand received from the downstream player in week $t$ (for the Retailer, the demand from customers)

According to the temporal ordering of the MIT Beer Game, each player's cost for a given time period, e.g., a week, can be calculated as following: If $IN_i(t) \geq 0$, then $C_i(t)=IN_i(t)\times H_i$ else $C_i(t)=|IN_i(t)|\times P_i$, where $IN_i(t)=IN_i(t-1)+S_i(t)-D_i(t)$ and $S_i(t)$ is a function of both information lead time and physical lead time. The total cost for the supply chain after $M$ periods is

$$\sum_{i=1}^{N}\sum_{t=1}^{M} C_i(t) \tag{1}$$

### 2.4 GA operators

*1) Selection Operator:* In the proposed GA, for selection of the chromosomes from the current population, the tournament method is chose. In this method, at each time two chromosomes are selected randomly from the current population and then the chromosome with the minimum cost will be selected as a member of the next population. This process continues until the required chromosomes are chosen for the new population.

*2) Mutation Operator:* Mutation in the proposed GA, includes the replacement of the zero-cells with one-cells and vice versa. The Mutation type indicates that how many cells should change.

*3) Crossover Operator:* Crossover operator randomly chooses $2*M$ columns ($M$: Crossover Type) from the randomly chosen chromosome from the current population. Then, the position of two columns changes in the selected chromosome.

*4) Rearrangement Operator as Local Search of GA:* Rearrangement operator, first randomly choose a chromosome from the chromosomes selected by the Selection method, then choose two cells randomly and change the positions of those cells randomly. If the new chromosome had a smaller cost function, then the operator adds the new chromosome to the new population. Otherwise, the operator repeats the process until an improvement occurs.

## 3. Results and conclusions

To validate the proposed system, some experiments are designed. The experiments and their results are summarized in Tables 1 and 2. In the following, each experiment is described in detail.

| Experiment | Number Of Bytes | W | Best Ordering Policy | Lead Time |
|---|---|---|---|---|
| 1 | 4 | 1 | [0,0,0,0] | 2 for all echelons |
| 2 | 5 | 1 | [0,1,2,2] | 2 for all echelons |
| 3 | 5 | 2 | [1,0,6,0;1,8,4,9] | 2 for all echelons |
| 4 | 5 | 4 | [0,2,12,4;4,8,5,8;0,4,4,8;0,9,3,2] | 2 for all echelons |
| 5 | 5 | 1 | [0,0,1,0] | Unifrom [0-4] |
| 6 | 5 | 2 | [0,0,1,4;0,0,2,0] | Unifrom [0-4] |
| 7 | 5 | 3 | [0,0,1,0;0,0,2,0;0,1,2,4] | Unifrom [0-4] |
| 8 | 5 | 4 | [0,0,0,7;0,0,9,9;0,6,4,0;0,0,0,1] | Unifrom [0-4] |
| 9 | 5 | 5 | [0,0,10,1;0,0,4,8;0,0,2,2;0,1,6,5;0,01,3] | Unifrom [0-4] |
| 10 | 5 | 4 | [0,1,2,15;0,3,8,0;0,2,4,10;0,1,8,3] | Unifrom [0-4] |
| 11 | 5 | 4 | [0,0,4,0;0,0,6,8;0,0,4,4;0,0,9,0] | Unifrom [0-4] |
| 12 | 5 | 2 | [0,0,3,7;0,0,5,3] | Unifrom [0-4] |
| 13 | 4 | 1 | [1,1,1,1] | 2 for all echelons |
| 14 | 4 | 2 | [0,1,4,2;0,5,2,3] | 2 for all echelons |
| 15 | 4 | 3 | [0,3,0,5;0,2,5,1;0,4,5,3] | 2 for all echelons |
| 16 | 4 | 4 | [0,1,3,3;1,3,5,6;0,2,6,6;0,0,7,3] | 2 for all echelons |

Table 1. Best ordering policies achieved by the method

In the first experiment, the performance of the multi-agent system is tested under deterministic conditions. The customer demands four cases of beer in the first 4 weeks, and then demands eight cases of beer per week starting from week 5 and continuing until the end of the game (35 weeks). When facing deterministic demand with penalty costs for every player (The MIT Beer Game), the optimal order for every player is the so-called ‘‘pass order,’’ or ‘‘one for one’’ (1–1) policy—order whatever is ordered from your own customer. As the result shows (*[0, 0, 0, 0]*) we found that the artificial agents can learn the 1–1 policy consistently.

In the second experiment, we explored the case of stochastic demand where demand is randomly generated from a known distribution, uniformly distributed between *[0, 15]*. Lead time for all echelon is a constant value through the time and is 2. In this case the model is compared with (Kimbrough et al., 2002) as the result show, the model outperforms Kimbrough's model.

In experiment 3 and 4, the influence of window basis ($w$) on the objective function of the problem is studied. As it can be seen, more number of rules leads to smaller values of total cost. This supports the idea that more number of rules enables the agents to be more adaptive and flexible to the environmental changes.

| Experiment | Demand | Best Total Cost | Worst Total Cost | Average Total Cost | 1-1 Best Total Cost | GA Best Total | RL Best Total Cost |
|---|---|---|---|---|---|---|---|
| 1 | All the demands are 8 except 4 first weeks which is 4 | 400 | 400 | 400 | 400 | 400 | - |
| 2 | Uniform [0-15] | **<u>1536</u>** | 1586 | 1561 | 3890 | 1820 | - |
| 3 | Uniform [0-15] | 1514 | 1570 | 1548 | - | - | - |
| 4 | Uniform [0-15] | 1458 | 1545 | 1487 | - | - | - |
| 5 | Uniform [0-15] | **<u>2124</u>** | 2124 | 2124 | 7463 | 2555 | 2417 |
| 6 | Uniform [0-15] | 2030 | 2030 | 2030 | - | - | - |
| 7 | Uniform [0-15] | 2010 | 2067 | 2030 | - | - | - |
| 8 | Uniform [0-15] | 1979 | 2010 | 1992 | - | - | - |
| 9 | Uniform [0-15] | 2056 | 2234 | 2134 | - | - | - |
| 10 | Uniform [0-15] | **<u>1667</u>** | - | - | 5453 | 3109 | 3169 |
| 11 | Uniform [0-15] | **<u>1896</u>** | - | - | 8397 | 4156 | 4038 |
| 12 | Uniform [0-15] | **<u>1967</u>** | - | - | 7826 | 4330 | 4205 |
| 13 | *F(x) = \|Max Demand*sin(x.Π/Period)\|* | 793.715 | 793.715 | 793.715 | - | - | - |
| 14 | *F(x)= \|Max Demand*sin(x.Π/Period)\|* | 744.826 | 774.237 | 762.079 | - | - | - |
| 15 | *F(x)= \|Max Demand*sin(x.Π/Period)\|* | 779.689 | 799.455 | 789.174 | - | - | - |
| 16 | *F(x)= \|Max Demand*sin(x.Π/Period)\|* | 644.872 | 699.865 | 668.943 | - | - | - |

Table 2. Comparison of models with other models in the literature

In experiments 5 to 9, the model is evaluated under more challenging conditions. The demand and lead time are both nondeterministic and have distribution function uniform *[0, 15]* and *[0, 4]* respectively. The results are compared with 1-1 ordering policy (Chaharsooghi et al., 2008; Kimbrough et al., 2002). The best objective function achieved by the model is 1979 which is much smaller than (Chaharsooghi et al., 2008) results (2417). Again the positive effect of window basis can be seen as the number of window basis increases to some extent the best objective function value decreases. A trend stops at window basis equal to 5. This can be due to the exponential growth in the search space, which makes the search process so complex for GA (with the current encoding schema 25*5*4 = 2100 possible solutions exist).

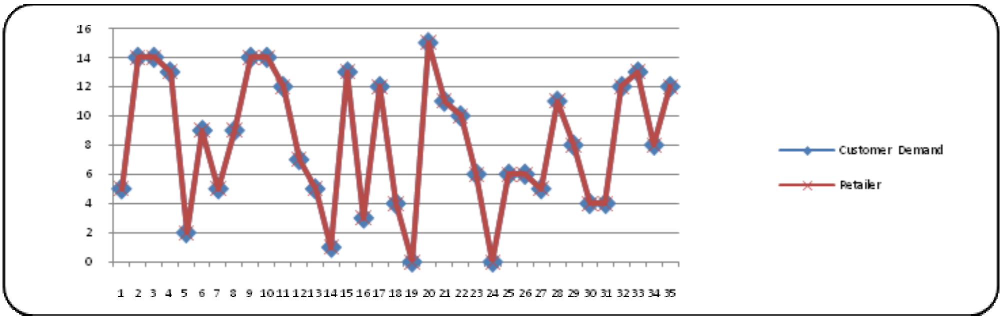


Fig. 4. Customer Demand in comparison with retailer

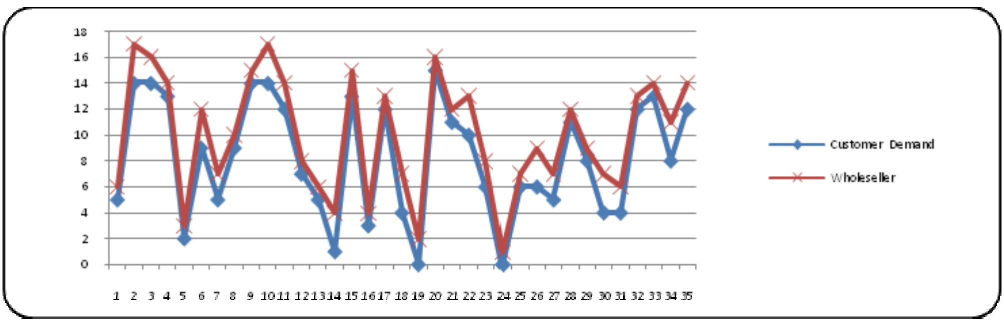


Fig. 5. Customer Demand in comparison with wholeseller

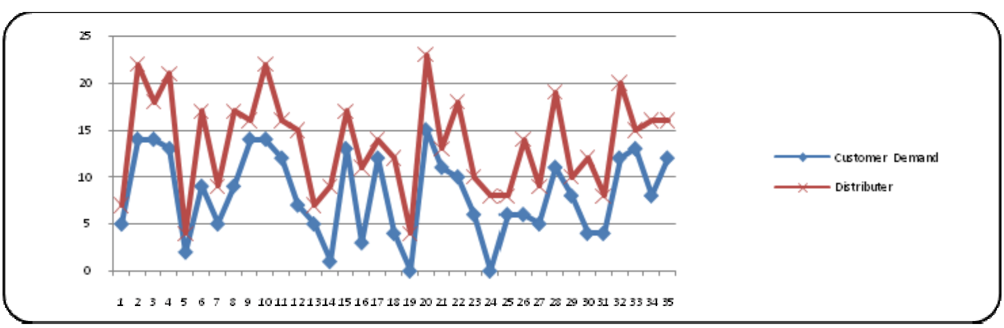


Fig. 6. Customer Demand in comparison with Distributer

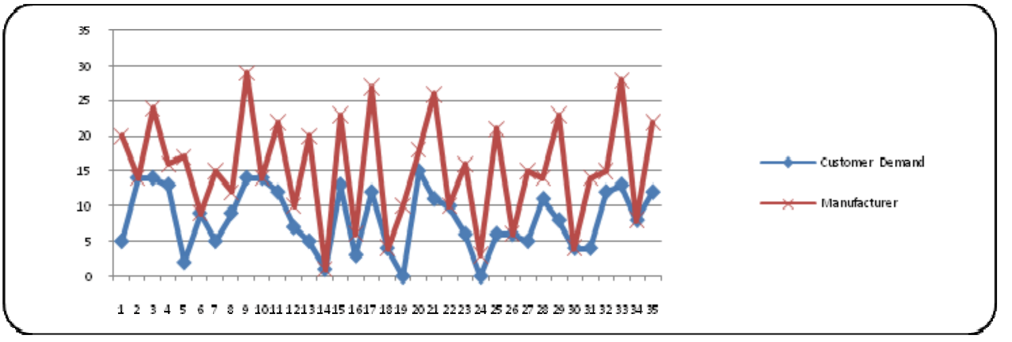


Fig. 7. Customer Demand in comparison with manufacturer

In experiments 10, 11 and 12, the proposed window basis model is again compared with 1-1 ordering policy. 1-1 ordering policy is described in (Kimbrough et al., 2002; Sterman, 1989). In all cases, the model has a better performance. The ordering values of four echelons base on the best ordering policy achieved by the model for experiment 10 are depicted in fig. 4, 5, 6 and 7.

In the last 4 experiments, the model is applied on a periodic function with the function of

$$F(x)=|MaxDemand*\sin(x.\Pi/Period)| \quad (2)$$

and the impact of different window basis is studied. in this function Max Demand is 7 and period is 8. As table 2 shows, models with window basis with the 2 multiples have a better performance.

It should be noted that in the first 12 experiments, the genetic population is 100, the number of generation is 400, the mutation, crossover and the rearrangement ration are 0.2. In the last four experiments, the genetic population is 300, the number of generation is 400, the crossover and mutation ratio are 0.3 and the rearrangement ratio is 0.2.

## 4. Conclusion

In this a new intelligent multi-agent system is proposed for determination of the best ordering policy in order to minimize the cost of supply chain.

The model is compared with previous models in the literature and as the results show, the model outperforms all the previous models.

The best ordering policy is obtained by a new genetic algorithm which is equipped with some local searches. One limitation of the previous presented GA-based algorithms is the constraint of fixed ordering rule for each member through the time. To resolve this problem a new concept –window- is introduced in this book chapter. Application of the window basis enables the agents to have different ordering rules throw the time. Experiment results prove that the new multi-agent system is capable of finding patterns in nondeterministic and periodic data both.

## 5. References


Chaharsooghi, S.K., Heydari, J. & Zegordi, S. H. (2008). A reinforcement learning model for supply chain ordering management: An application to the beer game. *Decision Support Systems*. Vol. 45, page numbers 949–959.

Fazel Zarandi, M.H. & Avazbeigi, M. (2008). A Fuzzy Logic Approach to prove Bullwhip Effect in Supply Chains, *Proceedings of AMERICA*, Toronto, ON., Canada.

Fazel Zarandi, M.H., Avazbeigi, M. & Turksen, I. B. (2009). An intelligent fuzzy Multi-Agent System for reduction of bullwhip effect in supply chains, *Proceedings of NAFIPS09*, Cincinnati, Ohio, USA.

Forrester, J. W. (1961). *Industrial Dynamics*, Cambridge, MIT Press, Massachusetts.

Giannoccaro, I., Pontrandolfo, P. & Scozzi, B. (2003). A fuzzy echelon approach for inventory management in supply chains. *European Journal of Operational Research,* Vol. 149, page numbers 185–196.

Kimbrough, S.O., Wu, D. J. & Zhong, F., 2002. Computers play the beer game: can artificial agents manage supply chains?. *Decision Support Systems*, Vol. 33, page numbers 323–333.

Lee, H. & Whang, S. (1999). Decentralized multi-echelon supply chains: incentives and information. *Management Science*, Vol. 45(5), page numbers 633– 640.

Lee, H. T. & Wu, J. C. (2006). A study on inventory replenishment policies in a two echelon supply chain system. *Computers & Industrial Engineering*, Vol. 51, page numbers 257–263.

Masatoshi, S. (2002). *Genetic Algorithms and Fuzzy Multiobjective Optimization,* (Operations Research Computer Science Interfaces Series), Massachusetts: Kluwer Academic Publishers.

Mahadevan, S., Marchalleck, N., Das, K. T. & Gosavi, A. (1997). Self-improving factory simulation using continuous-time average-reward reinforcement learning. *Proceedings of the 14th International Conference on Machine Learning*, page numbers 202–210.

Petrovic, D., Roy, R. & Petrovic, R. (1999). Modeling and simulation of a supply chain in an uncertain environment. *European Journal of Operational Research,* Vol. 109, page numbers 299–309.

Petrovic, D., Xie, Y., Burnham, K. & Petrovic, R. (2008). Coordinated control of distribution supply chains in the presence of fuzzy customer demand. *European Journal of Operational Research,* Vol. 185, page numbers 146–158.

Sterman, J. (1989). Modeling managerial behavior: misperceptions of feedback in a dynamic decision making experiment. *Management Science,* Vol. 35 (3), page numbers 321–339.

Strozzi, F., Bosch, J. & Zaldívar, J. M. (2007). Beer game order policy optimization under changing customer demand. *Decision Support Systems*, Vol. 42, page numbers 2153–2163.

Wang, J. & Shu, Y.-F. (2005). Fuzzy decision modeling for supply chain management. *Fuzzy Sets and Systems,* Vol. 150, page numbers 107–127.

Wang, J. & Shu, Y.-F. (2007). A possibilistic decision model for new product supply chain design, *Journal of Operational Research*, Vol. 177, page numbers 1044–1061

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# A Collaborative Vendor – Buyer Deteriorating Inventory Model for Optimal Pricing, Shipment and Payment Policy with Two – Part Trade Credit

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## 1. Introduction

The classical economic order quantity model of Wilson's was developed with the assumption that the buyer must pay off immediately on arrival of the goods in the inventory system. In fact, offering buyers to delays payment for goods received is considered as a sales promotional tool in the business world. With offer of trade credit, vendor increases sales, attracts more buyers and reduces on – hand stock level. Under this marketing strategy, the time of the buyer's capital tied up in stock reduced which eventually reduces the buyer's holding cost of finance. In addition, during this allowable credit period, the buyer can earn interest on the generated revenue. For the small – scale industries having a limited finance, the trade credit acts as a source of short – term funds. Goyal (1985) developed an economic order quantity model with a constant demand rate under the condition of permissible delay in payments. After that numbers of variants of the trade credit problem have been analyzed. For example Shah (1993a, 1993b), Aggarwal and Jaggi (1995), Kim et al. (1995), Jamal et al. (1997), Shinn (1997), Chu et al. (1998), Chen and Chung (1999), Chang and Dye (2001), Teng (2002), Chung and Huang (2003), Shinn and Hwang (2003), Chung and Liao (2004, 2006), Chung et al. (2005), Teng et al. (2005), Ouyang et al. (2005) and their cited references. For up – to day available literature on permissible delay period, refer to the article by Shah et al. (2010).

The above cited references assume that the vendor offer the buyer a "one – part" trade credit, i.e. the vendor offers a permissible delay period. If the account is settled within this period, no interest is charged to the buyer. As a result, with no incentive for making early payments, and earning interest through generated revenue during the credit period, the buyer postpones payment up to the last day of the permissible period offered by the vendor. As an outset, from the vendor's end, offering trade credit leads to delayed cash inflow and increases the risk of cash flow shortage and bad debt. To increase cash inflow and reduce the risk of a cash crisis and bad debt, the vendor may offer a cash discount to attract the buyer to pay for goods earlier. i.e. the vendor offers a "two – part" trade credit to the buyer to balance the trade off between delayed payment and cash discount. For example, under an agreement, the vendor agrees to a 2% discount to the buyer's purchase price if payment is made within 10 days. Otherwise, full payment is to be settled within 30 days after the

delivery. In financial management, this credit is denoted as "2|10 net 30". If the vendor only offers the buyer a 30 days credit period, i.e. "one – part" trade credit, then this is denoted as "net 30" (Brigham, 1995). The papers related to this credit policy are by Lieber and Orgler (1975), Hill and Riener (1979), Kim and Chung (1990), Arcelus and Srinivasan (1993), Arcelus et al. (2001, 2003). Ouyang et al. (2002), Chang (2002) and Huang and Chung (2003) developed inventory models when two – credit policy is offered by the vendor to the buyer.
The above cited model's are derived either from the vendor's or the buyer's end. However, the two players may have their own goals. The decision taken from the buyer's end may not be agreeable to vendor and vice versa. Lee et al. (1997) argued that without coordinated inventory management in the supply chain may result in excessive inventory investment, revenue reduction and delays in response to customer satisfaction. Therefore, the joint discussion is more beneficial as compared to the individual decision. Goyal (1976) first developed a single vendor – single buyer integrated inventory model. Banerjee (1986) extended Goyal's (1976) model under assumption of a lot – for – lot production for the vendor. Later, Goyal (1988) established that if vendor produces an integer multiple of the buyer's purchase quantity then the inventory cost can be reduced. Lu (1995) generalized Goyal's (1988) model by relaxing the assumption that the vendor can supply to the buyer only after finishing the entire lot size. Bhatnagar et al. (1993), Goyal (1995), Viswanathan (1998), Hill (1997, 1999), Kim and Ha (2003), Kalle et al. (2003), Li and Liu (2006) developed more batching and shipping policies for an integrated inventory model. However, these articles did not incorporate the effect of trade credit on the integrated optimal decision. Abad and Jaggi (2003) developed a vendor – buyer integrated model assuming lot – for – lot production under a permissible delay in payments. Later, Shah (2009) extended Abad and Jaggi's(2003) model for deteriorating items. In both the articles, the vendor offered a "one – part" trade credit to the buyer.
Ho et al. (2008) studied impact of a "two – part" trade credit policy in the integrated inventory model. This model assumed that units in inventory remain of 100% utility during the cycle time. However, the products like medicines and drugs, food products, vegetables and fruits, fashion goods, x – ray films etc loose its 100% utility in due course of time. In this chapter, we analyze effect of a "two – part" trade credit policy in the integrated inventory model when units are subject to constant deterioration and demand is retail price sensitive. The supplier offers the buyer a cash discount if payment is made before an allowable period, and if the buyer does not pay within the allowable period, the full account against purchases made before the delay payment due date. The joint profit is maximized with respect to the optimal payment policy, selling price, lot – size and the number of shipments from vendor to buyer in one production run. An algorithm is developed to determine the optimal policy. Numerical examples are given to validate the theoretical results. The sensitivity analysis of the optimal solutions with respect to model parameters is also carried out.

## 2. Assumptions and notations

The proposed model is formulated using the following assumptions and notations.

1. The integrated inventory system comprises of a single – vendor and single buyer for a single item.
2. Shortages are not allowed.
3. The inventory holding cost rates excluding interest charges for the vendor is $I_v$ and for the buyer is $I_b$.
4. To accelerate the cash inflow and reduce the risk of bad debt, the vendor offers a discount $\beta$ ($0 < \beta < 1$) off the purchase price, if the buyer settles the account within time $M_1$. Otherwise, the full account is due within time $M_2$, where $M_2 > M_1 \geq 0$.

5. The vendor's unit production cost is \$ $C_v$ and unit sale price is \$ $C_b$. The buyer's unit retail price is \$ P. Here $P > C_b > (1-\beta)C_b > C_v$ .
6. During the allowable credit period to the buyer, the vendor opts to give up an immediate cash inflow until a later date. Thus, the vendor endures a capital opportunity cost at a rate $I_{vo}$ during the time between delivery and payment of the item.
7. During period [$M_1$, $M_2$], a cash flexibility rate $f_{vc}$ is available to quantize the advantage of early cash income for the vendor.
8. During the credit period (i.e. $M_1$ or $M_2$), the buyer earns interest at a rate of $I_{be}$ on the revenue generated by selling the product.
9. The demand rate for the item is a decreasing function of the sale price and is given by $R(P) = aP^{-\eta}$ , where a > 0 is scaling demand, and η > 1 is a price – elasticity coefficient.
10. The capacity utilization "$\rho$" is defined as the ratio of the demand rate, R(P) to the production rate p(P), i.e. $\rho$ = R(P)/p(P) where ρ < 1 and is fixed.
11. The buyer's cycle time is T, order quantity is Q per order.
12. The buyer's ordering cost per order is $A_b$.
13. During the production period, the vendor produces in batches of size nQ (where n is a positive integer) and incurs a batch set up cost $A_v$. After the production of first Q units, the vendor ships them to the buyer and then makes continuous shipping at every T-units of time until the vendor's inventory level depletes to zero.
14. The units in inventory deteriorate at a constant rate, $\theta$ ($0 < \theta < 1$). The deteriorated can neither be repaired nor replaced during the cycle time T.

## 3. Mathematical model

The inventory on hand depletes due to price – sensitive demand and deterioration of units. The rate of change of inventory at any instant of time 't' is governed by the differential equation,

$$\frac{dI(t)}{dt} = -R(P) - \theta I(t); \qquad 0 \le t \le T$$

with initial condition I(0) = Q and boundary condition I(T) = 0. The solution of the differential equation is

$$I(t) = \frac{R(P)}{\theta}\left\{e^{\theta(T-t)} - 1\right\}; \qquad 0 \le t \le T$$

and procurement quantity, Q is

$$Q = I(0) = \frac{R(P)}{\theta}\left\{e^{\theta T} - 1\right\}$$

### 3.1 Vendor's total profit per unit time

During each production run, the vendor produces in batches of the size nQ with a batch set up cost $A_v$. The cycle length of the vendor is nT- units. Therefore, the vendor's set up cost per unit time is ($A_v$/nT). Using method given by Joglekar (1988), with the unit production cost $C_v$, the inventory holding cost rate excluding interest charges $I_v$ and capital opportunity cost per $ per unit time $I_{vo}$, the vendor's carrying cost per unit time is

$$\frac{C_v(I_v+I_{vo})}{T}\left[(n-1)(1-\rho)+\rho\right]\int_0^T I(t)dt$$
$$=\frac{C_v(I_v+I_{vo})}{T}R(P)\left[(n-1)(1-\rho)+\rho\right]\left[e^{\theta T}-\theta T-1\right]$$

For each unit of item, the vendor charges $\left(\left(1-K_j\beta\right)C_b\right)$ if the buyer pays at time $M_j$,j=1,2, $K_1$ = 1 and $K_2$ = 0. The opportunity cost at the finance rate $I_{vo}$ per unit time for offering trade credit is $\left(\left(1-K_j\beta\right)C_b\cdot I_{vo}\cdot M_j\cdot Q/T\right)$. However, if the buyer pays at $M_1$ - time, during $M_2$ – $M_1$ the vendor can use the revenue ((1 – $\beta$)$C_b$) to avoid a cash flow crisis. The advantage gain per unit time from early payment at a cash flexibility rate $f_{vc}$ is $\left(K_j\cdot(1-\beta)C_b\cdot f_{vc}\cdot(M_2-M_1)Q/T\right)$.

Thus, the vendor's total profit per unit time is the revenue generated plus the advantage from early payment minus production cost, set up cost, inventory holding cost and opportunity cost for offering trade credit.

$$\begin{aligned}TVP_j(n)=&\left(1-K_j\beta\right)C_b\frac{Q}{T}-C_v\frac{Q}{T}-\frac{A_v}{nT}\\&-\frac{C_v(I_v+I_{vo})R(P)}{\theta^2 T}\left[(n-1)(1-\rho)+\rho\right]\left[e^{\theta T}-\theta T-1\right]\\&-(1-K_j\beta)vI_{vo}M_j\frac{Q}{T}+K_j(1-\beta)C_b f_{vc}(M_2-M_1)\frac{Q}{T},\end{aligned}\tag{1}$$

$$j=1,2;\quad K_1=1,\quad K_2=0$$

### 3.2 Buyer's total profit per unit time

The buyer's ordering cost is $A_b$ for each order of Q – units, so the ordering cost per unit time is ($A_b$/T). The inventory holding cost excluding interest charges per unit time is

$$\left(\frac{\left(1-K_j\beta\right)C_b I_b R(P)}{\theta^2 T}\left[e^{\theta T}-\theta T-1\right]\right)$$

On the basis of length of the payment time, two cases arise: (i) T< $M_j$ and (ii) T ≥ $M_j$ ; j=1,2 These two cases are shown in Figure 1.

**Case: (i)** T < $M_j$; j = 1, 2.

Here, the buyer's cycle time ends before the payment time. So buyer does not pay opportunity cost for the items kept in stock. The buyer earns interest at the rate of $I_{be}$ on the revenue generated; hence, the interest earned per unit time is,

$$\frac{1}{T}\left[PI_{be}\int_0^T R(P)tdt+PI_{be}Q(M_j-T)\right]=\frac{PI_{be}R(P)}{T}\left[\frac{T^2}{2}+\frac{1}{\theta}\left(e^{\theta T}-1\right)\left(M_j-T\right)\right]$$

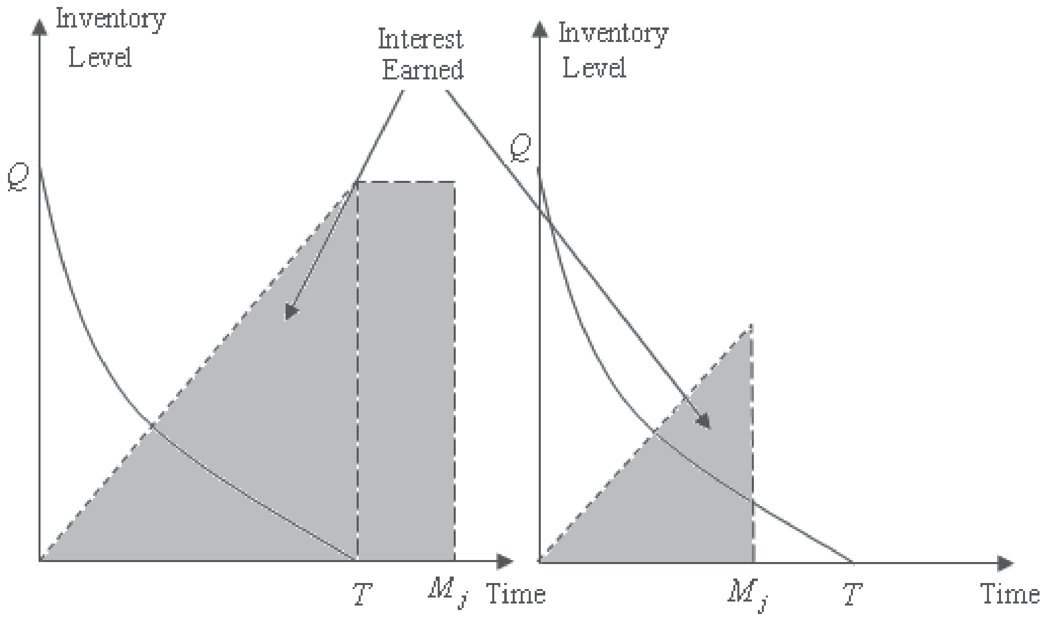


Fig. 1. Inventory and interest earned for the buyer under trade credit

**Case: (ii)** T ≥ Mj; j = 1, 2

In this case, the buyer's allowable payment time ends on or before the inventory is depleted to zero. The interest earned per unit time is

$$\frac{PI_{be}}{T}\int_{0}^{M_j} R(P)tdt = \frac{PI_{be}R(P)M_j^2}{2T}.$$

After the due date $M_j$, the buyer pays interest charges at the rate of $I_{bc}$. Therefore, the interest charges payable per unit time is,

$$\frac{\left(1-K_j\beta\right)C_bI_{bc}}{T}\int_{M_j}^{T} I(t)dt = \frac{\left(1-K_j\beta\right)C_bI_{bc}R(P)}{\theta^2 T}\left[e^{\theta(T-M_j)}-\theta(T-M_j)-1\right]$$

The buyer purchase cost per unit time is ((1 – $K_j\beta$) $C_b$ Q/T) and revenue generated per unit time is (PQ/T). Therefore, the buyer's total profit per unit time is revenue generated plus interest earned minus the total cost comprises of the purchase cost, ordering cost, inventory holding cost excluding interest charges and interest charges payable, i.e.

$$TBP_j(P,T) = \begin{cases} TBP_{j1}(P,T) & T < M_j \\ TBP_{j2}(P,T) & T \ge M_j \end{cases}; j = 1,2 \tag{2}$$

Where

$$TBP_{j1}(P,T)=\frac{PQ}{T}-\left(1-K_j\beta\right)\frac{C_bQ}{T}-\frac{A_b}{T}$$
$$-\frac{\left(1-K_j\beta\right)C_bI_bR(P)}{\theta^2T}\left[e^{\theta T}-\theta T-1\right] \tag{3}$$
$$+\frac{PI_{be}R(P)}{T}\left[\frac{T^2}{2}+\frac{1}{\theta}\left(e^{\theta T}-1\right)\left(M_j-T\right)\right]$$

And

$$TBP_{j2}(P,T)=\frac{PQ}{T}-\left(1-K_j\beta\right)\frac{C_bQ}{T}-\frac{A_b}{T}$$
$$-\frac{\left(1-K_j\beta\right)C_bI_bR(P)}{\theta^2T}\left[e^{\theta T}-\theta T-1\right]+\frac{PI_{be}R(P)M_j^2}{2T} \tag{4}$$
$$-\frac{\left(1-K_j\beta\right)C_bI_{bc}R(P)}{\theta^2T}\left[e^{\theta(T-M_j)}-\theta(T-M_j)-1\right]$$

**3.3 The joint total profit per unit time**

When the buyer and vendor opt for the joint decision, the joint total profit per unit time is,

$$TP_j(n,P,T)=\begin{cases}TP_{j1}(n,P,T) & T<M_j\\ TP_{j2}(n,P,T) & T\geq M_j\end{cases};j=1,2 \tag{5}$$

Where

$$TP_{j1}(n,P,T)=TVP_j(n)+TBP_{j1}(P,T)$$
$$=\left(P-C_v\right)\frac{Q}{T}-\frac{1}{T}\left(\frac{A_v}{n}+A_b\right)-\frac{\left(1-K_j\beta\right)C_bI_{vo}M_jQ}{T}$$
$$+\frac{C_v(I_v+I_{vo})R(P)}{\theta^2T}\left[(n-1)(1-\rho)+\rho\right]\left[e^{\theta T}-\theta T-1\right]$$
$$+\frac{K_j(1-\beta)C_bf_{vc}(M_2-M_1)Q}{T} \tag{6}$$
$$+\frac{PI_{be}R(P)}{T}\left[\frac{T^2}{2}+\frac{1}{\theta}\left(e^{\theta T}-1\right)\left(M_j-T\right)\right]$$
$$-\frac{\left(1-K_j\beta\right)C_bI_bR(P)}{\theta^2T}\left[e^{\theta T}-\theta T-1\right]$$
$$+\frac{PI_{be}R(P)}{T}\left[\frac{T^2}{2}+\frac{1}{\theta}\left(e^{\theta T}-1\right)\left(M_j-T\right)\right]$$

And

$$\begin{aligned}TP_{j2}(n,P,T) &= TVP_j(n) + TBP_{j2}(P,T)\\ &= (P - C_v)\frac{Q}{T} - \frac{1}{T}\left(\frac{A_v}{n} + A_b\right) - \frac{\left(1-K_j\beta\right)C_b I_{vo} M_j Q}{T}\\ &-\frac{C_v(I_v + I_{vo})R(P)}{\theta^2 T}\left[(n-1)(1-\rho)+\rho\right]\left[e^{\theta T} - \theta T - 1\right]\\ &+\frac{K_j(1-\beta)C_b f_{vc}(M_2 - M_1)Q}{T} + \frac{PI_{be}R(P)M_j^2}{2T}\\ &-\frac{\left(1-K_j\beta\right)C_b I_b R(P)}{\theta^2 T}\left[e^{\theta T} - \theta T - 1\right]\\ &-\frac{\left(1-K_j\beta\right)v I_{bc} R(P)}{\theta^2 T}\left[e^{\theta(T-M_j)} - \theta(T-M_j) - 1\right]\end{aligned} \tag{7}$$

Assuming $\theta$ to be very small, ignoring $\theta^2$ and its higher powers, we get

$$\begin{aligned}TP_{j1} &= (P - c_v)R(P)\left(1+\frac{\theta T}{2}\right) - \frac{\left(1-K_j\beta\right)C_b I_b R(P) T}{2}\\ &-\frac{C_v(I_v + I_{vo})R(P)\left[(n-1)(1-\rho)+\rho\right]T}{2} + \frac{PI_{be}R(P)}{T}\left[M_j\left(1+\frac{\theta T}{2}\right) - \frac{T}{2}\right]\\ &-\left(1-K_j\beta\right)C_b I_{vo} M_j R(P)\left(1+\frac{\theta T}{2}\right) - \frac{1}{T}\left(\frac{A_v}{n} + A_b\right)\\ &+K_j(1-\beta)C_b f_{vc}(M_2 - M_1)R(P)\left(1+\frac{\theta T}{2}\right)\end{aligned} \tag{6a}$$

Also

$$\begin{aligned}TP_{j2} &= (P - C_v)R(P)\left(1+\frac{\theta T}{2}\right) - \left(1-K_j\beta\right)C_b I_{vo} M_j R(P)\left(1+\frac{\theta T}{2}\right)\\ &-\frac{C_v(I_v + I_{vo})R(P)\left[(n-1)(1-\rho)+\rho\right]T}{2} - \frac{1}{T}\left(\frac{A_v}{n} + A_b\right)\\ &+K_j(1-\beta)C_b f_{vc}(M_2 - M_1)R(P)\left(1+\frac{\theta T}{2}\right) + \frac{PI_{be}R(P)M_j^2}{2T}\\ &-\frac{\left(1-K_j\beta\right)C_b(I_b + I_{bc})R(P)T}{2} - \left(1-K_j\beta\right)C_b I_{bc} R(P) M_j\\ &+\frac{\left(1-K_j\beta\right)C_b I_{bc} R(P) M_j^2}{2T}\end{aligned} \tag{7a}$$

The problem now is to compute the optimal values of n, P and T such that $TP_j$ (n, P, T); j=1, 2 in equation (5) is maximized.

## 4. Solution methodology

For fixed P and T, the second order partial derivative of equation (5) with respect to 'n' is, $\frac{\partial^2 TP_j(n,P,T)}{\partial n^2} = \frac{-2A_v}{n^3 T} < 0$ for j = 1, 2 suggest that $TP_j$ (n, P, T) is a concave function in 'n'. This guarantees that the search for the optimal shipment number n* is reduced to find a local optimal solution.

### 4.1 Determination of the optimal cycle time 'T' for any given 'n' and 'P'

For given n and P, the partial derivative of $TP_{j1}$ (n, P, T) in (6 – a) with respect to T, $\frac{\partial^2 TP_{j1}(n,P,T)}{\partial T^2} = -\frac{2}{T^3}\left(\frac{A_v}{n} + A_b\right) < 0$ suggests that $TP_{j1}$ (n, P, T) is a concave function in T. Hence, there exists unique value of T = $T_{j1}$(n, P) (say) which maximizes $TP_{j1}$(n, P, T). $T_{j1}$(n, P) can be obtained by setting $\frac{\partial TP_{j1}(n,P,T)}{\partial T} = 0$ and is given by,

$$T_{j1} = \sqrt{\frac{2\left(\frac{A_v}{n} + A_b\right)}{R(P)\left\{\begin{array}{l} C_v\left(I_v + I_{vo}\right)\left[(n-1)(\rho-1)+\rho\right] - (P - C_v)\theta \\ +\left(1-K_j\beta\right)C_b I_{vo} M_j \theta - K_j(1-\beta)C_b f_{vc}(M_2 - M_1)\theta \\ +\left(1-K_j\beta\right)C_b I_b + PI_{be}\left(1-\theta M_j\right) \end{array}\right\}}} \tag{8}$$

To ensure $T_{j1}$ (n, P) < $M_j$, we substitute (8) into inequality $T_{j1}$(n, P) < $M_j$ and obtain

$$\frac{A_v}{n} + A_b < \frac{R(P)M_j^2}{2}\left[\begin{array}{l} C_v\left(I_v + I_{vo}\right)\left[(n-1)(\rho-1)+\rho\right] - (P - C_v)\theta \\ -K_j(1-\beta)C_b f_{vc}(M_2 - M_1)\theta \\ +\left(1-K_j\beta\right)C_b\left(I_b + I_{vo}M_j\theta\right) + PI_{be}\left(1-\theta M_j\right) \end{array}\right] \tag{9}$$

Substituting (8) into (6), the joint total profit for case 1 is,

$$TP_{j1}(n, P) = TP_j(n, P, T_{j1}(n, P)) \tag{10}$$

Furthermore, from (9), we have $T_{j2}$ (n, P) ≥ $M_j$ if and only if

$$\frac{A_v}{n} + A_b \geq \frac{R(P)M_j^2}{2}\left[\begin{array}{l} C_v\left(I_v + I_{vo}\right)\left[(n-1)(\rho-1)+\rho\right] - (P - C_v)\theta \\ -K_j(1-\beta)C_b f_{vc}(M_2 - M_1)\theta \\ +\left(1-K_j\beta\right)C_b\left(I_b + I_{vo}M_j\theta\right) + PI_{be}\left(1-\theta M_j\right) \end{array}\right] \tag{11}$$

The second order partial derivative of $TP_{j2}$ (n, P, T) in (7 – a) is,

$$\frac{\partial^2 TP_{j2}(n,P,T)}{\partial T^2} = -\frac{1}{T^3}\left\{R(P)M_j^2\left[\left(1-K_j\beta\right)C_b I_{bc} - PI_{be}\right] + 2\left(\frac{A_v}{n}+A_b\right)\right\} < 0 \tag{12}$$

which suggests that for fixed n and P, $TP_{j2}$ (n, P, T) is a concave function in T.

By solving the equation $\frac{\partial TP_{j2}(n,P,T)}{\partial T} = 0$, we obtain the value of T= $T_{j2}$ (n, P) (say) which maximizes $TP_{j2}$ (n, P, T) and is given by

$$T_{j2} = \sqrt{\frac{2\left(\frac{A_v}{n}+A_b\right) - PI_{be}R(P)M_j^2 + \left(1-K_j\beta\right)C_b I_{bc}R(P)M_j^2}{R(P)\left\{\begin{array}{l} C_v\left(I_v+I_{vo}\right)\left[(n-1)(\rho-1)+\rho\right] - K_j(1-\beta)C_b f_{vc}\left(M_2-M_1\right)\theta \\ -(P-C_v)\theta + \left(1-K_j\beta\right)C_b\left(I_b+I_{bc}+I_{vo}\theta M_j\right) \end{array}\right\}}} \tag{13}$$

Substituting (13) into (7 – a), the joint total profit for case 2 is

$$TP_{j2}(n, P) = TP_j(n, P, T_{j2}(n, P)) \tag{14}$$

For simplicity, define

$$\Delta_j = \frac{R(P)M_j^2}{2}\left[\begin{array}{l} C_v\left(I_v+I_{vo}\right)\left[(n-1)(1-\rho)+\rho\right] + (P-C_v)\theta \\ +\left(1-K_j\beta\right)C_b\left(I_b+I_{bc}+I_{vo}\theta M_j\right) \\ +K_j(1-\beta)C_b f_{vc}\left(M_2-M_1\right)\theta + PI_{be}\left(1-\theta M_j\right) \end{array}\right], \ j=1,2 \tag{15}$$

Since, $M_2 > M_1 \geq 0$, $K_1 = 1$ and $K_2 = 0$, we have $\Delta_2 > \Delta_1$.

**Theorem 1:** For given n and P,

a. When $\frac{A_v}{n} + A_b < \Delta_1$, if max {$TP_{11}$ (n, P), $TP_{21}$ (n, P)} = $TP_{11}$ (n, P) then the optimal payment time is $M_1$ and optimum cycle time is $TP_{11}$ (n, P). Otherwise, the optimal payment time is $M_2$ and optimum cycle time is $TP_{21}$ (n, P).

b. When $\Delta_1 \leq \frac{A_v}{n} + A_b < \Delta_2$, if max {$TP_{21}$ (n, P), $TP_{12}$ (n, P)} = $TP_{21}$ (n, P) then the optimal payment time is $M_2$ and optimum cycle time is $TP_{21}$ (n, P). Otherwise the optimal payment time is $M_1$ and optimum cycle time is $TP_{12}$ (n, P)

c. When $\frac{A_v}{n} + A_b \geq \Delta_2$, if max {$TP_{12}$ (n, P), $TP_{22}$ (n, P)} = $TP_{12}$ (n, P) then the optimal payment time is $M_1$ and optimum cycle time is $TP_{12}$ (n, P) Otherwise the optimal payment time is $M_2$ and optimum cycle time is $TP_{22}$ (n, P)

**Proof:** It immediately follows from (9), (11) and (15).

### 4.2 Determination of the buyer's optimal retail price for any given n

For computing optimal value of retail price; P we follows methodology given by Teng et al. (2005).

Define

$$f_j(P) = \Delta_j,\ j = 1, 2 \tag{16}$$

It is easy to check that $f_j(P)$ is strictly decreasing function of P for given n. Also $\lim_{P \to 0} f_j(P) = \infty$ and $\lim_{P \to \infty} f_j(P) = 0$ for fixed n, guarantees that there exist a unique value of $P_{jo}$ such that

$$f_j(P_{jo}) = \frac{A_v}{n} + A_b \tag{17}$$

Then, (9) and (11) reduce to

if and only if $P < P_{jo}$, then $T_{j1}(n, P) < M_j$ (18)

and

if and only if $P \geq P_{jo}$, then $T_{j2}(n, P) \geq M_j$ (19)

respectively.

Now our problem is to find the optimal value of retail price; P which maximize the joint total profit

$$TP_j(n,P) = \begin{cases} TP_{j1}(n,P), & if \quad P < P_{jo} \\ TP_{j2}(n,P), & if \quad P \geq P_{jo} \end{cases} \quad j = 1,2 \tag{20}$$

For fixed n, the optimal value of P which maximizes $TP_{ji}(n, P)$, j = 1, 2 and i =1,2, can be obtained by first order necessary condition $\frac{\partial TP_{ji}(n,P)}{\partial P} = 0$ and examining the second order sufficient condition $\frac{\partial^2 TP_{ji}(n,P)}{\partial P^2} < 0$ for concavity.

From the above arguments, we outline the computational algorithm to find the optimal solution (n*, P*, T*).

**Computational algorithm**

***Step 1*** Set n =1.

***Step 2*** For j = 1,2.

i. Determine $P_{jo}$ by solving (17).

ii. If there exists a $P_{j1}$ such that $P_{j1} < P_{j0}$, $\frac{\partial TP_{j1}(n,P)}{\partial P} = 0$ and $\frac{\partial^2 TP_{j1}(n,P)}{\partial P^2} < 0$, then compute $T_{j1}(n, P_{j1})$ using (8) and $T_{j1}(n, P_{j1})$ using (10).
Otherwise, set $TP_{j1}(n, P_{j1}, T_{j1}(n, P_{j1})) = 0$.

iii. If there exists a $P_{j2}$ such that $P_{j2} \geq P_{j0}$, $\frac{\partial TP_{j2}(n,P)}{\partial P} = 0$ and $\frac{\partial^2 TP_{j2}(n,P)}{\partial P^2} < 0$, then compute $T_{j2}(n, P_{j2})$ using (13) and $T_{j2}(n, P_{j2})$ using (14).
Otherwise, set $TP_{j2}(n, P_{j2}, T_{j2}(n, P_{j2})) = 0$.

***Step 3*** Set $TP\left(n,P^{(n)},T^{(n)}\right)=\max_{\substack{j=1,2\\ i=1,2}} TP_{ij}\left(n,P_{ji},T_{ji}\left(n,P_{ji}\right)\right)$ then ($P^{(n)}$, $T^{(n)}$) is the optimal solution for given n.

***Step 4*** If TP (n, $P^{(n)}$, $T^{(n)}$) ≥ TP (n-1, $P^{(n-1)}$, $T^{(n-1)}$), then go to step 5. Otherwise, go to step 6.

***Step 5*** Set n = n + 1, go to step 2.

***Step 6*** Set TP (n, P*, T*) ≥ TP (n-1, $P^{(n-1)}$, $T^{(n-1)}$), then (n*, P*, T*)is the optimal solution.

Knowing the optimal solution (n*, P*, T*), the optimal order quantity per order for the buyer Q* can be obtained using $Q^*=\frac{R(P^*)}{\theta}\left\{e^{\theta T^*}-1\right\}$.

## 5. Numerical illustration

**Example 1** In order to validate the solution procedure, consider an integrated inventory system with following parametric values: a=250,000, $\rho$=0.9, $\eta$=1.25, $C_v$=\$2/unit, $C_b$=\$4.5/unit, $A_v$=\$1000/Set up, $A_b$=\$300/Order, $I_v$=0.08/\$/annum, $I_b$=0.08/\$/annum, $I_{vo}$=0.09/\$/annum, $I_{bc}$=0.16/\$/annum, $I_{be}$=0.12/\$/annum and $f_{vc}$=0.17/\$/annum. Consider, a trade credit term "2|10 net 30", i.e. $M_1$=10 days, $M_2$=30 days and $\beta$=2% is offered by the vendor to the buyer. The deterioration rate of units in inventory is 5%.

Using the computational procedure, the maximum total joint profit of the integrated system is TP(n*, P*, T*) = \$ 109628.38. The buyer makes the payment within 10 days and avails of 2% discount in purchase cost, the retail price is P*=\$ 10.6616/unit, the replenishment cycle time T* = $T_{12}$ = 0.2330 year = 85.04 days and the ordering quantity Q*=3041.09units/order.

The optimal shipment from the vendor to the buyer us n*= 10.

**Example 2** In Table 1, we study the effects of credit terms $M_1$ and $M_2$. The no trade credit is taken as a bench mark. The relationship between credit terms and profits of buyer, vendor and total are calculated.

It is observed that the profit gain in percentage is positive for the integrated decision. i.e. total profit for the integrated decision under the two – part trade credit policy is beneficial than the total profit when no credit is offered. It is also observed that the profit gain in percentage is not always positive for the vendor. Under credit terms "2|10, net 30" or if vendor extends the due date to $M_2$=30 days after the delivery, the vendor's profit gains in percentage are negative.

Table 1 also suggests that if the vendor offers the payment due date at 30 days then offering a 2% discount can encourage the buyer to settle the payment earlier. However, if the vendor extends the due date to 60 days or 90 days, the integrated profit will be maximized as the buyer pays at the end of the net period. The offer of due date at 60 days or 90 days after delivery by the vendor will not accelerate cash inflows. Hence, in an integrated supply chain, the vendor needs to decide the credit policy very carefully to get mutual benefit from a two – part trade credit scenario.

**Example 3** Using the same data as in Example 1, we compare the impact of trade credit for independent and coordinated decision in Table 2. The optimal solutions of "cash on delivery" (i.e.$M_1$ = $M_2$ = 0 and $\beta$ = 0) and "2|10 net 30" are computed.

In independent decision, buyer is dominant decision maker and then the vendor defines his policy.

| $M_1$ | $M_2$ | Optimum Payment time | n | P | T | R(P) | Q | Profit | | | Profit gain (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Buyer | Vendor | Integrated | Buyer | Vendor | Integrated |
| 0 | 0 | - | 10 | 10.75 | 87.47 | 12843 | 3096 | 78100 | 30961 | 109061 | - | - | - |
| | | | | | | | | | | | | | |
| 0 | 30 | 30 | 12 | 10.59 | $T_2$=84.95 | 13076 | 3061 | 78292 | 31312 | 109604 | 0.25 | 1.13 | 0.49 |
| 10 | | 10 | 10 | 10.66 | $T_{12}$=85.04 | 12976 | 3041 | 78706 | 30922 | 109628 | 0.78 | -0.13 | 0.52 |
| 20 | | 20 | 10 | 10.73 | $T_{12}$=84.52 | 12876 | 2999 | 78947 | 30560 | 109507 | 1.084 | -1.23 | 0.41 |
| | | | | | | | | | | | | | |
| 0 | 60 | 60 | 13 | 10.66 | $T_2$=65.80 | 12975 | 2350 | 79996 | 30074 | 110070 | 2.43 | -2.86 | 0.93 |
| 10 | | 60 | 13 | 10.66 | $T_{12}$=65.81 | 12975 | 2350 | 79996 | 30075 | 110071 | 2.43 | -2.86 | 0.93 |
| 20 | | 60 | 13 | 10.66 | $T_{12}$=65.81 | 12975 | 2350 | 79997 | 30077 | 110074 | 2.43 | -2.86 | 0.93 |
| | | | | | | | | | | | | | |
| 0 | 90 | 90 | 13 | 10.72 | $T_2$=66.03 | 12882 | 2341 | 78870 | 32131 | 111001 | 0.98 | 3.78 | 1.78 |
| 10 | | 90 | 13 | 10.72 | $T_{12}$=66.03 | 12882 | 2341 | 78870 | 32133 | 111003 | 0.98 | 3.78 | 1.78 |
| 20 | | 90 | 13 | 10.72 | $T_{12}$=66.03 | 12882 | 2341 | 78870 | 32134 | 111005 | 0.98 | 3.78 | 1.78 |

Table 1. Optimal solution under different payment time

Table 2 suggests that under both an independent and coordinated policy, offer of trade credit to the buyer fallout in a lower retail price and hence, pushes up market demand and total joint profit. However, when the vendor and buyer work independently, irrespective of whether or not the vendor offers trade credit to the buyer, the retail price which maximizes the buyer's profit is much higher than that in a coordinated policy. This in turn reduces demand and hence the buyer's order quantity decreases for each subsequent order. This lowers profit of the vendor as well as the channel significantly. Therefore, the joint decision

| Decision making | Credit terms | Payment time | *n* | *P* | *T* (days) | *R(P)* | *Q* | *nQ* | Profit | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Buyer | Vendor | Integrated |
| | | | | | | | | | | | |
| Independent | Cash on Delivery | 0 | 11 | 24.05 | 114.72 | 4696 | 1487 | 16357 | 89348 | 10539 | 99887 |
| | Trade Credit (2\|10 net 30) | 10 | 11 | 23.89 | 112.47 | 4733 | 1460 | 16060 | 91296 | 10754 | 102050 |
| | | | | | | | | | | | |
| Coordinated | Cash on Delivery | 0 | 10 | 10.75 | 87.47 | 12843 | 3096 | 30960 | 78100 | 30961 | 109061 |
| | Trade Credit (2\|10 net 30) | 10 | 10 | 10.66 | 85.04 | 12976 | 3041 | 30410 | 78706 | 30922 | 109628 |
| | | | | | | | | | | | |
| Allocated | | | | | | | | | 98075 | 11553 | 109628 |

Table 2. Optimal solution under different payment scenario

opted by the players of the supply chain can significantly improve the profit of the entire supply chain. From the vendor's end a joint decision is more advantageous than the independent decision. This is not true for the buyer. Therefore, to make the joint decision beneficial to the vendor and buyer both, Goyal (1976)'s method is implemented to enjoy long term partnership which benefits both the vendor and buyer.
We reallocate TP(n*, P*, T*) and obtained

$$\text{Buyer's profit} = TP\left(n^*, P^*, T^*\right) \times \frac{TBP\left(P_B^*, T_B^*\right)}{\left[TBP\left(P_B^*, T_B^*\right) + TVP\left(n_v^*\right)\right]}$$

$$= 109628 \times \frac{91296}{102050}$$

$$= 98075$$

and

$$\text{Vendor's profit} = TP\left(n^*, P^*, T^*\right) \times \frac{TVP\left(n_v^*\right)}{\left[TBP\left(P_B^*, T_B^*\right) + TVP\left(n_j^*\right)\right]}$$

$$= 109628 \times \frac{10754}{102050}$$

$$= 11553$$

The allocated results are listed at the bottom of Table 2.
Table 3 exhibits the benefits of a collaborative lot size credit policy. This shows that the profit increase of a joint decision is $ 9174 (= 10906 – 9987) for the "cash on delivery scenario and $ 7578(= 109628 – 102050) for the "2|10 net 30" scenario respectively. Under independent decision, offer of trade credit improves profit by 2.17% as compared to cash on delivery. The joint decision improves profit by 0.52%. The surplus capital generated for the supply chain by joint decision and trade credit policy is $ 9741 which is 8.93% increase in the profit. This concludes that the player can expect larger channel profit from the coordination and trade credit policy.

| | Independent | Coordinated | Improvement |
|---|---|---|---|
| Cash on delivery | 99887 | 109061 | 9174 (9.18%) |
| Trade credit (2\|10, net 30) | 102050 | 109628 | 7578 (7.43 %) |
| Improvement | 2163 (2.17 %) | 567 (0.52 %) | 9741 (8.93 %) |

Table 3. Improvement solution for coordinated system

**Example 4** In this example, we compute the relative performances for various values of the model parameters. The values of $\rho$, ($A_b/A_v$) and ($I_b/I_v$) are varied. The other model parameters take values as given in Example 1. The offer of "2|10 net 30" by the vendor is consider. The optimal solutions and the integrated profit are exhibited in Table 4.
It is observed that increase in $\rho$, lowers the buyer cycle time and tempted to take advantage of a trade credit more frequently. The buyer's retail price decreases and integrated profit increases significantly. The number of shipments increases significantly.

| $A_b/A_v$ | $I_b/I_v$ | n | | | P | | | T | | | Integrated Profit | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | ρ=0.1 | ρ=0.5 | ρ=0.9 | ρ=0.1 | ρ=0.5 | ρ=0.9 | ρ=0.1 | ρ=0.5 | ρ=0.9 | ρ=0.1 | ρ=0.5 | ρ=0.9 |
| | | | | | | | | | | | | | |
| 0.01 | 1.0 | 31 | 48 | 133 | 10.64 | 10.59 | 10.43 | 10.00 | 8.89 | 8.15 | 110166 | 110758 | 111773 |
| | 1.5 | 31 | 49 | 139 | 10.66 | 10.60 | 10.43 | 9.93 | 8.69 | 7.82 | 110144 | 110735 | 111747 |
| | 2.0 | 32 | 49 | 141 | 10.66 | 10.60 | 10.43 | 9.61 | 8.62 | 7.65 | 110119 | 110718 | 111728 |
| | 2.5 | 33 | 50 | 143 | 10.66 | 10.61 | 10.44 | 9.29 | 8.43 | 7.51 | 110095 | 110696 | 111709 |
| | 3.0 | 34 | 51 | 144 | 10.66 | 10.61 | 10.46 | 9.00 | 8.23 | 7.40 | 110071 | 110676 | 111690 |
| | | | | | | | | | | | | | |
| 0.1 | 1.0 | 10 | 16 | 45 | 10.80 | 10.68 | 10.52 | 38.47 | 36.69 | 34.88 | 109257 | 109674 | 110576 |
| | 1.5 | 11 | 15 | 46 | 10.83 | 10.72 | 10.57 | 35.41 | 35.43 | 33.78 | 109112 | 109647 | 110492 |
| | 2.0 | 11 | 15 | 46 | 10.85 | 10.76 | 10.61 | 34.85 | 34.82 | 33.02 | 109043 | 109576 | 110424 |
| | 2.5 | 11 | 15 | 47 | 10.87 | 10.79 | 10.64 | 34.31 | 34.22 | 32.04 | 108976 | 109507 | 110346 |
| | 3.0 | 12 | 15 | 47 | 10.88 | 10.82 | 10.67 | 33.96 | 33.36 | 31.39 | 108851 | 109439 | 110282 |
| | | | | | | | | | | | | | |
| 0.5 | 1.0 | 4 | 6 | 16 | 10.99 | 10.92 | 10.81 | 112.49 | 103.20 | 100.57 | 108085 | 108262 | 108931 |
| | 1.5 | 5 | 6 | 17 | 11.04 | 10.96 | 10.87 | 96.10 | 95.84 | 95.17 | 107621 | 108071 | 108710 |
| | 2.0 | 5 | 6 | 17 | 11.07 | 10.99 | 10.90 | 93.19 | 92.02 | 91.55 | 107444 | 107887 | 108532 |
| | 2.5 | 5 | 6 | 17 | 11.12 | 11.04 | 10.94 | 90.67 | 89.08 | 88.41 | 107274 | 107710 | 108361 |
| | 3.0 | 5 | 6 | 18 | 11.15 | 11.07 | 10.96 | 88.24 | 86.29 | 84.49 | 107108 | 107539 | 108169 |

Table 4. Sensitivity analysis of optimal solution for changes in model parameters

Furthermore, the increase in the value of ($A_b/A_v$) (i.e. the relative ordering cost for the buyer increases), the number of shipment decreases, cycle time and retail price increases but integrated profit lowers down. When the relating holding cost rate (excluding interest charge) for the buyer increases, the buyer's cycle time will decrease and hence number of shipment increases marginally. The integrated profit decreases. See figures 2 – 19.

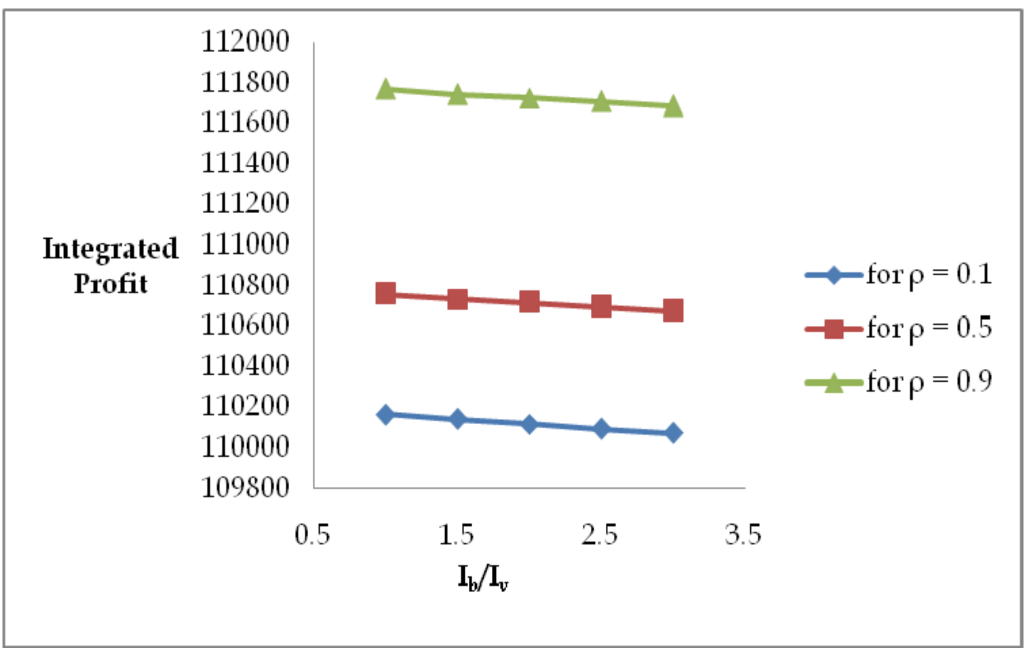


Fig. 2. Sensitivity analysis of Integrated Profit with respect to $I_b/I_v$ for ρ.

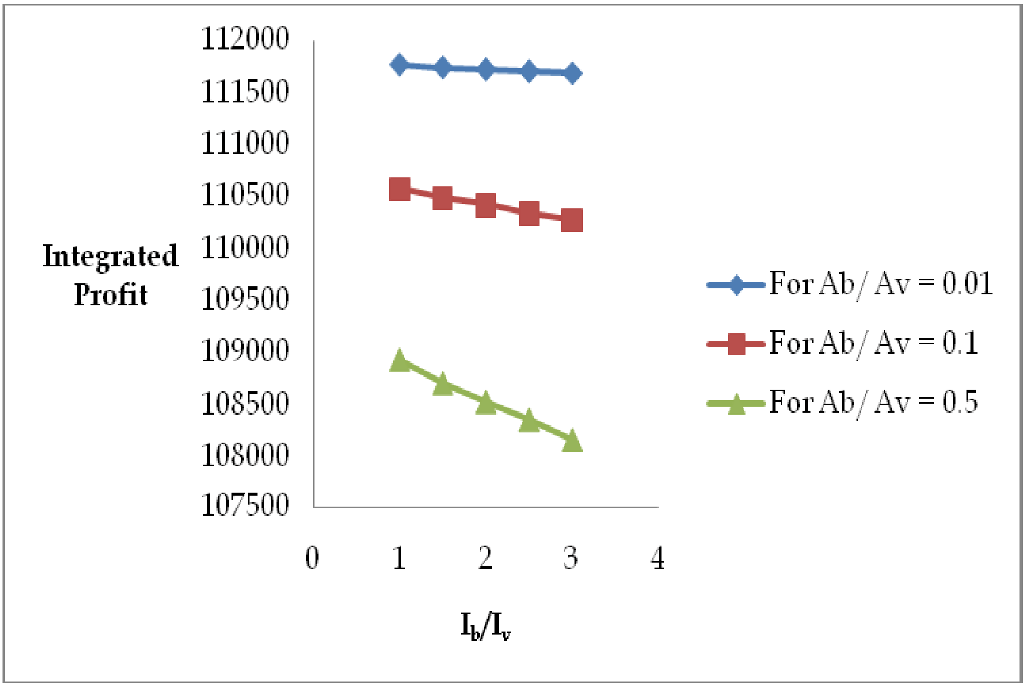


Fig. 3. Sensitivity analysis of Integrated Profit with respect to $I_b/I_v$ for $A_b/A_v$.

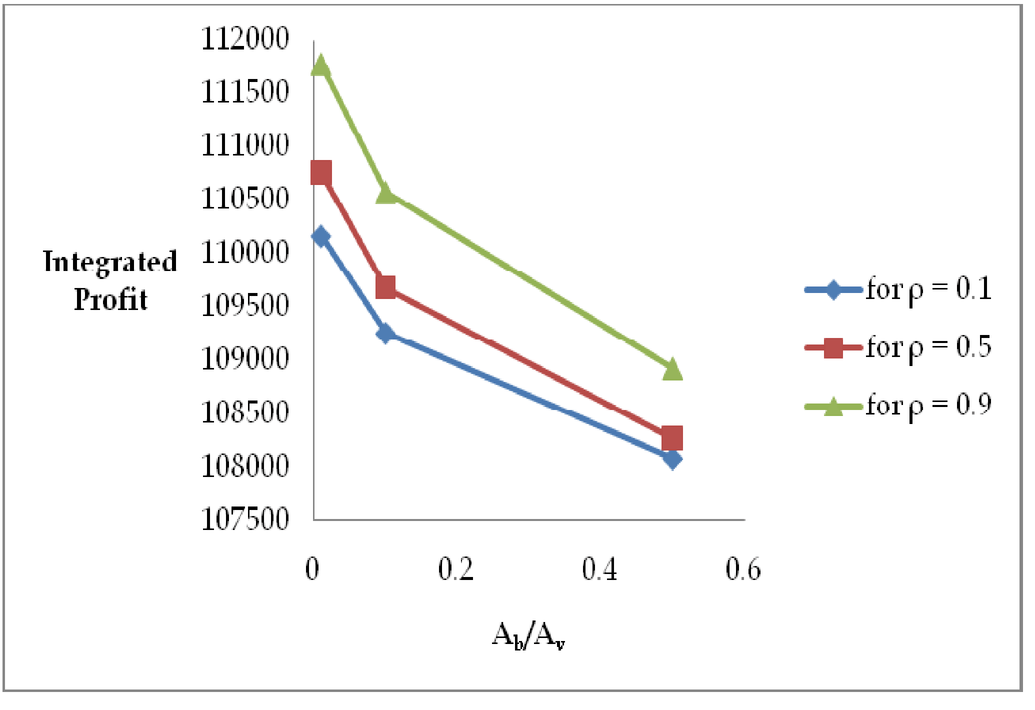


Fig. 4. Sensitivity analysis of Integrated Profit with respect to $A_b/A_v$ for ρ.

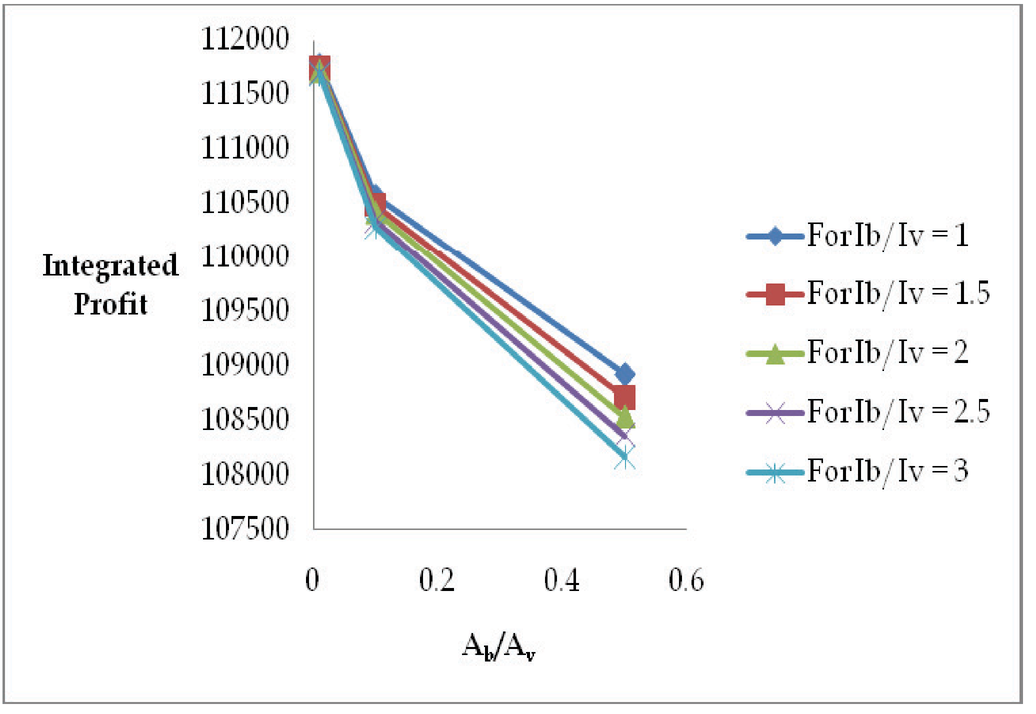


Fig. 5. Sensitivity analysis of Integrated Profit with respect to $A_b/A_v$ for $I_b/I_v$.

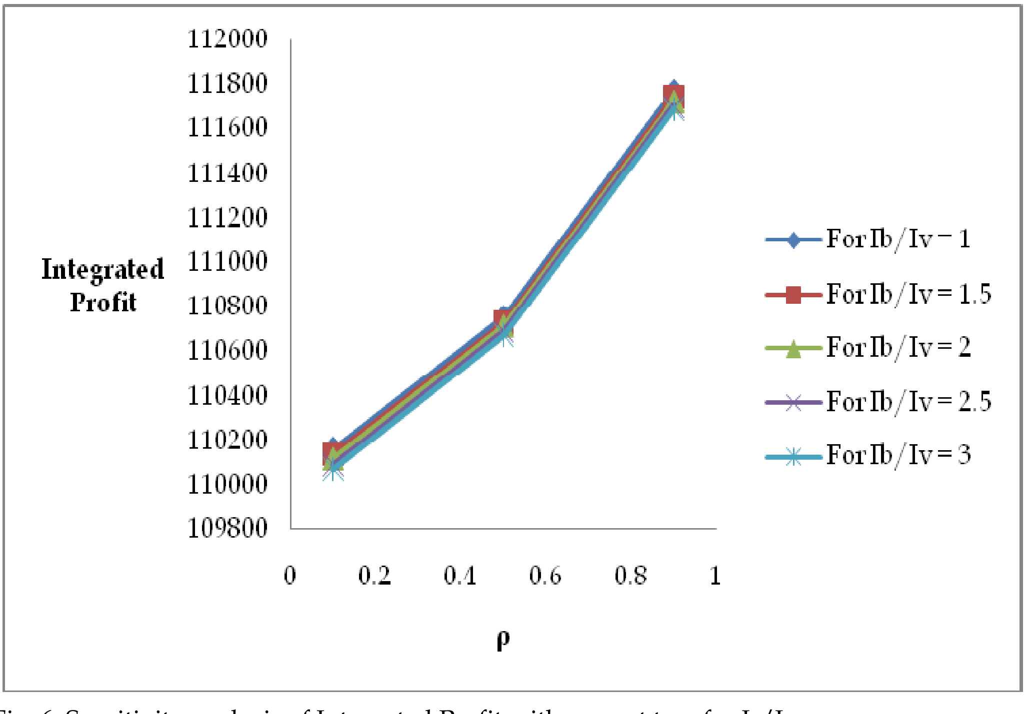


Fig. 6. Sensitivity analysis of Integrated Profit with respect to $\rho$ for $I_b/I_v$.

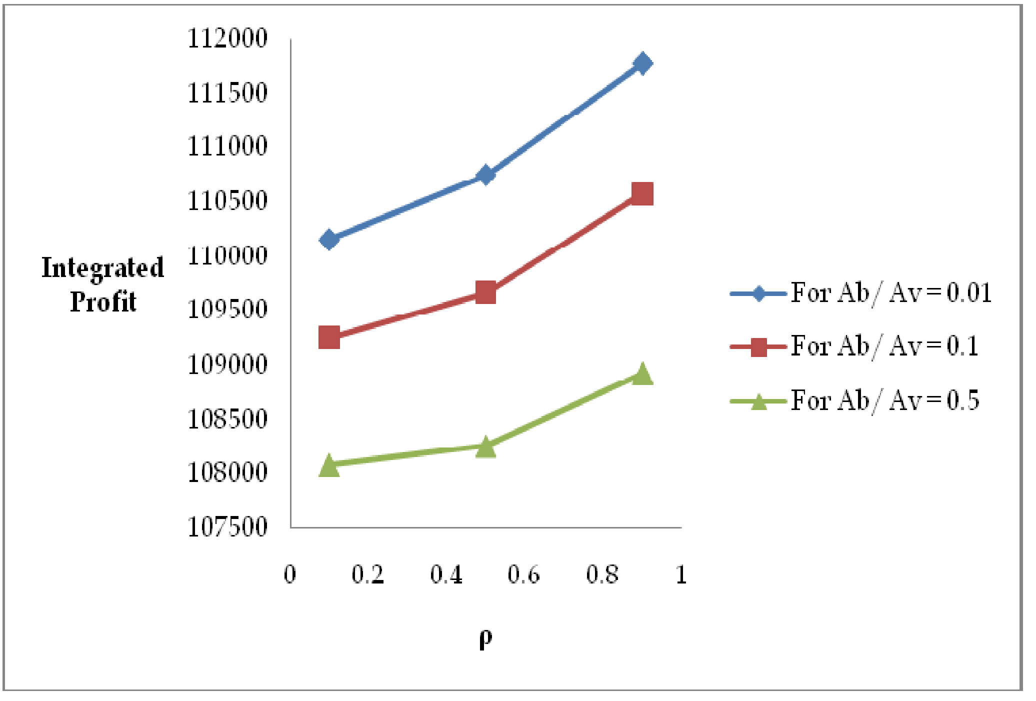


Fig. 7. Sensitivity analysis of Integrated Profit with respect to ρ for $A_b/A_v$.

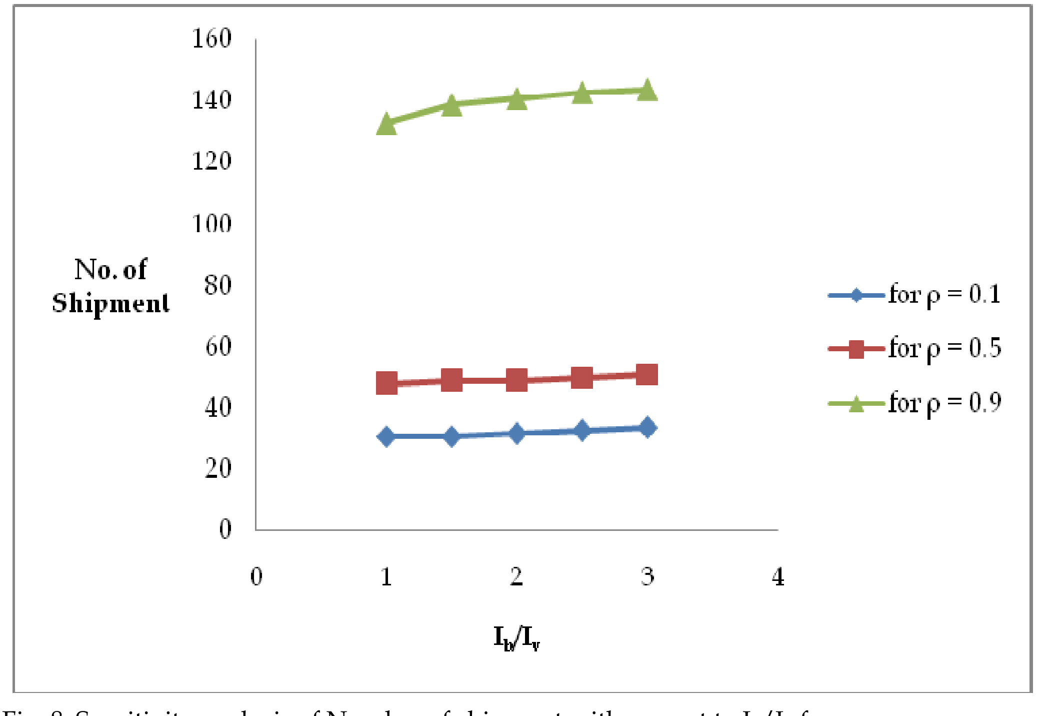


Fig. 8. Sensitivity analysis of Number of shipment with respect to $I_b/I_v$ for ρ.

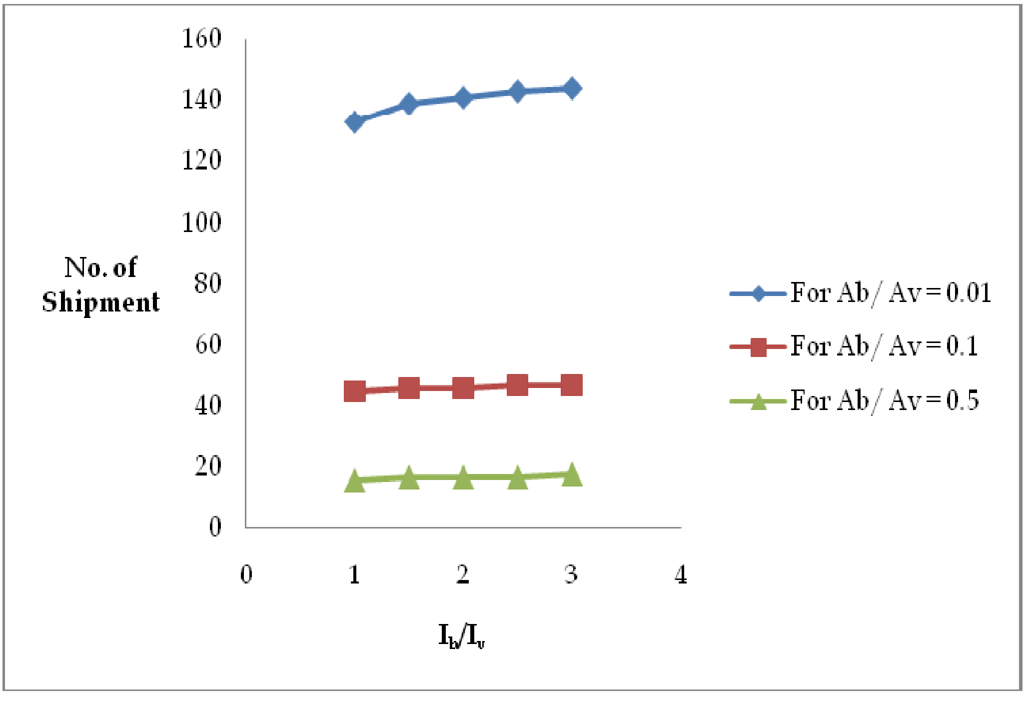


Fig. 9. Sensitivity analysis of Number of shipment with respect to $I_b/I_v$ for $A_b/A_v$.

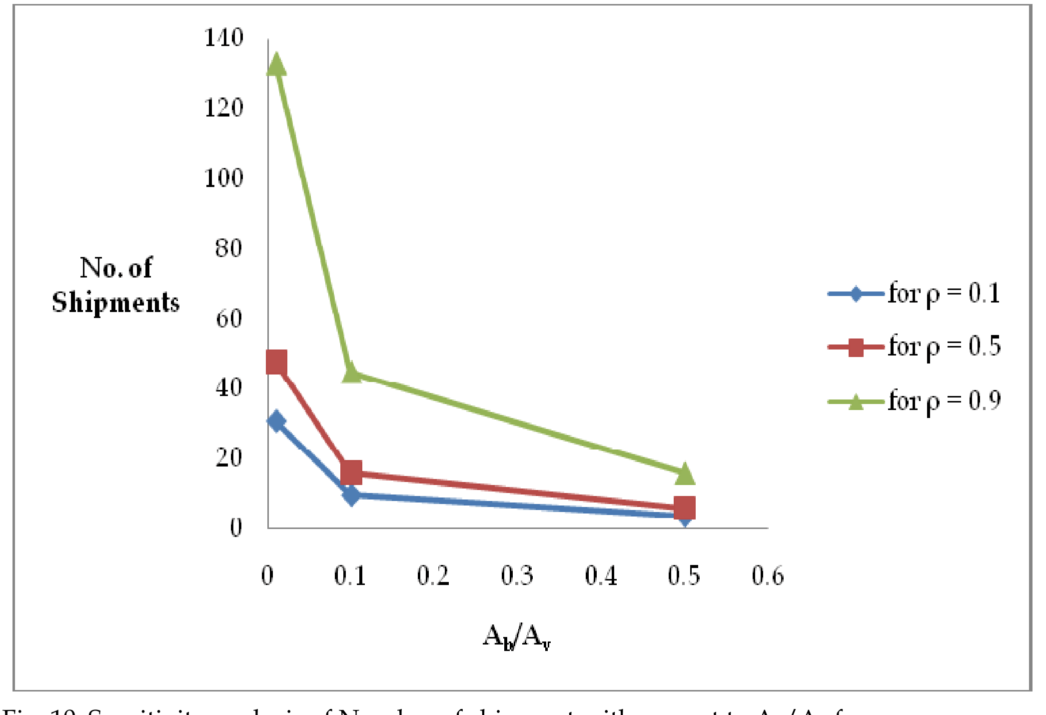


Fig. 10. Sensitivity analysis of Number of shipment with respect to $A_b/A_v$ for $\rho$.

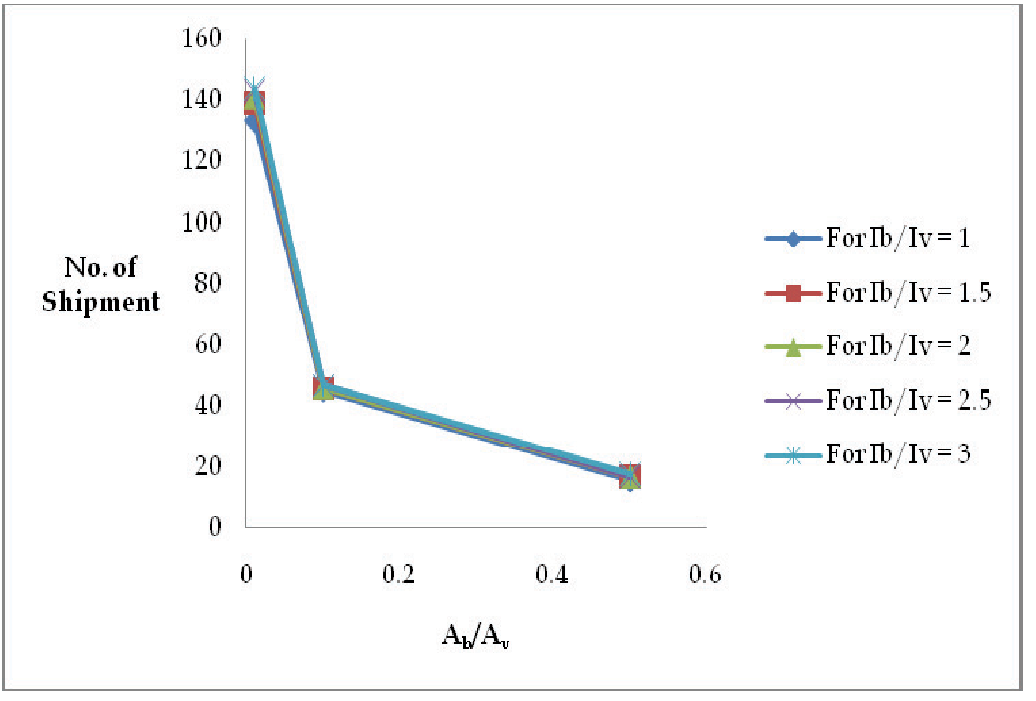


Fig. 11. Sensitivity analysis of Number of shipment with respect to $A_b/A_v$ for $I_b/I_v$.

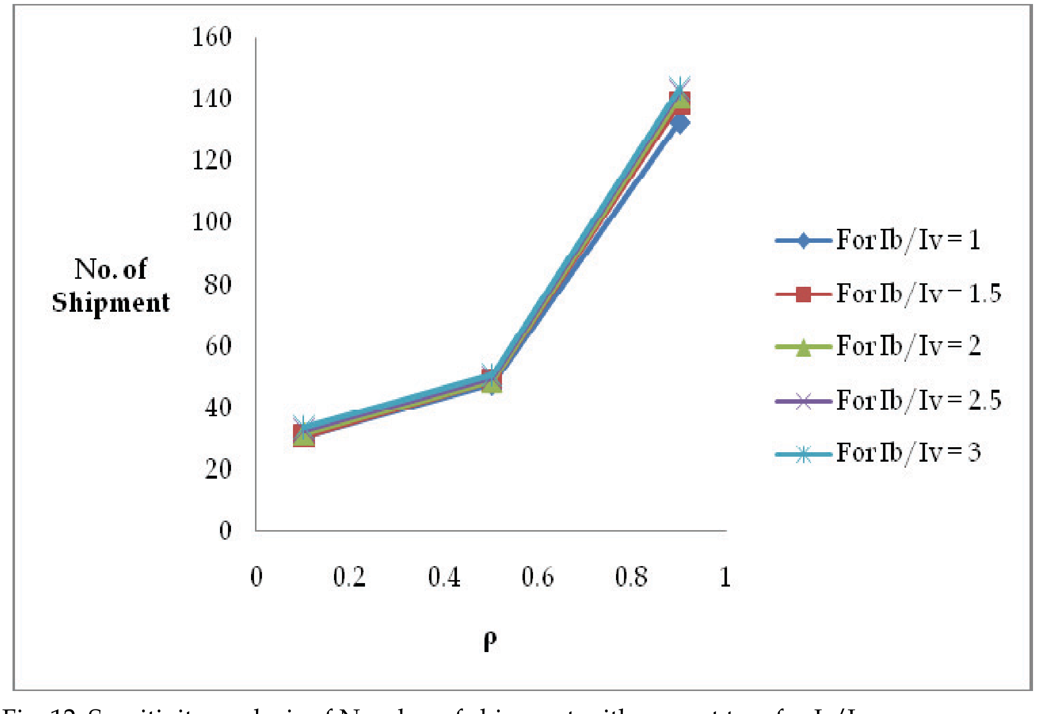


Fig. 12. Sensitivity analysis of Number of shipment with respect to ρ for $I_b/I_v$.

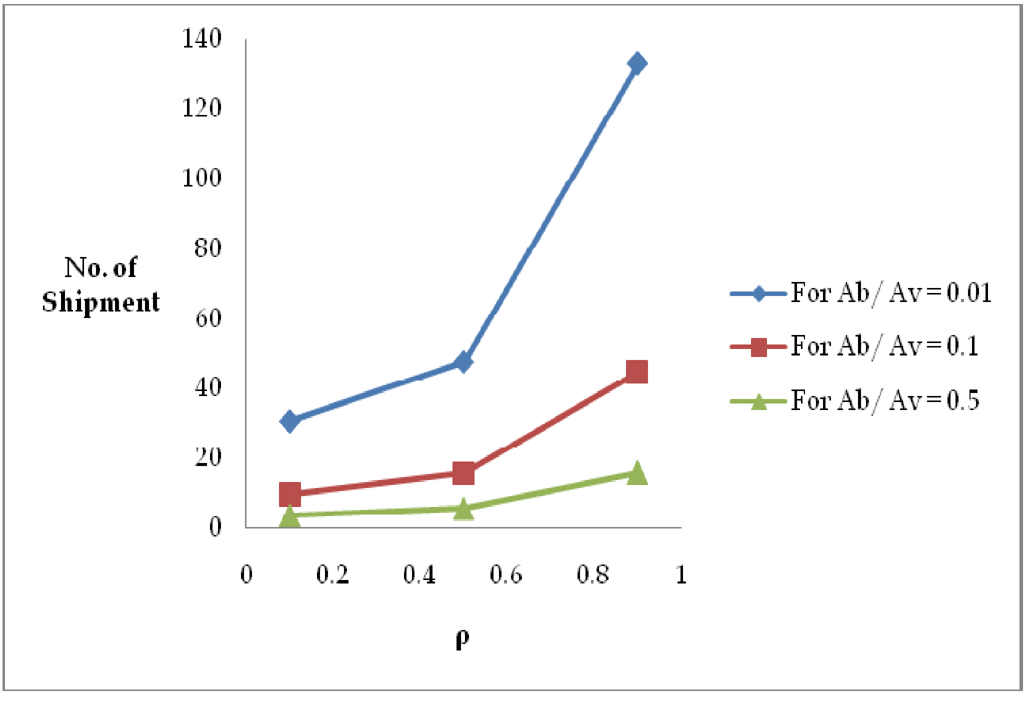


Fig. 13. Sensitivity analysis of Number of shipment with respect to ρ for $A_b/A_v$.

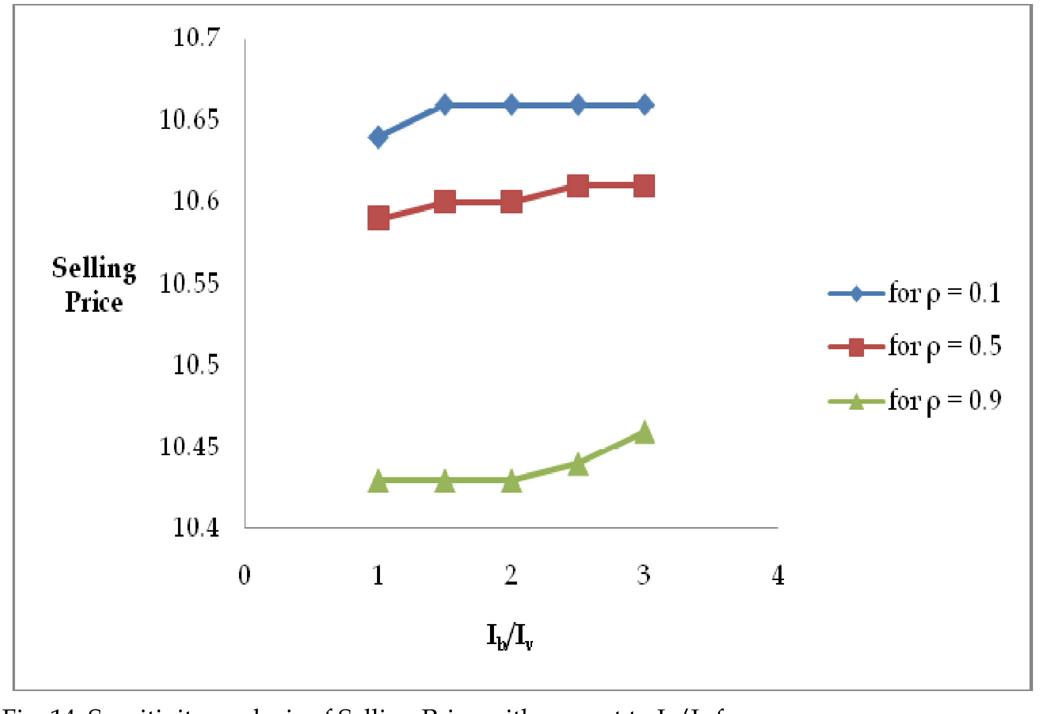


Fig. 14. Sensitivity analysis of Selling Price with respect to $I_b/I_v$ for ρ.

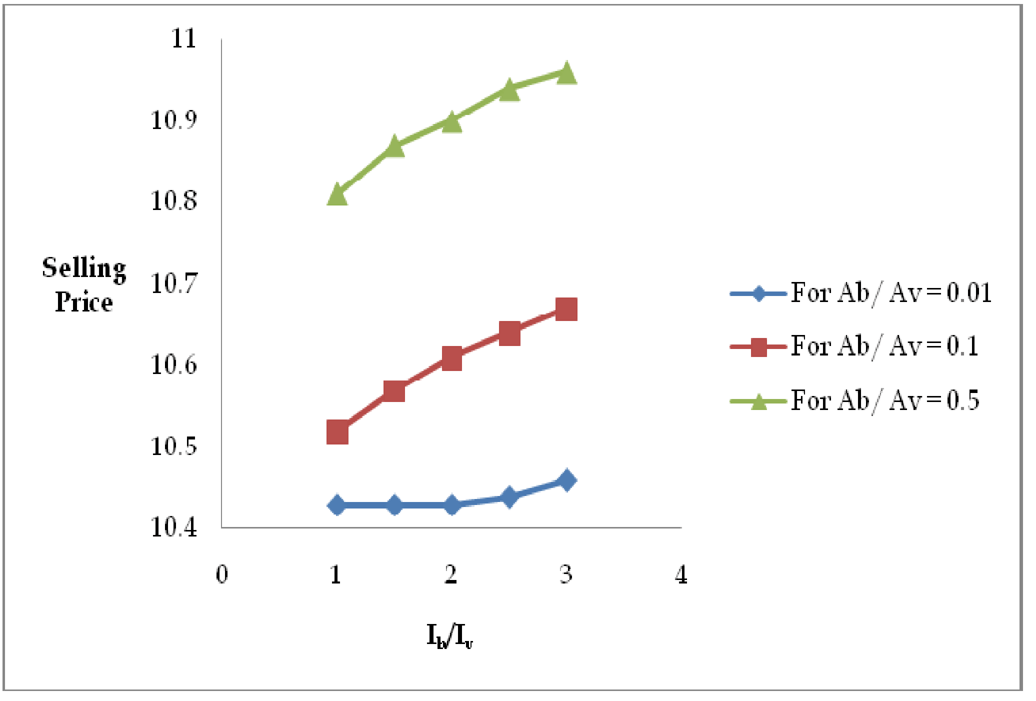


Fig. 15. Sensitivity analysis of Selling Price with respect to $I_b/I_v$ for $A_b/A_v$.

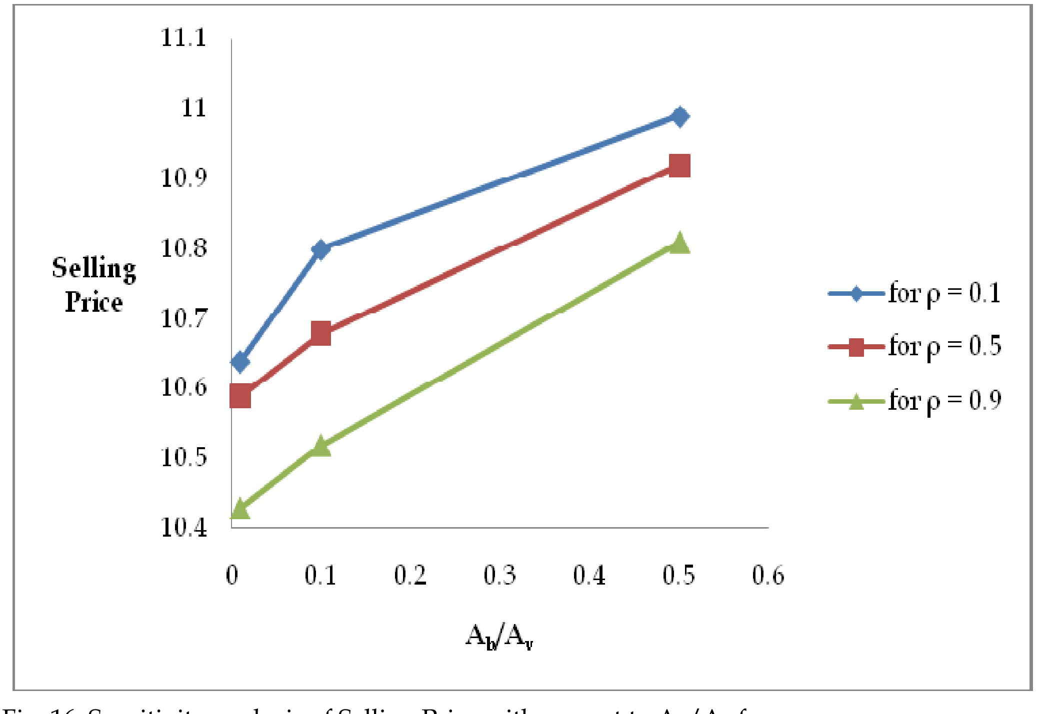


Fig. 16. Sensitivity analysis of Selling Price with respect to $A_b/A_v$ for ρ.

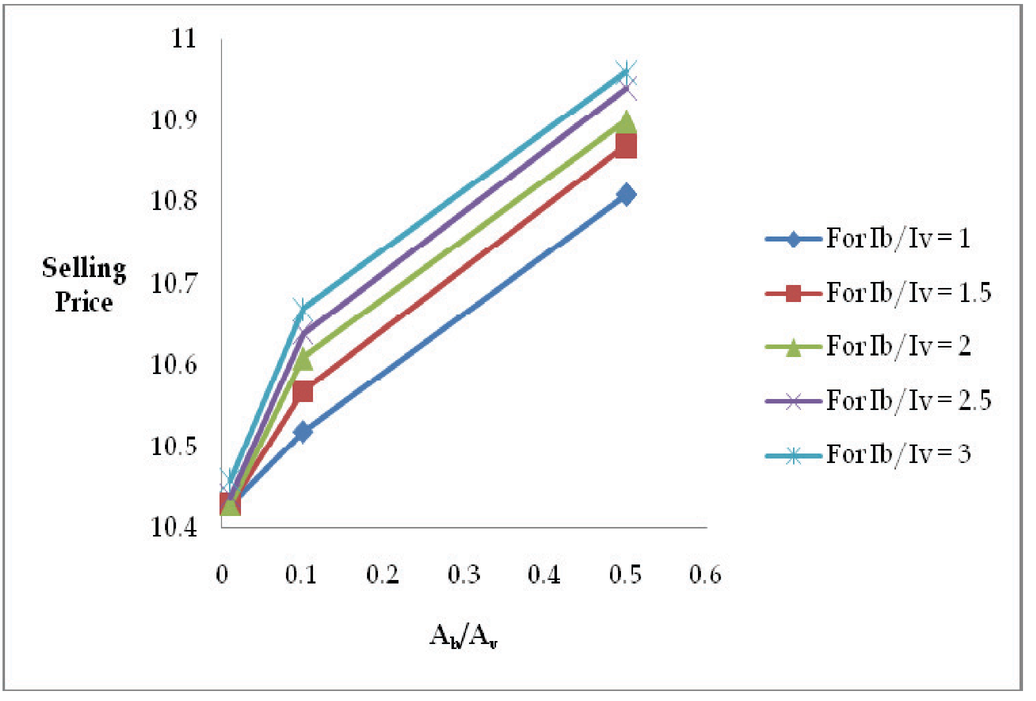


Fig. 17. Sensitivity analysis of Selling Price with respect to $A_b/A_v$ for $I_b/I_v$.

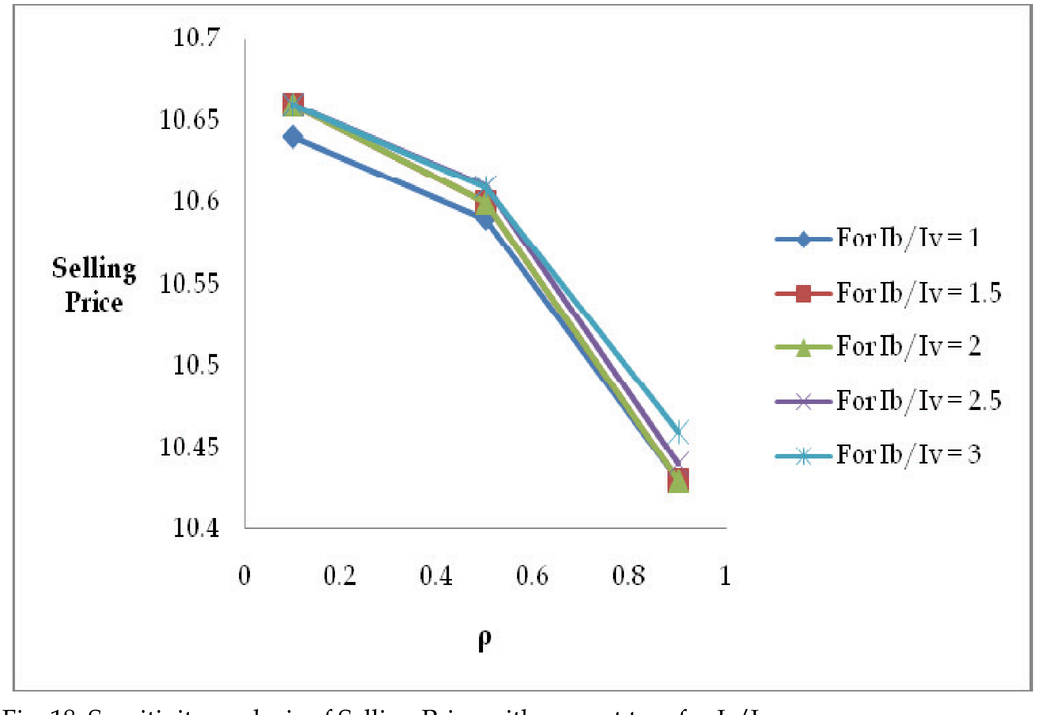


Fig. 18. Sensitivity analysis of Selling Price with respect to $\rho$ for $I_b/I_v$.

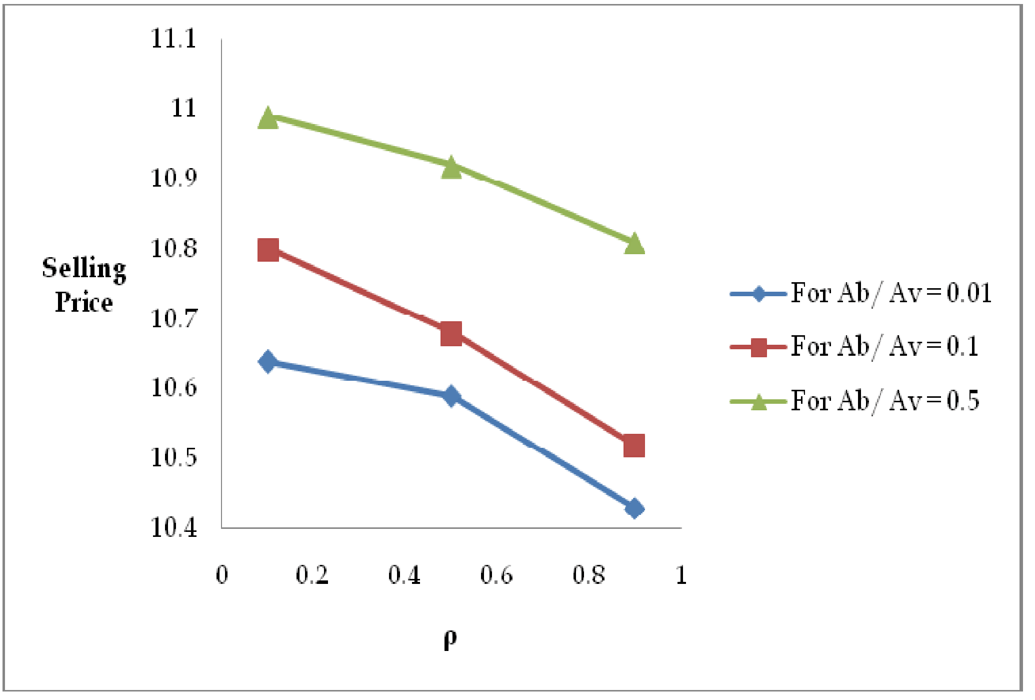


Fig. 19. Sensitivity analysis of Selling Price with respect to ρ for $A_b/A_v$.

## 6. Conclusions

In this chapter, a collaborative vendor – buyer inventory model is analyzed when the market demand is sensitive to the retail price, units in inventory deteriorate at a constant rate and the vendor offers two payment options namely trade credit and early – payments with discount in purchase price to the buyer. A solution procedure is constructed to compute the best payment option, the optimal retail price, cycle time, order quantity and the numbers of shipments per production run from the vendor to the buyer which maximizes the integrated profit. Numerical examples are given to validate the proposed model.
It is concluded that a two – part trade credit offer can increase profits of the buyer, vendor and the entire supply chain. It is observed that as the vendor and buyer take joint decision, the channel profit will increase significantly. Supply chain integration is useful in the vendor's profit gain and buyer's cash flow management. To entire buyer to opt for joint decision, the vendor should share additional profits.

## 7. References

Abad, P.L., Jaggi, C.K., 2003. A joint approach for setting unit price and the length of the credit period for a seller when end demand is price sensitive. *International Journal of Production Economics*, Vol. 83, pp. 115 – 122.

Aggarwal, S.P., Jaggi, C.K., 1995. Ordering policies of deteriorating items under permissible delay in payments. *Journal of the Operational Research Society*, Vol. 46, pp. 658 – 662.

Arcelus, F.J., Srinivasan, G., 1993. Integrating working capital decisions. *The Engineering Economist*, Vol. 39, pp. 1 – 15.

Arcelus, F.J., Shah, N.H., Srinivasan, G., 2001. Retailer's response to special sales: price discount vs. trade credit. *OMEGA*, Vol. 29, pp. 417 – 428.

Arcelus, F.J., Shah, N.H., Srinivasan, G., 2003. Forward buying policies for deteriorating items under price sensitive demand and temporary price discounts. *International Journal of Operations and Quantitative Management*, Vol. 9, pp. 87 – 102.

Banerjee, A., 1986. A joint economic – lot – size model for purchaser and vendor. *Decision Sciences*, Vol. 17, pp. 292 – 311.

Bhatnagar, R., Chandra, P., Goyal, S.K., 1993. Models for multi – plant coordination. *European Journal of Operational Research*, Vol. 67, pp. 141 – 160.

Brigham, E.F., 1995. Fundamentals of Financial Management. *The Dryden Pren.*, Florida.

Chang, C.T., 2002. Extended economic order quantity model under cash discount and payment delay. *International Journal of Information and Management Sciences*, Vol. 13, pp. 57 – 69.

Chang, H.J., Dye, C.Y., 2001. An inventory model for deteriorating items with partial backlogging and permissible delay in payment. *International Journal of System Science*, Vol. 32, pp. 345 – 352.

Chen, M.S., Chung, C.C., 1999. An analysis of light buyer's economic order model under trade credit. *Asia – Pacific Journal of Operational Research*, Vol. 16, pp. 23 – 34.

Chu, P., Chung, K.L., Lan, S.P., 1998. Economic order quantity of deteriorating items under permissible delay in payments. *Computers and Operations Research*, Vol. 25, pp. 817 – 824.

Chung, K.J., Huang, Y.F., 2003. The optimal cycle time for EPQ inventory model under permissible delay in payments. *International Journal of Production Economics*, Vol. 84, pp. 307 – 318.

Chung, K.J., Liao, J.J., 2004. Lot – sizing decisions under trade credit depending on the ordering quantity. *Computers and Operations Research*, Vol. 31, pp. 909 – 928.

Chung, K.J., Liao, J.J., 2006. The optimal ordering policy in a DCF analysis for deteriorating items when trade credit depends on the order quantity. *International Journal of Production Economics*, Vol. 100, pp. 116 – 130.

Chung, K.J., Goyal, S.K., Huang, Y.F., 2005. The optimal inventory policies under permissible delay in payments depending on the ordering quantity. *International Journal of Production Economics*. Vol. 95, pp. 203 – 213.

Goyal, S.K., 1976. An integrated inventory model for a single supplier – single customer problem. *International Journal of Production Research*, Vol. 15, pp. 107 – 111.

Goyal, S.K., 1985. Economic order quantity under conditions of permissible delay in payments. *Journal of the Operational Research Society*, Vol. 36, pp. 335 – 338.

Goyal, S.K., 1988. A joint economic – lot – size model for purchaser and vendor: a comment. *Decision Sciences*, Vol. 19, pp. 236 – 241.

Goyal, S.K., 1995. A one – vendor multi – buyer integrated inventory model: a comment. *European Journal of Operational Research*, Vol. 82, pp. 209 – 210.

Hill, R.M., 1997. The single – vendor single – buyer integrated production – inventory model with a generalized policy. *European Journal of operational Research*, Vol. 97, pp. 493 – 499.

Hill, R.M., 1999. The optimal production and shipment policy for the single – vendor single – buyer integrated production – inventory problem. *International Journal of Production Research*, Vol. 37, pp. 2463 – 2475.

Hill, N.C., Riener, K.D., 1979. Determining the cash discount in the firm's credit policy. *Financial Management*, Vol. 8, pp. 68 – 73.

Ho, C.H., Ouyang, L.Y., Su, C.H., 2008. Optimal pricing, shipment and payment policy for an integrated supplier – buyer inventory model with two – part trade credit. *European Journal of Operational Research*, Vol. 187, pp. 496 – 510.

Huang, Y.F., Chung, K.J., 2003. Optimal replenishment and payment policies in the EOQ model under cash discount and trade credit. *Asia – Pacific Journal of Operation Research*, Vol. 20, pp. 177 – 190.

Jamal, A.M.M., Sarker, B.R., Wang, S., 1997. An ordering policy for deteriorating items with allowable shortage and permissible delay in payments. *Journal of the Operational Research Society*, Vol. 48, pp. 826 – 833.

Joglekar, P.N., 1988. Comments on "A quantity discount pricing model to increase vendor profits". *Management Science*, Vol. 34, pp. 1391 – 1398.

Kelle, P., Al – Khatee, F., Miller, A.P., 2003. Partnership and negotiation support by joint optimal ordering / setup policies for JIT. *International Journal of Production Economics*, Vol. 81 – 82, pp. 431 – 441.

Kim, Y.H., Chung, K.H., 1990. An integrated evaluation of investment in inventory and credit: a cash flow approach. *Journal of Business Finance and Accounting*, Vol. 17, pp. 381 – 390.

Kim, S.L., Ha, D., 2003. A JIT lot – splitting model for supply chain management: enhancing buyer – supplier linkage. *International Journal of Production Economics*, Vol. 86, pp. 1 – 10.

Kim, J.S., Hwang, H., Shinn, S.W., 1995. An optimal credit policy to increase supplier's profit with price dependent demand function. *Production Planning and Control*, Vol. 6, pp. 45 – 50.

Lee, H.L., Padmanabhan, V., Whang, S., 1997. The bullwhip effect in the supply chains. *Sloan Management Review*, Vol. 38, pp. 93 – 102.

Li, J., Liu, L., 2006. Supply chain coordination with quantity discount policy. *International Journal of Production Economics*, Vol. 101, pp. 89 – 98.

Lieber, Z., Orgler, Y.E., 1975. An integrated model for accounts receivable management. *Management Science*, Vol. 22, pp. 212 – 219.

Lu, L., 1995. A one – vendor multi – buyer integrated inventory model. *European Journal of Operational Research*, Vol. 81, pp. 312 – 322.

Ouyang, L.Y., Chen, M.S., Chuang, K.W., 2002. Economic Order quantity model under cash discount and payment delay. *International Journal of Information and Management Sciences*, Vol. 13, pp. 1 – 10.

Ouyang, L.Y., Teng, J.T., Chuang, K.W., Chuang, B.R., 2005. Optimal inventory policy with non instantaneous receipt under trade credit. *International Journal of Production Economics*, Vol. 98, pp. 290 – 300.

Shah, N.H., 1993 – a. A lot –size model for exponentially decaying inventory when delay in payments is permissible, *CERO*, Vol. 35, pp. 1 – 9.

Shah, N.H., 1993 – b. A probabilistic order level system when delay in payments is permissible. *Journal of the Korean Operations Research and Management Science*, Vol. 18, pp. 175 – 183.

Shah, N.H., 2009. Optimization of pricing and ordering policy for deteriorating inventory when end demand is price and credit period sensitive. *International Journal of Business Performance and Supply Chain Modeling*, Vol. 1, pp. 229 – 239.

Shah, N.H., Soni, H., Jaggi, C.K., 2010. Inventory models and trade credit: Review will appear in *Control and Cybernetics*, Vol. 39, No.3, pp. 1 – 16.

Shinn, S.W., 1997. Determining optimal retail price and lot size under day – terms supplier credit. *Computers and Industrial Engineering*, Vol. 33, pp. 717 – 720.

Shinn, S.W., Hwang, H., 2003. Optimal pricing and ordering policies for retailers under order – size – dependent delay in payments, Computers and Operations Research, Vol. 30, No. 1, pp. 35 – 50.

Teng, J.T., 2002. On the economic order quantity under conditions of permissible delay in payments. *Journal of the Operational Research Society*, Vol. 53, pp. 915 – 918.

Teng, J.T., Chang, C.T., Goyal, S.K., 2005. Optimal pricing and ordering policy under permissible delay in payments. *International Journal of Production Economics*, Vol. 97, pp. 121 – 129.

Viswanathan, S., 1998. Optimal strategy for the integrated vendor – buyer inventory model. *European Journal of Operational Research*, Vol. 105, pp. 38 – 42

# 22

# Quantifying the Demand Fulfillment Capability of a Manufacturing Organization

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## 1. Introduction

According to [1], competition among manufacturing enterprises is fought between supply chains (SC). In this scenario, competitiveness becomes something holistic [2], as the satisfaction of the end customer is determined by the effectiveness and efficiency of the SC as a whole [3]. This goal of 'operating as a whole' is the result of the degree of interaction between the SC partners, which in turn depends on the type of business models used by them [4], i.e. engineer-to-order (ETO), make-to-order (MTO), assembly-to-order (ATO), make-to-stock (MTS), etc. According to [5] and [6], a poor SC performance can be attributed to a mismatch between the intended market and the business model used to address it. As the market changes from being sales-oriented to being market-oriented [7], an adequate response requires shifting between business models [8]. This last is not a trivial task in real-life as it requires each SC partner to realign their SC structural elements [9], from the strategic level of customer and supply issues to the operational level of process and equipment issues [10]. The reason behind this requirement is that decisions taken at the strategic level have a deep impact at the operational level [11], and the correct management of the operational level has a big impact on the efficiency of the strategic level [12], so even though strategic issues are important to achieve responsiveness to market changes, they are not sufficient without achieving responsiveness at the operational level [13].
In this paper we understand the strategic and operational levels of a manufacturing organization, in terms of the CPPR framework proposed by [14]: the strategic level of a manufacturing enterprise corresponds to the customer level of the CPPR framework, while the operational level corresponds to the process level of the CPPR framework.

### 1.1 Alignment relationships of the strategic - operational levels

According to the definition provided by [14], SC structural elements are the customer, product, process, and resource attributes of a manufacturing organization that allows its representation from a SC standpoint. Table 1 shows the set of SC structural elements and their configuration variables: a manufacturing organization is said to be 'aligned' when most of its configuration attributes fall under the same column (in this paper we use the term 'alignment' in the same sense). When these SC structural elements are analyzed from the standpoint of the 'what', 'when' and 'how much' of customer service [15], the following alignment relationships are found:

| | C Business model | MTO | MTO-ATO | ATO | MTS |
|---|---|---|---|---|---|
| BUSINESS | C Company size | Very small (E<50) | Medium size (50<E<500) | Large size (E> 500) | Multinational firm |
| | C Management style | Entrepreneurial | | | Bureaucratic |
| | Pd Type | Machine tools | Motors | TV | Watches |
| | Pc Environment | Job shop | Batch | Repetitive | Mass |
| | R Layout | Functional | Cellular | U-line | Assembly line |
| SUPPLIER | C Logistics structure | Single plant/single warehouse | Multi plant/multi warehouses | Production/Distribution | Warehousing/Distribution |
| | C Procurement | Vertical production | Extensive outsourcing | Final assembly only | Extended enterprise |
| | Pc Delivery/total lead | 1 – 4/5 | 4/5 – 2/5 | 2/5 – 1/5 | 1/5 - 0 |
| | Pc Production/delivery | P/D<<1 | P/D<1 | P/D>1 | P/D>>1 |
| MANUFACTURING | Pd Composition | complex mfg.+assy. | simple mfg.+assy. | assy. | single part |
| | Pd Standardization | Customer's specs) | Own catalog, non-standard options | Standard with options | Standard, no options |
| | Pd Variety | many (100<n<1,000) | many –several (50<n<100) | several-few (5<n<50) | few (1<n<5) |
| | Pc Lead time | months-weeks | weeks-day | day-minutes | minutes-seconds |
| | Pc Volume | low (1-100 batch size) | low (100-1000 batch size) | medium -high (1,000-10,000 batch size) | high (10,000-1M batch size) |
| | R Process flow | varied | varied with patterns | One-piece | Connected line |
| | R Technology | Universal | General purpose | General purpose-dedicated | Dedicated |
| PLANNING | C Management focus | Capacity | Capacity, innovation | Innovation | Distribution |
| | C Order promise | material/capacity availab. | Capacity, components stock availab. | Components stock availab. | FG stock availab. |
| | CVariables fixed | Capacity, due date | Capacity, due date / Cost , due date | Cost, due date / Cost, capacity | Cost, capacity |
| | Pc SFC approach | Push | Push / Push/Pull | Push/Pull / Pull | Pull |
| | Pc PPC strategy | LOP | MRP | JIT | Process scheduling |
| | Pc Volume/mix manag. | Through order backing | Through order backing WIP/FG inventory | Through WIP/FG inventory | Through FG inventory |
| MARKETING | C Order winners/qualifiers | flexibility, innovation | flexibility, innovation, performance | performance, delivery, cost, quality | delivery, cost, quality |
| | PcOperations complexity | Component manufacturing | | | Physical distribution |
| | Pc Operations uncertainty | Production processes | | | Product life cycles |
| | R Labor requirements | High | | | Low |
| | R Materials requirements | As required/low | | | Planned with safety stocks/low |
| CUSTOMER | C Demand uncertainty | Volatile | | | Predictable |
| | C Product destination | Known | | | Unknown |
| | Pd BOM | A type, V type | A type, V type, X type, T type, | X type, T type, I type | I type |
| | Pc FG level | Low | | | High |
| | Pc WIP level | High | | | Low |
| | R Direct labor costs | High | | | Low |
| | R Direct material costs | Low | High | High | Low |

C = customer Pd = product Pc = process R = resource

Table 1. SC structural elements and their configuration variables

- The consumer's behavior (demand uncertainty) impacts the planning horizon of the market opportunity. In this way, demand uncertainty determines the level of customer feedback provided by the business model, i.e. as the demand becomes more unpredictable, no planning ahead of time can not take place and there is the need to wait for customer info.
- The business model establishes the Organization's approach to the identified market opportunity, understood in terms of order winners/qualifiers. In this way, the business model relies on the process environment, i.e. a make-to-stock (MTS) business model that requires having always ready-to-sell finished goods, must be supported by a mass production environment that produces high volumes of short-lead time products.
- The market opportunity is translated into a specific product. The capability of the Organization to manufacture different varieties of products depends in great deal on how much standardized the products' BOM structures are (as they allow the use of postponement and/or modularization approaches). In this way, product standardization allows the achievement of the order winners/qualifiers, i.e. the order winners/qualifiers delivery, cost, and quality are achievable when the product is of simple assembly.
- The process required to produce a product have time components that are greatly influenced by product's features (operations complexity, i.e. level of standardization) and process' capabilities (operations uncertainties, i.e. production volumes). In this way, the process environment is conditioned by the product standardization, i.e. a product with high levels of standardization (and simple to produce) allows high levels of production volumes.

It must be noted that there are four recurrent elements present in these alignment conditions: demand uncertainty, business model, product standardization, and process environment flexibility. In the next section we use these four elements to derive an analytical expression of the impact the strategic - operational levels alignment has on the performance of the manufacturing organization. Section 3 illustrates the usefulness of the analytical expression via the development of a simulation model, section 4 shows the sensitivity analysis performed over the proposed simulation model, and section 5 closes with the conclusions and future research.

## 2. Analytical expression of the demand fulfillment capability

According to [16] and [17], metrics used to measure the performance of the SC can be classified as strategic, tactical, and operational, where the performance of a SC partner can be expressed in terms such as customer satisfaction, product quality, speed in completing manufacturing orders, productivity, diversity of product line, flexibility in manufacturing new products, etc [18]. In this paper we use demand fulfillment - understood as the achievement of the demanded volume - as it relates to the four recurrent elements present in the alignment conditions of the previous section:

- Demand uncertainty (U); according to [19], when demand uncertainty is low, a make-to-stock (MTS) business model is recommended. When demand uncertainty is high, a make-to-order (MTO) business model is recommended.
- Business model (BM); according to [20], in a MTS business model production planning is made based on a forecast (rather than actual orders), allowing to produce ahead of time,

keep a stock, and ship upon receipt of orders. According to [21], when using this business model, an inventory-oriented level strategy should be used, where a steady production is maintained and finished goods inventory is used to absorb ongoing differences between output and sales. In the case of the case of the MTO business model, according to [20], production planning is made on actual orders (rather than on forecast), allowing to eliminate finished goods inventories. When using this business model, a capacity-oriented chase strategy should be used [21], where the expected demand is tracked and the corresponding capacity is computed, raising it or lowering it accordingly.

- Process environment flexibility (F); according to [19], when following a level strategy, a rigid continuous production line should be used. When following a chase strategy, a flexible job shop should be used.
- Product standardization (S); according to [22], a continuous production line uses special-purpose equipment - grouped around the product - to profitably manufacture high-volumes of standardized products. In the case of the of the job shop, it uses general-purpose equipment - grouped around the process – to profitably manufacture low-volumes of customized products.

As we can see in Figure 1, there is trade-off between the inventory-oriented and capacity-oriented strategies (or demand fulfillment strategies): the contribution increase/decrease of one implies the contribution decrease/increase of the other. This can be express in an analytical way:

- When uncertainty U is low (0), business model BM is MTS (0), standardization S is high (1), and flexibility F is low (0), demand is fulfilled 100% from inventory, Equation (1):

$$\text{Inventory contribution to demand fulfillment} = D * (1-U) * (1-BM) * S * (1-F) \quad (1)$$

- When uncertainty U is high (1), business model BM is MTO (1), standardization S is low (0), and flexibility F is high (1), demand is fulfilled 100% from capacity, Equation (2):

$$\text{Capacity contribution to demand fulfillment} = D * U * BM *(1- S) * F \quad (2)$$

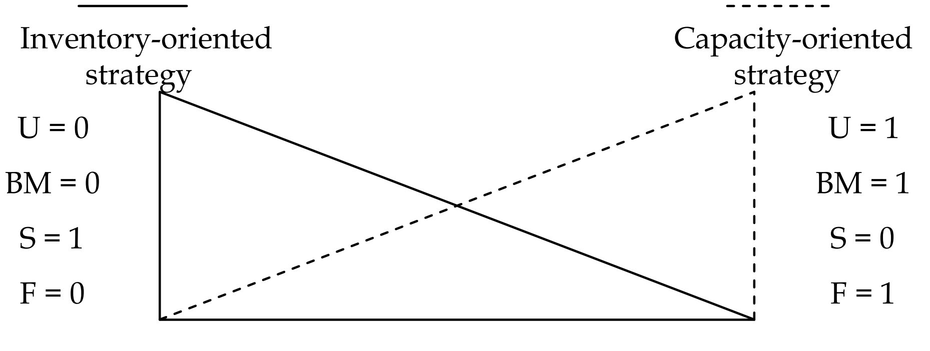


Fig. 1. Demand fulfillment relationships

In this way, demand fulfillment would be sum of the contributions made by the inventory-oriented and capacity-oriented strategies: for a totally aligned scenario (left or right sides of Figure 1), demand will be fulfilled by a 100% inventory-oriented or 100% capacity-oriented strategy; for a misaligned scenario, demand will be fulfilled by a combination of both strategies. Table 3 presents all the different combinations of limit conditions (that is, the 0's or 1's in Table 2), for a demand level of 100 units. As we can see, Equation (1) and (2) represent accurately the trade-off between the demand fulfillment strategies. Note: when the demand fulfillment equals to zero it means that even though some level of production takes place, the achieved demand volume is really low - when compared to the demanded volume - that it can be considered to be zero. For example, if demand equals to 100 units, there is high uncertainty in the demand (U = 1), the business model used is MTO (BM = 1), the product is totally standardized (S = 1), and it uses a functional job shop (F = 1). Here the high uncertainty of the demand requires waiting for customer feedback (provided by the MTO business model). However, the totally standardized product is characterized by using simple manufacturing and/or assembly operations (that take a really short time). In this case, the functional job shop used would affect the fulfillment of the 100 units, by presenting two obstacles to the flow of the process: 1) the set up times proper of the universal equipment used (very long compared to the production run), and 2) the moving time from one operation to the next (as all the equipment is grouped based on their functionality). In this way, the analytical expression of the alignment impact can not be taken as an estimator of the final values of the fulfilled demand, but instead, as an indicator of the capability of the manufacturing organization to achieve the demanded volume (or demand fulfillment capability indicator): the closer this indicator is to the demand volume, the more feasible it will be for the manufacturing organization to achieve the demanded volume.

Before proceeding to the next section, it must be noted that the customer service and the demand fulfillment relationships (presented in the previous sections), are well-known facts - by production managers and industrial engineers - that have been reported previously in the literature. What we consider to be an original contribution of this paper is taking these well-known facts of production engineering, and putting them in the form of the demand fulfillment capability indicator, an analytical expression that relates the degree of alignment (between the structural and operational levels) with demand fulfillment. Two similar demand fulfillment equations are presented in [23], but they only consider the uncertainty and business model configuration attributes. In our proposal, we extend that work by including the standardization and flexibility configuration attributes. Next section present the practical applications (and therefore its usefulness) of the derived analytical expression.

| | **0** | **0.25** | **0.5** | **0.75** | **1** |
|---|---|---|---|---|---|
| Uncertainty | Low, std = 0% of demand | Low-medium, std = 7.5% of demand | Medium, std = 15% of demand | Medium-high, std = 22.5% of demand | High, std = 30% of demand |
| Business model | MTS | MTS-ATO | ATO | ATO-MTO | MTO |
| Standardization | Customer's specs | Own catalog, non-standard options | Own catalog, with standard options | Standard with options | Standard, no options |
| Flexibility | Mass assembly line | Repetitive U line | Batch U line | Batch cellular | Functional job shop |

Table 2. Numeric values of the recurrent elements

| | Demand fulfillment strategy | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 100% inventory- -oriented | | | | | | | | | 100% Capacity- -oriented | | | |
| D | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| U | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| BM | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| S | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 |
| F | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 |
| Equation (1) result | 0 | 0 | 0 | **100** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0** | 0 | 0 | 0 |
| Equation (2) result | 0 | 0 | 0 | **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **100** | 0 | 0 | 0 |

Table 3. Results for different combinations of limit conditions

## 3. Practical application of the demand fulfillment capability indicator

Reference [24] presents the case of Company ABC, a furniture company experiencing unforeseen problems due to the implementation of company-wide policies that put into conflicts the alignment relationships (between the strategic and operational levels) mentioned in section 1.1. The impact these policies have on Company ABC's performance, can be evaluated by using Equation (1) and (2) and the following values (from Table 2):

- U = 0.25, for a somewhat predictable market demand.
- BM = 0.5, for having products stocked in a ready-to-assemble condition.
- S = 0.25, for the offered own catalog – no standards options.
- F = 0.75, for the use of manufacturing cells.

In this way, for a demand level of 100 units, the demand fulfillment feasibility indicator shows a total value of 9.37 (meaning that Company ABC has a really hard time trying to achieve the demanded volume of 100 units):

| | | | |
|---|---|---|---|
| Inventory contribution | = 100 * (1-0.25) * (1-0.5) * 0.25 * (1-0.75) | = | 2.34 |
| Capacity contribution | = 100 * 0.25 * 0.5 *(1- 0.25) * 0.75…………… | = | 7.03 |
| Total | = | | 9.37 |

At this point, Company ABC needs to explore the possibility of making some adjustments to their policies, by migrating from their current alignment conditions to new ones. This migration process implies either increasing or decreasing some of the business model, standardization, and/or flexibility values. Examples of such migration process can be found in [14]. The question becomes then which values to increase/decrease and in what amount. An alternative that Company ABC has to answer these questions is the development of a simulation model that guides its search for more advantageous alignment conditions. Some important business applications of simulation within SC scenarios are:

- A simulation model is generally accepted as a valuable aid for gaining insights into and making decisions about the manufacturing system [25].
- A simulation model provides a mean to evaluate the impact of policy changes and to answer 'what if?'and 'what's best?' questions [26].
- A simulation model is useful for performance prediction [27] and for representing time varying behaviors [28].
- A simulation model is maybe the only approach for analyzing the complex and comprehensive strategic level issues that need to consider the tactical and operational levels [29].

For this reason, and in order to show the practical use of our research contribution, Equations (1) and (2), in this paper we proceed in the following way:

- Develop of a simulation model of an automotive SC partner; following a similar approach to the one presented by [30], where a discrete event simulation model (of a SC) is implemented and an application example is proposed for a better understanding of the simulation model potential. The reason for choosing the case of an automotive SC partner obeys to the following reason: [31] presents a SC modeling methodology and uses the automotive SC in order to exemplify it. It must be noted that point 3 of the modeling methodology presented in [31] assumes that the demand fulfillment capability, of the partners within the automotive SC, depends only on the business model used. This is where we consider our research contribution can complement the modeling methodology presented in [31], by adding the uncertainty, standardization, and flexibility elements (Equations 1 and 2).
- Use of system dynamics (SD) as the simulation paradigm; following a similar approach to the one presented by [32], where a SD is employed to analyze the behavior and operation of a hybrid push/pull CONWIP-controlled lamp manufacturing SC. SD is one of the four simulation types mentioned by [33], and it is a system thinking approach that is not data driven, and that focuses on how the structure of a system and the taken policies affect its behavior [34]. According to [32], SD can be applied from macro perspective modeling (SC system) to micro perspective modeling (production floor system), and when applied to SC systems, it allows the analysis and decision on an aggregate level (which is more appropriate for supporting management decision-making, than conventional quantitative simulation).

Within this context, we use Equations (1) and (2) to develop an SD simulation model and use the situation of the automotive SC partner as an application example. In the case the simulation model is used as a decision making tool, then a Design of Experiment (DOE) or an Analysis of Variance (ANOVA) needs to be perform on the statistical analysis of the output, as the result of the decision making process depends on how experiments are planned and how experiments results are analyzed.

### 3.1 Simulation model of an automotive SC partner

Based on Equations (1) and (2), an SD simulation model was built using the simulation software [35]. The SD simulation model was verified and validated following a similar approach to the one in [36]: it was presented to experienced professionals in the area of simulation model building, and the simulation model output was examined for reasonableness under a variety of settings of input parameters. The SD simulation model developed for a partner of the automotive SC is presented in Figure 2. This model complies with the analytical model presented by [31]:

1. The SC has several independent partners.
2. There is no global coordinator to make decisions at all levels, decisions are made locally and decentralized.
3. The partners have only two kinds of inputs and outputs, material and information flows. Material and information flows are described using inventory level and order backlog equations.
4. Each partner operates as a pull system (driven by orders between the partners involved in the SC) that processes or satisfies orders only when it has a backlog or orders to be processed.

5. Each partner can handle one product family (i.e. wipers) or one a single product (i.e. a specific type of wiper). For SC of the automotive industry, modeling partners that are able only to handle one product represents a sufficient and realistic requirement.

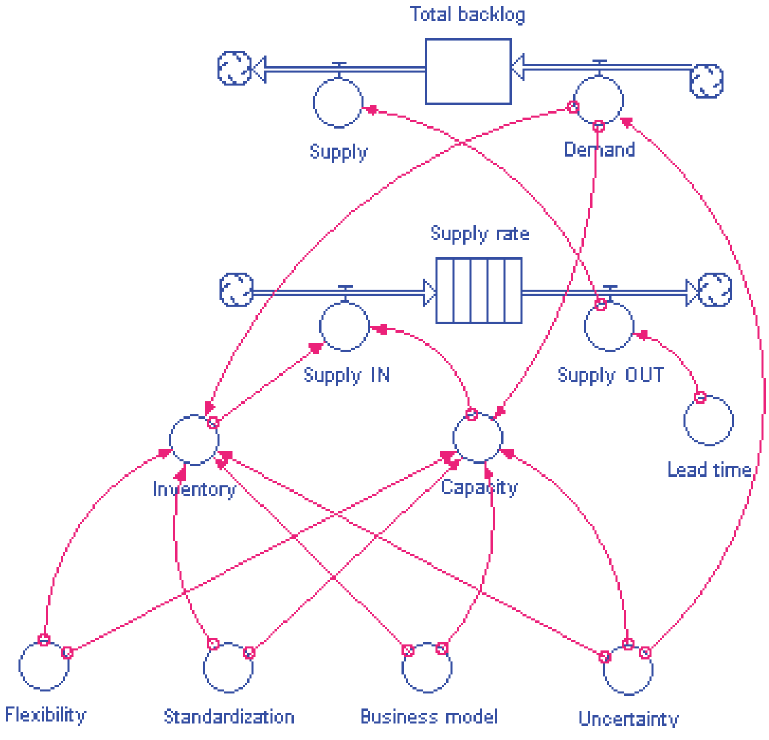


Fig. 2. SD simulation model of an automotive supply chain partner, as proposed by [31]

The performance criteria considered is demand fulfillment (in the form of the accumulated total backlog at the end of planning period T). The most important assumptions made in the simulation model are the following:

- *Total backlog* $_i$ is the difference between *Demand* $_i$ and *Supply* $_i$, during period *i* of the planning period T.
- *Demand* $_i$ varies according to a normal distribution, with a mean of 100 units and a standard deviation of *Uncertainty*. The normal distribution is used to represent a symmetrically variation above and below a mean value [37].
- *Uncertainty* ranges from 0 units (low) to 30 units (high).
- Supply $_i$ is equal to supply $_i$ OUT.
- *Supply* $_i$ *OUT* is equal to *Supply* $_i$ *IN* after a delay of *lead time* $_i$.
- *Lead time* $_i$ varies according to a uniform distribution and is given in weeks. The uniform distribution is used to represent the 'worst case' result of variances in the lead time [37].
- *Supply* $_i$ *IN* is the sum of the contribution made by *Inventory* $_i$ and *Capacity* $_i$. This is done with the intention to reflect the different demand fulfillment strategies, i.e. level strategy (inventory-oriented) for MTS environments and chase strategy (capacity-oriented) for MTO environments.
- *Business model* ranges from 0 (MTS environment) to 1 (MTO environment).
- *Standardization* ranges from 0 (low) to high (1).
- *Flexibility* ranges from 0 (low) to high (1).

- *Inventory* $_i$ is equal to Equation (1):

Demand * (1- Uncertainty) * (1- Business model) * Standardization * (1- Flexibility)

- *Capacity* $P_i$ is equal to Equation (2):

Demand * Uncertainty * Business model * (1- Standardization) * Flexibility

Figure 3 shows the analysis of a partner of the automotive supply chain. Stock elements were used to represent the *Backlog* $P_i$, due to its accumulating nature, while Conveyor elements were used to represent the delay of lead time units for fulfilling the order, due to its transit time feature.

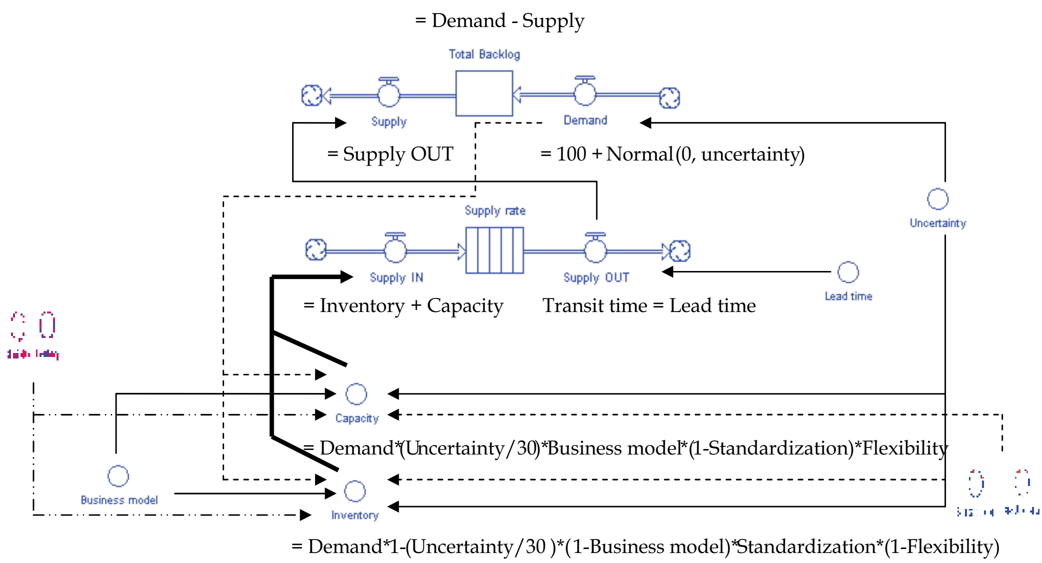


Fig. 3. Explanation of the elements of the SD simulation model

## 4. Sensitivity analysis

In order to study the effect of varying the level of demand uncertainty and lead time variation, 1875 different scenarios were tested:

- *Uncertainty* levels of 0, 7.5, 15, 22.5, and 30. As it was stated previously, these values represent the standard deviation (given in units) of the normal distribution used to represent the demand variation.
- *Business model*, *Standardization*, and *Flexibility* levels of 0, 0.25, 0.5, 0.75, and 1.
- *Lead time* levels of Uniform (1, 1), Uniform (1, 3), and Uniform (1, 5). In a uniform distribution, values spread uniformly between a minimum and a maximum value. In this way, Uniform (1,1) represent a low lead time variation (no variation), Uniform (1,3) represent medium lead time variation (values spread between 1 and 3 weeks), and Uniform (1,5) represent a high lead time variation (values spread between 1 and 5 weeks).

For a planning period T = 100 and thirty replications per scenario, confidence intervals of 95% level were constructed and reported in Tables 4, 5, and 6, which summarize the behavior of the total backlog values as standardization, flexibility, and business model increases from 0 to 1, uncertainty increases from 0 to 30, and lead time increases from low - Uniform (1, 1) - to high - Uniform (1, 5).

| | | u = 0 | | | | | u = 7.5 | | | | | u = 15 | | | | | u = 22.5 | | | | | u = 30 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | s | | | | | s | | | | | s | | | | | s | | | | | s | | | | |
| bm | f | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 |
| 0 | 0 | 10000 | 7525 | 5050 | 2575 | 100 | 9949.47 | 8142 | 6286.03 | 4429.3 | 2572.43 | 9949.5 | 8760.77 | 7523.13 | 6285.57 | 5047.6 | 9948.47 | 9379.5 | 8760.03 | 8140.87 | 7521.43 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 8218 | 6337 | 4456 | 2575 | 9949.47 | 8605.9 | 7214 | 5821.7 | 4429.3 | 9949.5 | 9070.63 | 8141.53 | 7213.3 | 6285.57 | 9948.47 | 9533.97 | 9069.43 | 8605.67 | 8140.87 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.5 | 10000 | 8812 | 7525 | 6337 | 5050 | 9949.47 | 9070.7 | 8142 | 7214 | 6286.03 | 9949.5 | 9377.79 | 8760.77 | 8141.53 | 7523.13 | 9948.47 | 9688.57 | 9379.5 | 9069.43 | 8760.03 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.75 | 10000 | 9406 | 8812 | 8218 | 7525 | 9949.47 | 9537.23 | 9070.7 | 8605.9 | 8142 | 9949.5 | 9688.23 | 9379.77 | 9070.63 | 8760.77 | 9948.47 | 9845.07 | 9688.57 | 9533.97 | 9379.5 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| 0.25 | 0 | 10000 | 8218 | 6337 | 4456 | 2575 | 9949.47 | 8605.9 | 7214 | 5821.7 | 4429.3 | 9949.5 | 9070.63 | 8141.53 | 7213.3 | 6285.57 | 9948.47 | 9533.97 | 9069.43 | 8605.67 | 8140.87 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 8614 | 7228 | 5842 | 4456 | 9850.47 | 8838.1 | 7833.47 | 6827.63 | 5821.7 | 9688.23 | 9070.63 | 8451.13 | 7831.87 | 7213.3 | 9533.97 | 9302.47 | 9069.43 | 8836.77 | 8605.67 | 9378.77 | 9533.43 | 9688.37 | 9844 | 9948.73 |
| | 0.5 | 10000 | 9109 | 8218 | 7228 | 6337 | 9681.83 | 9070.7 | 8452.37 | 7833.47 | 7214 | 9379.77 | 9070.63 | 8760.77 | 8451.13 | 8141.53 | 9069.43 | 9069.43 | 9069.43 | 9069.43 | 9069.43 | 8760.03 | 9069.93 | 9378.77 | 9688.37 | 9948.73 |
| | 0.75 | 10000 | 9604 | 9109 | 8614 | 8218 | 9537.23 | 9301.93 | 9070.7 | 8838.1 | 8605.9 | 9070.63 | 9070.63 | 9070.63 | 9070.63 | 9070.63 | 8605.67 | 8836.77 | 9069.43 | 9302.47 | 9533.97 | 8140.53 | 8604.27 | 9069.93 | 9533.43 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 9379.4 | 9537.23 | 9681.83 | 9850.47 | 9949.47 | 8760.77 | 9070.63 | 9379.77 | 9688.23 | 9949.5 | 8140.87 | 8605.67 | 9069.43 | 9533.97 | 9948.47 | 7521.67 | 8140.53 | 8760.03 | 9378.77 | 9948.73 |
| 0.5 | 0 | 10000 | 8812 | 7525 | 6337 | 5050 | 9949.47 | 9070.7 | 8142 | 7214 | 6286.03 | 9949.5 | 9379.77 | 8760.77 | 8141.53 | 7523.13 | 9948.47 | 9688.57 | 9379.5 | 9069.43 | 8760.03 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 9109 | 8218 | 7228 | 6337 | 9681.83 | 9070.7 | 8452.37 | 7833.47 | 7214 | 9379.77 | 9070.63 | 8760.77 | 8451.13 | 8141.53 | 9069.43 | 9069.43 | 9069.43 | 9069.43 | 9069.43 | 8760.03 | 9069.93 | 9378.77 | 9688.37 | 9948.73 |
| | 0.5 | 10000 | 9406 | 8812 | 8218 | 7525 | 9379.4 | 9070.7 | 8762.03 | 8452.37 | 8142 | 8760.77 | 8760.77 | 8760.77 | 8760.77 | 8760.77 | 8140.87 | 8450.33 | 8760.03 | 9069.43 | 9379.5 | 7521.67 | 8140.53 | 8760.03 | 9378.77 | 9948.73 |
| | 0.75 | 10000 | 9703 | 9406 | 9109 | 8812 | 9070.7 | 9070.7 | 9070.7 | 9070.7 | 9070.7 | 8141.53 | 8451.13 | 8760.77 | 9070.63 | 9379.77 | 7212.03 | 7826.4 | 8450.33 | 9069.43 | 9688.57 | 6283.8 | 7210.97 | 8140.53 | 9069.93 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 8762.03 | 9070.7 | 9379.4 | 9681.83 | 9949.47 | 7523.13 | 8141.53 | 8760.77 | 9379.77 | 9949.5 | 6283.7 | 7212.03 | 8140.87 | 9069.43 | 9948.47 | 5044.73 | 6283.8 | 7521.67 | 8760.03 | 9948.73 |
| 0.75 | 0 | 10000 | 9406 | 8812 | 8218 | 7525 | 9949.47 | 9537.23 | 9070.7 | 8605.9 | 8142 | 9949.5 | 9688.23 | 9379.77 | 9070.63 | 8760.77 | 9948.47 | 9845.07 | 9688.57 | 9533.97 | 9379.5 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 9604 | 9109 | 8614 | 8218 | 9537.23 | 9301.93 | 9070.7 | 8838.1 | 8605.9 | 9070.63 | 9070.63 | 9070.63 | 9070.63 | 9070.63 | 8605.67 | 8836.77 | 9069.43 | 9302.47 | 9533.97 | 8140.53 | 8604.27 | 9069.93 | 9533.43 | 9948.73 |
| | 0.5 | 10000 | 9703 | 9406 | 9109 | 8812 | 9070.7 | 9070.7 | 9070.7 | 9070.7 | 9070.7 | 8141.53 | 8451.13 | 8760.77 | 9070.63 | 9379.77 | 7212.03 | 7832.3 | 8450.33 | 9069.43 | 9688.57 | 6283.8 | 7210.97 | 8140.53 | 9069.93 | 9948.73 |
| | 0.75 | 10000 | 9901 | 9703 | 9604 | 9406 | 8605.9 | 8838.1 | 9070.7 | 9301.93 | 9537.23 | 7213.3 | 7831.87 | 8451.13 | 9070.63 | 9688.23 | 5280.03 | 6825.23 | 7832.3 | 8836.77 | 9845.07 | 4425.7 | 5818.9 | 7210.97 | 8604.27 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 8142 | 8605.9 | 9070.7 | 9537.23 | 9949.47 | 6285.57 | 7213.3 | 8141.53 | 9007.63 | 9949.5 | 4426.9 | 5820.03 | 7212.03 | 8605.67 | 9948.47 | 2568.33 | 4425.7 | 6283.8 | 8140.53 | 9948.73 |
| 1 | 0 | 10000 | 10000 | 10000 | 10000 | 10000 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 10000 | 10000 | 10000 | 10000 | 9379.4 | 9537.23 | 9681.83 | 9850.47 | 9949.47 | 8760.77 | 9070.63 | 9379.77 | 9688.23 | 9949.5 | 8140.87 | 8605.67 | 9069.43 | 9533.97 | 9948.47 | 7521.67 | 8140.53 | 8760.03 | 9378.77 | 9948.73 |
| | 0.5 | 10000 | 10000 | 10000 | 10000 | 10000 | 8762.03 | 9070.7 | 9379.4 | 9681.83 | 9949.47 | 7523.13 | 8141.53 | 8760.77 | 9379.77 | 9949.5 | 6283.7 | 7212.03 | 8410.87 | 9069.43 | 9948.47 | 5044.73 | 6283.8 | 7521.67 | 8760.03 | 9948.73 |
| | 0.75 | 10000 | 10000 | 10000 | 10000 | 10000 | 8142 | 8605.9 | 9070.7 | 9537.23 | 9949.47 | 6285.57 | 7213.3 | 8141.53 | 9070.63 | 9949.5 | 4426.9 | 5820.03 | 7212.03 | 8605.67 | 9948.47 | 2568.83 | 4425.7 | 6283.8 | 8140.53 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 7523.83 | 8142 | 8762.03 | 9379.4 | 9949.47 | 5047.6 | 6283.57 | 7523.13 | 8760.77 | 9949.5 | 2568.77 | 4426.9 | 6283.7 | 8140.87 | 9948.47 | 91.73 | 2568.83 | 5044.73 | 7521.67 | 9948.73 |

Table 4. Simulation output, low lead time variation

| | | u = 0 | | | | | u = 7.5 | | | | | u = 15 | | | | | u = 22.5 | | | | | u = 30 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | s | | | | | s | | | | | s | | | | | s | | | | | s | | | | |
| bm | f | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 |
| 0 | 0 | 10000 | 7560.83 | 5121.67 | 2682.5 | 243.33 | 9949.47 | 8167.73 | 6338.07 | 4507.9 | 2677.33 | 9949.5 | 8777.4 | 7557.1 | 6336.83 | 5116.27 | 9948.47 | 9387.17 | 8776.23 | 8165.57 | 7554.67 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 8243.8 | 6390.03 | 4536.27 | 2682.5 | 9949.47 | 8625.1 | 7253 | 5880.4 | 4507.9 | 9949.5 | 9083 | 8166.87 | 7251.63 | 6336.83 | 9948.47 | 9539.53 | 9081.37 | 8624.17 | 8165.57 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.5 | 10000 | 8829.2 | 7560.83 | 6390.03 | 5121.67 | 9949.47 | 9083.23 | 8167.73 | 7253 | 6338.07 | 9949.5 | 9387.7 | 8777.4 | 8166.87 | 7557.1 | 9948.47 | 9691.93 | 9387.17 | 9081.37 | 8776.23 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.75 | 10000 | 9414.6 | 8829.2 | 8243.8 | 7560.83 | 9949.47 | 9543.17 | 9083.23 | 8625.1 | 8167.73 | 9949.5 | 9691.87 | 9387.7 | 9083 | 8777.4 | 9948.47 | 9846.37 | 9691.93 | 9539.53 | 9387.17 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| 0.25 | 0 | 10000 | 8243.8 | 6390.03 | 4536.27 | 2682.5 | 9949.47 | 8625.1 | 7253 | 5880.4 | 4507.9 | 9949.5 | 9083 | 8166.87 | 7251.63 | 6336.83 | 9948.47 | 9539.53 | 9081.37 | 8624.17 | 8165.57 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 8634.07 | 7268.13 | 5902.2 | 4536.27 | 9851.9 | 8853.97 | 7863.63 | 6871.97 | 5880.4 | 9691.87 | 9083 | 8472.1 | 7861.5 | 7251.63 | 9539.53 | 9311.3 | 9081.37 | 8852.13 | 8624.17 | 9386.43 | 9539.07 | 9691.8 | 9845.37 | 9948.73 |
| | 0.5 | 10000 | 9121.9 | 8243.8 | 7268.13 | 6390.03 | 9685.57 | 9083.23 | 8473.6 | 7863.63 | 7253 | 9387.7 | 9083 | 8777.4 | 8472.1 | 8166.87 | 9081.37 | 9081.37 | 9081.37 | 9081.37 | 9081.37 | 8776.1 | 9081.67 | 9386.43 | 9691.8 | 9948.73 |
| | 0.75 | 10000 | 9609.73 | 9121.9 | 8634.07 | 8243.8 | 9543.17 | 9311.17 | 9083.23 | 8853.97 | 8625.1 | 9083 | 9083 | 9083 | 9083 | 9083 | 8624.17 | 8852.13 | 9081.37 | 9311.3 | 9539.53 | 8164.93 | 8622.43 | 9081.67 | 9539.07 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 9387.47 | 9543.17 | 9685.57 | 9851.9 | 9949.47 | 8777.4 | 9083 | 9387.7 | 9691.87 | 9949.5 | 8165.57 | 8624.17 | 9081.37 | 9539.53 | 9948.47 | 7554.5 | 8164.93 | 8776.1 | 9386.43 | 9948.73 |
| 0.5 | 0 | 10000 | 8829.2 | 7560.83 | 6390.03 | 5121.67 | 9949.47 | 9083.23 | 8167.73 | 7253 | 6338.07 | 9949.5 | 9387.7 | 8777.4 | 8166.87 | 7557.1 | 9948.47 | 9691.93 | 9387.17 | 9081.37 | 8776.23 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 9121.9 | 8243.8 | 7268.13 | 6390.03 | 9685.57 | 9083.23 | 8473.6 | 7863.63 | 7253 | 9387.7 | 9083 | 8777.4 | 8472.1 | 8166.87 | 9081.37 | 9081.37 | 9081.37 | 9081.37 | 9081.37 | 8776.1 | 9081.67 | 9386.43 | 9691.8 | 9948.73 |
| | 0.5 | 10000 | 9414.6 | 8829.2 | 8243.8 | 7560.83 | 9387.47 | 9083.23 | 8778.9 | 8473.6 | 8167.73 | 8777.4 | 8777.4 | 8777.4 | 8777.4 | 8777.4 | 8165.57 | 8470.87 | 8776.23 | 9081.37 | 9387.17 | 7554.5 | 8164.93 | 8776.1 | 9386.43 | 9948.73 |
| | 0.75 | 10000 | 9707.3 | 9414.6 | 9121.9 | 8829.2 | 9083.23 | 9083.23 | 9083.23 | 9083.23 | 9083.23 | 8166.87 | 8472.1 | 8777.4 | 9083 | 9387.7 | 7249.67 | 7861.33 | 8470.87 | 9081.37 | 9691.93 | 6333.33 | 7247.9 | 8164.93 | 9081.67 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 8778.9 | 9083.23 | 9387.47 | 9685.57 | 9949.47 | 7557.1 | 8166.87 | 8777.4 | 9387.7 | 9949.5 | 6333.97 | 7249.67 | 8165.57 | 9081.37 | 9948.47 | 5110.97 | 6333.33 | 7554.5 | 8776.1 | 9948.73 |
| 0.75 | 0 | 10000 | 9414.6 | 8829.2 | 8243.8 | 7560.83 | 9949.47 | 9543.17 | 9083.23 | 8625.1 | 8167.73 | 9949.5 | 9691.87 | 9387.7 | 9083 | 8777.4 | 9948.47 | 9846.37 | 9691.93 | 9539.53 | 9387.17 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 9609.73 | 9121.9 | 8634.07 | 8243.8 | 9543.17 | 9311.17 | 9083.23 | 8853.97 | 8625.1 | 9083 | 9083 | 9083 | 9083 | 9083 | 8624.17 | 8852.13 | 9081.37 | 9311.3 | 9539.53 | 8164.93 | 8622.43 | 9081.67 | 9539.07 | 9948.73 |
| | 0.5 | 10000 | 9707.3 | 9414.6 | 9121.9 | 8829.2 | 9083.23 | 9083.23 | 9083.23 | 9083.23 | 9083.23 | 8166.87 | 8472.1 | 8777.4 | 9083 | 9387.7 | 7249.67 | 7861.33 | 8470.87 | 9081.37 | 9691.93 | 6333.33 | 7247.9 | 8164.93 | 9081.67 | 9948.73 |
| | 0.75 | 10000 | 9902.43 | 9707.3 | 9609.73 | 9414.6 | 8625.1 | 8853.97 | 9083.23 | 9311.17 | 9543.17 | 7251.63 | 7861.5 | 8472.1 | 9083 | 9691.87 | 5876.73 | 6868.03 | 7861.33 | 8852.13 | 9846.37 | 4500.3 | 5874.57 | 7247.9 | 8622.43 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 8167.73 | 8625.1 | 9083.23 | 9543.17 | 9949.47 | 6336.83 | 7251.63 | 8166.87 | 9083 | 9949.5 | 4502.77 | 5876.73 | 7249.67 | 8624.17 | 9948.47 | 2668.47 | 4500.3 | 6333.33 | 8164.93 | 9948.73 |
| 1 | 0 | 10000 | 10000 | 10000 | 10000 | 10000 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9949.5 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000 | 10000 | 10000 | 10000 | 10000 | 9387.47 | 9543.17 | 9685.57 | 9851.9 | 9949.47 | 8777.4 | 9083 | 9387.87 | 9691.87 | 9949.5 | 8165.57 | 8624.17 | 9081.37 | 9539.53 | 9948.47 | 7554.5 | 8164.93 | 8776.1 | 9386.43 | 9948.73 |
| | 0.5 | 10000 | 10000 | 10000 | 10000 | 10000 | 8778.9 | 9083.23 | 9387.47 | 9685.57 | 9949.47 | 7557.1 | 8166.87 | 8777.4 | 9387.7 | 9949.5 | 6333.97 | 7249.67 | 8165.57 | 9081.37 | 9948.47 | 5110.97 | 6333.33 | 7554.5 | 8776.1 | 9948.73 |
| | 0.75 | 10000 | 10000 | 10000 | 10000 | 10000 | 8167.73 | 8625.1 | 9083.23 | 9543.17 | 9949.47 | 6336.83 | 7251.63 | 8166.87 | 9083 | 9949.5 | 4502.77 | 5876.73 | 7249.67 | 8624.17 | 9948.47 | 2668.47 | 4500.3 | 6333.33 | 8164.93 | 9948.73 |
| | 1 | 10000 | 10000 | 10000 | 10000 | 10000 | 7558.37 | 8167.73 | 8778.9 | 9387.47 | 9949.47 | 5116.27 | 6336.83 | 7557.1 | 8777.4 | 9949.5 | 2670.17 | 4502.77 | 6333.97 | 8165.57 | 9948.47 | 224.87 | 2668.47 | 5110.97 | 7554.5 | 9948.73 |

Table 5. Simulation output, medium lead time variation

| | | u = 0 | | | | | u = 7.5 | | | | | u = 15 | | | | | u = 22.5 | | | | | u = 30 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | s | | | | | s | | | | | s | | | | | s | | | | | s | | | |
| bm | f | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 | 1 | 0 | 0.25 | 0.5 | 0.75 |
| 0 | 0 | 10000.00 | 7587.50 | 5175.00 | 2762.50 | 350.00 | 9949.47 | 8187.00 | 6377.30 | 4567.03 | 2756.30 | 9949.50 | 8790.13 | 7583.03 | 6375.87 | 5168.50 | 9948.47 | 9393.27 | 8788.80 | 8184.67 | 7580.30 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000.00 | 8263.00 | 6429.50 | 4596.00 | 2762.50 | 9949.47 | 8639.47 | 7282.30 | 5924.60 | 4567.03 | 9949.50 | 9092.40 | 8186.13 | 7280.77 | 6375.87 | 9948.47 | 9543.87 | 9090.63 | 8638.40 | 8184.67 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.5 | 10000.00 | 8842.00 | 7587.50 | 6429.50 | 5175.00 | 9949.47 | 9092.67 | 8187.00 | 7282.30 | 6377.30 | 9949.50 | 9393.83 | 8790.13 | 8186.13 | 7583.03 | 9948.47 | 9694.67 | 9393.27 | 9090.63 | 8788.80 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.75 | 10000.00 | 9421.00 | 8842.00 | 8263.00 | 7587.50 | 9949.47 | 9547.53 | 9092.67 | 8639.47 | 8187.00 | 9949.50 | 9694.67 | 9393.83 | 9092.40 | 8790.13 | 9948.47 | 9847.47 | 9694.67 | 9543.87 | 9393.27 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 1 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.50 | 9949.50 | 9949.50 | 9949.50 | 9949.50 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| 0.25 | 0 | 10000.00 | 8263.00 | 6429.50 | 4596.00 | 2762.50 | 9949.47 | 8639.47 | 7282.30 | 5924.60 | 4567.03 | 9949.50 | 9092.40 | 8186.13 | 7280.77 | 6375.87 | 9948.47 | 9543.87 | 9090.63 | 8638.40 | 8184.67 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000.00 | 8649.00 | 7298.00 | 5947.00 | 4596.00 | 9852.97 | 8865.83 | 7886.30 | 6905.47 | 5924.60 | 9694.67 | 9092.40 | 8488.03 | 7884.10 | 7280.77 | 9543.87 | 9318.17 | 9090.63 | 8863.93 | 8638.40 | 9392.33 | 9543.33 | 9694.47 | 9846.43 |
| | 0.5 | 10000.00 | 9131.50 | 8263.00 | 7298.00 | 6429.50 | 9688.47 | 9092.67 | 8489.60 | 7886.30 | 7282.30 | 9393.83 | 9092.40 | 8790.13 | 8488.03 | 8186.13 | 9090.63 | 9090.63 | 9090.63 | 9090.63 | 9090.63 | 8788.53 | 9090.93 | 9392.33 | 9694.47 |
| | 0.75 | 10000.00 | 9614.00 | 9131.50 | 8649.00 | 8263.00 | 9547.53 | 9318.07 | 9092.67 | 8865.83 | 8639.47 | 9092.40 | 9092.40 | 9092.40 | 9092.40 | 9092.40 | 8638.40 | 8863.93 | 9090.63 | 9318.17 | 9543.87 | 8183.93 | 8636.57 | 9090.93 | 9543.33 |
| | 1 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 9393.60 | 9547.53 | 9688.47 | 9852.97 | 9949.47 | 8790.13 | 9092.40 | 9393.83 | 9694.67 | 9949.50 | 8184.67 | 8638.40 | 9090.63 | 9543.87 | 9948.47 | 7580.07 | 8183.93 | 8788.53 | 9392.33 |
| 0.5 | 0 | 10000.00 | 8842.00 | 7587.50 | 6429.50 | 5175.00 | 9949.47 | 9092.67 | 8187.00 | 7282.30 | 6377.30 | 9949.50 | 9393.83 | 8790.13 | 8186.13 | 7583.03 | 9948.47 | 9694.67 | 9393.27 | 9090.63 | 8788.80 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000.00 | 9131.50 | 8263.00 | 7298.00 | 6429.50 | 9688.47 | 9092.67 | 8489.60 | 7886.30 | 7282.30 | 9393.83 | 9092.40 | 8790.13 | 8488.03 | 8186.13 | 9090.63 | 9090.63 | 9090.63 | 9090.63 | 9090.63 | 8788.53 | 9090.93 | 9392.33 | 9694.47 |
| | 0.5 | 10000.00 | 9421.00 | 8842.00 | 8263.00 | 7587.50 | 9393.60 | 9092.67 | 8791.70 | 8489.60 | 8187.00 | 8790.13 | 8790.13 | 8790.13 | 8790.13 | 8790.13 | 8184.67 | 8486.63 | 8788.80 | 9090.63 | 9393.27 | 7580.07 | 8183.93 | 8788.53 | 9392.33 |
| | 0.75 | 10000.00 | 9710.50 | 9421.00 | 9131.50 | 8842.00 | 9092.67 | 9092.67 | 9092.67 | 9092.67 | 9092.67 | 8186.13 | 8488.03 | 8790.13 | 9092.40 | 9393.83 | 7278.67 | 7883.77 | 8486.63 | 9090.63 | 9694.67 | 6371.83 | 7276.73 | 8183.93 | 9090.93 |
| | 1 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 8791.70 | 9092.67 | 9393.60 | 9688.47 | 9949.47 | 7583.03 | 8186.13 | 8790.13 | 9393.83 | 9949.50 | 6372.73 | 7278.67 | 8184.67 | 9090.63 | 9948.47 | 5162.50 | 6371.83 | 7580.07 | 8788.53 |
| 0.75 | 0 | 10000.00 | 9421.00 | 8842.00 | 8263.00 | 7587.50 | 9949.47 | 9547.53 | 9092.67 | 8639.47 | 8187.00 | 9949.50 | 9694.67 | 9393.83 | 9092.40 | 8790.13 | 9948.47 | 9847.47 | 9694.67 | 9543.87 | 9393.27 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000.00 | 9614.00 | 9131.50 | 8649.00 | 8263.00 | 9547.53 | 9318.07 | 9092.67 | 8865.83 | 8639.47 | 9092.40 | 9092.40 | 9092.40 | 9092.40 | 9092.40 | 8638.40 | 8863.93 | 9090.63 | 9318.17 | 9543.87 | 8183.93 | 8636.57 | 9090.93 | 9543.33 |
| | 0.5 | 10000.00 | 9710.50 | 9421.00 | 9131.50 | 8842.00 | 9092.67 | 9092.67 | 9092.67 | 9092.67 | 9092.67 | 8186.13 | 8488.03 | 8790.13 | 9092.40 | 9393.83 | 7278.67 | 7883.77 | 8486.63 | 9090.63 | 9694.67 | 6371.83 | 7276.73 | 8183.93 | 9090.93 |
| | 0.75 | 10000.00 | 9903.50 | 9710.50 | 9614.00 | 9421.00 | 8639.47 | 8865.83 | 9092.67 | 9318.07 | 9547.53 | 7280.77 | 7884.10 | 8488.03 | 9092.40 | 9694.67 | 5920.43 | 6901.13 | 7883.77 | 8863.93 | 9847.47 | 4558.40 | 5918.07 | 7276.73 | 8636.57 |
| | 1 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 8187.00 | 8639.47 | 9092.67 | 9547.53 | 9949.47 | 6375.87 | 7280.77 | 8186.13 | 9092.40 | 9949.50 | 4561.20 | 5920.43 | 7278.67 | 8638.40 | 9948.47 | 2746.03 | 4558.40 | 6371.83 | 8183.93 |
| 1 | 0 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.47 | 9949.50 | 9949.50 | 9949.50 | 9949.50 | 9949.50 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.47 | 9948.73 | 9948.73 | 9948.73 | 9948.73 |
| | 0.25 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 9393.60 | 9547.53 | 9688.47 | 9852.97 | 9949.47 | 8790.13 | 9092.40 | 9393.83 | 9694.67 | 9949.50 | 8184.67 | 8638.40 | 9090.63 | 9543.87 | 9948.47 | 7580.07 | 8183.93 | 8788.53 | 9392.33 |
| | 0.5 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 8791.70 | 9092.67 | 9393.60 | 9688.47 | 9949.47 | 7583.03 | 8186.13 | 8790.13 | 9393.83 | 9949.50 | 6372.73 | 7278.67 | 8184.67 | 9090.63 | 9948.47 | 5162.50 | 6371.83 | 7580.07 | 8788.53 |
| | 0.75 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 8187.00 | 8639.47 | 9092.67 | 9547.53 | 9949.47 | 6375.87 | 7280.77 | 8186.13 | 9092.40 | 9949.50 | 4561.20 | 5920.43 | 7278.67 | 8638.40 | 9948.47 | 2746.03 | 4558.40 | 6371.83 | 8183.93 |
| | 1 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 10000.00 | 7584.37 | 8187.00 | 8791.70 | 9393.60 | 9949.47 | 5168.50 | 6375.87 | 7583.03 | 8790.13 | 9949.50 | 2748.30 | 4561.20 | 6372.73 | 8184.67 | 9948.47 | 328.60 | 2746.03 | 5162.50 | 7580.07 |

Table 6. Simulation output, high lead time variation

### 4.1 Standardization increase

When using the scenarios with a standardization level of zero as a comparison basis, an analysis of Tables 4, 5, and 6 reveals the same behavior:

- Below the diagonal that goes from BM = 1, U = 0 to BM = 0, U = 1 (Figure 4), the total backlog values decrease 76% of the time, remains the same 18% of the time, and increase 6% of the time. These results are explained by the fact that the U, BM and S values tend to the alignment conditions of a 100% inventory-oriented demand fulfillment strategy (U = 0, BM = 0, S = 1).
- Within the diagonal, the total backlog values decrease 24% of the time, remains the same 52% of the time, and increase 24% of the time.
- Above the diagonal, the total backlog values decrease 6% of the time, remains the same 18% of the time, and increase 76% of the time. These results are explained by the fact that the U and BM values tend to the alignment conditions of a 100% capacity-oriented demand fulfillment strategy (U = 1, BM = 1), but the S values are moving away (S = 0).

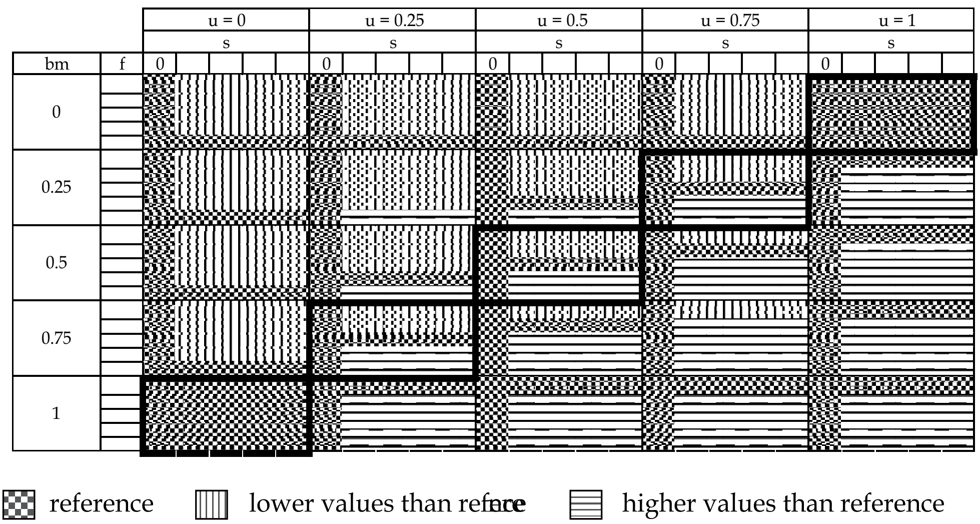


Fig. 4. Standardization increase

### 4.2 Flexibility increase

When using the scenarios with a flexibility level of zero as a comparison basis, an analysis of Tables 4, 5, and 6 reveals the same behavior:

- Below the diagonal, the total backlog values decrease 76% of the time, remains the same 18% of the time, and increase 6% of the time. These results are explained by the fact that the U, BM, and F values tend to the alignment conditions of a 100% capacity-oriented demand fulfillment strategy (U = 1, BM = 1, F = 1).
- Within the diagonal, the total backlog values decrease 24% of the time, remains the same 52% of the time, and increase 24% of the time.
- Above the diagonal that goes from BM = 1, U = 0 to BM = 0, U = 1 (Figure 5), the total backlog values decrease 6% of the time, remains the same 18% of the time, and increase 76% of the time. These results are explained by the fact that the U and BM values tend to the alignment conditions of a 100% inventory-oriented demand fulfillment strategy (U = 0, BM = 0), but the F values are moving away (F = 0).

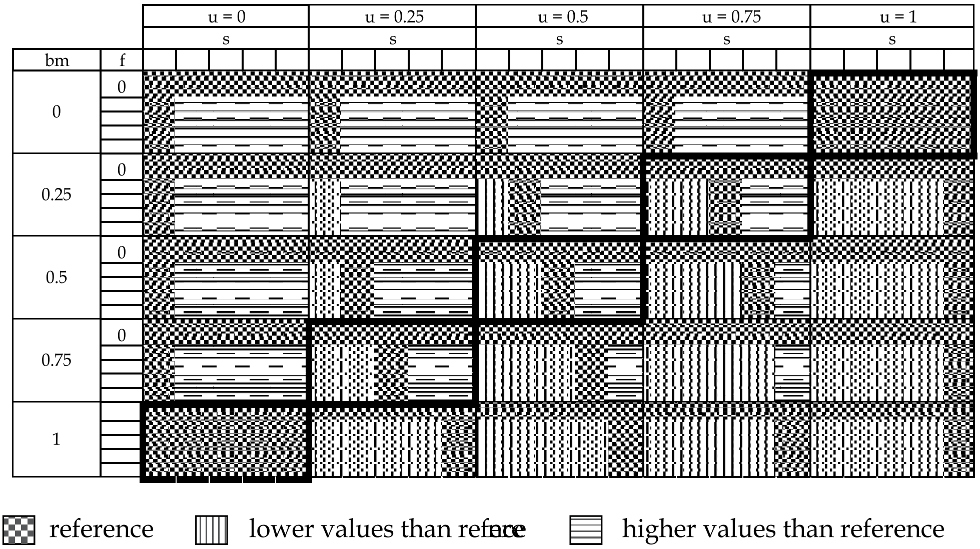


Fig. 5. Flexibility increase

### 4.3 Uncertainty and business model increase

When using (as a comparison basis) the total backlog values of the scenarios with uncertainty and business model equal to 0, we found that higher (or equal) total backlog values are found more frequently than lower values when there is a mismatch between the level of demand uncertainty present and the business model used to cope with it (lower left quadrant and upper right quadrant of Figure 6). An interesting fact is the role played by uncertainty in this mismatch: when uncertainty is low, 100% of the time higher (or equal) total backlog values are found (lower left quadrant of Figure 6). But when uncertainty is total then lower total backlog values can be found (lower right quadrant of Figure 6). This suggests that as the level of uncertainty increases, lower total backlog values are to be found (independently of the level of business model used).

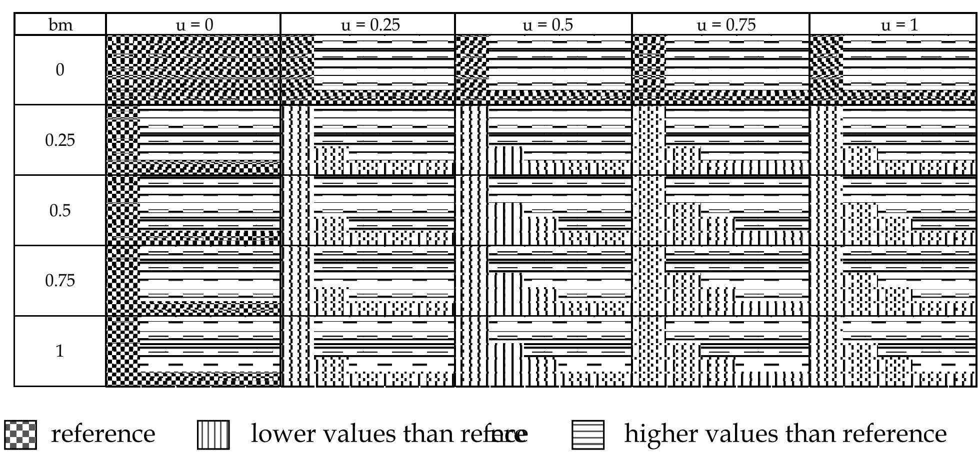


Fig. 6. Comparison of scenarios, uncertainty and business model values increase

In fact, when using the scenarios with a business model level of zero as a comparison basis, an analysis of Tables 4, 5, and 6 reveals the same behavior: within the same level of uncertainty, all the different business model levels (i.e. bm = 0, 0.25, 0.5, etc.), present the same the total backlog values behavior. In this way, for an uncertainty level of:

- 0; total backlog values decrease 0% of the time, remain the same 36% of the time, and increase 64% of the time.
- 0.25; total backlog values decrease 32% of the time, remain the same 16% of the time, and increase 52% of the time.
- 0.5; total backlog values decrease 40% of the time, remain the same 20% of the time, and increase 40% of the time.
- 0.75; total backlog values decrease 52% of the time, remain the same 16% of the time, and increase 32% of the time.
- 1.0; total backlog values decrease 64% of the time, remain the same 36% of the time, and increase 0% of the time.

### 4.4 Total backlog values frequency

When the values of Tables 4, 5, and 6 are classified according to the frequency a value appears within certain range, we found that:

- The distribution of the values is symmetrical (for the most part). This behavior has to do with the assumption that there is a continuum betwen the contributions made to demand fulfillment, by the inventory and the capacity strategies, Equations (1) and (2).

Total backlog values can be obtained through different combinations of u, bm, s, and f (Table 7), i.e. eight total backlog values in the range of 2,000 – 3,000.

| Value range | frequency | frequency % |
|---|---|---|
| 10000+ | 62 | 9.76 |
| 9000-10000 | 314 | 50.4 |
| 8000-9000 | 134 | 21.6 |
| 7000-8000 | 52 | 8.32 |
| 6000-7000 | 26 | 4.16 |
| 5000-6000 | 16 | 2.56 |
| 4000-5000 | 12 | 1.76 |
| 2000-3000 | 8 | 1.28 |
| 0-1000 | 2 | 0.16 |

Table 7. Total backlog values frequency

### 4.5 Implications for the automotive SC partner

As the level of uncertainty can not be controlled by the automotive SC partner, this last has to focus in adjusting the levels of standardization and/or flexibility rather than in adjusting the level of business model: while a total match between the business model used an the level of uncertainty present is not a guarantee of 100% lower total backlog values, neither a total mismatch guarantee 100% higher total backlog values. In fact, [38] reports that the standardization of a small number of semi-finished products resulted in a large reduction in the average lead times and with this, the increasing of volume of customer orders that can be processed during a certain period of volatile demand. If we take into account that a business model can be understood in terms of its level of customer feedback [23], i.e. all the activities in a pure MTO environment are driven by customer's information (so uncertainty of what to do next, when to do it, and for how long to do it, is at its maximum), then further research is called in the area of optimum customer feedback **(**that is, the level of customer feedback information with the least cost that allows the maximum reduction of the total backlog value**)**. A second implication is related to the frequency of the total backlog values: the automotive SC partner should follow and adaptive strategy in the management of its operations, as the same total backlog values can be obtained through different combinations of uncertainty, business model, standardization, and flexibility. Therefore, it is necessary to not only determine the optimum level customer feedback (as proposed earlier), but also the range of matchness (between uncertainty and the business model used) that would allow achieving a high frecuency of lower total backlog values, in the event of dealing with a high varying environment.

## 5. Conclusions

Manufacturing enterprises are pressured to shift from the traditional MTS to the MTO production model, and at the same time, compete against each other as part of a SC, in order to respond to changes in the customers' demands. As the decisions taken at the strategic level of the SC have a deep impact at the operational level of the manufacturing organization, it becomes necessary the alignment of activities, from the strategic level through the operational level. The objective of this paper was to quantitatively evaluate the impact of such alignment of the total backlog value of a manufacturing organization. For this reason, an analytical expression was derived a system dynamics (SD) simulation model was developed and tested under different scenarios (in order to collect statistical data regarding total backlog). The usefulness of the analytical expression was illustrated via a case study of an automotive SC partner and conclusions were derived regarding actions to improve its demand fulfillment capability. This research effort acknowledges that the misalignment between the strategic and operational levels creates an obstacle to demand fulfillment: the bigger the misalignment is, the bigger the obstacle to achieve the demanded volume will be. This idea resembles the concept of structural complexity proposed by [39], whom states that a high level of complexity in the structure of a production system (i.e. the number of operations and machines present in the routing sheets of a product family), has the effect of building obstacles that impedes the process flow. Future research will explore this venue and also, the use of a simulation-by-optimization approach (that is, finding out values of the decision variables which optimize a quantitative objective function under constraints).

## 6. References

[1] Ismail, H.S., Sharifi, H., A balanced approach to building agile supply chains, International Journal of Physical Distribution & Logistics Management 36 (6) (2006) 431-444.
[2] Duclos, L., Vokurka, R., Lummus, R. A conceptual model of supply chain flexibility, Industrial Management & Data Systems 103 (6) (2000) 446-456.
[3] Terzi, S., Cavalieri, S. Simulation in the supply chain context: a survey, Computers in Industry 53 (2004) 3–16.
[4] Ngai, E.W.T., Gunasekaran, A. Build-to-order supply chain management: a literature review and framework for development, Journal of Operations Management 23 (2005) 423–451.

[5] Li, D., O'Brien, C. 1999. Integrated decision modeling of supply chain efficiency, International Journal of Production Economics 59 (1999) 147-157.

[6] Li, D., O'Brien, C. A quantitative analysis of relationships between product types and supply chain strategies, International Journal of Production Economics 73 (2001) 29-39.

[7] Vonderembse, M.A., Uppal, M., Huang, S.H., Dismukes, J.P. Designing supply chains: Towards theory development, International Journal of Production Economics 100 (006) 223–238.

[8] Olhager, J. Strategic positioning of the order penetration point, International Journal of Production Economics 85 (3) (2003) 2335-2351.

[9] Vernadat, F. UEML: towards a unified enterprise modeling language, International Journal of Production Research 40 (17) (2002) 4309-4321.

[10] Angelides, M.C., Angerhofer, B.J. A model and a performance measurement system for collaborative supply chains, Decision Support Systems 42 (2006) 283– 301.

[11] Son, Y.J., Venkateswaran, J. Hybrid system dynamic: discrete event simulation-based architecture for hierarchical production planning, International Journal of Production Research 43 (20) (2005) 4397–4429.

[12] Khoo, L.P., Yin, X.F. An extended graph-based virtual clustering-enhanced approach to supply chain optimization, International Journal of Advanced Manufacturing Technology 22 (2003) 836–847.

[13] Zhang, D.Z., Anosike, A.I., Lim, M.K., Akanle,O.M. An agent-based approach for e-manufacturing and supply chain integration, Computers & Industrial Engineering 51 (2006) 343–360.

[14] Martinez-Olvera, C., Shunk, D. A comprehensive framework for the development of a supply chain strategy, International Journal of Production Research 44 (21) (2006) 4511–4528.

[15] Griffiths, J., James, R., Kempson, J. Focusing customer demand through manufacturing supply chains by the use of customer focused cells: an appraisal. International Journal of Production Economics 65 (1) (2000) 111-120.

[16] Chibba, A., Ake Horte, S., Supply chain performance – A Meta Analysis, European operations management association & Production and operations management society, Joint conference, June, 16-18 (2003).

[17] Gunasekaran, A., Patelb, C., McGaughey, R.E. A framework for supply chain performance measurement, International Journal of Production Economics 87 (2004) 333–347.

[18] Chen, C., C. An objective-oriented and product-line-based manufacturing performance measurement, International Journal of Production Economics 112 (2008) 380–390.

[19] Safizadeh, M.H., Ritzman, L.P. Linking performance drivers in production planning and inventory control to process choice, Journal of Operations Management 15 (1997) 389-403

[20] Gupta, D., Benjaafar, S. Make-to-order, make-to-stock, or delay product differentiation? A common framework for modeling and analysis, IIE Transactions 36 (2004) 529–546.

[21] Buxey, G. Strategy not tactics drives aggregate planning, International Journal of Production Economics 85 (2003) 331–346.

[22] Miltenburg, J. Manufacturing Strategy: How to Formulate and Implement a Winning Plan, Productivity Press, Portland, Oregon (1995).

[23] Martinez-Olvera, C. Impact of hybrid business models in the supply chain performance, book chapter. Supply Chain: Theory and Applications, ISBN 978-3-902613-22-6. I-Tech Education and Publishing, Vienna, Austria, European Union (2008a).
[24] Martinez-Olvera, C. Methodology for realignment of supply-chain structural, International Journal of Production Economics, doi:10.1016/j.ijpe.2008.03.008 (2008b),
[25] Huang, S.H., Uppal, M., Shi, J. A product driven approach to manufacturing supply chain selection, Supply chain management 7 (4) (2002) 189-199.
[26] Shah, N., Hung, W.Y., Kucherenko, S., Samsatli, N.J. A flexible and generic approach to dynamic modelling of supply chains, Journal of the Operational Research Society 55 (2004) 801–813.
[27] Towill, D.R. Time compression and supply chain management – a guided tour. Supply chain management 1 (1) (1996) 15-27.
[28] Venkateswaran, J., Son, Y. J. Impact of modeling approximations in supply chain analysis – an experimental study, International Journal of Production Research 42 (15) (2004) 2971–2992.
[29] Zhao, Z.Y., Ball, M., Chen, C.Y. A scalable supply chain infrastructure research test-bed. Department of decision & information technology. Robert H. Smith, School of Business, University of Maryland (2002).
[30] Longo, F., Mirabelli, G. An advanced supply chain management tool based on modeling and simulation, Computers & Industrial Engineering 54 (2008) 570–588.
[31] Roder, A., Tibken, B. A methodology for modeling inter-company supply chains and for evaluating a method of integrated product and process documentation, European Journal of Operational Research 169 (2006) 1010–1029.
[32] Huang, M., Ip, W.H., Yung, K.L., Wang, X., Wang, D. Simulation study using system dynamics for a CONWIP-controlled lamp supply chain, International Journal of Advanced Manufacturing Technology 32 (2007) 184–193. DOI 10.1007/s00170-005-0324-2
[33] Kleijnen, J.P.C. Supply chain simulation tools and techniques: a survey, International Journal of Simulation & Process Modelling 1 (1/2) (2005) 82-89.
[34] Eskandari, H., Rabelo, L., Shaalan, T., Helal, M. Value chain analysis using hybrid simulation and AHP, International Journal of Production Economics 105 (2007) 536–547.
[35] iThink Analyst Technical Documentation, High Performance Systems, Inc. (1996)
[36] Hwarng, H. B., Chong, C. S. P., Xie, N., Burgess, T.F., 2005. Modeling a complex supply chain: understanding the effect of simplified assumptions, International Journal of Production Research 43 (13) (2005) 2829–2872.
[37] Banks, J. Discrete-event system simulation, Upper Saddle River, NJ : Prentice Hall. (2000)
[38] Kuroda, M., Mihira, H. Strategic inventory holding to allow the estimation of earlier due dates in make-to-order production, International Journal of Production Research 46 (2) (2008) 495–508.
[39] Frizelle, G., Woodcock, E. Measuring complexity as an aid to developing strategy, International Journal of Operations & Production Management 15 (5) (1995) 268-270.

# 23

# Continuum-Discrete Models for Supply Chains and Networks

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## 1. Introduction

A supply network consists of suppliers, manufacturers, warehouses, and stores, that perform the functions of materials procurement, their transformation into intermediate and finished goods, and the distribution of the final products to customers among different production facilities. Mathematical models are used to monitor cost-efficient distribution of parts and to measure current business processes. The main aim is to plan supply networks so as to reduce the dead times and to avoid bottlenecks, obtaining as a result a greater coordination leading to the optimization of the production process of a given good. Several questions arise in the design of optimal supply chain networks: can we control the maximum processing rates, or the processing velocities, or the input flow in such way to minimize the value the queues attain and to achieve an expected outflow? The formulation of optimization problems for supply chain management is an immediate consequence of performing successful supply modeling and hence simulations.

Depending on the scale, supply networks modelling is characterized by different mathematical approaches: discrete event simulations and continuous models. Since discrete event models are based on considerations of individual parts, the principal drawback of them, however, is their enormous computational effort. A cost-effective alternative to discrete event models is continuous models (e.g. for models based on ordinary differential equations see Daganzo (2003), Helbing et al. (2004), Nagatani & Helbing (2004), Helbing & Lämmer (2005), Helbing et al. (2006)), in particular fluid-like network models using partial differential equations describing averaged quantities like density and average velocity (see Armbruster et al. (2004), Göttlich et al. (2005), Armbruster et al. (2006a), Armbruster et al. (2006b), Armbruster et al. (2006c), Göttlich et al. (2006), Herty et al. (2007), D'Apice et al. (2010)). Probably the first paper for supply chains in continuous direction was Armbruster et al. (2006b) where the authors, taking the limit on the number of parts and suppliers, have obtained a conservation law, whose flux is described by the minimum among the parts density and the maximal productive capacity.

Due to the difficulty of finding solution for the general equation proposed in Armbruster et al. (2006b), other fluid dynamic models for supply chains were introduced in Göttlich et al. (2005), D'Apice & Manzo (2006) and Bretti et al. (2007).

The work D'Apice & Manzo (2006) is based on a mixed continuum-discrete model, i.e. the supply chain is described by a graph consisting of consecutive arcs separated by nodes. The arcs represent processors or sub-chains, while the nodes model connections between arcs at which the dynamics can be regulated. The chain load, expressed by the part density and the processing rate, follows a time-space continuous evolution on arcs, and at nodes the conservation of the goods density is imposed, but not of the processing rate. In fact, on each arc an hyperbolic system of two equations is considered: a conservation law for the goods density, and a semi-linear evolution equation for the processing rate. At nodes a way to solve Riemann Problems, i.e. Cauchy problems with constant initial data on each arc, is prescribed and a solution at nodes guaranteeing the conservation of fluxes is defined. Moreover, existence of solutions to Cauchy problems was proved.
The paper Göttlich et al. (2005) deals with a conservation law, with constant processing rate, inside each supply sub-chain, with an entering queue for exceeding parts. The dynamics at a node is solved considering an ode for the queue. Some optimization technique for the model described in Göttlich et al. (2005) is developed in Göttlich et al. (2006), while the existence of solutions to Cauchy problems with the front tracking method is proved in Herty et al. (2007). In particular in Göttlich et al. (2006) the question of optimal operating velocities for each individual processing unit is treated for a supply chain network consisting of three processors. The maximal processing rates are fixed and not subject to change. The controls are the processing velocities. Given some default initial velocities the processing velocities are found to minimize the height of the buffering queues and producing a certain outflow. Moreover given a supply chain network with a vertex of dispersing type, the distribution rate has been controlled in such way to minimize the queues.
It is evident that the models described in Göttlich et al. (2005) and D'Apice & Manzo (2006) complete each other. In fact, the approach of Göttlich et al. (2005) is more suitable when the presence of queue with buffer is fundamental to manage goods production. The model of D'Apice & Manzo (2006), on the other hand, is useful when there is the possibility to reorganize the supply chain: in particular, the productive capacity can be readapted for some contingent necessity.
Starting from the model introduced in D'Apice & Manzo (2006) and fixing the rule that the objects are processed in order to maximize the flux, two different Riemann Solvers are defined and equilibria at a node are discussed in Bretti et al. (2007). Moreover, discretization algorithms to find approximated solution to the problem are described, numerical experiments on sample supply chains are reported and discussed for both the Riemann Solvers.
In D'Apice et al. (2010) existence of solutions to Cauchy problems is proven for both continuum-discrete supply chains and networks models, deriving estimates on the total variation of the density flux, density and processing rate along a wave-front tracking approximate solution.
Observe that while the papers Armbruster et al. (2006b), D'Apice & Manzo (2006), Bretti et al. (2007) treat the case of chains, i.e. sequential processors, modelled by a real line seen as a sequence of sub-chains corresponding to real intervals, the model in Göttlich et al. (2005) and the extended results in Göttlich et al. (2006), Herty et al. (2007), D'Apice et al. (2009) refer to networks.
In this Chapter we describe the continuum-discrete models for supply chains and networks reporting the main results of D'Apice & Manzo (2006), Bretti et al. (2007) and D'Apice et al. (2009).

We recall the basic supply chain model under consideration: a supply chain consists of sequential processors or arcs which are going to assemble and construct parts. Each processor is characterized by a maximum processing rate $\mu^e$, its length $L^e$ and the processing time $T^e$. The rate $L^e/T^e$ represents the processing velocity.
The supply chain is modelled by a real line seen as a sequence of arcs corresponding to real intervals $[a^e, b^e]$ such that $[a^e, b^e] \cap [a^{e+1}, b^{e+1}] = v^e$: a node separating arcs. The dynamic of each arc is governed by a continuum system of the type

$$\rho_t + f_\varepsilon(\rho, \mu)_x = 0,$$

$$\mu_t - \mu_x = 0,$$

where $\rho(t,x) \in [0, \rho_{max}]$ is the density of objects processed by the supply chain at point $x$ and time $t$ and $\mu(t,x) \in [0, \mu_{max}]$ is the processing rate. For $\varepsilon > 0$, the flux $f_\varepsilon$ is given by:

$$f_\varepsilon(\rho, \mu) = \begin{cases} m\rho, & \text{if } \rho \leq \mu, \\ m\mu + \varepsilon(\rho - \mu), & \text{if } \rho \geq \mu, \end{cases}$$

where $m$ is the processing velocity.
The evolution at nodes $v^e$ has been interpreted thinking to it as Riemann Problems for the density equation with $\mu$ data as parameters. Keeping the analogy to Riemann Problems, we call the latter Riemann Solver at nodes. In D'Apice & Manzo (2006) the following rule was used:

- SC1 The incoming density flux is equal to the outgoing density flux. Then, if a solution with only waves in the density $\rho$ exists, then such solution is taken, otherwise the minimal $\mu$ wave is produced.

Rule SC1 corresponds to the case in which processing rate adjustments are done only if necessary, while the density $\rho$ can be regulated more freely. Thus, it is justified in all situations in which processing rate adjustments require re-building of the supply chain, while density adjustments are operated easily (e.g. by stocking). Even if rule SC1 is the most natural also from a geometric point of view, in the space of Riemann data, it produces waves only to lower the value of $\mu$. As a consequence in some cases the value of the processing rate does not increase and it is not possible to maximize the flux. In order to avoid this problem two additional rules to solve dynamics at a node have been analyzed in Bretti et al. (2007):

- SC2 The objects are processed in order to maximize the flux with the minimal value of the processing rate.
- SC3 The objects are processed in order to maximize the flux. Then, if a solution with only waves in the density $\rho$ exists, then such solution is taken, otherwise the minimal $\mu$ wave is produced.

The continuum-discrete model, regarding sequential supply chains, has been generalized to supply networks which consist of arcs and two types of nodes: nodes with one incoming arc and more outgoing ones and nodes with more incoming arcs and one outgoing arc.
The Riemann Problems are solved fixing two "routing" algorithms:

- RA1 Goods from an incoming arc are sent to outgoing ones according to their final destination in order to maximize the flux over incoming arcs. Goods are processed ordered by arrival time (FIFO policy).

RA2 Goods are processed by arrival time (FIFO policy) and are sent to outgoing arcs in order to maximize the flux over incoming and outgoing arcs.

For both routing algorithms the flux of goods is maximized considering one of the two additional rules, SC2 and SC3.
In order to motivate the introduction of the model and to understand the mechanism of the above rules, we show some examples of real supply networks.
We analyze the behaviour of a supply network for assembling pear and apple fruit juice bottles, whose scheme is in Figure 1 (left).
Bottles coming from arc $e^1$ are sterilized in node $v^1$. Then, the sterilized bottles, with a certain probability $\alpha$ are directed to node $v^3$, where apple fruit juice is bottled, and with probability $1-\alpha$ to node 4, where the pear fruit juice is bottled. In nodes $v^5$ and $v^6$, bottles are labelled. Finally, in node 7, produced bottles are corked. Assume that pear and apple fruit juice bottles are produced using two different bottle shapes. The bottles are addressed from arc $e^2$ to the outgoing sub-chains $e^3$ and $e^4$ in which they are filled up with apple or pear fruit juice according to the bottle shape and thus according to their final destination: production of apple or pear fruit juice bottles. In a model able to describe this situation, the dynamics at node $v^2$ is solved using the RA1 algorithm. In fact, the redirection of bottles in order to maximize the production on both incoming and outgoing sub-chains is not possible, since bottles with apple and pear fruit juice have different shapes.
Consider a supply network for colored cups (Figure 1, right). The white cups are addressed towards $n$ sub-chains in which they are colored using different colors. Since the aim is to maximize the cups production independently from the colors, a mechanism is realized which addresses the cups on the outgoing sub-chains by taking into account their loads in such way as to maximize flux on both incoming and outgoing sub-chains. It follows that a model realized to capture the behavior of the described supply network is based on rule RA2.
Let us now analyze an existing supply network where both algorithms shows up naturally: the chips production of the San Carlo enterprise. The productive processes follows various steps, that can be summarized in this way: when potatoes arrive at the enterprise, they are subjected to a goodness test. After this test, everything is ready for chips production, that starts with potatoes wash in drinking water. After washing potatoes, they are skinned off, rewashed and subjected to a qualification test. Then, they are cut by an automatic machine, and, finally, washed and dried by an air blow. At this point, potatoes are ready to be fried in vegetable oil for some minutes and, after this, the surplus oil is dripped. Potatoes are then salted by a dispenser, that nebulizes salt spreading it on potatoes. An opportune chooser

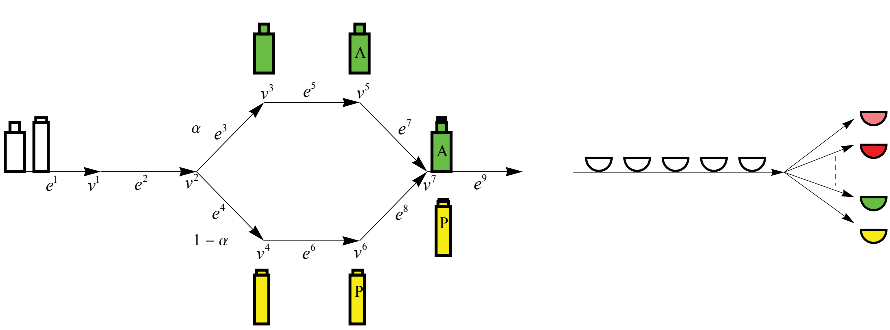


Fig. 1. Fruit juice network and cups production.

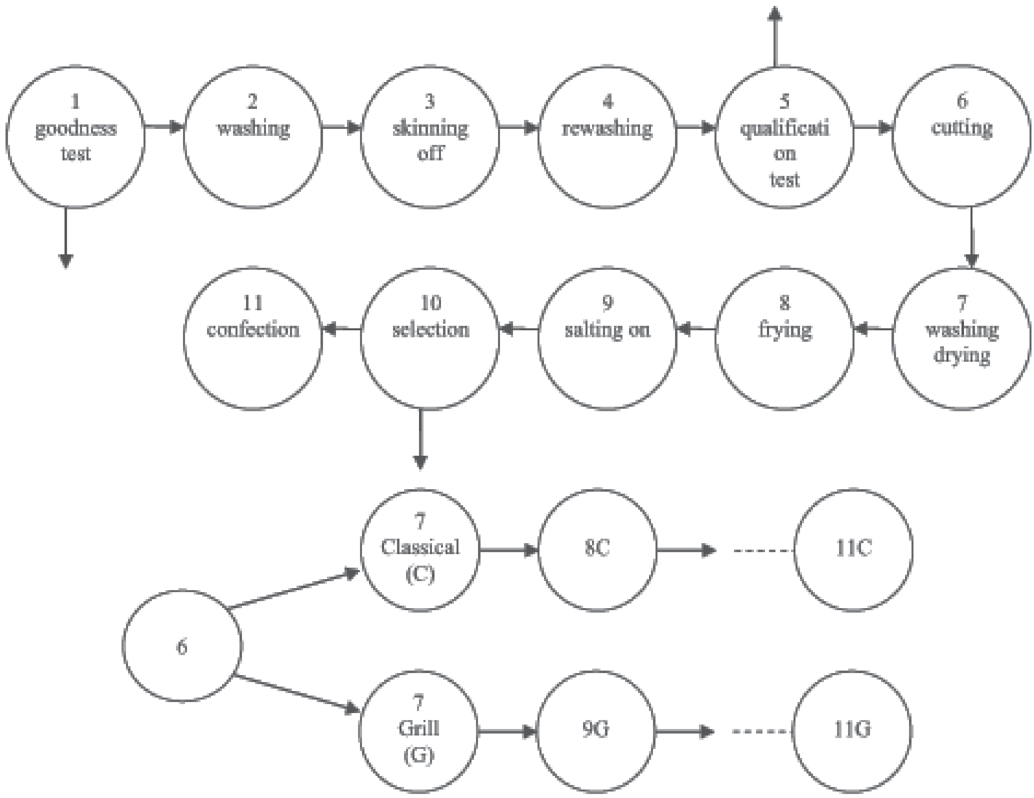


Fig. 2. Graph of the supply network for chips production (top) and possible arcs (bottom).

is useful to select the best products. The final phase of the process is given by potatoes confection. A simplified vision of the supply chain network is in Fig. 2 (top).
In phases 1, 5 and 10 a discrimination is made in production in order to distinguish good and bad products. In such sense, we can say that there is a statistical percentage $\alpha$ of product, that follows the production steps, while the percentage $1-\alpha$ is the product discarded (obviously, the percentage $\alpha$ can be different for different phases). Therefore, the goods routing in these nodes follows the algorithm RA1. On the other side, phase 6 concerns the potatoes cut: as the enterprise produces different types of fried potatoes (classical, grill, light, stick, etc.), different ways of cutting potatoes must be considered. Assume that, for simplicity, there are only two types of potatoes production, then the supply network is as in Fig. 2 (bottom). If the aim is only the production maximization independently from the type, then the potatoes are addressed from node 6 towards the outgoing arcs according to the RA2 algorithm.
The Chapter is organized as follows. Section 2 is devoted the description of the continuum-discrete model for supply chain. In particular Subsection 2.1 gives the basic definitions of supply chain and Riemann Solver. Then the dynamics inside an arc is studied. In Subsection 2.2 particular Riemann Solvers according to rules SC1, SC2 and SC3 are defined and explicit unique solutions are given. Moreover test simulations are reported. Section 3 extends the model to simple supply networks.

## 2. A continuum-discrete model for supply chains

In this Section we present a model able to describe the load dynamics on supply chains, i.e. sequential processors, modelled by a real line seen as a sequence of sub-chains corresponding to real intervals.

### 2.1 Basic definitions

We start from the conservation law model of Armbruster et al. (2006b):

$$\rho_t + (\min\{\mu(t,x),\rho\})_x = 0. \tag{1}$$

To avoid problems of existence of solutions, we assume $\mu$ piecewise constant and an evolution equation of semi-linear type:

$$\mu_t + \overline{V}\mu_x = 0, \tag{2}$$

where $\overline{V}$ is some constant velocity. Taking $\overline{V} = 0$, we may have no solution to a Riemann Problem for the system (1)–(2) with data $(\rho_l, \mu_l)$ and $(\rho_r, \mu_r)$ if $\min\{\mu_l, \rho_l\} > \mu_r$. Since we expect the chain to influence backward the processing rate we assume $\overline{V} < 0$ and for simplicity we set $\overline{V} = -1$.

We define a mixed continuum-discrete model in the following way. On each arc $e$, the evolution is given by (1)–(2). On the other side, the evolution at nodes $v^e$ is given solving Riemann Problems for the density equation (1) with $\mu$s as parameters. Such Riemann Problems may still admit no solution as before if we keep the values of the parameters $\mu$s constant, thus we expect $\mu$ waves to be generated and then follow equation (2). The vanishing of the characteristic velocity for (1), in case $\rho > \mu$, can provoke resonances with the nodes (which can be thought as waves with zero velocities). Therefore, we slightly modify the model as follows.

Each arc $e$ is characterized by a maximum density $\rho^e_{\max}$, a maximum processing rate $\mu^e_{\max}$ and a flux $f^e_\varepsilon$. For a fixed $\varepsilon > 0$, the dynamics is given by:

$$\begin{cases} \rho_t + f^e_\varepsilon(\rho,\mu)_x = 0, \\ \mu_t - \mu_x = 0. \end{cases} \tag{3}$$

The flux is defined as:

**(F)** $$f^e_\varepsilon(\rho,\mu) = \begin{cases} \rho, & 0 \le \rho \le \mu, \\ \mu + \varepsilon(\rho - \mu), & \mu \le \rho \le \rho^e_{\max}, \end{cases}$$

$$f^e_\varepsilon(\rho,\mu) = \begin{cases} \varepsilon\rho + (1-\varepsilon)\mu, & 0 \le \mu \le \rho, \\ \rho, & \rho \le \mu \le \mu^e_{\max}, \end{cases}$$

see Figure 3.

The conservation law for the good density in (3) is a $\varepsilon$ perturbation of (1) in the sense that $\|f - f_\varepsilon\|_\infty \le C\varepsilon$, where $f$ is the flux of (1). The equation has the advantage of producing waves with always strictly positive speed, thus avoiding resonance with the "boundary"problems at nodes $v^e$.

**Remark 1** *We can consider a slope $m$, defining the flux*

$$f_\varepsilon(\rho,\mu) = \begin{cases} m\rho, & \text{if } \rho \le \mu, \\ m\mu + \varepsilon(\rho - \mu), & \text{if } \rho \ge \mu, \end{cases} \tag{4}$$

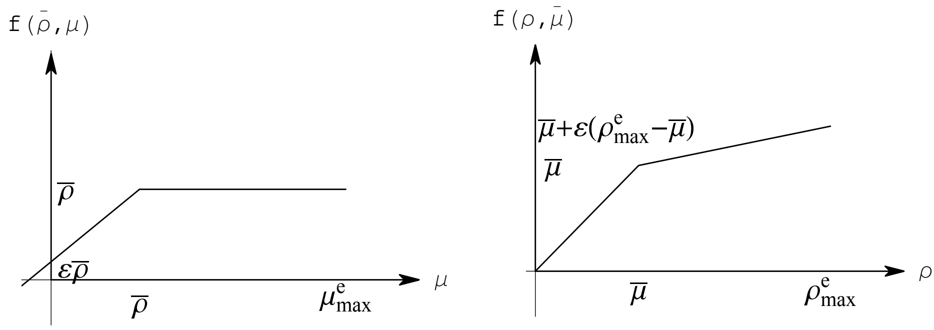


Fig. 3. Flux (F): Left, $f(\bar{\rho},\mu)$. Right, $f(\rho,\bar{\mu})$.

*or different slopes $m^e$, considering the flux*

$$f_\varepsilon^e(\rho,\mu) = \begin{cases} m^e\rho, & 0 \le \rho \le \mu, \\ m^e\mu + \varepsilon(\rho - \mu), & \mu \le \rho \le \rho^e_{\max}, \end{cases} \tag{5}$$

*where $m^e \ge 0$ represents the velocity of each processor and is given by $m^e = \frac{L^e}{T^e}$, with $L^e$ and $T^e$, respectively, fixed length and processing time of processor $e$.*

From now on, for simplicity we assume that $\varepsilon$ is fixed and the flux is the same for each arc $e$, we then drop the indices thus indicate the flux by $f(\rho,\mu)$. The general case can be treated similarly.

The supply chain evolution is described by a finite set of functions $\rho^e, \mu^e$ defined on $[0,+\infty[\, \times [a^e,b^e]$. On each sub-chain $[a^e,b^e]$, we say that $U^e := (\rho^e,\mu^e) : [0,+\infty[\, \times [a^e,b^e] \mapsto \mathbb{R}$ is a weak solution to (3) if, for every $C^\infty$-function $\varphi : [0,+\infty[\, \times [a^e,b^e] \mapsto \mathbb{R}^2$ with compact support in $]0,+\infty[\, \times\, ]a^e,b^e[$,

$$\int_0^{+\infty}\int_{a^e}^{b^e} \left( U^e \cdot \frac{\partial\varphi}{\partial t} + f(U^e)\cdot\frac{\partial\varphi}{\partial x} \right) dx\, dt = 0,$$

where

$$f(U^e) = \begin{pmatrix} f(\rho^e,\mu^e) \\ -\mu^e \end{pmatrix},$$

is the flux function of the system (3). For the definition of entropy solution, we refer to Bressan (2000).

For a scalar conservation law, a Riemann Problem (RP) is a Cauchy problem for an initial data of Heavyside type, that is piecewise constant with only one discontinuity. One looks for centered solutions, i.e. $\rho(t,x) = \phi(\frac{x}{t})$ formed by simple waves, which are the building blocks to construct solutions to the Cauchy problem via wave- front tracking algorithm. These solutions are formed by continuous waves called rarefactions and by travelling discontinuities called shocks. The speed of waves are related to the values of $f'$, see Bressan (2000).

Analogously, we call Riemann Problem for a junction the Cauchy problem corresponding to an initial data which is constant on each supply line.

**Definition 2** *A Riemann Solver for the node $v^e$ consists in a map $RS : [0,\rho^e_{\max}] \times [0,\mu^e_{\max}] \times [0,\rho^{e+1}_{\max}] \times [0,\mu^{e+1}_{\max}] \mapsto [0,\rho^e_{\max}] \times [0,\mu^e_{\max}] \times [0,\rho^{e+1}_{\max}] \times [0,\mu^{e+1}_{\max}]$ that associates to a Riemann data $(\rho^{e,0},\mu^{e,0},\rho^{e+1,0},\mu^{e+1,0})$ at $v^e$ a vector*

*$(\hat{\rho}^e, \hat{\mu}^e, \hat{\rho}^{e+1}, \hat{\mu}^{e+1})$ so that the solution is given by the waves $(\rho^{e,0}, \hat{\rho}^e)$ and $(\mu^{e,0}, \hat{\mu}^e)$ on the arc e and by the waves $(\hat{\rho}^{e+1}, \rho^{e+1,0})$, and $(\hat{\mu}^{e+1}, \mu^{e+1,0})$ on the arc $e+1$. We require the consistency condition*

*(CC)* $RS(RS(\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0})) = RS((\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0}))$.

Once a Riemann Solver is assigned we can define admissible solutions at $v^e$.

**Definition 3** *Assume a Riemann Solver RS is assigned for the node $v^e$. Let $U = (U^e, U^{e+1})$ be such that $U^e(t, \cdot)$ and $U^{e+1}(t, \cdot)$ are of bounded variation for every $t \geq 0$. Then $U$ is an admissible weak solution of (3) related to RS at the junction $v^e$ if and only if the following property holds for almost every t. Setting*

$$\widetilde{U}^e(t) = (U^e(\cdot, b^e-), U^{e+1}(\cdot, a^e+))$$

*we have $RS(\widetilde{U}^e(t)) = \widetilde{U}^e(t)$.*

Our aim is to solve the Cauchy problem for $t \geq 0$ for given initial data.

### 2.1.1 Dynamics on arcs

Let us fix an arc $e$ and analyze system (3): it is a system of conservation laws in the variables $U = (\rho, \mu)$:

$$U_t + F(U)_x = 0, \tag{6}$$

with flux function given by $F(U) = (f(\rho, \mu), -\mu)$, thus the Jacobian matrix of the flux is:

$$DF(\rho,\mu) = \begin{cases} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, & \text{if } \rho < \mu, \\ \\ \begin{pmatrix} \varepsilon & 1-\varepsilon \\ 0 & -1 \end{pmatrix}, & \text{if } \rho > \mu. \end{cases}$$

The eigenvalues and eigenvectors are given by:

$$\lambda_1(\rho,\mu) = -1, \qquad r_1(\rho,\mu) = \begin{cases} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, & \text{if } \rho < \mu, \\ \\ \begin{pmatrix} -\frac{1-\varepsilon}{1+\varepsilon} \\ 1 \end{pmatrix}, & \text{if } \rho > \mu, \end{cases}$$

$$\lambda_2(\rho,\mu) = \begin{cases} 1, & \text{if } \rho < \mu, \\ \varepsilon, & \text{if } \rho > \mu, \end{cases} \qquad r_2(\rho,\mu) = \begin{pmatrix} 1 \\ 0 \end{pmatrix}.$$

Hence the Hugoniot curves for the first family are vertical lines above the secant $\rho = \mu$ and lines with slope close to $-1/2$ below the same secant. The Hugoniot curves for the second family are just horizontal lines. Since we consider positive and bounded values for the variables, we fix the invariant region:

$$\mathcal{D} = \{(\rho,\mu) : 0 \leq \rho \leq \rho_{max},\ 0 \leq \mu \leq \mu_{max},$$

$$0 \leq (1+\varepsilon)\rho + (1-\varepsilon)\mu \leq (1+\varepsilon)\rho_{max} = 2(1-\varepsilon)\mu_{max}\}$$

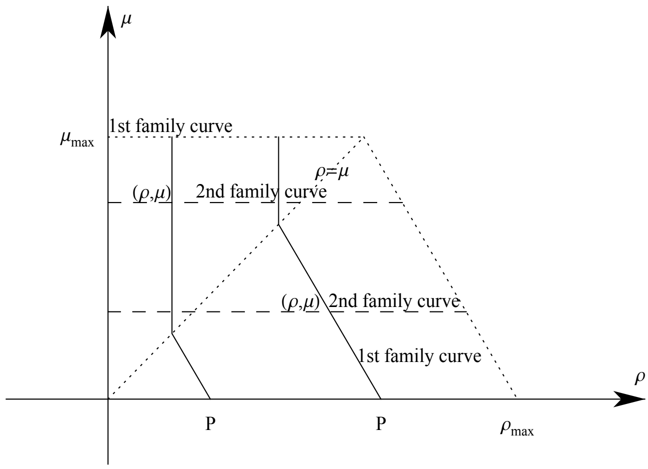


Fig. 4. First and second family curves.

see Figure 4.
Observe that

$$\rho_{\max} = \mu_{\max} \frac{2}{1+\varepsilon}. \tag{7}$$

**Proposition 4** *Given $(\rho^0, \mu^0)$, the minimal value of the flux at points of the curve of the first family passing through $(\rho^0, \mu^0)$ is given by:*

$$f_{min}((\rho^0, \mu^0)) = \begin{cases} \frac{2\varepsilon}{1+\varepsilon}\rho^0, & if\ \rho^0 \le \mu^0, \\ \varepsilon\rho^0 + \frac{\varepsilon(1-\varepsilon)}{1+\varepsilon}\mu^0, & if\ \rho^0 > \mu^0. \end{cases}$$

**Lemma 5** *Given an initial datum $(\rho^0, \mu^0)$, the maximum value of the density of the curve of the second family passing through $(\rho^0, \mu^0)$ and belonging to the invariant region is given by*

$$\rho_M(\mu^0) = \rho_{\max} - \mu^0 \frac{\rho_{\max} - \mu_{\max}}{\mu_{\max}}. \tag{8}$$

### 2.2 Riemann Solvers at nodes

In this Section we discuss possible definitions of a general Riemann Solver, which conserves the flux at nodes. We fix a node $v^e$ and a Riemann initial datum: constantly equal to $(\rho^{e,0}, \mu^{e,0})$ on $e$ and constantly equal to $(\rho^{e+1,0}, \mu^{e+1,0})$ on $e+1$.
First observe that the following Lemmas hold:

**Lemma 6** *On the incoming arc, only waves of the first family may be produced, while on the outgoing arc only waves of the second family may be produced.*

**Lemma 7** *The Riemann Problem at node $v^e$ admits a solution if the following holds.*
*If $\rho^{e,0} \le \mu^{e,0}$ then*

$$\mu^{e+1,0}(1-\varepsilon) + \varepsilon(\rho^{e+1}_{\max} - \frac{2}{1+\varepsilon}\rho^{e,0}) \ge 0. \tag{9}$$

*If* $\rho^{e,0} > \mu^{e,0}$ *then*

$$(1-\varepsilon)\left(\mu^{e+1,0} - \frac{\varepsilon}{1+\varepsilon}\mu^{e,0}\right) + \varepsilon(\rho^{e+1}_{\max} - \rho^{e,0}) \geq 0. \tag{10}$$

**Remark 8** *Conditions (9) and (10) are fulfilled if* $\rho^{e+1}_{\max} \geq 2\rho^{e,0}$ *and* $\mu^{e+1,0} \geq \mu^{e,0}$*, which is a condition on the initial datum.*

We are now ready to describe a general solution to a Riemann Problem at $v^e$. From Lemma 6, given the initial datum $(\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0})$, for every Riemann Solver it follows that

$$\hat{\rho}^e = \varphi(\hat{\mu}^e),$$

$$\hat{\mu}^{e+1} = \mu^{e+1,0},$$

where the function $\varphi(\cdot)$ describes the first family curve through $(\rho^{e,0}, \mu^{e,0})$ as function of $\hat{\mu}^e$:

$$\varphi(\hat{\mu}^e) = \begin{cases} \bar{\mu}^e, & \text{if } \hat{\mu}^e \geq \bar{\mu}^e, \\ \frac{(\varepsilon-1)\hat{\mu}^e + 2\rho^{e,0}}{1+\varepsilon}, & \text{if } \hat{\mu}^e < \bar{\mu}^e, \rho^{e,0} \leq \mu^{e,0}, \\ \frac{(\varepsilon-1)(\hat{\mu}^e - \mu^{e,0}) + (1+\varepsilon)\rho^{e,0}}{1+\varepsilon}, & \text{if } \hat{\mu}^e < \bar{\mu}^e, \rho^{e,0} > \mu^{e,0}, \end{cases}$$

with $\bar{\mu}^e$ the value in which the expression of such curve changes:

$$\bar{\mu}^e = \begin{cases} \rho^{e,0}, & \text{if } \rho^{e,0} \leq \mu^{e,0}, \\ \frac{1+\varepsilon}{2}\rho^{e,0} + \frac{1-\varepsilon}{2}\mu^{e,0}, & \text{if } \rho^{e,0} > \mu^{e,0}. \end{cases} \tag{11}$$

Let us now discuss how $\hat{\rho}^{e+1}$ and $\hat{\mu}^e$ can be chosen. The conservation of flux at the node can be written as

$$f(\varphi(\hat{\mu}^e), \hat{\mu}^e) = f(\hat{\rho}^{e+1}, \mu^{e+1,0}). \tag{12}$$

We have to distinguish two cases:

**Case** $\alpha$) $\mu^{e+1,0} < \bar{\mu}^e$;

**Case** $\beta$) $\bar{\mu}^e \leq \mu^{e+1,0}$.

In both cases $\bar{\mu}^e$ and $\mu^{e+1,0}$ individuate in the plane $(\hat{\rho}^{e+1}, \hat{\mu}^e)$ four regions, A, B, C, D, so defined:

$$\begin{aligned} A &= \{(\hat{\rho}^{e+1}, \hat{\mu}^e) : 0 \leq \hat{\rho}^{e+1} \leq \mu^{e+1,0}, \bar{\mu}^e \leq \hat{\mu}^e \leq \mu^e_{\max}\}; \\ B &= \{(\hat{\rho}^{e+1}, \hat{\mu}^e) : \mu^{e+1,0} \leq \hat{\rho}^{e+1} \leq \rho^{e+1}_{\max}, \bar{\mu}^e \leq \hat{\mu}^e \leq \mu^e_{\max}\}; \\ C &= \{(\hat{\rho}^{e+1}, \hat{\mu}^e) : 0 \leq \hat{\rho}^{e+1} \leq \mu^{e+1,0}, 0 \leq \hat{\mu}^e \leq \bar{\mu}^e\}; \\ D &= \{(\hat{\rho}^{e+1}, \hat{\mu}^e) : \mu^{e+1,0} \leq \hat{\rho}^{e+1} \leq \rho^{e+1}_{\max}, 0 \leq \hat{\mu}^e \leq \bar{\mu}^e\}. \end{aligned}$$

The equation (12) is satisfied in case $\beta$) along the line depicted in Figure 5 and in case $\alpha$) there are solutions, only under some conditions, along the dashed line.

### 2.2.1 A Riemann Solver according to rule SC1.

A geometrically natural Riemann Solver is the following. In case $\beta$) we can define a Riemann Solver mapping every initial datum on the line $\hat{\mu}^e = c$ to the intersection of the same line with that drawn in Figure 5.
In case $\alpha$), it may happen that there is no admissible solution on a given line $\hat{\mu}^e = c$. Therefore, we can use the same procedure if the line $\hat{\mu}^e = c$ intersects the dashed line of Figure 5, while mapping all other points to the admissible solution with the highest value of $\hat{\mu}^e$.
The obtained Riemann Solver is depicted in Figure 6 and satisfies the policy SC1. On the left, there is case $\beta$) with all points mapped horizontally, while, on the right, there is case $\alpha$): all points of the white region are mapped horizontally and all points of the dark region are mapped to the point indicated by the arrow.

**Remark 9** *If $\hat{\rho}^{e+1} \leq \mu^{e+1,0}$, then the solution $(\hat{\rho}^{e+1}, \rho^{e+1,0})$ is a contact discontinuity. The same happens if $\hat{\rho}^{e+1} \geq \mu^{e+1,0}$ and $\hat{\rho}^{e+1} > \mu^{e+1,0}$. If $\hat{\rho}^{e+1} > \mu^{e+1,0}$ and $\rho^{e+1,0} < \mu^{e+1,0}$, the solution consists of two contact discontinuities.*

Let us define in detail the Riemann Solver described in Figure 6. We introduce the notations:

$$f^e_{\max} = f(\rho^e_{\max}, \mu^{e,0}),$$

$$f^{e+1}_{\max} = f(\rho^{e+1}_{\max}, \mu^{e+1,0}).$$

**Proposition 10** *Fix a node $v^e$. For every Riemann initial datum $(\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0})$ at $v^e$ there exists a unique vector $(\hat{\rho}^e, \hat{\mu}^e, \hat{\rho}^{e+1}, \hat{\mu}^{e+1})$ such that:*

*a) if $f(\rho^{e,0}, \mu^{e,0}) \leq f^{e+1}_{\max}$, then*

$$\hat{\mu}^e = \mu^{e,0}, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

$$\hat{\rho}^e = \rho^{e,0},$$

$$\hat{\rho}^{e+1} = \begin{cases} f(\rho^{e,0}, \mu^{e,0}), & \text{if } f(\rho^{e,0}, \mu^{e,0}) \leq \mu^{e+1,0}, \\ \frac{f(\rho^{e,0}, \mu^{e,0}) - \mu^{e+1,0}}{\varepsilon} + \mu^{e+1,0}, & \text{if } \mu^{e+1,0} \leq f(\rho^{e,0}, \mu^{e,0}) \leq f^{e+1}_{\max}, \end{cases}$$

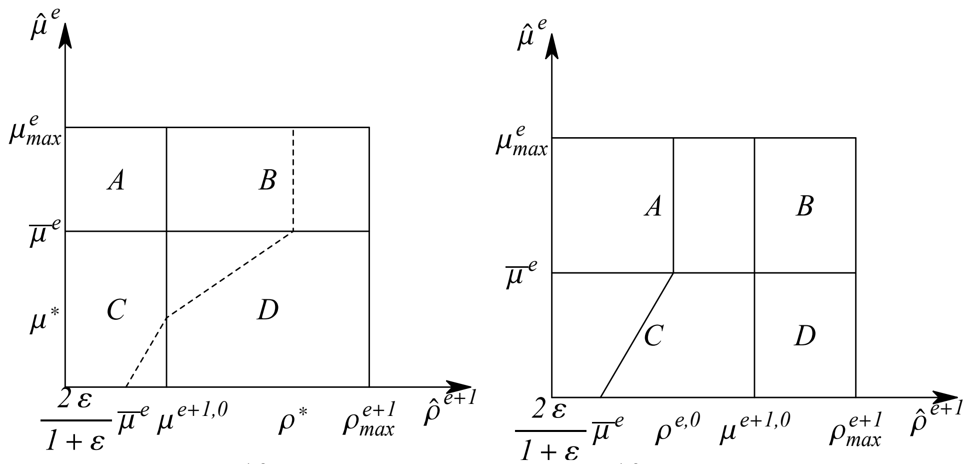


Fig. 5. Left: Case $\alpha) : \mu^{e+1,0} < \bar{\mu}^e$. Right: Case $\beta) : \bar{\mu}^e \leq \mu^{e+1,0}$.

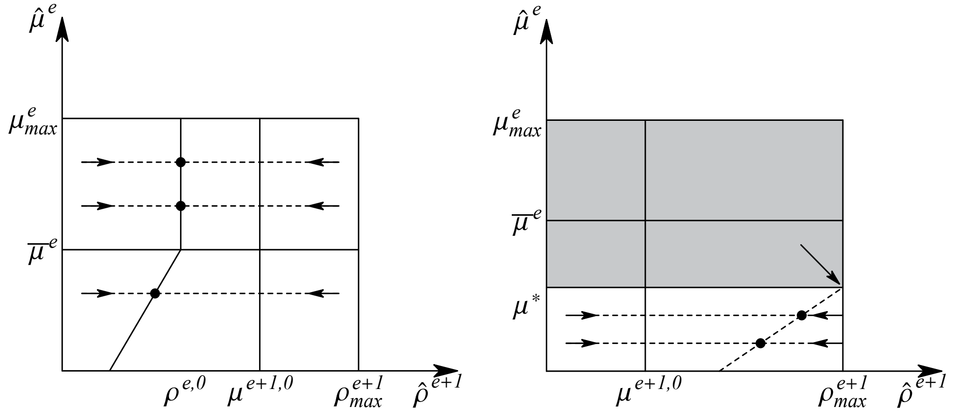


Fig. 6. An example of Riemann Solver: case $\beta$) (on the left) and $\alpha$) (on the right).

*b) if* $f(\rho^{e,0}, \mu^{e,0}) > f^{e+1}_{\max}$*, then*

$$\hat{\rho}^e = \rho^{e,0}, \quad \hat{\rho}^{e+1} = \rho^{e+1}_{\max},$$

$$\hat{\mu}^e = \frac{f^{e+1}_{\max} - \varepsilon\rho^{e,0}}{1-\varepsilon}, \quad \hat{\mu}^{e+1} = \mu^{e+1,0}.$$

**Theorem 11** *The Riemann Solver described in Proposition 10 is in accordance to rule SC1.*

Let us pass now to consider solvability of Riemann Problems according to the Riemann Solver above.

**Lemma 12** *Consider a supply chain on which the initial datum verifies* $\mu^{e,0} = \mu^e_{\max}$*, i.e. the production rate is at its maximum. A sufficient condition for the solvability of all Riemann Problems, according to rule SC1, on the supply chain at every time is*

$$\rho^{e+2}_{\max} \geq \rho^e_{\max}, \forall e.$$

#### 2.2.2 A Riemann Solver according to rule SC2.

Rule SC2 individuates a unique Riemann Solver as shown by next:

**Theorem 13** *Fix a node* $v^e$*. For every Riemann initial datum* $(\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0})$ *at* $v^e$ *there exists a unique vector* $(\hat{\rho}^e, \hat{\mu}^e, \hat{\rho}^{e+1}, \hat{\mu}^{e+1})$ *solution of the Riemann Problem according to rule SC2.*

**Case** $\alpha$) $\mu^{e+1,0} < \bar{\mu}^e$

**Case** $\alpha_1$) $\rho^* \leq \rho_M(\mu^{e+1,0})$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \min\{\mu^e_{\max}, \rho^*\},$$

$$\hat{\rho}^{e+1} = \rho^*, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

**Case** $\alpha_2$) $\rho^* > \rho_M(\mu^{e+1,0})$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \tilde{\mu},$$

$$\hat{\rho}^{e+1} = \rho_M(\mu^{e+1,0}), \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

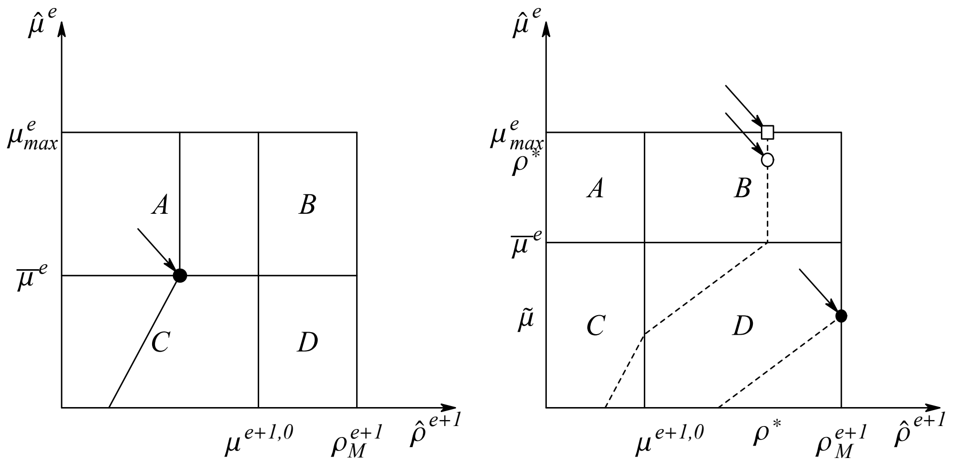


Fig. 7. Case $\beta$) (on the left) and $\alpha$) (on the right) for the Riemann solver SC2.

**Case** $\beta$) $\mu^{e+1,0} \geq \bar{\mu}^e$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \bar{\mu}^e,$$
$$\hat{\rho}^{e+1} = \bar{\mu}^e, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

*where* $\rho^* = \frac{\bar{\mu}^e - (1-\varepsilon)\mu^{e+1,0}}{\varepsilon}$, *and* $\tilde{\mu} = \frac{2\varepsilon}{1-\varepsilon}(\mu^e_{\max} - \bar{\mu}^e) + \mu^{e+1,0}$.

This Riemann Solver is depicted in Figure 7. In case $\beta$) we can define a Riemann Solver mapping every initial datum to the point $(\bar{\mu}^e, \bar{\mu}^e)$, indicated by the arrow.
In case $\alpha$), we can define a Riemann Solver mapping every initial datum to the circle or to the square point if $\rho^* \leq \rho_M$ and to the filled point if $\rho^* > \rho_M$.

### 2.2.3 A Riemann Solver according to rule SC3.

Also rule SC3 determines a unique Riemann Solver as shown by next:

**Theorem 14** *Fix a node $v^e$. For every Riemann initial datum $(\rho^{e,0}, \mu^{e,0}, \rho^{e+1,0}, \mu^{e+1,0})$ at $v^e$ there exists a unique vector $(\hat{\rho}^e, \hat{\mu}^e, \hat{\rho}^{e+1}, \hat{\mu}^{e+1})$ solution of the Riemann Problem according to rule SC3.*

**Case** $\alpha$) $\mu^{e+1,0} < \bar{\mu}^e$

***Case*** $\alpha_1$) $\rho^* \leq \rho_M(\mu^{e+1,0})$

***Case*** $\alpha_{1.1}$) $\rho^* > \mu^e_{\max}$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \mu^e_{\max},$$
$$\hat{\rho}^{e+1} = \rho^*, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

***Case*** $\alpha_{1.2}$) $\rho^* \leq \mu^e_{\max}$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \max\{\rho^*, \mu^{e,0}\},$$
$$\hat{\rho}^{e+1} = \rho^*, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

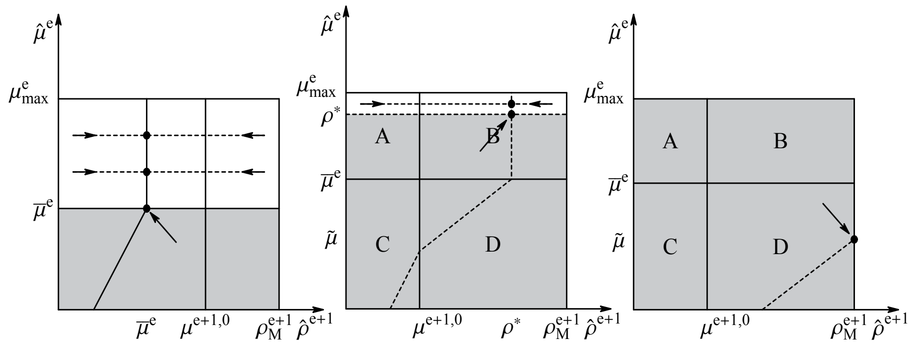


Fig. 8. Case $\beta$) and $\alpha$) (namely $\alpha_1$) and $\alpha_2$)) for the Riemann Solver SC3.

***Case*** $\alpha_2$) $\rho^* > \rho_M(\mu^{e+1,0})$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \tilde{\mu},$$
$$\hat{\rho}^{e+1} = \rho_M(\mu^{e+1,0}), \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

**Case** $\beta$) $\mu^{e+1,0} \geq \bar{\mu}^e$

$$\hat{\rho}^e = \varphi(\hat{\mu}^e), \quad \hat{\mu}^e = \begin{cases} \bar{\mu}^e, & \text{if } \mu^{e,0} < \bar{\mu}^e, \\ \mu^{e,0}, & \text{if } \mu^{e,0} \geq \bar{\mu}^e, \end{cases}$$
$$\hat{\rho}^{e+1} = \bar{\mu}^e, \quad \hat{\mu}^{e+1} = \mu^{e+1,0},$$

*where* $\rho^* = \frac{\bar{\mu}^e - (1-\varepsilon)\mu^{e+1,0}}{\varepsilon}$, *and* $\tilde{\mu} = \frac{2\varepsilon}{1-\varepsilon}(\mu^e_{\max} - \bar{\mu}^e) + \mu^{e+1,0}$.

The obtained Riemann Solver is depicted in Figure 8: all points of the white region are mapped horizontally and all points of the dark regions are mapped to the point indicated by the arrows.
Analogously to the case of rule SC1, we can give conditions for solvability of Riemann Problems, more precisely:

**Lemma 15** *Consider a supply chain on which the initial datum verifies* $\mu^{e,0} = \mu^e_{\max}$*, i.e. the production rate is at its maximum. A sufficient condition for the solvability of all Riemann Problems, according to rule SC2 or SC3, on the supply chain at every time is*

$$\rho^{e+2}_{\max} \geq \rho^e_{\max}, \forall e.$$

### 2.3 Numerical tests

As an application of the supply chain dynamics we present some experiments on sample cases. The problem (3) is discretized using Godunov and Upwind schemes. We set space increment equal on each arc, namely $N^e = \frac{L^e}{\Delta x}$, where $N^e$ is the number of space discretization points. The time steps $\Delta t$ are constants and are obtained imposing the CFL condition on each arc.
In the following Tests 1 and 2 we refer to numerical examples presented in Göttlich et al. (2005; 2006) in such a way to establish a comparison between their and our approach. To this aim we consider the flux function with different slopes (5).
**Test 1.** As in Göttlich et al. (2005), we analyze a supply chain network consisting of $N = 4$ arcs and we use the data in Table 1.

| Processor $e$ | $\mu^e$ | $m^e$ | $L^e$ |
|---|---|---|---|
| 1 | 25 | 1 | 1 |
| 2 | 15 | 0.2 | 0.2 |
| 3 | 10 | 0.2 | 0.6 |
| 4 | 15 | 0.2 | 0.2 |

Table 1. Parameters of the test problem 1.

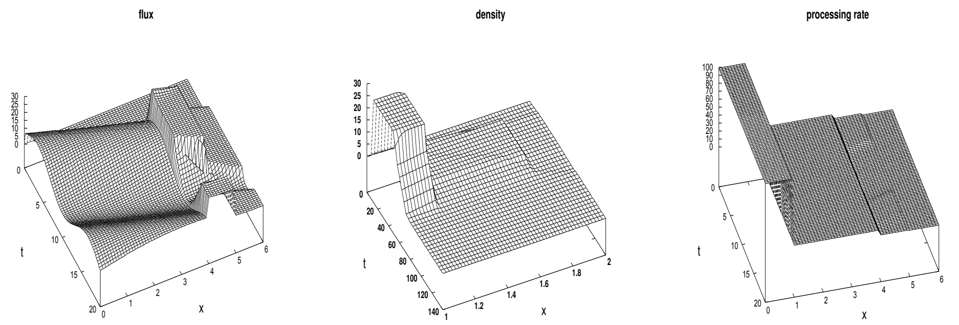


Fig. 9. Test 1: evolution on processors 2, 3, 4, of $f$ (left), $\rho$ (central) and $\mu$ (right) using SC1, with data in Table 1 and $\varepsilon = 0.1$.

Let us assume the following initial and boundary data:

$$\rho^1(0,x) = \rho^2(0,x) = \rho^3(0,x) = \rho^4(0,x) = 0,$$

$$\rho^1(t,0) = \begin{cases} \frac{18}{35}t, & 0 \leq t \leq 35, \\ -\frac{18}{35}t + 36, & 35 < t \leq 70, \\ 0, & t > 70, \end{cases}$$

and the space and time intervals are, respectively, $[0,2]$ and $[0,140]$, with $\Delta x = 0.02$ and $\Delta t = 0.01$. On each processor $e = 1,2,3,4$ we assume as the initial datum $\mu(0,x)$ the value $\mu^e$, which is also imposed at the incoming and outgoing boundaries. Notice that the inflow profile $\rho^1(t,0)$ is assigned on the first processor, which can be considered as an artificial arc, and it exceeds the maximum capacity of the other processors. In Fig. 9 it is depicted the evolution in time on processors 2, 3, 4, of flux, density and processing rate, obtained by the Riemann Solver SC1 for $\varepsilon = 0.1$. From the analysis of graphics in Fig. 9, we can deduce that the processing rate, according to SC1, is minimized and, consequently, the flux and the density are considerably lowered and are almost plateau shaped on processors 3 and 4. On the other hand, SC2 determines the behaviour showed in Fig. 10, where the flux and the density are correctly developed on processors 2, 3, 4, due to the behaviour of the processing rate depicted in the graphics, which assumes the minimum possible value in order to maximize the flux.
In the following Figg. 11, 12 and 13 it is depicted the evolution in time on processors 2, 3, 4, of flux, density and processing rate, as obtained by the Riemann Solver SC3 with, respectively, $\varepsilon = 0.1$, $\varepsilon = 0.5$ and $\varepsilon = 0.01$.
As showed by the graphics obtained, $\varepsilon$ varying determines a different evolution. In particular, for $\varepsilon$ tending to zero, the maximum values assumed by the flux and the density decrease.

| Processor $e$ | $\mu^e$ | $L^e$ |
|---|---|---|
| 1 | 99 | 1 |
| 2 | 15 | 1 |
| 3 | 10 | 3 |
| 4 | 8 | 1 |

Table 2. Parameters of the test problem 2.

From the analysis of graphics in Figg. 11, 12 and 13, obtained by applying Riemann Solver SC3, we can deduce that adjustments of processing rate determine the expected behaviour of the density, also in accordance with results reported in Göttlich et al. (2005).

**Test 2.**

Referring to Göttlich et al. (2006), we consider again a supply chain of $N = 4$ arcs and impose the following initial and boundary data:

$$\rho^1(0,x) = \rho^2(0,x) = \rho^3(0,x) = \rho^4(0,x) = 0,$$

$$\rho^1(t,0) = \frac{\mu^2}{2}(1 + \sin(3\pi t/T_{max})),$$

where the space interval is $[0,6]$ and the observation time is $T_{max} = 20$, with $\Delta x = 0.1$ and $\Delta t = 0.05$. On each processor $e = 1,2,3,4$ we assume $\mu(0,x) = \mu^e$ and incoming and outgoing boundary data are given by $\mu^e$. Observe that even in this case the inflow profile $\rho^1(t,0)$ exceeds the maximum capacity of the processors.

Referring to Göttlich et al. (2006) we make simulations setting parameters as in Table 2 and we assume to have default processing velocities on each processor, namely $m^e = 1, e = 1,2,3,4$.

In the next Fig. 14 it is depicted the evolution in time of flux, density and processing rate obtained by the Riemann Solver SC1 for $\varepsilon = 0.1$, while in Figg. 15 and 16 we show the behaviour of flux, density and processing rate obtained, respectively, by the Riemann Solvers SC2 and SC3.

Let us make a comparison between graphics in Figg. 14 and 15. We observe that with Solver SC2 the productivity collapses, thus provoking a lowering in the values of the flux and the density. On the other hand, SC1 maintains the level of productivity. Using Solver SC3, which maximizes the flux and adjusts the processing rate if necessary, results are in accordance with those obtained in Göttlich et al. (2006), see Fig. 16.

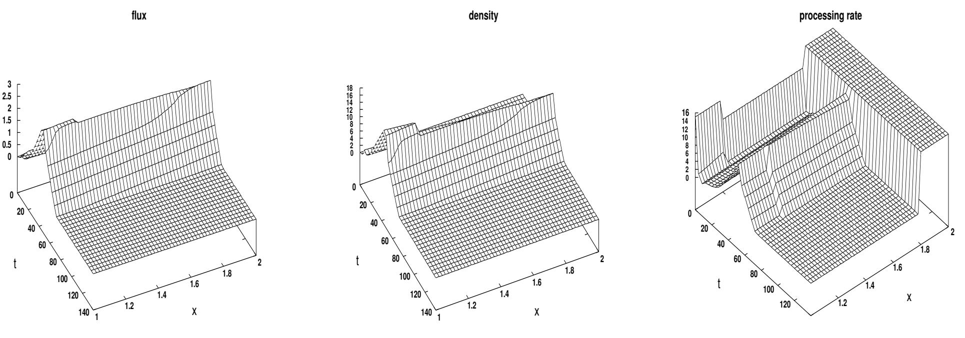


Fig. 10. Test 1: evolution on processors 2, 3, 4, of $f$ (left), $\rho$ (central) and $\mu$ (right) using SC2, with data in Table 1 and $\varepsilon = 0.1$.

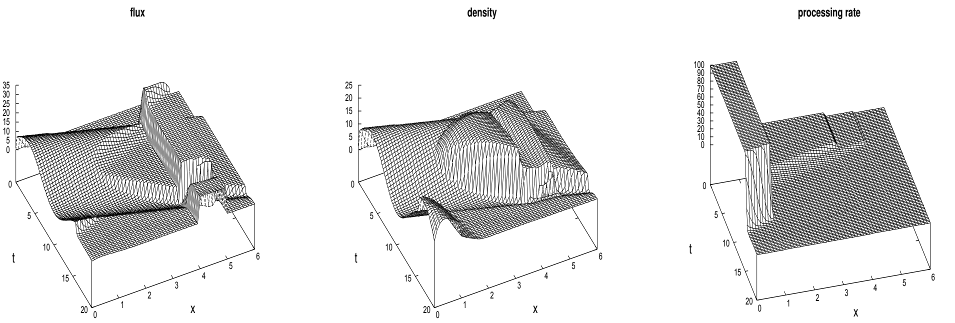


Fig. 11. Test 1: evolution on processors 2, 3, 4, of $f$ (left), $\rho$ (central) and $\mu$ (right) using SC3, with data in Table 1 and $\varepsilon = 0.1$.

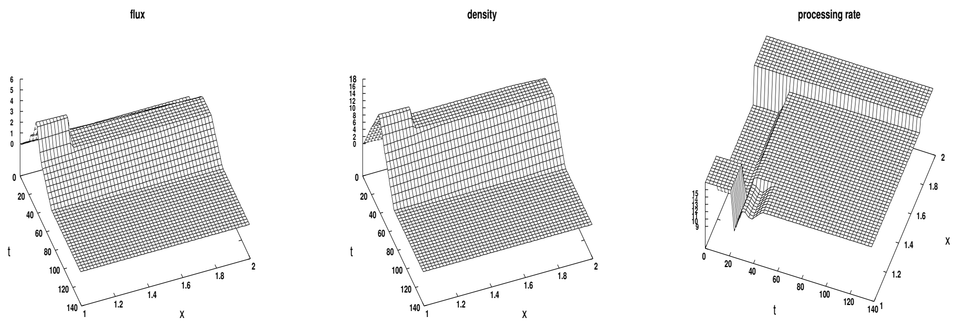


Fig. 12. Test 1: evolution on processors 2, 3, 4, of $f$ (left), $\rho$ (central) and $\mu$ (right) using SC3, with data in Table 1 and $\varepsilon = 0.5$.

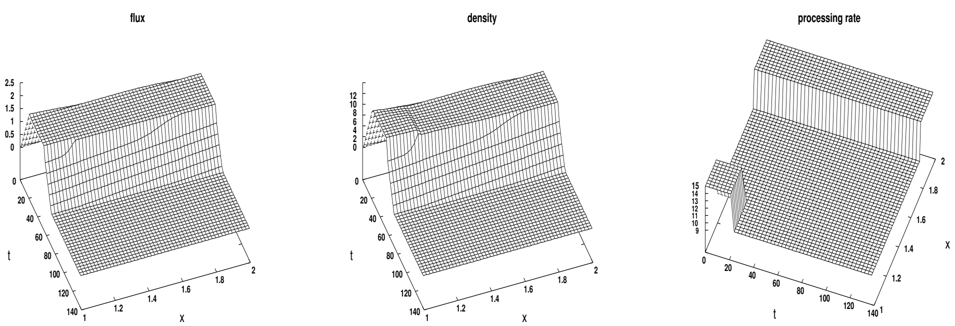


Fig. 13. Test 1: evolution on processors 2, 3, 4, of $f$ (left), $\rho$ (central) and $\mu$ (right) using SC3, with data in Table 1 and $\varepsilon = 0.01$.

## 3. A continuum-discrete model for supply networks

The aim of this Section is to extend the continuum-discrete model regarding sequential supply chains to supply networks which consist of arcs and two types of nodes: nodes with one incoming arc and more outgoing ones and nodes with more incoming arcs and one outgoing arc (see Figure 17). In fact, these two types of nodes are the most common in real supply networks.

### 3.1 Model description

Let us introduce briefly the model.

**Definition 16** *(Network definition) A supply network is a finite, connected directed graph consisting of a finite set of arcs* $\mathcal{A} = \{1, ..., N+1\}$ *and a finite set of junctions* $\mathcal{V}$.

On each arc the load dynamic is given again by a continuum system of type (3). The Riemann Problems at the nodes are solved fixing two "routing" algorithms:

**RA1** We assume that

(A) the flow from incoming arcs is distributed on outgoing arcs according to fixed coefficients;

(B) respecting (A) the processor chooses to process goods in order to maximize fluxes (i.e., the number of goods which are processed).

**RA2** We assume that the number of goods through the junction is maximized both over incoming and outgoing arcs.

The two algorithms were already used in D'Apice et al. (2006) for the analysis of packets flows in telecommunication networks. Notice that the second algorithm allows the redirection of goods, taking into account possible high loads of outgoing arcs. For both routing algorithms the flux of goods is maximized considering one of the two additional rules, SC2 and SC3.

### 3.2 Solution of Riemann Problems at nodes

In this Section we discuss Riemann Solvers, which conserve the flux at nodes. We consider two kinds of nodes:

- a node with more incoming arcs and one outgoing one;

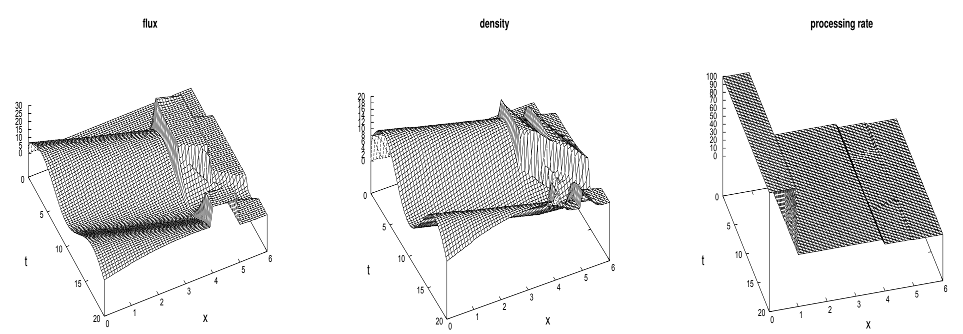


Fig. 14. Test 2: evolution of $f$ (left), $\rho$ (central), $\mu$ (right) for the default velocities using SC1, with data in Table 2 and $\varepsilon = 0.1$.

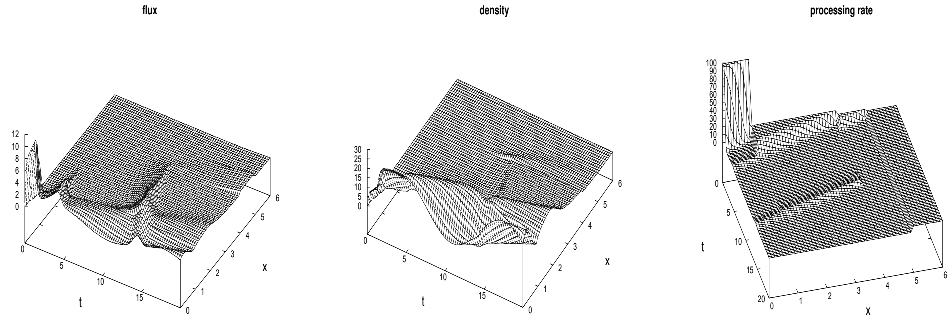


Fig. 15. Test 2: evolution of $f$ (left), $\rho$ (central), $\mu$ (right) using SC2, with data in Table 2 and $\varepsilon = 0.1$.

- a node with one incoming arc and more outgoing ones.

We consider a node $v^e$ with $n$ incoming arcs and $m$ outgoing ones and a Riemann initial datum $(\rho^{1,0}, \mu^{1,0}, ..., \rho^{n,0}, \mu^{n,0}, \rho^{n+1,0}, \mu^{n+1,0}, ..., \rho^{n+m,0}, \mu^{n+m,0})$.
The following Lemma holds:

**Lemma 17** *On the incoming arcs, only waves of the first family may be produced, while on the outgoing arcs only waves of the second family may be produced.*

From Lemma 17, given the initial datum, for every Riemann Solver it follows that

$$\begin{aligned} \hat{\rho}^e &= \varphi(\hat{\mu}^e), \quad e \in \delta_v^-, \\ \hat{\mu}^e &= \mu^{e,0}, \qquad e \in \delta_v^+, \end{aligned} \tag{13}$$

where again $\varphi(\cdot)$ describes the first family curve through $(\rho^{e,0}, \mu^{e,0})$ as function of $\hat{\mu}^e$ and for a fixed vertex $v$, $\delta_v^-$ denotes the sets of ingoing arcs and $\delta_v^+$ the set of outgoing ones.
We define two different Riemann Solvers at a junction that represent the two different routing algorithms RA1 and RA2. For both routing algorithms we can maximize the flux of goods considering one of the two additional rules SC2 and SC3.
To define Riemann Problems according to rule RA1 and RA2 let us introduce the notation:

$$f^e = f(\rho^e, \mu^e).$$

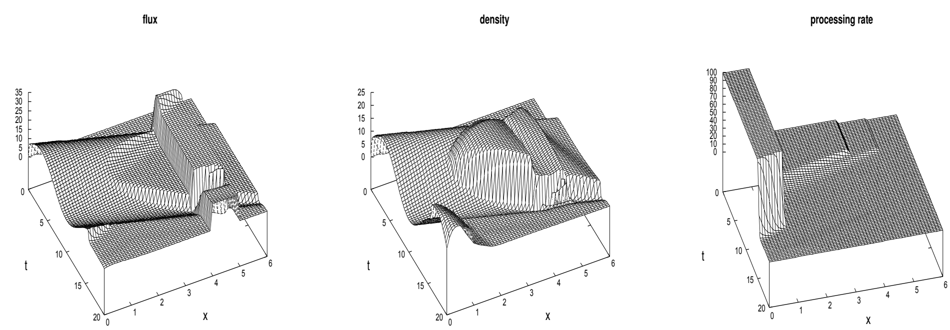


Fig. 16. Test 2: evolution of $f$ (left), $\rho$ (central), $\mu$ (right) using SC3, with data in Table 2 and $\varepsilon = 0.1$.

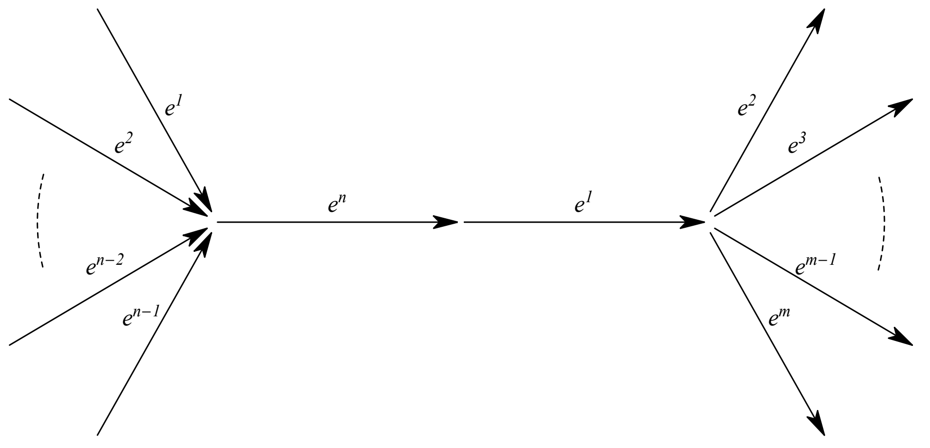


Fig. 17. One outgoing arc (left); one incoming arc (right).

Define the maximum flux that can be obtained by a wave solution on each production arc:

$$f^e_{\max} = \begin{cases} \bar{\mu}^e, & e \in \delta_v^-, \\ \mu^{e,0} + \varepsilon(\rho_M(\mu^{e,0}) - \mu^{e,0}), & e \in \delta_v^+. \end{cases}$$

Since $\hat{f}^e \in [f^e_{\min}, f^e_{\max} = \bar{\mu}^e], e \in \delta_v^-$ and $\hat{f}^e \in [0, f^e_{\max} = \mu^{e,0} + \varepsilon(\rho_M(\mu^{e,0}) - \mu^{e,0})], e \in \delta_v^+$ it follows that if

$$\sum_{e\in\delta_v^-} f^e_{\min} > \sum_{e\in\delta_v^+} f^e_{\max}$$

the Riemann Problem does not admit solution. Thus we get the following condition for the solvability of the supply network.

**Lemma 18** *A necessary and sufficient condition for the solvability of the Riemann Problems is that*

$$\sum_{e\in\delta_v^-} f^e_{\min} \le \sum_{e\in\delta_v^+} \mu^{e,o} + \varepsilon(\rho^M(\mu^{e,o}) - \mu^{e,o}).$$

**Lemma 19** *A sufficient condition for the solvability of the Riemann Problems, independent of the initial data, is the following*

$$\sum_{e\in\delta_v^-} \rho^e_{\max} \le \sum_{e\in\delta_v^+} \mu^e_{\max}.$$

In what follows, first we consider a single junction $v^e \in \mathcal{V}$ with $n-1$ incoming arcs and 1 outgoing arc (shortly, a node of type $(n-1)\times 1$) and then a junction with 1 incoming arc and $m-1$ outgoing ones (shortly, a node of type $1 \times (m-1)$).

#### 3.2.1 One outgoing arc

In this case the two algorithms RA1 and RA2 coincide since there is only one outgoing arc.
We fix a node $v^e$ with $n-1$ incoming arcs and 1 outgoing one and a Riemann initial datum $(\rho^0, \mu^0) = (\rho^{1,0}, \mu^{1,0}, ..., \rho^{n-1,0}, \mu^{n-1,0}, \rho^{n,0}, \mu^{n,0})$. Let us denote with $(\hat{\rho}, \hat{\mu}) =$

$(\hat{\rho}^1, \hat{\mu}^1, ..., \hat{\rho}^{n-1}, \hat{\mu}^{n-1}, \hat{\rho}^n, \hat{\mu}^n)$ the solution of the Riemann Problem. In order to solve the dynamics we have to introduce the priority parameters $(q_1, q_2, ..., q_{n-1})$ which determine a *level of priority* at the junction of incoming arcs.
Let us define

$$\Gamma_{inc} = \sum_{i=1}^{n-1} f_{\max}^i,$$

$$\Gamma_{out} = f_{\max}^n,$$

and $\Gamma = \min\{\Gamma_{inc}, \Gamma_{out}\}$.
We analyze for simplicity the case in which $n = 3$, in this case we need only one priority parameter $q \in ]0,1[$. Think, for example, of a filling station for soda cans. The arc 3 fills the cans, whereas arcs 1 and 2 produce plastic and aluminium cans, respectively.
First, we compute $\hat{f}^e$ $e = 1,2,3$ and then $\hat{\rho}^e$ and $\hat{\mu}^e, e = 1,2,3$.
We have to distinguish two cases:

**Case 1)** $\Gamma = \Gamma_{inc}$,

**Case 2)** $\Gamma < \Gamma_{inc}$.

In the first case we set $\hat{f}^i = f_{\max}^i$, $i = 1,2$. Let us analyze the second case in which we use the priority parameter $q$.
Not all objects can enter the junction, so let $C$ be the amount of objects that can go through. Then $qC$ objects come from first arc and $(1-q)C$ objects from the second. Consider the space $(f^1, f^2)$ and define the following lines:

$$r_q : f^2 = \frac{1-q}{q} f^1,$$

$$r_\Gamma : f^1 + f^2 = \Gamma.$$

Define $P$ to be the point of intersection of the lines $r_q$ and $r_\Gamma$. Recall that the final fluxes should belong to the region (see Fig. 18):

$$\Omega = \left\{ \left(f^1, f^2\right) : 0 \leq f^i \leq f_{\max}^i, i = 1,2 \right\}.$$

We distinguish two cases:

a) $P$ belongs to $\Omega$,

b) $P$ is outside $\Omega$.

In the first case we set $\left(\hat{f}^1, \hat{f}^2\right) = P$, while in the second case we set $\left(\hat{f}^1, \hat{f}^2\right) = Q$, with $Q = proj_{\Omega \cap r_\Gamma}(P)$ where *proj* is the usual projection on a convex set, see Fig. 18.
Notice that $\hat{f}^3 = \Gamma$.

**Remark 20** *The reasoning can be repeated also in the case of $n-1$ incoming arcs. In $\mathbb{R}^{n-1}$ the line $r_q$ is given by $r_q = th_q, t \in \mathbb{R}$, with $h_q \in \Delta_{n-2}$ where*

$$\Delta_{n-2} = \left\{ (f^1, ..., f^{n-1}) : f^i \geq 0, i = 1, ..., n-1, \sum_{i=1}^{n-1} f^i = 1 \right\}$$

*is the* $(n-2)$ *dimensional simplex and*

$$H_\Gamma = \left\{ (f^1, ..., f^{n-1}) : \sum_{i=1}^{n-1} f^i = \Gamma \right\}$$

*is a hyperplane. Since* $h_q \in \Delta_{n-2}$*, there exists a unique point* $P = r_q \cap H_\Gamma$*. If* $P \in \Omega$*, then we set* $(\hat{f}^1, ..., \hat{f}^{n-1}) = P$*. If* $P \notin \Omega$ *, then we set* $(\hat{f}^1, ..., \hat{f}^{n-1}) = Q = proj_{\Omega \cap H_\Gamma}(P)$*, the projection over the subset* $\Omega \cap H_\Gamma$*. Observe that the projection is unique since* $\Omega \cap H_\Gamma$ *is a closed convex subset of* $H_\Gamma$*.*

Let us compute $\hat{\rho}^e$ and $\hat{\mu}^e, e = 1,2,3$.
On the incoming arcs we have to distinguish two subcases:

**Case 2.1)** $\hat{f}^i = f^i_{\max}$. We set according to rules SC2 and SC3,

$$SC2: \begin{array}{l} \hat{\rho}^i = \bar{\mu}^i, \\ \hat{\mu}^i = \bar{\mu}^i, \end{array} \quad i = 1,2,$$

$$SC3: \begin{array}{l} \hat{\rho}^i = \bar{\mu}^i, \\ \hat{\mu}^i = \max\{\bar{\mu}^i, \mu^{i,0}\}, \end{array} \quad i = 1,2.$$

**Case 2.2)** $\hat{f}^i < f^i_{\max}$. In this case there exists a unique $\hat{\mu}^i$ such that $\hat{\mu}^i + \varepsilon(\varphi(\hat{\mu}^i) - \hat{\mu}^i) = \hat{f}^i$. According to (13), we set $\hat{\rho}^i = \varphi(\hat{\mu}^i), i = 1,2$.

Observe that in case 2.1) $\hat{\rho}^i = \varphi(\hat{\mu}^i) = \bar{\mu}^i, i = 1,2$.
On the outgoing arc we have:

$$\hat{\mu}^3 = \mu^{3,0},$$

while $\hat{\rho}^3$ is the unique value such that $f_\varepsilon(\mu^{3,0}, \hat{\rho}^3) = \hat{f}^3$.

### 3.2.2 One incoming arc

We fix a node $v^e$ with 1 incoming arc and $m-1$ outgoing ones and a Riemann initial datum $(\rho^0, \mu^0) = (\rho^{1,0}, \mu^{1,0}, \rho^{2,0}, \mu^{2,0}, ..., \rho^{m,0}, \mu^{m,0})$. Let us denote with $(\hat{\rho}, \hat{\mu}) = (\hat{\rho}^1, \hat{\mu}^1, \hat{\rho}^2, \hat{\mu}^2, ..., \hat{\rho}^m, \hat{\mu}^m)$ the solution of the Riemann Problem. Since we have more than one outgoing arc, we need to define the distribution of goods from the incoming arc.

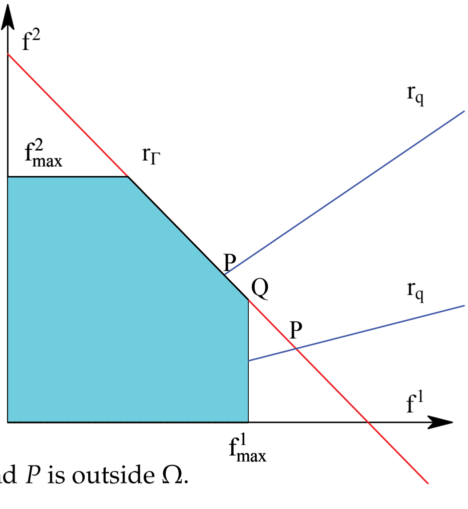


Fig. 18. $P$ belongs to $\Omega$ and $P$ is outside $\Omega$.

Introduce the flux distribution parameters $\alpha_j$, $j = 2, ..., m$, where

$$0 < \alpha_j < 1, \ \sum_{j=2}^{m} \alpha_j = 1.$$

The coefficient $\alpha_j$ denotes the percentage of objects addressed from the arc 1 to the arc $j$. The flux on the arc $j$ is thus given by

$$f^j = \alpha_j f^1, \ j = 2, ..., m,$$

where $f^1$ is the incoming flux on the arc 1.
Let us define

$$\Gamma_{inc} = f^1_{\max},$$
$$\Gamma_{out} = \sum_{j=2}^{m} f^j_{\max},$$

and $\Gamma = \min\{\Gamma_{inc}, \Gamma_{out}\}$.
We have to determine $\hat{\mu}^e$ and $\hat{\rho}^e, e = 1, ..., m$ for both algorithms RA1 and RA2.

### 3.2.3 Riemann Solver according to RA1.

Analyze the general case with $m$ arcs. Consider, for example, the filling station for fruit juice bottle of Introduction. The arcs $e^3$ and $e^4$ fill bottles with pear and apple fruit juices, respectively, according to the bottle shapes. The dynamics at node $v^2$ is solved using the algorithm we are going to describe. Since $\hat{f}^j \leq f^j_{\max}$ it follows that

$$\hat{f}^1 \leq \frac{f^j_{\max}}{\alpha_j}, j = 2, ..., m.$$

We set

$$\begin{array}{l} \hat{f}^1 = \min\{f^1_{\max}, \frac{f^j_{\max}}{\alpha_j}\}, \\ \hat{f}^j = \alpha_j \hat{f}^1, \end{array} \quad j = 2, ..., m.$$

On the incoming arc we have to distinguish two subcases:

**Case 1)** $\hat{f}^1 = f^1_{\max}$. According to rules SC2 and SC3, respectively, we set

$$SC2: \begin{array}{l} \hat{\rho}^1 = \bar{\mu}^1, \\ \hat{\mu}^1 = \bar{\mu}^1, \end{array}$$

$$SC3: \begin{array}{l} \hat{\rho}^1 = \bar{\mu}^1, \\ \hat{\mu}^1 = \max\{\bar{\mu}^1, \mu^{1,0}\}. \end{array}$$

**Case 2)** $\hat{f}^1 < f^1_{\max}$. In this case there exists a unique $\hat{\mu}^1$ such that $\hat{\mu}^1 + \varepsilon(\varphi(\hat{\mu}^1) - \hat{\mu}^1) = \hat{f}^1$. According to (13), we set $\hat{\rho}^1 = \varphi(\hat{\mu}^1)$.

On the outgoing arc we have:

$$\hat{\mu}^j = \mu^{j,0}, j = 2, 3,$$

while $\hat{\rho}^j$ is the unique value such that $f_\varepsilon(\mu^{j,0}, \hat{\rho}^j) = \hat{f}^j, j = 2, 3$.

#### 3.2.4 Riemann Solver according to RA2.

Let us analyze for simplicity the case in which $m = 3$, in this case we need only one distribution parameter $\alpha \in ]0,1[$. Think, for example, the supply network of cup production described in the Introduction. The dynamics at the node is solved according to the algorithm RA2. Compute $\hat{f}^e, e = 1,2,3$.
We have to distinguish two cases:

**Case 1)** $\Gamma = \Gamma_{out}$,

**Case 2)** $\Gamma < \Gamma_{out}$.

In the first case we set $\hat{f}^j = f^j_{\max}, j = 2,3$. Let us analyze the second case in which we use the priority parameter $\alpha$.
Not all objects can enter the junction, so let $C$ be the amount of objects that can go through. Then $\alpha C$ objects come from the first arc and $(1-\alpha)C$ objects from the second. Consider the space $(f^2, f^3)$ and define the following lines:

$$r_\alpha : f^3 = \frac{1-\alpha}{\alpha} f^2,$$

$$r_\Gamma : f^2 + f^3 = \Gamma.$$

Define $P$ to be the point of intersection of the lines $r_\alpha$ and $r_\Gamma$. Recall that the final fluxes should belong to the region:

$$\Omega = \left\{ \left(f^2, f^3\right) : 0 \le f^j \le f^j_{\max}, j = 2,3 \right\}.$$

We distinguish two cases:

a) $P$ belongs to $\Omega$,

b) $P$ is outside $\Omega$.

In the first case we set $\left(\hat{f}^2, \hat{f}^3\right) = P$ , while in the second case we set $\left(\hat{f}^2, \hat{f}^3\right) = Q$, with $Q = proj_{\Omega \cap r_\Gamma}(P)$ where $proj$ is the usual projection on a convex set. Observe that $\hat{f}^1 = \Gamma$.
Again, we can extend the reasoning to the case of $m-1$ outgoing arcs as for the incoming arcs defining the hyperplane

$$H_\Gamma = \left\{ (f^2, ..., f^m) : \sum_{j=2}^{m} f^j = \Gamma \right\}$$

and choosing a vector $h_\alpha \in \Delta_{m-2}$. Moreover, we compute $\hat{\rho}^e$ and $\hat{\mu}^e$ in the same way described for the Riemann Solver RA1.

### 3.3 Numerical experiments

In what follows we report the densities and production rates at the instant $t = 0$ and after some times (at $t = 1$) for different initial data using different routing algorithms. Since a constant state is an equilibrium for the single line model, a modification of the state may only appear initially at the junction. In Table 3 and in Fig. 19-20 we report the Riemann Solver for a node of type $1 \times 2$ and assume $\varepsilon = 0.2, \mu^e_{\max} = 1, e = 1,2,3, \alpha = 0.8, (\rho^{1,0}, \rho^{2,0}, \rho^{3,0}) = (0.7, 0.1, 0), (\mu^{1,0}, \mu^{2,0}, \mu^{3,0}) = (1, 0.2, 1)$. Observe that the algorithm RA2 redirects the goods, in fact taking into account the initial loads of the outgoing sub-chains, the number of goods processed by the sub-chain with density $\rho^{3,0} = 0$ increases.
In Table 4 and in Figg. 21-22 we report numerical results for a node of type $2 \times 1$, and assume $\varepsilon = 0.2, \mu^e_{\max} = 1, e = 1,2,3, q = 0.6, (\rho^{1,0}, \rho^{2,0}, \rho^{3,0}) = (0.3, 0.7, 0.8)$, $(\mu^{1,0}, \mu^{2,0}, \mu^{3,0}) = (0.8, 0.7, 0.4)$.

| | RA1 | | RA2 | |
|---|---|---|---|---|
| | SC2 | SC3 | SC2 | SC3 |
| $\hat{f}^e$ | (0.58,0.47,0.12) | (0.58,0.47,0.12) | (0.7,0.47,0.23) | (0.7,0.47,0.23) |
| $\hat{\rho}^e$ | (0.82,1.53,0.12) | (0.82,1.53,0.12) | (0.7,1.53,0.23) | (0.7,1.53,0.23) |
| $\hat{\mu}^e$ | (0.52,0.2,1) | (0.52,0.2,1) | (0.7,0.2,1) | (1,0.2,1) |

Table 3. A node of type $1 \times 2$.

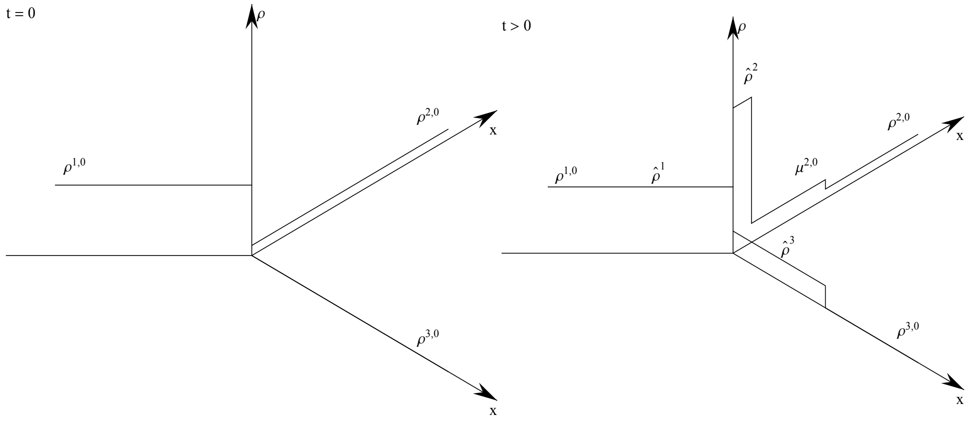


Fig. 19. A RP for the RA2-SC3 algorithm: the initial density and the density after some times.

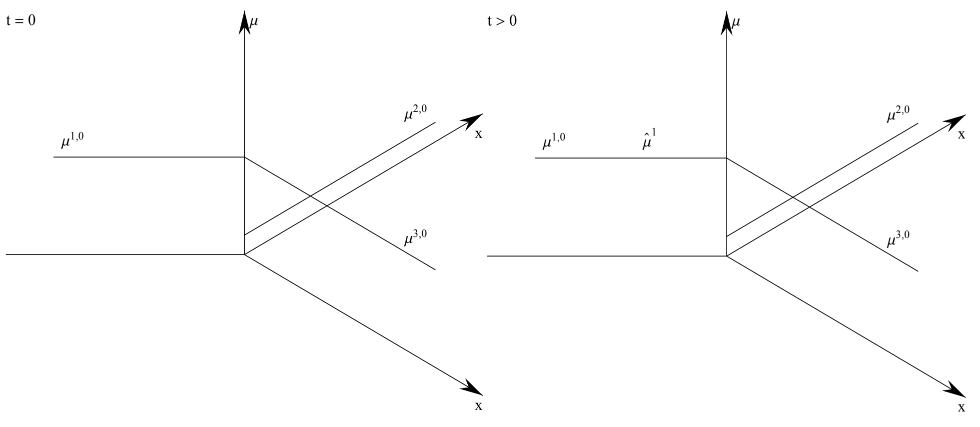


Fig. 20. A RP for the RA2-SC3 algorithm: the initial production rate and the production rate after some times.

| | RA1=RA2 | |
|---|---|---|
| | SC2 | SC3 |
| $\hat{f}^e$ | (0.3,0.3,0.6) | (0.3,0.3,0.6) |
| $\hat{\rho}^e$ | (0.3,1.1,1.4) | (0.3,1.1,1.4) |
| $\hat{\mu}^e$ | (0.3,0.1,0.4) | (0.8,0.1,0.4) |

Table 4. A node of type $2 \times 1$.

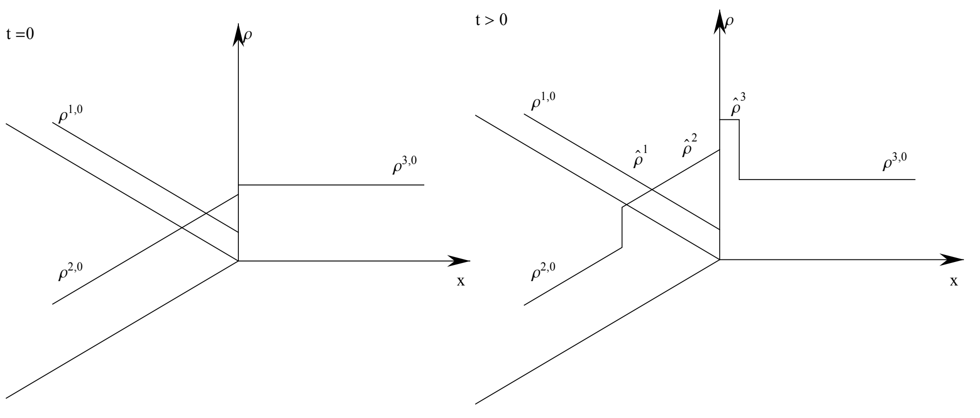


Fig. 21. A RP for the SC2 algorithm: the initial density and the density after some times.

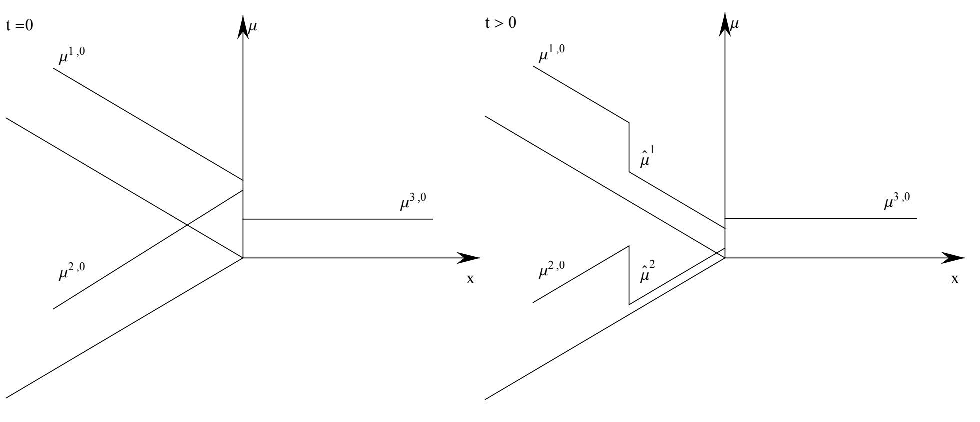


Fig. 22. A RP for the SC2 algorithm: the initial production rate and the production rate after some times.

## 4. Conclusions

In this Chapter we have proposed a mixed continuum-discrete model, i.e. the supply chain is described by continuous arcs and discrete nodes, it means that the load dynamics is solved in a continuous way on the arcs, and at the nodes imposing conservation of goods density, but not of the processing rate. In fact, each arc is modelled by a system of two equations: a conservation law for the goods density, and an evolution equation for the processing rate. The mixed continuum-discrete model is useful when there is the possibility to reorganize the supply chain: in particular, the productive capacity can be readapted for some contingent necessity. Possible choices of solutions at nodes guaranteeing the conservation of fluxes are analyzed. In particular Riemann Solvers are defined fixing the rules SC1, SC2, SC3. The numerical experiments show that SC1 appears to be very conservative (as expected), while SC2 and SC3 are more elastic, thus allowing more rich dynamics. Then, the main difference between SC2 and SC3 is the following. SC2 tends to make adjustments of the processing rate more than SC3, even when it is not necessary for purpose of flux maximization. Thus, when oscillating waves reach an arc, then SC2 reacts by cutting such oscillations. In conclusion, SC3 is more appropriate to reproduce also the well known "bull-whip" effect. The continuum-discrete model, regarding sequential supply chains, has been extended to supply networks with nodes of type $1 \times n$ and $m \times 1$. The Riemann Problems are solved fixing two "routing" algorithms RA1 and RA2, already used for the analysis of packets flows in telecommunication networks. For both routing algorithms the flux of goods is maximized considering one of the two additional rules, SC2 and SC3.

In future we aim to develop efficient numerics for the optimal configuration of a supply chain, in particular of the processing rates, facing the problem to adjust the production according to the supply demand in order to obtain an expected pre-assigned outflow.

## 5. References

Armbruster, D.; De Beer, C.; Freitag, M.; Jagalski, T.; Ringhofer, C. & Rascle, M. (2006). Autonomous Control of Production Networks using a Pheromone Approach, *Physica A: Statistical Mechanics and its applications*, Vol. 363, Issue 1, pp. 916-938.

Armbruster, D.; Degond, P. & Ringhofer, C. (2006). A model for the dynamics of large queuing networks and supply chains, *SIAM Journal on Applied Mathematics*, Vol. 66, Issue 3, pp. 896-920.

Armbruster, D.; Degond, P. & Ringhofer, C. (2006). Kinetic and fluid Models for supply chains supporting policy attributes, *Transportation Theory Statist. Phys.*

Armbruster, D.; Marthaler, D. & Ringhofer, C. (2004). Kinetic and fluid model hierarchies for supply chains, *SIAM J. on Multiscale Modeling*, Vol. 2, No. 1, pp. 43-61.

Bressan, A. (2000). *Hyperbolic Systems of Conservation Laws - The One-dimensional Cauchy Problem*, Oxford Univ. Press.

Bretti, G.; D'Apice, C.; Manzo, R. & Piccoli, B. (2007). A continuum-discrete model for supply chains dynamics, *Networks and Heterogeneous Media*, Vol. 2, No. 4, pp. 661-694.

Daganzo, C.F. (2003). *A theory of supply chains*, Lecture Notes in Economics and Mathematical Systems. 526. Berlin: Springer. viii, 123 p.

D'Apice, C. & Manzo, R. (2006). A fluid-dynamic model for supply chain, *Networks and Heterogeneous Media*, Vol. 1, No. 3, pp. 379-389.

D'Apice, C.; Manzo, R. & Piccoli, B. (2006). Packet flow on telecommunication networks, *SIAM J. Math. Anal.*, Vol. 38, No. 3, pp. 717-740.

D'Apice, C.; Manzo, R. & Piccoli, B. (2009). Modelling supply networks with partial differential equations, *Quarterly of Applied Mathematics*, Vol. 67, No. 3, pp. 419-440.

D'Apice, C.; Manzo, R. & Piccoli, B. (2010). Existence of solutions to Cauchy problems for a mixed continuum-discrete model for supply chains and networks, *Journal of Mathematical Analysis and Applications*, Vol. 362, No. 2, pp. 374-386.

Göttlich, S.; Herty, M. & Klar, A. (2005). Network models for supply chains, *Comm. Math. Sci.*, Vol. 3, No. 4, pp. 545-559.

Göttlich, S.; Herty, M. & Klar, A. (2006). Modelling and optimization of Supply Chains on Complex Networks, *Comm. Math. Sci.*, Vol. 4, No. 2, pp. 315-330.

Helbing D.; Armbruste D. ; Mikhailov A. & Lefeber E (2006). Information and material flows in complex networks, *Phys. A*, Vol. 363, pp. xi–xvi.

Helbing, D.; Lämmer, S.; Seidel, T.; Seba, P. & Platkowski, T. (2004). Physics, stability and dynamics of supply networks, *Physical Review E*, Vol. 3, 066116.

Helbing, D. & Lämmer, S. (2005). Supply and production networks: From the bullwhip effect to business cycles, *Armbruster, D.; Mikhailov A. S.; & Kaneko; K. (eds.) Networks of Interacting Machines: Production Organization in Complex Industrial Systems and Biological Cells, World Scientific, Singapore*, pp. 33–66.

Herty, M.; Klar, A. & Piccoli, B. (2007). Existence of solutions for supply chain models based on partial differential equations, *SIAM J. Math. Anal.*, Vol. 39, No. 1, pp. 160-173.

Nagatani, T. & Helbing, D. (2004). Stability analysis and stabilization strategies for linear supply chains, *Physica A: Statistical and Theoretical Physics*, Vol. 335, Issues 3-4, pp. 644-660.

# 24

# Services and Support Supply Chain Design for Complex Engineering Systems

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## 1. Introduction

The design and operation of complex engineering systems such as an aircraft or a refinery require substantial planning and flexibility in delivery of services and logistics support. Classical services and maintenance plans are designed on the principle that mean time between failure is a constant and hence the focus is to replace components before it is expected to fail (Armstrong, 1997). Service activities including inspection, adjustment and replacement are scheduled in fixed intervals (Chan *et al*, 2005). These intervals, which are prescribed by the Original Equipment Manufacturer (OEM), are often suboptimal because of deviations in the multifaceted relationship between the operating context and expectations on the complex system's performance from the intended circumstances (Tam *et al*, 2006). The rigid maintenance plans are unable to unveil inherent issues in complex systems. To improve this situation, Reliability Centred Maintenance (RCM) regime has been developed to focus on reliability and safety issues (Moubray, 1997; Abdul-Nour *et al*, 2002). However, the process tended to ignore some secondary issues and rendered the system in sub-optimal operating conditions (Sherwin, 2005). Modern machine systems are of increasing complexity and sophistication. Focussing only on system reliability does not meet the demand on the performance of complex engineering systems due to business requirements and competitions. From the point of view of the engineering system's owner, the system is an expensive asset that is required to fulfil certain business functions. For the purpose of discussions in this chapter, the term asset is used as synonym of a complex engineering system rather than the common understanding of a static investment.
In maintenance oriented service regime, many factors are governing the operations of the asset (Colombo and Demichela, 2008). The consequences of system failures can cause losses in opportunity costs. Unfortunately, these losses are often difficult to quantify and measure. Many service decisions on assets are therefore made on rules of thumbs rather than using analysed system performance data. Replacement of assets should be made at the time when the asset is about to fail so that the value of the asset over its usable life can be utilised (Huang, 1997). The strategy is to minimise expenditure that should be spent on the asset. Many complex systems are therefore left vulnerable with high risks of failure. The performance of the asset will degrade over time as the asset gets old and technologically out-of-date. However, an expensive engineering system is expected to be in service for years. In addition, due to technology improvement, capability of the system should keep increasing in order to meet functional demand by end users (Fig. 1).

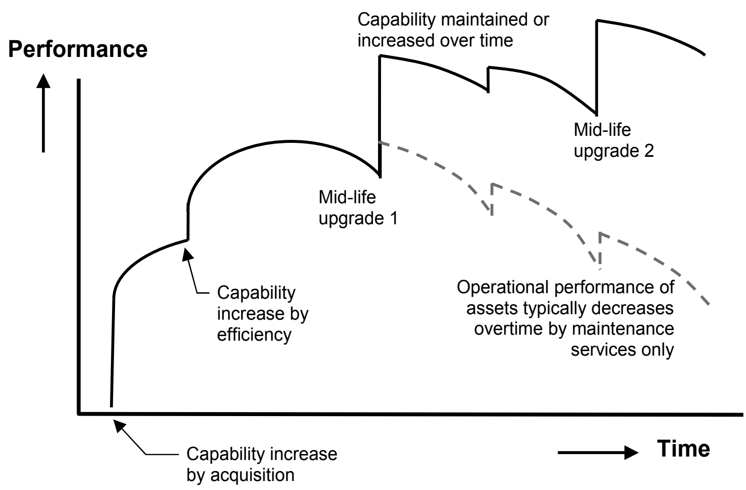



Fig. 1. Performance improvements due to mid-life upgrade

If the operating performance of an engineering system diminishes over time, the asset owner has to take the risk of either continue operating the equipment at unsatisfactory level or initiate a major investment project replacing the aging asset. This is not a desirable situation for the asset owner because there are significant risks in operating the asset after what is normally known as the service life of the asset. From the owner's point of view, it is necessary that the performance of the asset should increase over time to meet changing demands of the customers. To achieve this goal, many assets undergo significant mid-life upgrade (solid line in Fig. 1) but due to limitations in the original system design, this route is often not practicable.

In recent years, there is an increasing trend for complex engineering systems' operators to outsource their services and support activities. Instead of an effort based maintenance contract, customers demand performance and reliability on the asset that they operate. Performance based contracting has emerged in recent years as one of the favourable choices of contracting mechanisms for the public sector and asset intensive industries such as water, transport, defence and chemicals (Mo *et al*, 2008). Performance based contracting is a service agreement based on satisfaction of operating outcomes of the asset. Hence, how the asset is serviced or supported over time is irrelevant to the customer. The responsibility of maintaining an agreed service level is shifted from the asset operator to the service provider, under the constraint of a set price. The performance based contractor is expected to take all risks in the provision of services, including operations support, emergency and planned stoppages, upgrades, supplies and other asset services while fulfilling the contractual requirements of providing a satisfactory level of asset performance over a long period of time. Provision of these services will be strongly influenced by the business environment including customer's operational schedule, logistics support, spare parts inventory, customer relations, knowledge management, finance, etc.

Decisions such as asset replacement, upgrade or system overhaul are in many respects equivalent to a major investment, which is risk sensitive. This chapter examines past experiences of services and support of complex engineering systems and discusses the need for integrating with services research and business process management in order to keep these complex systems to perform at a satisfactory level. The rest of the chapter is organised as follows. In the next three sections, the key aspects of a services and support system are examined with cases reported in literature. Understanding of these characteristics and issues is essential for designing services and support supply chains for complex engineering systems because they form irreplaceable ingredients in these supply chains. This chapter concludes with a conceptual model of services and support systems and identities the body of knowledge that can be used to design a customer focused services and support solution.

## 2. Performance monitoring and reliability prediction

First, we examine the technological requirement of services to complex engineering systems. System health condition monitoring plays a critical role in preventative maintenance and product quality control of modern industrial manufacturing operations and therefore directly impacts their efficiency and cost-effectiveness. Uusitalo (1998) describes an operations support system for a paper pulp processing plant. The system is a process prediction and monitoring system that has a direct connection between the plant (in Australia) and the manufacturer (in Finland) so that operating data can be transmitted back to the engineering department in intervals of one set of parameters per minute. The operating data are compared to simulated process model of the plant so that discrepancies can be diagnosed.

In the power industry, the electricity market is highly volatile by design due to the need to balance regulation, competition, public and private investment risks, power network coordination. Hence, services to this industry require thorough understanding of the market operating conditions. Hu *et al* (2005) has developed a simulation system that integrated historical market data with weather conditions, market behaviour and individual's preference, in order to predict electricity prices. When this information is integrated with real market data, companies can explore the impact of different sustainable maintenance plans and the effect of outage due to all types of breakdowns.

The use of predictive and condition monitoring systems greatly enhances the ability of system owners to predict failure. Reliability centred maintenance relies on the availability and accuracy of facts acquired through such monitoring systems (Pujades and Chen, 1996). Maintenance decisions are then made according to the prediction. The problem is that it depends on data accuracy which is not always collectable at the required level of precision (Apeland and Aven, 2000). To extract more efficiency from the large amount of operating data and reduce waste of resources in standby components, more sophisticated methodologies have been developed for maintaining performance of processes that are sensitive to variations (Marmo *et al*, 2009). The key to these studies is the recognition of continuously monitored performance metrics that provide the basis for modern day reliability decisions.

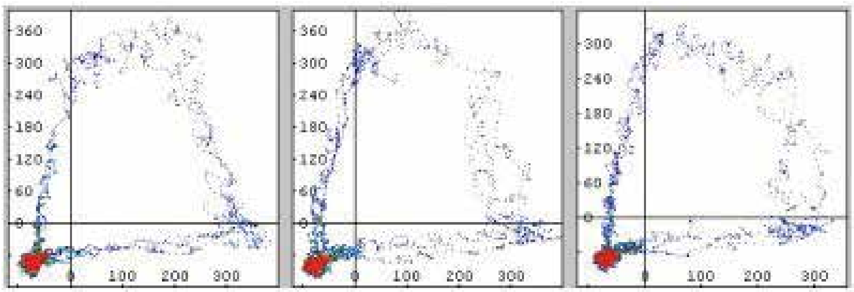
Advancement of IT networks has enabled more sophisticated, distributed health condition monitoring of complex systems to be commissioned and integrated with operation controls in real time (Leger *et al*, 1999). Essentially, a condition monitoring system acquires time-varying signal generated by the system. The signal data are processed using various classical methods of signal analysis such as spectrum or regression analyses. After initial signal data transformation, abnormal signal patterns are detected indicating problems in the machine.

Yang *et al* (2003a) has applied chaotic theory to analyse axes movement signals from a computer controlled multiple axes grinding machine and developed a 2-tier diagnostics system. This type of grinding machines has very stringent accuracy requirements. If the axis accuracy drops by a few microns, the surface finish of manufactured parts can become

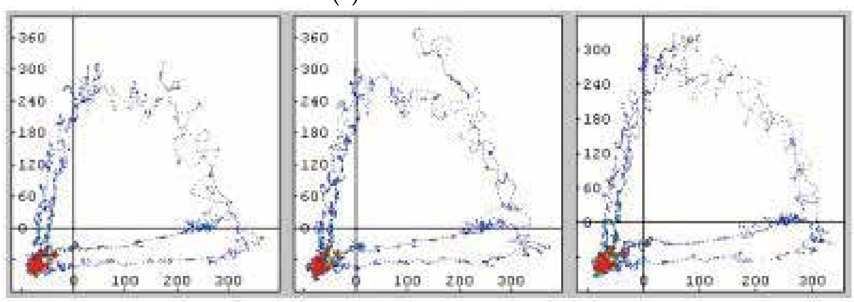
unacceptable. Successful and timely identification of faults that cause surface finish problems on machines can reduce the time-to-fix as well as downtime and materials wastage.
Similar signal analysis techniques have been used for monitoring of consumable conditions for plasma metal plate cutting process (Fig. 2). In this case, the voltage between the torch and the grounded plate is used as the monitoring signal data stream (Yang *et al*, 2003b). This voltage is characteristics of the process and is used to generate an arc. Unavoidably, any electric arc contains noise, including thermal, digital, high frequency, etc. Hence, the monitored voltage data consists of two components: the signal component (relates to the conditions of the system), and the noise component. The difference between the two is that the signal component is correlated whereas the noise component is un-correlated and eliminated by a polynomial filter (Schreiber and Grassberger, 1991; Gong *et al.*, 1999).

Fig. 2. Plasma cutting process for metal plates

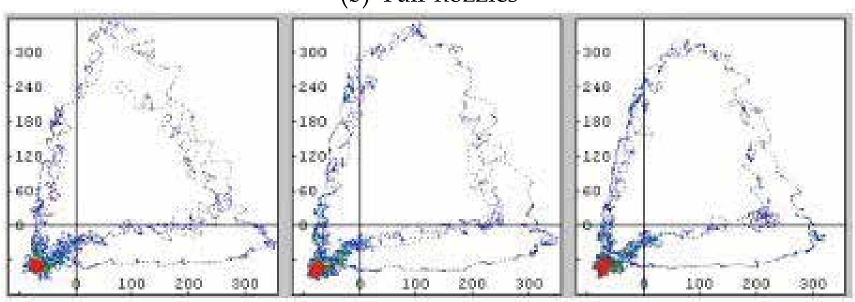
The voltage data is a time series that can be processed to generate the attractors using a phase-space reconstruction technique (Fig. 3). The experiment has been planned such that it captures data from three consumable conditions: good, fair and bad. For each consumable condition, three tests are performed. It can be seen from Fig. 3 that, for the same condition, the graphical pattern of the attractors are similar. For different conditions, the lower parts of the attractors show significant difference. Where the condition of the consumables is deteriorating, the lower parts of the attractors show a distinctive split. With a suitable image recognition algorithm, the graphical difference can be recognized and used as an indicator for consumable condition.
These researches show that most engineering intensive service providers are focussing on data driven technologies that assist them to predict performance of the system when it is operating under different conditions. There is no doubt that this is an important part of service system research but the question is, is it sufficient?




(a) Good nozzles




(b) Fair nozzles




(c) Bad nozzles

Fig. 3. Reconstructed Poincaré section graphs using time-lagged embedding of the total arc voltage time-series data for plasma metal plate cutting process.

## 3. Service virtual enterprise

A complex engineering system is built from a large number of components by many engineers and contractors. In the past, customers as system owners usually maintain their own service department. However, the increasing complexity of the system and operating conditions such as environmental considerations require service personnel to have a higher level of analysis and judgment capability. The concept of designing support services to these assets as a system is not new. Rathwell and Williams (1996) has studied Flour Daniel and used enterprise engineering methodology to analyse the company. They concluded that companies providing services to complex engineering products need a management and engineering technology which can 'minimize the apparent complexity' of these systems. Mo and Menzel (1998) have developed a methodology to capture process operation knowledge and deployed operations support services as a dynamic web based customer support system. The system is linked to a global services model repository where service engineers of the vendor and operations engineers of the customer can help to build a knowledge base for continuous support of the complex asset.

A service system comprises people and technologies that adaptively compute and adjust a system's changing value of knowledge (Spohrer *et al*, 2007). Abe (2005) describes a service-oriented solution framework designed for Internet banking. In the enterprise model, common business functionalities are built as shared services to be reused across lines of business as well as delivery channels, and the Internet channel-specific SOA is defined by applying the hybrid methodology. The Institute of Manufacturing at University of Cambridge summarises the nature of services systems as "dynamic configurations of people, technologies, organisations and shared information that create and deliver value to customers, providers and other stakeholders" (IfM and IBM, 2007). It is generally accepted that an important element in the design of service systems is the architecture of the system itself. Research is required to develop a general theory of service with well-defined questions, tools, methods and practical implications for society.

Johannson and Olhager (2006) have examined the linkage between goods manufacturing and service operations and developed a framework for process choice in joint manufacturing and after-sales service operations. Services in this case are closely related to the supply chain that supports the product. In a performance oriented service system, decisions for optimization can be quite different from maintenance oriented service concepts. For example, in order to reduce time to service to customers, Shen and Daskin (2005) propose that a relatively small incremental inventory cost will be necessary to achieve significant service improvements.

In managing the design and manufacture of a chemical plant for their customer, Kamio *et al* (2002) have established a service virtual enterprise (SVE) with several partner companies around the world providing after-sales services to a customer (Fig. 4). A "virtual enterprise" is a consortium of companies working together in a non-legal binding environment towards a common goal. It is the equivalence of a supply chain in which the "products" are services or similar intangible business entities. Each partner in the virtual enterprise is an independent entity that is equipped with its own unique capabilities and competencies, assuming responsibility to perform the allocated work.

In Fig. 4, the system provider of the complex engineering system is located in Europe. The system is owned by a customer in South Asia. The ability of providing support services by the European system provider is restricted by time zone difference. By partnering with a component supplier in Australia and a service company in North Asia, the SVE is designed as a "hosting service" which has a broad range of services including plant monitoring, preventive maintenance, trouble-shooting, performance simulation and evaluation, operator training, knowledge management and risk assessment. It is clear from the structure of SVE that all participants have well-defined roles and responsibilities. Services and support to the customer are much more responsive through the SVE which has both the supplier and the service company in more or less the same time zone as the customer.

In another large scale complex engineering systems development project, Hall (2000) has developed a highly integrated documentation and configuration management system that serves the on-going need of ten ANZAC class frigates. Over the life time of the asset (30 years), changes due to new technologies, people and defence requirements are inevitable. Mo *et al* (2005) describes the project to develop the ANZAC Ship Alliance (ASA) as a SVE with three partners for continuous support and improvement of the capabilities of the frigates after completion of the design and build phase. The ASA has been charged with the

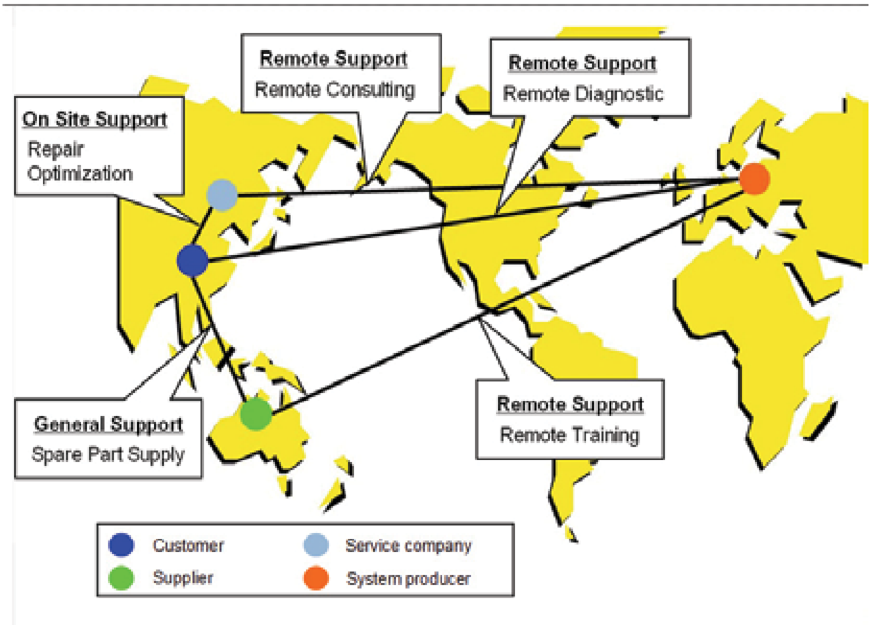



Fig. 4. A globally distributed service virtual enterprise

responsibility to upgrade the ships while they are in-service. To design the SVE, the system requirements are analysed by process modelling techniques to identify responsibilities and work flow in system upgrade projects (Fig. 5).

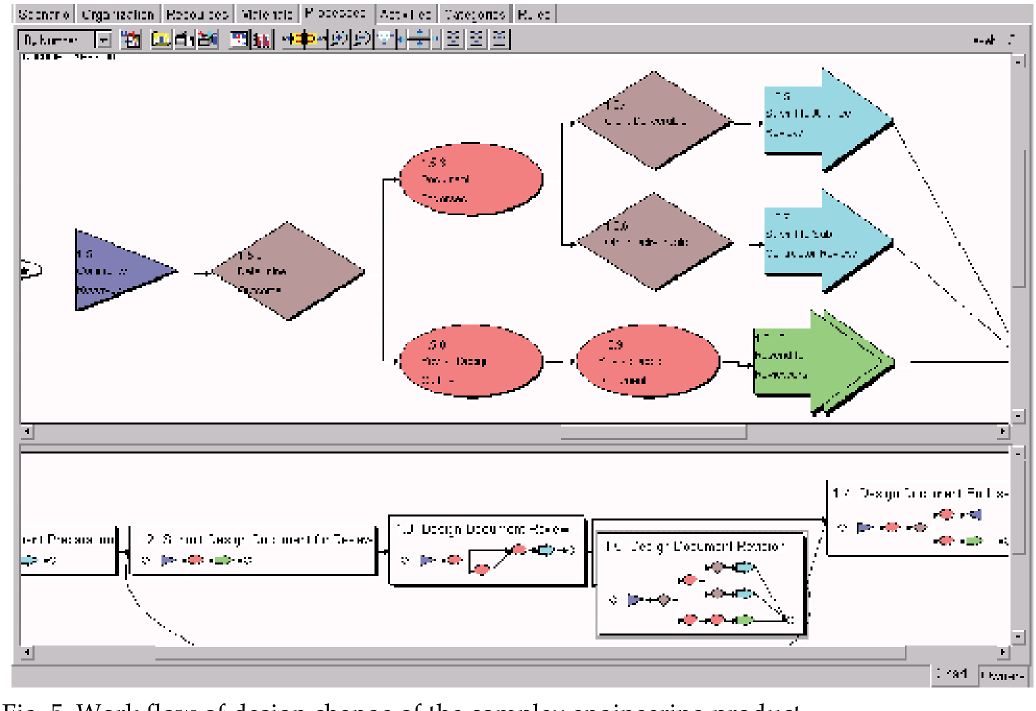


Fig. 5. Work flow of design change of the complex engineering product

A critical design development step of the SVE is to define the mission of the virtual enterprise. The SVE design team conducts a series of interviews with engineering and managerial personnel from all levels in the ASA and develops the mission fulfilment cycle of the ASA in Fig. 6. Within the ASA, the term "shareholders" are partners in the ASA charged with the mission of servicing and supporting the ANZAC frigates for the life of the assets. The activities of the "shareholders" are solution focussed, that is, developing solutions that can be implemented on the ANZAC assets for continual or improved capabilities. The ASA has the role of managing the change program, which can be done by one or two of the ASA partners, or by subcontracting outside of ASA.

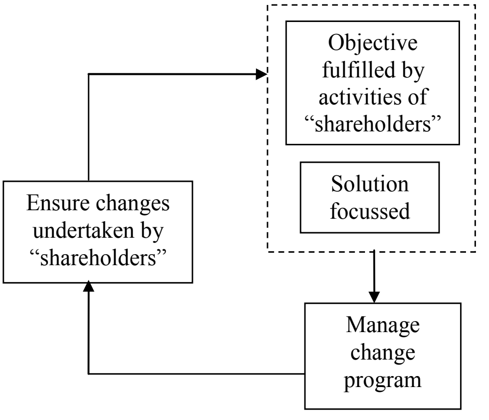



Fig. 6. Mission fulfilment cycle of the ASA

To fulfil this mission, the SVE design team has analysed the system requirements of the ASA using a thorough enterprise modelling methodology (Bernus & Nemes, 1996). The outcome of the enterprise design process that involves experts in enterprise analysts and designers and develops an enterprise structure that is consistent to a "Consultant VE" (Fig. 7).

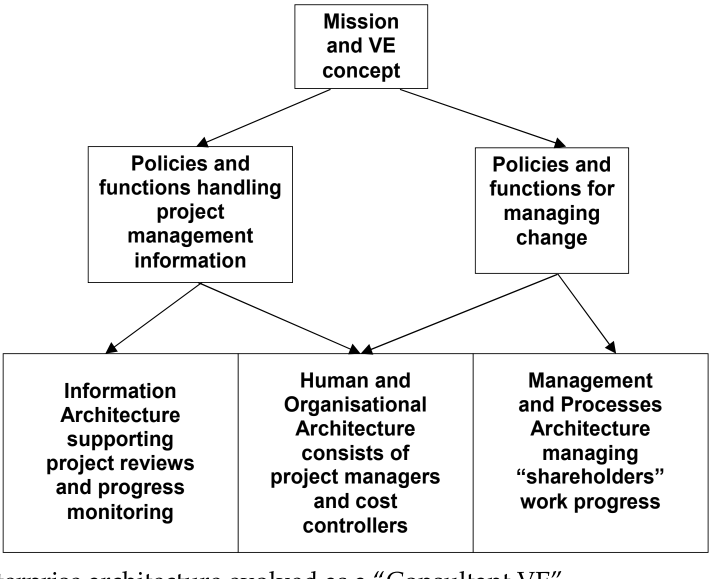



Fig. 7. ASA enterprise architecture evolved as a "Consultant VE"

A SVE is essentially a supply chain set up for providing service "products" for complex engineering systems. These cases show that a clearly defined enterprise infrastructure linking different parts of the service supply chain has to be created and managed for supporting large scale assets. An essential element in the design of a service enterprise is to develop efficient system architecture and provide the right resources to the right service tasks. By synchronising organisational activities, sharing information and reciprocating one another's the technologies and tools, each partner in the service enterprise will be able to provide services that would have been impossible by individual effort. The support solution therefore requires properly designed systems to support the use of technology in the provision of support services to customers. This illustrates that services system design is an integral part of a support system solution.

## 4. Whole of contract risk assessment

Due to the extremely long term commitment, a services and support contract presents a high risk to the service provider's business. If the risks are not well understood, small hiccups in the life of the services and support contract will result in a sizeable financial loss. Likewise, large mishaps in the operations under the contractual arrangement will impose significant liability to the service provider that may be driven out of business. Hence, apart from setting up the SVE and the corresponding condition monitoring system, the system designer should also ensure continuity of business. It is necessary to estimate the level of risk that the service virtual enterprise has to face over the life of the contract providing the service at the agreed price. This concept and the technique are illustrated with a simple worked example.

In a typical services and support scenario, a service provider (supported by partners in his/her own supply chain) wishes to bid for a 30 year long term contract for the services and support of a waste oil treatment plant. Due to continuous research and development of the oil treatment process, it is envisaged that the plant will undergo several major upgrades within this 30 years. The SVE is fully responsible for continual operational availability of the plant to the plant owner.

In order to achieve a a profitable contract, a thorough understanding of the nature of services is critical to the design of a successful system support solution. Given the aforementioned scenario, the question is how should the service provider assess viability of the service solutions? How much the contract should be? To analyse this scenario, some essential data are solicited, either from historical or comparable cases. It is assumed the following data are collected (all costs are in million dollars $M).

a. There are upgrades required in the 30 years. The year of upgrades $t$ depends on many factors. Table 1 shows the probability of timing of such upgrades.

| Year $t$ | Upgrade occurring in the year after first install or last upgrade |
|---|---|
| 5 | 0.4 |
| 10 | 0.3 |
| 15 | 0.2 |
| 20 | 0.1 |

Table 1. Probabilities of upgrade timing

b. The cost of upgrade $u$ depends on many factors and can be expressed as probabilities in Table 2.

| Cost $u$ (in \$M) | Probability |
|---|---|
| 20.0 | 0.1 |
| 40.0 | 0.2 |
| 60.0 | 0.2 |
| 80.0 | 0.2 |
| 100.0 | 0.3 |

Table 2. Probabilities of upgrade costs

c. The services and maintenance (S&M) costs $x$ in \$M vary over the years based on a probability function in Table 3. The average S&M costs will increase by \$0.5M every year, i.e. if the figures in Table 3 are used for determining the S&M costs in Year 1, then the cost figures in $x$ will be increased to 2.5, 3.5 and 4.5 respectively in Year 2.

| Cost $x$ (in \$M) | Probability |
|---|---|
| 20.0 | 0.4 |
| 30.0 | 0.5 |
| 40.0 | 0.1 |

Table 3. Probabilities of services and maintenance costs

d. After an upgrade, the average S&M costs $x$ in \$M will be reduced by \$1M from the year immediately before the upgrade.

The key to risk assessment is to determine a "reasonable" cost of the contract. This is often computed using expected value method.

Expected year of upgrade: $\mu_t = E(t) = \sum_{i=1} t_i p_i = 10$ (1)

Expected upgrade cost (\$M): $\mu_u = E(u) = \sum_{i=1} u_i p_i = 68.0$ (2)

Expected S&M costs depend on the time after first operation or the years of upgrade $t$. Since the expected year of upgrade is 10, there are two upgrades in 30 years. The expected S&M costs at different year $y$ up to the year before an upgrade occurs is given by eq.(3).

$$\mu_{x,10} = E(x,y) = \sum_{i=1} (x_i + 0.5y)p_i \qquad \text{where } y < 10 \tag{3}$$

$$\mu_{x,20} = E(x,y) = \sum_{i=1} (x_i + 0.5y - 1.0)p_i \qquad \text{where } 10 \le y < 20 \tag{4}$$

$$\mu_{x,30} = E(x,y) = \sum_{i=1} (x_i + 0.5y - 2.0)p_i \qquad \text{where } 20 \le y < 30 \tag{5}$$

If the marginal rate of return $r$ is 10%, the net present value of total costs of the service contract in \$M is:

$$S = \sum_{i=0}^{9} \frac{\mu_{x,10}(y)}{(1+r)^y} + \frac{\mu_{u,10}}{(1+r)^{10}} + \sum_{i=10}^{19} \frac{\mu_{x,20}(y)}{(1+r)^y} + \frac{\mu_{u,20}}{(1+r)^{20}} + \sum_{i=20}^{30} \frac{\mu_{x,30}(y)}{(1+r)^y} = 319.047 \quad (6)$$

Note that the SVE is still servicing in Year 30 but there is no further upgrade agreement requirement in the last year of the contract.

However, eq.(6) only provides an estimate of a "likely" total cost $S$ of the contract. Is it a good deal for the asset owner? Is it a risky endeavour for the contractor? To answer these questions, we need a way to compute the distribution of the total cost.

A simulation model is set up to calculate an instantaneous total cost for each simulated scenario. We use the notation $|j$ to denote a scenario generated by a random number generator that determines the corresponding stochastic values in Tables 1 to 3. Note that $j$ is generated separately for all variables so that their values are independent. The model can be represented by the following equations:

An instant of years of upgrade due to random number $j = t_k |_j$ (5)

where k = 0, 1, 2, 3, … (max. 5), subject to constraint $\sum_{k=0}^{5} t_k |_j \leq 30$ (6)

An instant of cost of upgrade due to random number $j = u_k |_j$ (7)

An instant of S&M cost due to random number $j = x |_j$ (8)

For upgrade period $k \in m$, the S&M cost of the plant is given by:

$$x |_{j,y} = x |_j + 0.5y - 1.0k \quad (9)$$

where $y$ is the year at which the S&M cost is evaluated.

Hence, the net present value of the instant of total cost is given by:

$$S = \sum_{k=0}^{5} \sum_{y=0}^{t_k|_j - 1} \frac{x |_{j,y}}{(1+r)^y} + \sum_{k=0}^{5} \frac{u_k |_j}{(1+r)^y} r^i \quad (10)$$

The simulation is run 200 times and the result is shown in Fig. 8.

It is important to analyse the risk of setting a quotation figure. If we assume a normal distribution, the mean and standard deviation of Fig. 8 are \$398.72M and \$47.74M respectively. If the contract cost is set at say \$450M (in order to compete), the risk of incurring a loss is 14.1%. This is a high risk contract and is not acceptable in normal business practice. On the other hand, if the SVE wants to have 99% certainty of a profit, the contract sum should be increased to \$509.79M.

This case study shows that a system support engineer will need to develop a mathematical model that represents behaviour of the system over a period to analyse sustainability of the support solution according to prevailing business conditions. The business requirements of service contracts drive a fundamental change in the way services to complex systems are designed. Minimising cost of replacement part will not be the objective. The main focus is to maintain or improve the performance with changes that is sustainable. Hence, it may mean change of parts at a higher rate but the savings in better performance from the system will pay for the increased component cost. The analytical techniques vary from case to case. A thorough research in the fundamental of support system sustainability is required to establish a standard methodology.

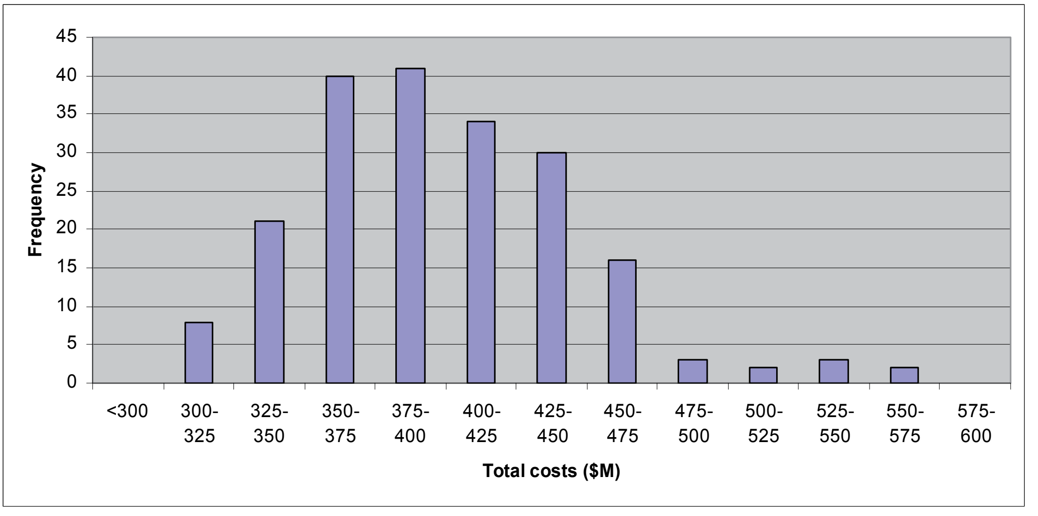



Fig. 8. Frequency of possible total costs for the service contract

## 5. Design of services and support virtual enterprise

A services and support contract will include incentives and penalties against agreed service levels. Hence, the service contract requires a thorough understanding of how the engineering system works and how the supporting systems around the asset should operate to achieve the desirable performance. Due to the highly complex nature of services provision, services and support contracts are all different. It is an extremely knowledge intensive, labour rich business. The support solution then becomes a one-off development which imposes significant system design issues to both asset owners and contractors. They will need to work through the contract which incorporates unfamiliar contractual metrics and risks. The shift in business environment and model has driven the research need for new methods and processes to design service solutions for complex systems, for example, intangible elements for achieving successful service delivery should be incorporated. The objective is to "get the best value for money" on supporting asset capabilities for the asset owner.

Hence, in designing support solutions, due to the interacting relationships between the customer and the service provider, the characteristics of both service elements and hard system components must be integrated into the service system with a critical reasoning process that aims to produce a solution design in unison with all parties involved in the performance based contract. Irrespective of industry sectors or types of customers, services are co-produced with and truly involving consumers. To illustrate this concept, Fig. 9 shows a generic model of a services and support system that has 4 interacting ingredients.

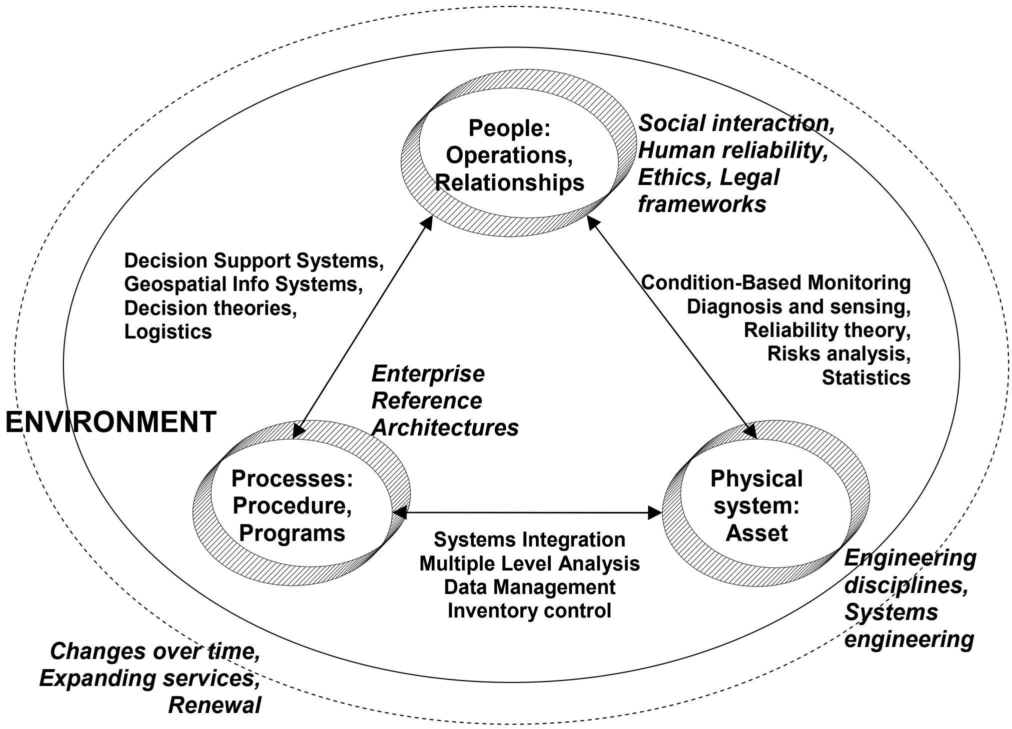



Fig. 9. Services and support systems have four interacting ingredients that need to be well understood for the formation of a SVE

### 5.1 Physical asset

A services and support solution must have a physical system on which the services and support requirements are defined. A complex engineering system is often either specially designed from conceptual requirements specified by the customer, or customized from an existing engineering system to the need of the customer. In this context, the knowledge of discipline based engineering domain coupled with systems engineering is necessary to design and build the engineering system. The structured, systematic approach in this design process is a risk minimized way of producing a workable physical asset.

Complex engineering systems are created through an intensive life cycle of data accumulation and information re-structuring. Usually the life cycle of such an engineering system can be divided into 6 phases as shown in Fig. 10 (Jannson et al, 2002).

It is obvious that the information in the complete product life cycle are particularly important to support both asset owners and service contractors. Knowledge from domain engineering (such as mechanical engineering) should be amalgamated with feedback from business aspects of system-in-service, within the life cycle of the system in order to design a workable SVE and develop a viable service solution. What is important in this case is therefore to make sure that information available at different stages should be archived in compatible formats so that future staff and systems can use the same data set for services and support.

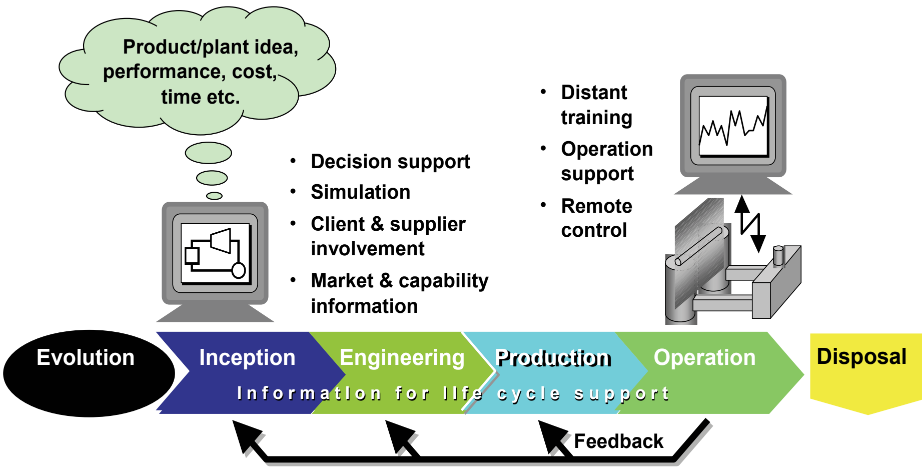



Fig. 10. Complete life cycle management of complex system

### 5.2 Processes

The hardware system design should be supported by corresponding processes that are required to operate, service and support the performance of the physical asset. Operations are related to the measurement of performance. Systems integration and data management regimes are required to support designing and structuring a system support solution. The provision of service is different to product-based business model. Service is a negotiated exchange with the asset owner (and operator) to provide intangible outputs together with the asset owner. A service is usually consumed at the time of production and cannot be stocked. Hence, the development of appropriate processes and performance metrics that help the people involved to synchronise their activities is essential. These processes are constrained by the environment in which the complex system and the business are operating. Most of these are supported by advanced information and computational technologies that integrate with on-asset systems such as sensors or signal processing capabilities.

In the design of the processes around the physical asset, the services solution designer draws upon principles derived from experience that are obtained in previous projects or recorded literature elsewhere. The use of enterprise reference architectures that forms the initial base for adopting to a wide range of scenarios is crucial to the success of the newly designed SVE and its support solutions. The enterprise model helps the system support engineer to take into account as many constraints as possible during the system design phase.

### 5.3 People

What is normally ignored in the design of systems are the people who are either involved (e.g. operators, beneficiary of use, etc), or not involved but are affected by the operation of the engineering system (e.g. by noise, pollution, etc.) People working on the physical asset will require data for them to judge the status of the asset and act accordingly. New developments in diagnostics and sensing technologies are important data capturing components that enable people to close the information loop. However, the need of human interaction in providing the required services and support imposes a different challenge, that is, the issue of human reliability. Many researches have been found in the area of human safety but the integration of human error in an engineering system scenario has never produced reliable risk assessment due to the variability of data (Kirwan, 1996). Hence, when assessing the risk of a services and support contract, it is necessary to allow for a higher level of uncertainty in the final decision.

Another issue with human involvement is the necessity for providing meanings to the people in the process. Participation of human should be on voluntary or incentive basis. The support solution design should contain adequate information that explains the meaning of the solution to anyone working in the SVE. The services solution must be characterised by the need to create value for both asset owner and the service provider. As such both sides are treated as co-innovators in the design of the service support solution. Many decisions are made based on incomplete data rather than fully analysed data set. There are a lot of risks, both from the point of view of data availability, as well as subjective human judgement and communication. In this context, decision theories that can draw upon information that are critical to the people around the asset are particularly useful to assist the group or society to a logical, win-win outcome.

### 5.4 Environment

All three elements physical asset, processes and people work within some kind of environment. The term environment does not limit to the natural system of mother nature. It also means artificial circumstances in which the three elements are made to work in. For example, a business environment created by the defence requirements of a country often defines its own rules and objectives that are totally different from the general civilian community. Companies in the defence environment will need a different set of data and process it in mission critical projects.

Sustainability issues are related to the continuity of business and viability of the support contract. A characteristics of the environment is change over time. Changes can be in the form of technological change, aging of people, loss of memory, renewal requirements due to regulatory or sociological changes. Unfortunately, the complexity of the changes in environment is difficult to predict.

## 6. Conclusion

In this chapter, we discussed the difference between a maintenance oriented regime and a services and support contract in the context of complex engineering systems. A complex engineering system is an expensive asset that the owner-operator is keen to keep and continues to use as long as possible. From the owner's point of view, it is important that capability should increase over time to meet changing demands. To achieve this goal, the business environment now favours the use of services and support contracting mechanism that puts responsibility to the services and support providers.

In the past decade, researches in the development of support systems have been fragmented. Due to the highly individualised nature of a service contract, it is an extremely knowledge intensive, labour rich business. These services are substantially more complex than routine, reliability based maintenance. In order to create a viable support solution, three essential elements are required:

- A condition prediction and monitoring system that provides feedback to the services provider assisting continuity of operations;
- A service virtual enterprise (SVE), which is a supply chain offering service "products" to customers with complex engineering systems;

- The knowledge that can be used to analyse the risks in committing to service levels agreed upon between the asset owner and the SVE.

In conjunction with these elements, a conceptual model that describes the interacting nature of four ingredients in a services and support system is also presented. Understanding how the ingredients work together and how they change over time is critical to the successful design of the SVE and its system support solution.

## 7. References

Abdul-Nour, G., Demers, M. & Vaillancourt, R. (2002). Probabilistic safety assessment and reliability based maintenance policies: application to the emergency diesel generators of a nuclear power plant. *Computers & Industrial Engineering*, 42(2-4):433-438

Abe, T. (2005). What is Service Science. *Research Report*, No.246, December. The Fujitsu Research Institute, Economic Research Centre, Tokyo, Japan

Apeland, S. & Aven, T. (2000). Risk based maintenance optimization: foundational issues, *Reliability Engineering & System Safety*, 67(3):285-292

Armstrong, M.J. (1997). Reliability -Importance and Dual Failure-Mode Components, *IEEE Transactions on Reliability*, June, 46(2):212-221

Bernus, P. & Nemes, L. (1996). A framework to define a generic enterprise reference architecture and methodology. *Computer Integrated Manufacturing Systems*, 9(3):179-191

Chan, F.T.S., Lau, H.C.W., Ip, R.W.L., Chan, H.K. & Kong, S. (2005). Implementation of total productive maintenance: A case study. *International Journal of Production Economics*. 95(1):71-94

Colombo, S. & Demichela, M. (2008). The systematic integration of human factors into safety analyses: An integrated engineering approach, *Reliability Engineering and System Safety*, Dec, 93(12):1911-1921

Gong, Y. F., Ren, W., Shi, X. Z., Xu, J. X. & Hu, S. J. (1999). Recovering strange attractors from noisy interspike intervals of neuronal firings, *Phys. Lett. A*, 258:253-263

Hall W.P. (2001). Managing Technical Documentation for Large Defence Projects: Engineering Corporate Knowledge, In *Global Engineering, Manufacturing and Enterprise Networks,* pp.370-378, pub. Kluwer Academic Press, ISBN 0-7923-7358-8

Hu, X., Grozev, G. & Batten D. (2005). Empirical observation of bidding patterns in Australia's National Electricity Market, *Energy Policy*, 33(16):2075-2086

Huang, H.-Z. (1997). Fuzzy Multi-Objective Optimization Decision-Making of Reliability of Series System, *Microelectron. Reliab.*, 37(3): 447-449

IfM & IBM (2008). Succeeding through Service Innovation: A service perspective for education, research, business and government, *A White Paper based on Cambridge Service Science, Management and Engineering Symposium (July 2007) and The consultation process (October – December 2007)*. ISBN: 978-1-902546-65-0, pub. University of Cambridge, UK, 33 pages

Jansson, K., Karvonen, I., Ollus, M., Hartel, I., Burger, G. & Kamio, Y. (2002). Virtual Organisations in the Sales and Service Life-cycle Phases of an One-of-a-kind Product. *VTT Symposium 224*, Espoo, Finland, 10-12 Dec, pp.125-134

Johansson, P. & Olhager, J. (2006). Linking product–process matrices for manufacturing and industrial service operations, *International Journal of Production Economics*, 104(2):615-624

Kamio, Y., Kasai, F., Kimura, T., Fukuda, Y., Hartel, I. & Zhou, M. (2002). Providing Remote Plant Maintenance Support through a Service Virtual Enterprise. *VTT Symposium 224, Global Engineering and Manufacturing in Enterprise Networks*, 9-10 December, Helsinki, Finland, pp.195-206

Kirwan, B. (1996). The validation of three Human Reliability Quantification techniques - THERP, HEART and JHEDI: Part I – Technique descriptions and validation issues, *Applied Ergonomics*, 27(6):359-373

Leger, J.B., Iung, B., Ferro De Beca, A. & Pinoteau, J. (1999). An innovative approach for new distributed maintenance system: application to hydro power plants of the REMAFEX project, *Computers in Industry*, 38:131-148

Marmo, L., Crivelletto, V. & Starace, A. (2009). Recursive Operability Analysis as a decision support tool for Risk-Based Maintenance, *Journal of Loss Prevention in the Process Industries*, Sept, 22(5):557-565

Mo J.P.T. & Menzel C. (1998). An integrated process model driven knowledge based system for remote customer support, *Computers in Industry*, 37:171-183

Mo J.P.T., Larden, D. & Wood, L. (2008). System Support Engineering: An Education Program for Performance Based Contracting. *4th Defence Skilling Summit 2008*, 8-9 September, Adelaide, Australia

Mo J.P.T., Zhou M., Anticev J., Nemes L., Jones M. & Hall W. (2006). A study on the logistics and performance of a real 'virtual enterprise', *International Journal of Business Performance Management*, 8(2-3):152-169

Moubray, J. (1997). Reliability Centred Maintenance, New York, Industrial Press, ISBN ISBN 0-8311-3146-2

Pujadas, W. & Chen, F.F. (1996). A reliability centered maintenance strategy for a discrete part manufacturing facility, *Computers & Industrial Engineering*, 31(1-2):241-244

Rathwell, G. A. & Williams, T. J. (1996). Use of the Purdue Enterprise Reference Architecture and Methodology in industry. *Model and Methodologies for Enterprise Integration*, Chapman and Hall, London, 12-44

Schreiber, T. & Grassberger, P. (1991). A simple noise-reduction method for real data, *Phys. Lett. A* 160:411-418

Shen, Z.J.M. & Daskin, M.S. (2005). Trade-offs Between Customer Service and Cost in Integrated Supply Chain Design, *Manufacturing and Service Operations Management*, 7(3):188-207

Sherwin, D.J A. (2005). The case for more comprehensive data collection and how it might be achieved: Part 1. *Journal of Maintenance and Asset Management*, 20(3):26-35

Spohrer, J., Maglio, P.P., Bailey, J. & Gruhl, D. (2007). Steps Toward a Science of Service Systems, *Computer*, Jan, 40(1):71-77

Tam, A.S.B., Chan, W.M. & Price, J.W.H. (2006). Optimal maintenance intervals for a multi-component system. *Production Planning and Control*, 17(8):769-779.

Uusitalo M., (1998). Operations Support System for DD Washer, *Control Systems '98*, Haikko, Porvoo, Finland, 31 August.

Yang S.Y.S., Kearney T., Mo J.P.T. & Boland P. (2003a). MachineGP: a new concept in signal-based machine condition monitoring and diagnostics, *New Engineer Journal*, 7(2):19-23

Yang, S.Y.S., Rogers, K.J., Gershenzon, M. & Mo, J.P.T. (2003b). Detecting abnormalities in high temperature manufacturing operations from process parameters, *9th International Conference on Manufacturing Excellence 2003* (ICME 2003), 13-15 October, Melbourne, Australia, ISBN 1-877040-17-7

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# Lifecycle Based Distributed Cooperative Service Supply Chain for Complex Product

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## 1. Introduction

With sharp expanding production capacity and drastically competitive market environment, the surviving precondition for modern enterprise is to promote productivity and competitiveness continuously. As the backbone of enterprise, complex products are always demanded to run with high reliability. However, high integration and intelligence of complex products make the existing industrial service mode not meet new requirements, it is necessary to build a new service mode to optimize the complex products operation.

A favourable industrial service not only makes complex products work in optimal status and high reliability, but also helps to upgrade and innovation of products within all service chain. Both consumer and supplier attach great importance to service support of complex products. The article describes a distributed cooperative service supply chain covered total lifecycle of complex products. Under the service supply chain, services may not only have a higher quality but also reach the customer in a shorter reaction time and at a low price. Consumers, manufacturers and supplierscan get their competition advantage through lifecycle based distributed cooperative service supply chain.

## 2. The industrial service concerned

### 2.1 Potential value of industrial service

Under the environment of sharp expanding of production capacity of traditional manufacturing and drastic market competition, product supply is in saturation status since 1990's. It is estimated that supply of 95 percent of products have been saturated or balanceable, the products which demand exceed supply account no more than 5 percent. The product average profit margin decrease continuously. When production capacity expanded to a certain degree, it is very difficult for enterprise to develop only depending on scale economy and scope economy. The hindered production expanding pushes the enterprises to find new expanding ways (ZHENG, 2003). Product service incremental strategy can also realize enterprise development, not through output increase, but innovative service supply that is throughout total product lifecycle.

For manufacturers and suppliers of complex products, the relationship of potential value of industrial service with product lifecycle is shown by Fig.1. Before product sale, the service potential value is negative because resources invested in consultation and planning for consumer. The service starts its increment when products being sold.

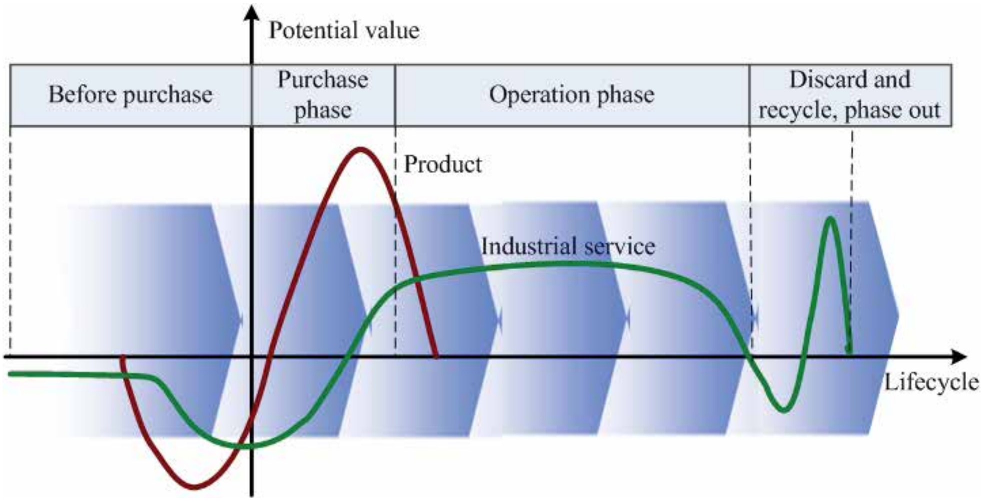


Fig. 1. Relationship of potential value of Industrial service with product lifecycle

### 2.2 The basis of industrial services

Industrial services concerned here treat the following three terms (McDonald & Payne, 2006; Meier and Kortmann, 2007):

- Intangibility. Services are usually intangible while products are generally concrete. The consequence of a service, however, is always inseparably connected to goods. Different states during needed service delivery are differently materially distinctive.
- Uno-actum-principle. Services are produced and consumed at the same time, hence they cannot be stored.
- Integration of customers. A direct contact between service providers and demanders is fundamental. The active role of customers during the service production leads to specific features with location restraint, because provided service is either carried out or stored in an object which is accessible for customers.

In addition to these characteristics industrial services have diverse definitions with regard to three dimensions: potential, process and result dimension (Meier, 2004). Potential dimension focuses on resources, which are supplied for providing a service. By combination of internal potential factors and corresponding resources, it can be prepared to provide a service according to generated qualification and preparedness. Process dimension regards service process as a connector for potential dimension with external factors, such as customers. Customers play the most important function in process dimension as they can be regarded as the initiator and accompanying elements alongside service procedures. Evidently it makes sense saying that integration of customers involved in service providing processes is necessary. With regard to result dimension, result conditions will be evaluated as an output from customers' view, in order to investigate how the target of the service provision has been reached (Meier et al., 2004).

## 3. Why provide industrial services cooperatively?

In the background of globalization and increasingly drastic competition, only the enterprise with strong kernel competitive power can survive and develop. For users, their motivation to purchase complex products is not to buy something usable, but to utilize the advantages brought by high-tech equipment to enhance competition dominance of their main products. It means that, for manufacturers and suppliers, the development of high-tech equipment is only one of preconditions to succeed in market competition. To win a dominant market position, high-tech equipment itself should associate with necessary technical services to form a 'binding body' of product and service assembled by product, service, information, concern and other factors. Through these technical services, manufacturers can share technical evolvement with users and upgrade equipment technically, and users can keep their equipment in good status and good reliability, promoting the kernel competition powers of both parties.

Normally, there will come forth some problems in running process of complex products. For users, complex products always, with high technology contents and complicated structures, include many integrated technologies and important parts of different manufacturers, it is too complicated to diagnose, maintain and repair. Even though getting training courses, it is difficult for users to judge and solve all problems in products running, this is to say users can't face market competition independently without the service support from manufacturers and suppliers of products; they need the manufacturers and suppliers to keep the running status of products optimal and increase their productivity and competitiveness. For the manufacturer and supplier, a series of questions will follow,

- With increase of parts supplier number, quality tracing, claim and settlement contain many procedures and take long time;
- The users distribute all over the world, the service personnel can't acquire needed locale information in time, resulting in high service cost and service delay;
- The technical field is too wide, mastering all correlative technologies is beyond ability of a technical person or single corporation of manufacturers and suppliers. Therefore, the traditional industrial service supply mode can't already meet the demands of consumers and enterprises, to study and establish a new distributed service supply chain is imperative under the situation.

To realize globalized distributed industrial services, cooperative relationship and network should be established. Since it is impossible that the service personnel of manufacturers or suppliers, no matter how large their scale is, reach every needed place in a short time. The enterprises, therefore, must discard old competition idea and build 'two-win' cooperative service supply, through the cooperation with sales partners, technical service suppliers and other manufacturers, supplying timely services supported by corresponding communication and information technology.

The evolution from traditional service mode to cooperative service mode is shown in Fig.2.

In traditional industrial service mode, consumers buy products and receive technical services from suppliers. However, the solution of most of problems already needs the supports of parts suppliers and machine tools manufacturers. For complex machine tools, its assembled parts are supplied by many manufacturers; many factors such as the communication and harmonization between corporations, the harmonization in corporation interior, the difference of excuted standards and document formats and so on can become barriers to service supply. Under this circumstance, the needed services are supplied in lower efficiency, as time passes, resulting in consumers' complaint and distrust, the potential users lost. For users, equipments, that can not run in their optimal capacity or which problems can not be solved in time, will mean low productivity and competitiveness.

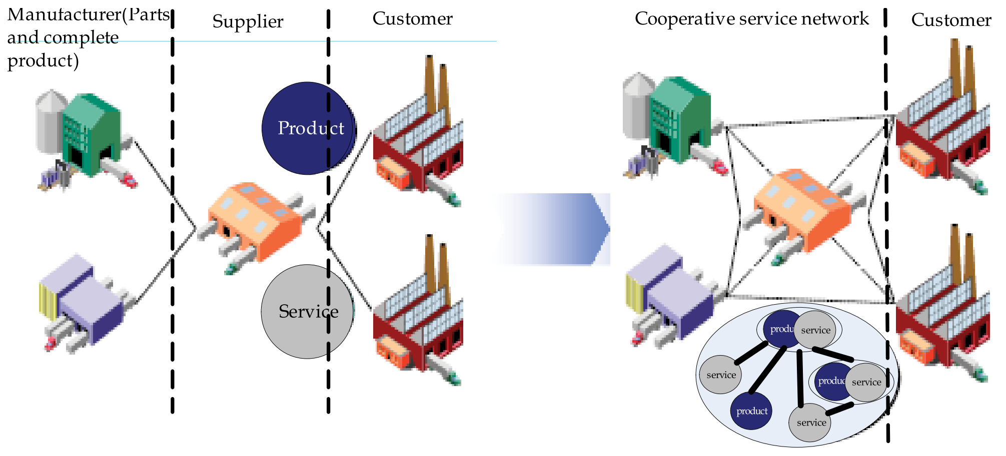


Fig. 2. Evolution from traditional service mode to cooperative service mode

A new service idea gives the answer to above existing problems. According to this idea, industrial service is supplied not by single supplier or manufacturer, but by a group, named cooperative service network, which is formed by parts manufacturers, complete machine tools manufacturers and suppliers through a certain harmonizing and switch-on mechanism. With this service mode, customers receive industrial services through cooperative service network in total product lifecycle from product choice and production line planning to equipments replacement, discard or recycle. The 'product' purchased by customer is not a product in traditional meaning, but a 'new product' formed by product itself band with cooperative service; the service begins from the beginning of the customer contacts with supplier.

With cooperative service, the customers receive the guarantee that machine tools run reliably, stably and efficiently, and through service network, the manufacturers and suppliers can obtain more available running information from customers, helping to grasp future market requirements and promoting improvement and innovation. In the course of collaboration with partners, members of service network can take complementary advantages to enhance their kernel competition power and expand their market share, realizing two-win development by market share, profit share, risk share and advantage mutual utilization.

## 4. Organization form and business model of distributed cooperative service network

Three important factors concerning distributed service system are given (Fig. 3) as follows,

- Form of Service Provider. It describes how, with the defined criterion, the local service provider can establish its term of business systematically.
- Type of Resource Distribution. It describes the structure of a service net, which consists of locations where availability of potential resources is given. It has various influence on dependency such as "number of machines" and "type of machines", "locations of customers", and "environment, frequency and continuousness of customer´s demanding of services", which are necessary to define distribution structure of services either centralized or decentralized.
- Operational organization of distribution system. It decides which company in the supply chain and which kinds of resources integrated in providing processes are suitable and available.

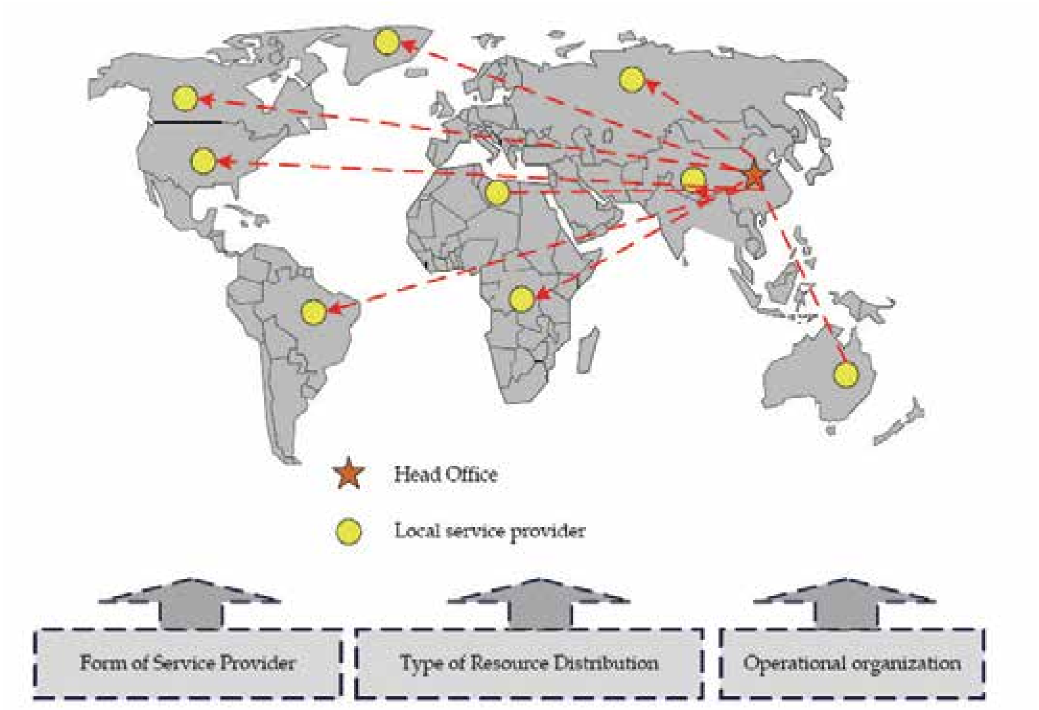


Fig. 3. Factors of service distributed system

### 4.1 Form of the service provider

In order to provide suitable services to customers in time, the company must establish a suitable allocation and form to support the providing service.

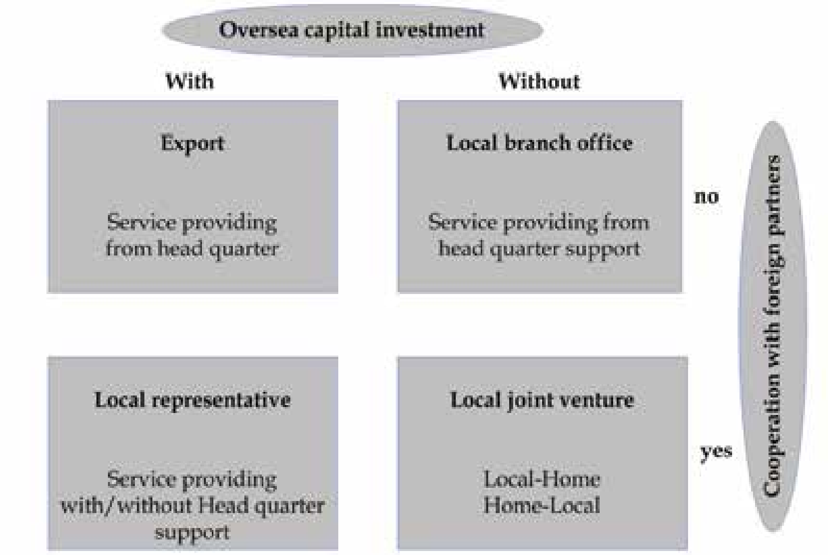


Fig. 4. System frame of distributed cooperative service

Following system frame shows form of a local service provider, with which the specific kind of business form can be established for a new service market (Fig. 4).

### 4.2 Type of resource distribution

Within the centralization of a service organization, the organization is structured as an unit to summarize all tasks for service providing. It can be regarded as a service central or service staff from which services are provided for customers worldwide.
In terms of decentralization of service organization tasks are assigned to several organization units, also known as local office respectively. All service units consist of a service network (Fig. 5).

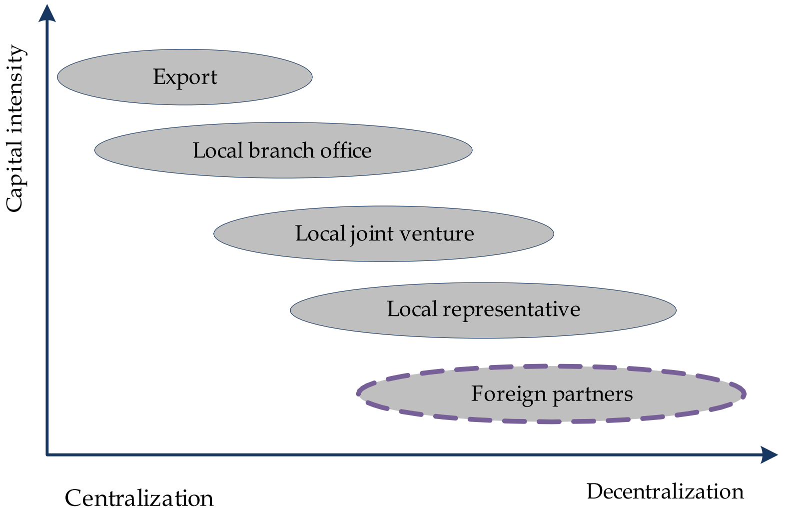


Fig. 5. Centralization level of local service provider

The service centralization occupies the competence advantages that local providers can use from head office. Further it is possible to advance the communication and coordination between local and homeland and not to mention the fact that the head office achieves almost every service feedback as service know-how is given. Unfortunately it takes a long reaction time to market abroad and it is proved to be difficult to forecast customers' demands and low flexibility.
Service decentralization leads decentralized local provider plan, coordination and operation of service provision. The provider can respond to the customer's demands quickly. In contrast to the centralization it can offer high flexibility and quick supplying of spare parts. As a disadvantage, lack of communication between local service provider and different markets will lead to lose an amount of feedback information regarding as know-how.

### 4.3 Cooperation and coordination of service provision on target market

Methods of supply chain managements (SCM) offer solutions in direct coherence with the problems of spare parts supply and maintenance logistic. A supply chain can be defined as a chain and most likely a network of different organizations, which work together in order to develop a product or service needed by end customer. Collaboration of all undertakings within a value chain is centre of a supply chain. This means that supply chain forms an alliance between network partners and tries to coordinate these bonds. The continuous adjustment to demands of end customers is a main characteristic of a supply chain and supply chain management (Scholz-Reiter & Ranft, 2000). In these terms, supply chain management aims goal of integrated scheduling, simulation, optimizing and control of goods, information and money, which flow along lines of a value chain between customer and commodity providers (Corsten & Gössinger, 2001).

These keynotes may also be assigned to cooperation of maintenance, because same targets are aimed at coordination of maintenance. Supply chains, which are formed out of these keynotes, will be called service supply chains (SSC). In this article reference scenarios for cooperative provision of maintenance services are introduced based on the assigned ability of SCM.

In order to ensure the manageability of observation of these scenarios, only Supplier 1 (1-tier) and supplier 2 (2-tier) are being observed within a network (Fig. 6).

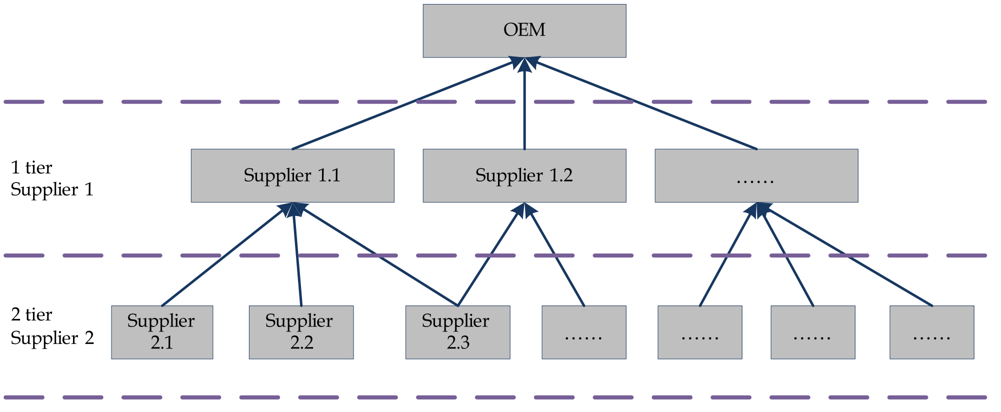


Fig. 6. Service delivery hierarchy

For operator of a complex machine, the machine maintenance including inspection, attendance and repair is an important factor, which has immanent influence on the purchase decision. This article consequently focuses on fields of maintenance logistics and spares parts supply, which is often related to maintenance logistics. Consequently the business of spare parts supply has to deal with temporal, regional and quantitative combination of spare parts with damaged primary product. The aim of maintenance logistics is the temporal, regional and quantitative combination of maintenance staff with required qualification, with the damaged primary product in order to provide maintenance services. Consequently a frictionless and safe spare parts supply would have an imminent importance for the assurance of availability and the conservation of value of the provided complexes machines. The continuous and accurate logistic of information and documentation, which is easy and fast to handle, is a precondition for the efficient accomplishment of the spare parts supply as well as maintenance logistic.

## 5. Reference scenarios for the cooperative provision of maintenance services

The reference scenarios consider all contingencies starting at bilateral relationship of customers and OEM, integrations of provider by OEM and ending at self coordinated maintenance supply by equal supply chain partners.

### 5.1 Scenario 1

The first scenario (Fig. 7) is strongly oriented to flow of materials along the value chain. In the case of maintenance, the OEM is the only contact person for the customer within a supply chain. This condition is based on grounds that collaboration of OEM and customer is formed during the course of purchase of a product. Most likely this happens quite earlier. The advantage of this scenario in the view of customer is transparent commissioning. The OEM adopts the responsibility for provision of maintenance services for end customers. Spare parts are provided by the supplier to the OEM. The OEM deputes his maintenance staff in the case of an assignment with access to suppliers' spare parts or own spare parts and performs the requested maintenance services. In order to fill the stock with spare parts a flow of information between OEM and supplier is precondition.

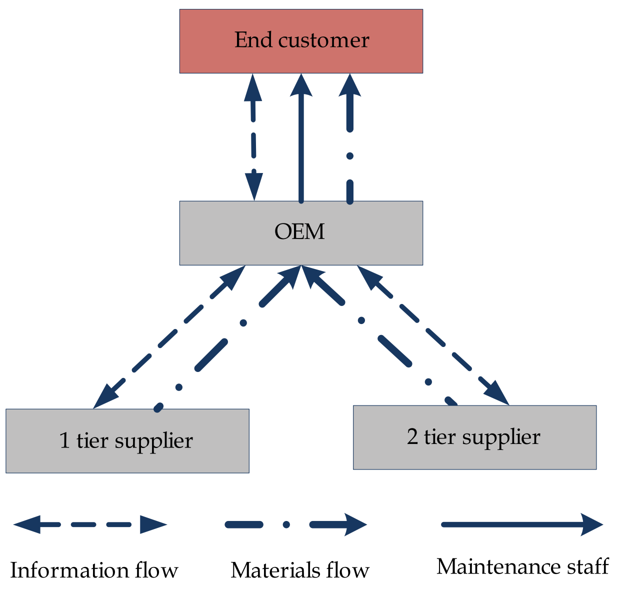


Fig. 7. Reference scenario 1 for cooperative provision of maintenance services

The supplier functions in the role of a subcontractor and can optionally be called by the OEM to perform services in form of support and professional competence. This is the case, for instance, if assistance of a supplier is needed during process maintenance process, if insolvable problems emerge for the OEM or if spare parts are requested at short notice. In this scenario, the OEM has a monopoly position.

### 5.2 Scenario 2

For the second scenario, the attention falls on parallels to the first scenario (Fig.8). The order acceptance and clearing happens solely by the OEM. In this case, provision of maintenance services is strongly oriented to the supply chain.

In case A, the OEM provides requested maintenance services to the customer with access to necessary spare parts of the supplier or with own spare parts. The OEM deputes the coordination of spare parts and maintenance staff. The filling of his spare part stock happens with help of information exchange or orders to the supplier. The supplier still provides his professional competence. The provision of requested maintenance services for cases B and C of this scenario are designed differently. The customer searches contact to the OEM when need repair. The OEM verifies the assignment and estimates whether the problem is within his fields of competence. If this is not the case, the assignment is transferred to the supplier.

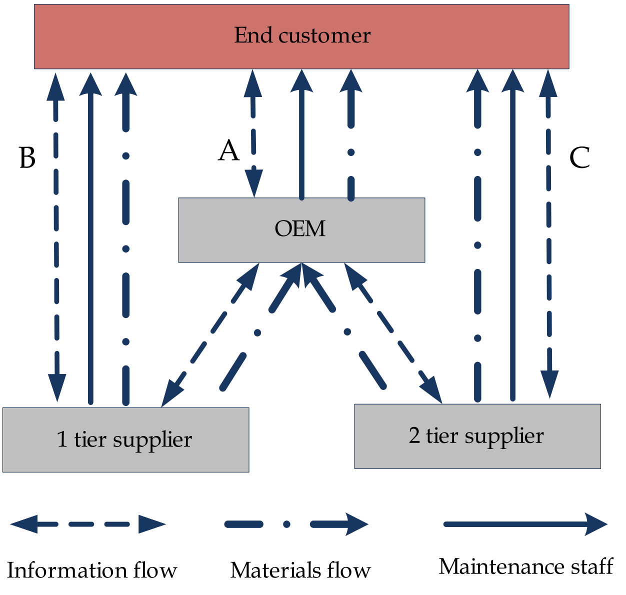


Fig. 8. Reference scenario 2 for cooperative provision of maintenance services

In case B for instance, the assignment is transferred to 1-tier. 1-tier gets the assignment and provides needed maintenance service in the name of the OEM, with the help of a coordinated spare parts supply and a deposited maintenance staff directly to the customer. 1-tier is not influenced by the OEM. The only possible intervention by the OEM happens during assistance. Assistance is, for instance, if the OEM happens to have needed knowledge about the product.

In case C actions take place: 2-tier gets the assignment of the OEM and the ongoing approach is identical to already depicted approach that 1tier is engaged in this case. The supplier get the possibility to present their company to the customer by providing maintenance services. In this scenario, the monopoly of OEM is partly undercut, because the OEM loses a part of his service business to the supplier. Nevertheless it means the advantage of a competence oriented service provision.

### 5.3 Scenario3

The situation, in which the customer can choose his service provider, is given in scenario 3 (Fig.9). The customer forms main authority with respect to principles of the free market economy. In this scenario the equal but factually bordered service situation for all supply chain partners is approached. For the case of repair, the customer can choose the most beneficial and in his view most competent offer. In all cases the customer contacts directly the chosen supply chain partner.

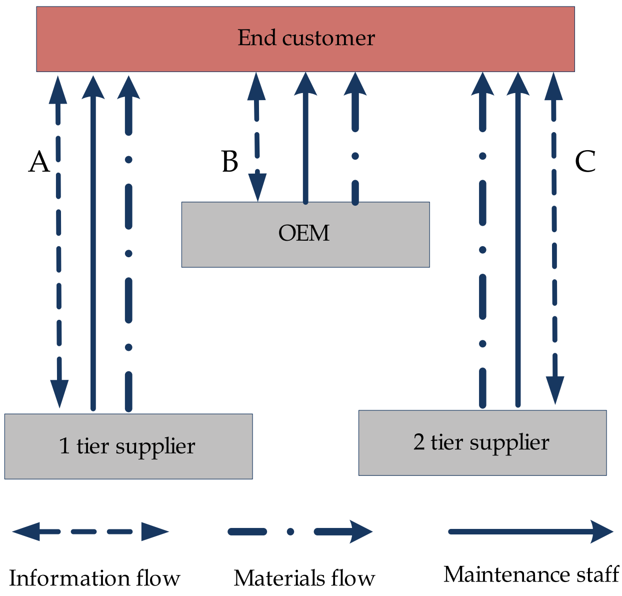


Fig. 9. Reference scenario 3 for cooperative provision of maintenance services

In case A, 1tier will be chosen. 1tier gets the customer assignment and provides the requested maintenance service with the help of his spare parts and maintenance staff. There is no influence taken by other members of the service chain.

A quite similar procedure of maintenance service is taking place in the cases B and C. The supply chain partner himself adopts responsibility towards the customer. Feedback is directly given by the customer during and after provision of the service. The condition that the customer is allowed to choose his service provider, can lead to the situation that a service provider is not requested to provide maintenance service for his product. The case will happen, for instance, as soon as the customer assigns the OEM for a suppliers' product. Even the OEM would necessarily need supplier's product in order to provide the service. In lines of a contribution oriented value chain, all parties act in form of a closed network. During the service provision these parties might be competitors. Nevertheless they are able to provide services in conjunction. This is the case if the cases A, B and C are connected.

## 6. Coordination during cooperative service provision

The cooperation of maintenance between numerous partners in the integrated value chain – like above 3 cases – requires a continuous interlocking of all business processes. Basic attribute is the company-wide optimization of the business process in service supply chain (Kaiser & Schramm, 2004). In the view of procedural-organization functional company oriented structures need to be converted into continuous area-wide and company-wide business processes. An appropriate instrument, which standardizes several steps within the supply chain, is supply chain operations reference (SCOR) model of supply chain council (SCC).

The SCOR model is based on the basic consideration that all supply chain assignments and activities can be relocated to the five main supply chain processes, which are planning, producing, providing, redelivering and purchasing. The visualization and analysis of the network is simplified. During this process, the SCOR model runs through different layers. On top layer the five basic procedures are set. The basic procedures are subdivided on the next layer, which is the configuration layer. On the third layer, the design layer, it is possible for the operator to define his own processes. Each deeper layer step ending at the bottom layer leads to a detailing of previously defined processes.

Basically, the basic procedures can be distinguished into heterogeneous types of process, which are process types of planning, executing and infrastructure. The process type of planning considers all actions allocated to the preparation of future flow of materials. The main aim is to match the demand and the internal company abilities. Typically these are purchase planning, production planning, delivery planning and prognosis planning. This type of process is documented by the planning process. The executing processes consider all activities allocated to the order processing and further on flow of information and materials. In executing process, change in state of material, goods and all associated control activities takes place. Main processes of source, make, delivery and return are associated to this process. Infrastructural processes, which are the premises for a smooth action and affect an efficient procedure, support and manage processes of planning and executing during supply procedure. Return of a faulty primary product or excessive products of a delivery can be depicted by return process of SCOR model. In this course, this process will not be considered, this article will focus on coordination of spare parts supply.

Fig. 10 shows that each SCOR process contains a category of process on configuration layer for categories of planning and infrastructural processes (P1 to P4). In executive process types, SCOR model divides SCOR processes of source (S), make (M) and delivery (D) in three categories of processes on configuration layer.

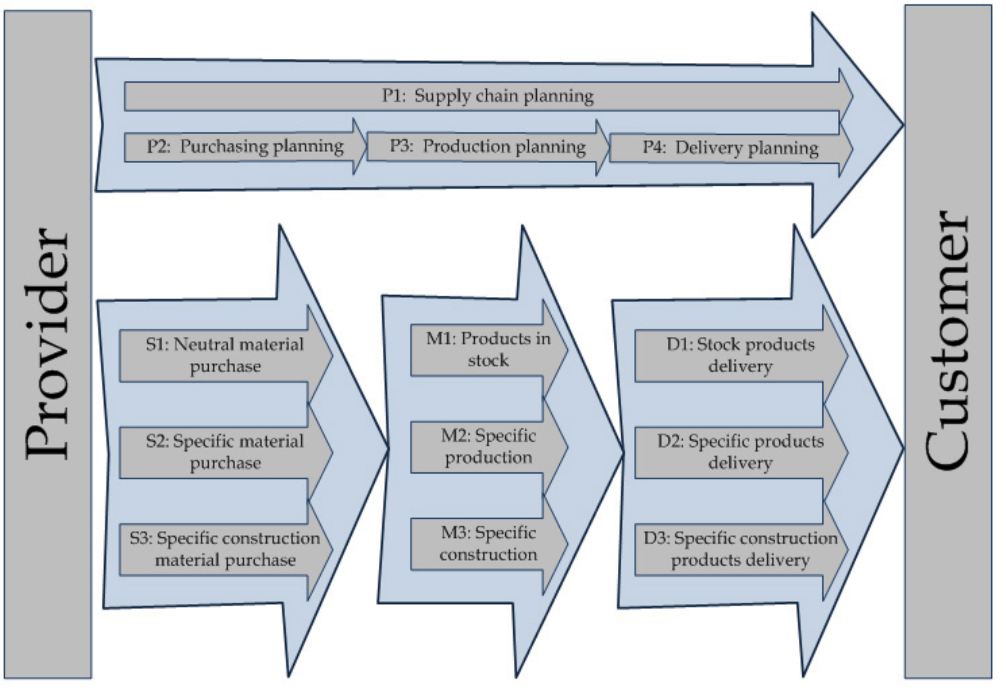


Fig. 10. SCOR process of the configuration layer (Meier et al, 2004)

During development of reference scenarios and transmission to SSC by SCOR model on configuration layer it was figured out that maintenance processes can be distinguished from the normal value chain process in the supply chain with help of a particular element. Normally supply chains have a horizontal hierarchical formation, which means that arrangement of companies in the lines of the supply chain is formed by providers (1tier, 2tier and so forth), the OEM and customers.
In these supply chains, flow of materials as well as flow of information partially runs statically (2tier to 1tier to OEM to customer). Considering the developed scenarios, it is obvious that in the fewest cases coordination of maintenance services in lines of SCC arrange itself in form of a hierarchical or static chain.
Maintenance services overtake traditional steps of the supply chain for some part. The provider probably delivers his spare parts directly to customers without considering the OEM in this process. The same condition can be depicted in reference to the maintenance staff.
These conditions are based on the following situations,

- Customer demands / pressure
- Subdivided core competences
- Availability of spare parts
- Geographic problems.
- Capacity bottlenecks

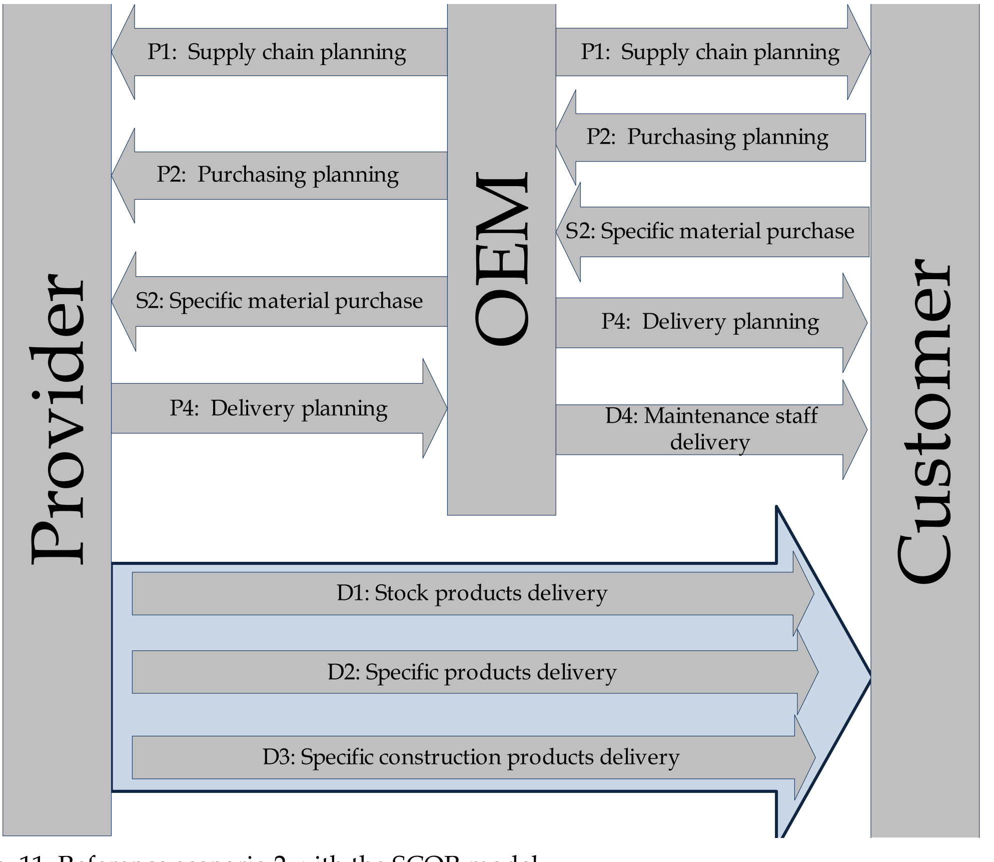


Fig. 11. Reference scenario 2 with the SCOR model

In order to ensure an accurate flow of information and, in this case, a flow of services, and make a detailed evaluation of problem zones in service provision, it is necessary to make some changes in SCOR model.
Fig. 11 shows maintenance service case B and C of the second reference scenario and depicts necessary changes in SCOR model. The OEM coordinates the service supply chain with help of the information and material flow (P1).
For the case that a spare parts purchase by the customer is needed, the OEM executes an order (P2, S2) toward the provider (1tier).
The provider plans the purchase with the OEM (P4) and delivers finally the demanded spare parts directly to the customer (D1-D3).
The OEM is overtaken within the service supply chain. Nevertheless the maintenance staff is posed by the OEM and coordinated to the customer (P4, D4) for the case of an assignment.

## 7. Support technology of cooperative service

To build cooperative service network, the embedded Web data acquisition system should be developed to acquire the running parameters of products. Special equipment control and IT-support system are developed to found technical base for cooperative service. The major works is to build the reference architeture of IT-support system for cooperative service and to develop cooperative industrial services which support different IT system. Industrial product oriented service contents and interface standard are extracted according to industrial features to form an intermediate unrelated to specific hardware. With this intermediate, product status monitoring, system parameters transmitting, software online upgrading and audio/video exchanging can be accomplished. A product (especially for machine tools) can conveniently switch-on cooperative service network as long as its controller meet the interface standard.

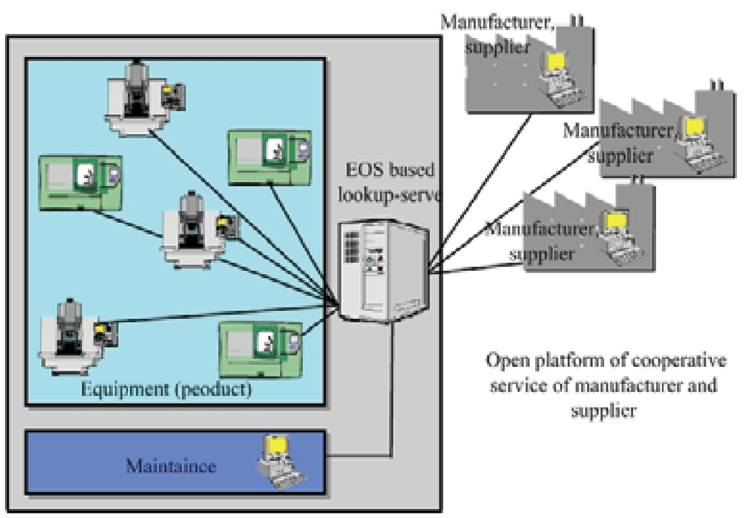


Fig. 12. Cooperative service pattern with EOS

An Embedded Online System (EOS) had been developed (Meier, 2004). Using this system, customer's machine tools can enter the cooperative service network and the service suppliers can finish some operations such as collecting running parameters, eliminating locale troubles, conducting AV conference and so forth. Cooperative service pattern under EOS is shown in Fig.12.

## 8. Discussion

The sequential value chain between supplier and customer was charted in respect of supply chain management. More likely it is imaginable that single steps of the supply chain are skipped and component supplier, which are more appropriate for special assignments and parts of the product-supporting service provision in contrast to the OEM, keeps contact with end customers. The flow of materials, which runs parallel to flow of information, could, even if it only partially affects the value chain, be relevant for all parties because there is to form a tie between all current information. Further on there are to coordinate delegations of staff, such as the delegation of technicians, for scheduled and not scheduled service assignments.
Regarding the different characteristics of the service and features of the global market with traditional service concepts, companies are unable to provide the machine based Life cycle service towards customers abroad with the traditional concept effectively and efficiently. This article describes a possible approach, designing a service structure of global distributed cooperative servicer based on supply chain. This will enhance the efficiencies of service provisions for enterprises, which are and intend to be active in global service business.

## 9. Acknowledgment

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## 10. References

ZHENG Jichang (2003). Product Service Increment and Contemporary Enterprise Competition Advantages. *Business Economics and Administration*, Vol.142, No.8, (August 2003), pp. 37-40, ISSN 1000-2154

McDonald, M. & Payne, A. (2006). *Marketing Plans for Service Business – A Complete Guide, 2nd Edition*, Elsevier Butterworth-Heinemann publications, ISBN 978-075-0667-46-3, Burlington, Canada

Meier, H. & Kortmann, D. (2007). *Dienstleistungsgestaltung innerhalb hybrider Leistungsbündel*, Shaker Verlag, ISBN 978-383-2266-22-6, Aachen, Germany

Meier, H. (2004). Service im globalen Umfeld – innovative Ansätze einer zukunftsorientierten Dienstleistungsgestaltung. In: *Dienstleistungsorientierte Geschäftsmodelle im Maschinen und Anlagenbau – vom Basisangebot bis zum Betreibermodell*. Springer-Verlag, ISBN 978-354-0408-16-1, Berlin, Germany

Meier, H., Kortmann, D. & Werding, A. (2004). Export Industrielle Dienstleistungen KMU-spezifische Anforderungen und Lösungsansätze. In :*ZWF-Zeitschrift für wirtschaftlichen Fabrikbetrieb*, pp. 707-710

Scholz-Reiter, B. & Ranft, L. (2000). Webbasierte Kooperation in Ersatzteilnetzwerken. In: *Effiziente Ersatzteil-Logistik*.VDI-Gesellschaft Fördertechnik, Materialfluss, Logistik, (October, 2000). Düsseldorf, Germany

Corsten, H. & Gössinger, R. (2001). *Einführung in das Supply Chain Management*. Oldenbourg Wissensch Verlag, ISBN 978-348-6258-19-6. Munich, Germany

Kaiser, A. & Schramm, J.J. (2004). Kooperationen innerhalb der Service-Chain. In: *Meier, H. (Hrsg.): Dienstleistungsorientierte Geschäftsmodelle im Maschinen- und Anlagenbau – Vom Basisangebot bis zum Betreibermodell.* Springer Verlag, ISBN 978-354-0408-16-1. Berlin, Germany

Meier, H. (2004). Embedded Online Service - Internetbasierte Dienstleistungsplattform für Produktionsbetriebe, VDMA Verlag, ISBN: 3-8163-0477-X. Frankfurt/Main, Germany

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# A Generalized Algebraic Model for Optimizing Inventory Decisions in a Centralized or Decentralized Three-Stage Multi-Firm Supply Chain with Complete Backorders for Some Retailers

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## 1. Introduction

Supply chain management has enabled numerous firms to enjoy great advantages by integrating all activities associated with the flow of material, information and capital between suppliers of raw materials and the ultimate customers. The benefits of a property managed supply chain include reduced costs, faster product delivery, greater efficiency, and lower costs for both the business and its customers. These competitive advantages are achieved through improved supply chain relationships and tightened links between chain partners such as suppliers, manufacturing facilities, distribution centers, wholesalers, and end users (Berger *et al.* 2004). Besides integrating all members in a supply chain, to improve the traditional method of solving inventory problems is also necessary. Without using derivatives, Grubbström (1995) first derived the optimal expressions for the classical economic order quantity (EOQ) model using the unity decomposition method, which is an algebraic approach. Adopting this method, Grubbström and Erdem (1999) and Cárdenas-Barrón (2001) respectively derived the optimal expressions for an EOQ and economic production quantity (EPQ) model with complete backorders. In this chapter, a generalized model for a three-stage multi-firm production-inventory integrated system is solved using the methods of complete squares and perfect squares adopted in Leung (2008a,b, 2009a,b, 2010a,b), which are also algebraic approaches; whereby optimal expressions of decision variables and the objective function are derived.
Assume that there is an uninterrupted production run. In the case of lot streaming in each of the upstream stages, shipments can be made from a production batch even before the whole batch is finished. However, some or all suppliers/manufacturers/assemblers cannot accommodate lot streaming because of regulations, material handling equipment, or production restrictions (Silver *et al.* 1998, p. 657). Without lot streaming, no shipments can be made from a production batch until the whole batch is finished. Sucky (2005) discussed the integrated single-vendor single-buyer system, with and without lot streaming, in detail.

In the inventory/production literature, all researchers have constructed their models under the assumption of either allowing lot streaming for all firms involving production (Khouia 2003) or not (Ben-Daya and Al-Nassar 2008), or both extremes (Sucky 2005, and Leung 2010a). The main purpose of the chapter is twofold: First, we build a generalized model incorporating a mixture of the two extremes and allowing compete backorders penalized by linear (i.e. time-dependent) shortage costs, and solve it algebraically. As a result, we can deduce and solve such special models as Khouja (2003), Cárdenas-Barrón (2007), Ben-Daya and Al-Nassar's (2008), Seliaman and Ahmad (2009), and Leung (2009a, 2010a,b). In addition, with appropriate assignments as in Section 5 of Leung (2010a), we can also deduce and solve other special models: Yang and Wee (2002), Wu and Ouyang (2003) or Wee and Chung (2007), and Chung and Wee (2007). Second, we derive expressions for sharing the coordination benefits based on Goyal's (1976) scheme, and introduce a further sharing scheme.
Some good review articles exist that provide an extensive overview of the topic under study and can be helpful as guidance through the literature. We mention surveys by Goyal and Gupta (1989), Goyal and Deshmukh (1992), Bhatnagar *et al.* (1993), Maloni and Benton (1997), Sarmah *et al.* (2006), and Ben-Daya *et al.* (2008). The well-known models of Goyal (1976), Banerjee (1986), Lu (1995), and Hill (1997) are extended by Ben-Daya, *et al.* (2008) as well. Other recently related articles include Chan and Kingsman (2007), Chiou *et al.* (2007), Cha *et al.* (2008), Leng and Parlat (2009 a,b), and Leng and Zhu (2009).

## 2. Assumptions, symbols and designations

The integrated production-inventory model is developed under the following assumptions:
1. A single item is considered.
2. There are two or more stages.
3. Production and demand rates (with the former greater than the latter) are independent of production or order quantity, and are constant.
4. Unit cost is independent of quantity purchased, and an order quantity will not vary from one cycle to another.
5. Neither a wait-in-process unit, nor a defective-in-transit unit, is considered.
6. Each upstream firm implements perfect inspection to guarantee that defective units are not delivered to any retailer. Three types of inspection suggested in Wee and Chung (2007) are executed .
7. Each type of inspection costs is different for all firms in each stage involving production.
8. Setup or ordering costs are different for all firms in the chain.
9. Holding costs of raw materials are different from those of finished products.
10. Holding costs of raw materials are different for all firms in the chain.
11. Holding costs of finished goods are different for all firms in the chain.
12. Lot streaming is allowed for some firms but no lot streaming is allowed for the rest in each stage involving production.
13. Shortages are allowed for some/all retailers and are completely backordered, and all backorders are made up at the beginning of the next order cycle.
14. All firms have complete information of each other.
15. The number of shipments of each supplier, manufacturer, assembler or retailer is a positive integer.
16. The planning horizon is infinite.

The following symbols (some as defined in Leung 2010b) are used in the expression of the joint total relevant cost per year.

$D_{ij}$ = demand rate of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n)$ [units per year]

$P_{ij}$ = production rate of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ [units per year]

$b_{nj} \equiv b_j$ = linear backordering cost of finished goods of firm $j\ (=1,\cdots,J_n)$ in stage $n$, where $0 < b_j \le \infty$ (Note that $b_j = 0$ means that no costs of operating an inventory system are incurred; this is not realistic and thus excluded, and $b_j = \infty$ means that the penalty of incurring a backorder is too large; this is pragmatic and thus included.) [$ per unit per year]

$g_{ij}$ = holding cost of incoming raw material of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ [$ per unit per year]

$h_{ij}$ = holding cost of finished goods of firm $j\ (=1,\cdots,J_i)$ in stage $i(=1,...n)$ [$ per unit per year]

$S_{ij}$ = setup or ordering cost of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n)$ [$ per cycle]

$A_{ij}$ = inspection cost per cycle of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ [$ per cycle]

$B_{ij}$ = inspection cost per delivery of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ [$ per delivery]

$C_{ij}$ = inspection cost per unit of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ [$ per unit]

For a centralized supply chain (or the integrated approach), we have

$t_{nj} \equiv t_j$ = backordering time of firm $j\ (=1,\cdots,J_n)$ in stage $n$; hereafter called retailer $j\ (=1,\cdots,J_n)$

($t_j$ are decision variables, each with *non-negative* real values) [a fraction of a year]

$T_{nj}^{(b)} = T_n$ = basic cycle time of retailer $j\ (=1,\cdots,J_n)$

($T_n$ is a decision variable with *non-negative* real values) [a fraction of a year]

$T_{ij} = T_n \prod_{k=i}^{n-1} K_k = T_n \prod_{k=i}^{n} K_k$ with $K_n \equiv 1$

= integer multiplier cycle time of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$

($K_1,\cdots,K_{n-1}$ are decision variables, each with *positive* integral values) [a fraction of a year]

$TC_{ij}$ = total relevant cost of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n)$ [$ per year]

$JTC(K_1,\cdots,K_{n-1},T_n,t_j) = \sum_{i=1}^{n}\sum_{j=1}^{J_i} TC_{ij}$ = joint total relevant cost as a function of $K_1,\cdots,K_{n-1}$, $T_n$ and $t_j$

(the objective function) [$ per year]

For a decentralized supply chain (or the independent approach), we have

$\mu_{nj} \equiv \mu_j$ = backordering time of retailer $j\ (=1,\cdots,J_n)$

($\mu_j$ are decision variables, each with *non-negative* real values) [a fraction of a year]

$\tau_{nj}^{(b)} \equiv \tau_n$ = basic cycle time of retailer $j\ (=1,\cdots,J_n)$

($\tau_n$ is a decision variable with *non-negative* real values) [a fraction of a year]

$\tau_{ij} = \tau_n \prod_{k=i}^{n-1} \lambda_k = \tau_n \prod_{k=i}^{n} \lambda_k$ with $\lambda_n \equiv 1$

= integer multiplier cycle time of firm $j$ $(=1,\cdots,J_i)$ in stage $i$ $(=n-1,\cdots,1)$

($\lambda_{n-1},\cdots,\lambda_1$ are decision variables, each with *positive* integral values) [a fraction of a year]

$TC(\tau_n,\mu_j)$ = total relevant cost of all retailers [$ per year]

$TC(\lambda_i)$ = total relevant cost of all firms in stage $i$ $(=n-1,\cdots,1)$ [$ per year]

To simplify the presentation of the subsequent mathematical expressions, we designate

$$\chi_{ij}=\begin{cases}0 & \text{without lot streaming}\\ 1 & \text{with lot streaming}\end{cases} \text{ and } \overline{\chi}_{ij}=1-\chi_{ij} \quad \text{for } i=1,\cdots,n-1;\ j=1,\cdots,J_i, \tag{1}$$

$$\varphi_{ij}=\frac{D_{ij}}{P_{ij}} \text{ and } \overline{\varphi}_{ij}=1-\varphi_{ij} \quad \text{for } i=1,\cdots,n-1;\ j=1,\cdots,J_i, \tag{2}$$

where the former represents the proportion of production that goes to meet demand and the latter reflects the proportion of production allocated to inventory,

$$G_0\equiv 0 \quad \text{and} \quad G_i=\sum_{j=1}^{J_i} D_{ij}h_{ij}[\chi_{ij}(\varphi_{ij}-\overline{\varphi}_{ij})-\overline{\chi}_{ij}] \quad \text{for } i=1,\cdots,n-1, \tag{3}$$

$$H_i=\sum_{j=1}^{J_i} D_{ij}[\varphi_{ij}g_{ij}+\chi_{ij}\overline{\varphi}_{ij}h_{ij}+\overline{\chi}_{ij}h_{ij}(1+\varphi_{ij})]+G_{i-1} \quad \text{for } i=1,\cdots,n-1, \tag{4}$$

$$H_n^{(b)}=\sum_{j=1}^{J_n}\frac{D_{nj}b_jh_{nj}}{b_j+h_{nj}}+G_{n-1}, \tag{5}$$

$$S_{iJ}=\sum_{j=1}^{J_i} S_{ij} \quad \text{for } i=1,\cdots,n, \tag{6}$$

$$A_{iJ}=\sum_{j=1}^{J_i} A_{ij} \quad \text{for } i=1,\cdots,n-1, \tag{7}$$

$$B_{iJ}=\sum_{j=1}^{J_i} B_{ij} \quad \text{for } i=1,\cdots,n-1, \tag{8}$$

$$C_{iJ}=\sum_{j=1}^{J_i} C_{ij}D_{ij} \quad \text{for } i=1,\cdots,n-1, \tag{9}$$

$$\alpha_1=S_{1J}+A_{1J}, \tag{10}$$

$$\alpha_i=S_{iJ}+A_{iJ}+B_{i-1,J} \quad \text{for } i=2,\cdots,n-1, \tag{11}$$

$$\alpha_n = S_{nJ} + B_{n-1,J}\,, \tag{12}$$

and

$$\beta_n = \sum_{i=1}^{n-1} C_{iJ}\ . \tag{13}$$

Assume that there is an uninterrupted production run. In the case of lot streaming in stage $i\ (=1,\cdots,n-1)$, shipments can be made from a production batch even before the whole batch is finished. According to Joglekar (1988, pp. 1397-8), the average inventory with lot streaming, for example, in stage 2 of a 3-stage supply chain, is $\frac{T_3 D_{2j}}{2}[\varphi_{2j} + (K_2 - 1)\overline{\varphi}_{2j}]$ units, which is the same as equation (7) of Ben-Daya and Al-Nassar (2008).
Without lot streaming, no shipments can be made from a production batch until the whole batch is finished. The opportunity of lot streaming affects supplier's average inventory. According to Goyal (1988, p. 237), the average inventory without lot streaming, for example, in stage 2 of a 3-stage supply chain, is $\frac{T_3 D_{2j}}{2}(\varphi_{2j}K_2 + K_2 - 1)$ units, which is the same as term 2 in equation (5) of Khouja (2003).
The total relevant cost per year of firm $j\ (=1,\cdots,J_i)$ in stage $i\ (=1,\cdots,n-1)$ is given by

$$\begin{aligned} TC_{ij} = {} & \frac{\prod_{k=i}^{n} K_k \cdot T_n D_{ij}^2}{2P_{ij}} \cdot (g_{ij} + \overline{\chi}_{ij} h_{ij}) + \frac{(\prod_{k=i}^{n} K_k - \prod_{k=i+1}^{n} K_k) T_n D_{ij}}{2} \cdot h_{ij}\overline{\chi}_{ij} \\ & + \frac{\prod_{k=i+1}^{n} K_k \cdot T_n D_{ij}^2}{2P_{ij}} \cdot \chi_{ij} h_{ij} + \frac{(\prod_{k=i}^{n} K_k - \prod_{k=i+1}^{n} K_k) T_n D_{ij} (1 - \frac{D_{ij}}{P_{ij}})}{2} \cdot h_{ij}\chi_{ij} \\ & + \frac{S_{ij}}{\prod_{k=i}^{n} K_k \cdot T_n} + \frac{A_{ij}}{\prod_{k=i}^{n} K_k \cdot T_n} + \frac{B_{ij}}{\prod_{k=i+1}^{n} K_k \cdot T_n} + C_{ij} D_{ij}\,, \end{aligned} \tag{14}$$

where without lot streaming, term 1 represents the sum of holding cost of raw material while they are being converted into finished goods and the cost of holding finished goods during the production process, and term 2 represents the holding cost of finished goods after production; but with lot streaming, term 1 represents the sum of holding cost of raw material while they are being converted into finished goods, and terms 3 and 4 represent the holding cost of finished goods during a production cycle; term 5 represents the setup cost, and the last three terms represent the sum of inspection costs.
Incorporating designation (2) in equation (14) yields

$$\begin{aligned} TC_{ij} = {} & \frac{D_{ij}[\varphi_{ij} g_{ij} + \chi_{ij}\overline{\varphi}_{ij} h_{ij} + \overline{\chi}_{ij} h_{ij}(1+\phi_{ij})] T_n \prod_{k=i}^{n} K_k}{2} + \frac{D_{ij} h_{ij}[\chi_{ij}(\varphi_{ij} - \overline{\varphi}_{ij}) - \overline{\chi}_{ij}] T_n \prod_{k=i+1}^{n} K_k}{2} \\ & + \frac{S_{ij} + A_{ij}}{T_n \prod_{k=i}^{n} K_k} + \frac{B_{ij}}{T_n \prod_{k=i+1}^{n} K_k} + C_{ij} D_{ij} \quad \text{for } i = 1,\cdots,n-1;\ j = 1,\cdots,J_i. \end{aligned} \tag{15}$$

The total relevant cost per year of retailer $j\ (=1,\cdots,J_n)$, each associated with complete backorders and each backorder penalized by a linear cost, is given by

$$TC_{nj} = \frac{D_{nj}h_{nj}(T_n - t_j)^2}{2T_n} + \frac{D_{nj}b_j t_j^2}{2T_n} + \frac{S_{nj}}{T_n} \text{ for } j = 1, \cdots, J_n, \tag{16}$$

where term 1 represents the holding cost of finished goods, term 2 represents the backordering cost of finished goods, and term 3 represents the ordering cost.
Expanding equation (16) and grouping like terms yield

$$TC_{nj} = \frac{D_{nj}(b_j + h_{nj})}{2T_n}\left[t_j^2 - \frac{2h_{nj}T_n t_j}{b_j + h_{nj}}\right] + \frac{D_{nj}h_{nj}T_n}{2} + \frac{S_{nj}}{T_n}.$$

Using the complete squares method (by taking half the coefficient of $v_j$) advocated in Leung (2008a,b, 2010a), we have

$$TC_{nj} = \frac{D_{nj}(b_j + h_{nj})}{2T_n}\left(t_j - \frac{h_{nj}T_n}{b_j + h_{nj}}\right)^2 - \frac{D_{nj}h_{nj}^2 T_n}{2(b_j + h_{nj})} + \frac{D_{nj}h_{nj}T_n}{2} + \frac{S_{nj}}{T_n}$$

$$= \frac{D_{nj}(b_j + h_{nj})}{2T_n}\left(t_j - \frac{h_{nj}T_n}{b_j + h_{nj}}\right)^2 + \frac{D_{nj}b_j h_{nj}T_n}{2(b_j + h_{nj})} + \frac{S_{nj}}{T_n}. \tag{17}$$

## 3. An algebraic solution to an integrated model of a three-stage multi-firm supply chain

Incorporating designations (3) to (9) with $n = 3$ in equations (15) and (17) yield the total relevant cost per year in stage $i$ $(=1, 2, 3)$ given by

$$\sum_{j=1}^{J_1} TC_{1j} = \frac{H_1K_1K_2T_3}{2} + \frac{G_1K_2T_3}{2} + \frac{S_{1J} + A_{1J}}{K_1K_2T_3} + \frac{B_{1J}}{K_2T_3} + C_{1J}, \tag{18}$$

$$\sum_{j=1}^{J_2} TC_{2j} = \frac{(H_2 - G_1)K_2T_3}{2} + \frac{G_2T_3}{2} + \frac{S_{2J} + A_{2J}}{K_2T_3} + \frac{B_{2J}}{T_3} + C_{2J}, \tag{19}$$

and

$$\sum_{j=1}^{J_3} TC_{3j} = \frac{1}{2T_3}\sum_{j=1}^{J_3} D_{3j}(b_j + h_{3j})\left(t_j - \frac{h_{3j}T_3}{b_j + h_{3j}}\right)^2 + \frac{T_3}{2}\sum_{j=1}^{J_3}\frac{D_{3j}b_j h_{3j}}{(b_j + h_{3j})} + \frac{S_{3J}}{T_3}$$

$$= \frac{(H_3^{(b)} - G_2)T_3}{2} + \frac{S_{3J}}{T_3} + \frac{1}{2T_3}\sum_{j=1}^{J_3} D_{3j}(b_j + h_{3j})\left(t_j - \frac{h_{3j}T_3}{b_j + h_{3j}}\right)^2. \tag{20}$$

The joint total relevant cost per year for the supply chain integrating multiple suppliers $(i = 1; j = 1, \cdots, J_1)$, multiple manufacturers $(i = 2; j = 1, \cdots, J_2)$ and multiple retailers $(i = 3; j = 1, \cdots, J_3)$ is given by

$$JTC(K_1,K_2,T_3,t_j) = \sum_{j=1}^{J_1} TC_{1j} + \sum_{j=1}^{J_2} TC_{2j} + \sum_{j=1}^{J_3} TC_{3j} \; . \tag{21}$$

Substituting equations (18) to (20) in (21) and incorporating designations (10) to (13) with $n = 3$ yield

$$\begin{aligned} JTC(K_1,K_2,T_3,t_j) = {} & \frac{1}{T_3}\left(\frac{\alpha_1}{K_1K_2} + \frac{\alpha_2}{K_2} + \alpha_3\right) + T_3\left(\frac{H_1K_1K_2 + H_2K_2 + H_3^{(b)}}{2}\right) \\ & + \frac{1}{2T_3}\sum_{j=1}^{J_3} D_{3j}(b_j + h_{3j})\left(t_j - \frac{h_{3j}T_3}{b_j + h_{3j}}\right)^2 + \beta_3. \end{aligned} \tag{22}$$

Adopting the perfect squares method advocated in Leung (2008a, p. 279) to terms 1 and 2 of equation (22), we have

$$\begin{aligned} JTC(K_1,K_2,T_3,t_j) = {} & \left[\sqrt{\frac{1}{T_3}\left(\frac{\alpha_1}{K_1K_2} + \frac{\alpha_2}{K_2} + \alpha_3\right)} - \sqrt{T_3\left(\frac{H_1K_1K_2 + H_2K_2 + H_3^{(b)}}{2}\right)}\right]^2 \\ & + \sqrt{2\left(\frac{\alpha_1}{K_1K_2} + \frac{\alpha_2}{K_2} + \alpha_3\right)(H_1K_1K_2 + H_2K_2 + H_3^{(b)})} \\ & + \frac{1}{2T_3}\sum_{j=1}^{J_3} D_{3j}(b_j + h_{3j})\left(t_j - \frac{h_{3j}T_3}{b_j + h_{3j}}\right)^2 + \beta_3. \end{aligned} \tag{23}$$

For two fixed positive integral values of the decision variables $K_1$ and $K_2$, equation (23) has a unique minimum value when the two quadratic non-negative terms, depending on $T_3$ and $t_j$, are made equal to zero. Therefore, the optimal value of the decision variables and the resulting minimum cost are denoted and determined by

$$T^\circ(K_1,K_2) = \sqrt{2\left(\frac{\alpha_1}{K_1K_2} + \frac{\alpha_2}{K_2} + \alpha_3\right)\left(\frac{1}{H_1K_1K_2 + H_2K_2 + H_3^{(b)}}\right)} \, , \tag{24}$$

$$t_j^\circ(K_1,K_2) = \frac{h_{3j}T^\circ(K_1,K_2)}{b_j + h_{3j}} \quad \text{for } j = 1,\cdots,J_3 \, , \tag{25}$$

and

$$JTC^\circ(K_1,K_2) \equiv JTC[K_1,K_2,T^\circ(K_1,K_2),t_j^\circ(K_1,K_2)]$$

$$= \sqrt{2\left(\frac{\alpha_1}{K_1K_2} + \frac{\alpha_2}{K_2} + \alpha_3\right)(H_1K_1K_2 + H_2K_2 + H_3^{(b)})} + \beta_3 \, . \tag{26}$$

Multiplying out the two factors inside the square root in equation (26) yields

$$JTC^{\circ}(K_1,K_2)=\sqrt{2}\cdot\sqrt{\tfrac{\alpha_1 H_2}{K_1}+\alpha_2 H_1 K_1+\tfrac{\alpha_2 H_3^{(b)}}{K_2}+\alpha_3 H_2 K_2+\tfrac{\alpha_1 H_3^{(b)}}{K_1 K_2}+\alpha_3 H_1 K_1 K_2+\alpha_1 H_1+\alpha_2 H_2+\alpha_3 H_3^{(b)}}+\beta_3 .$$

Clearly, to minimize $JTC^{\circ}(K_1,K_2)$ is equivalent to minimize

$$\zeta(K_1,K_2)=\tfrac{\alpha_1 H_2}{K_1}+\alpha_2 H_1 K_1+\tfrac{\alpha_2 H_3^{(b)}}{K_2}+\alpha_3 H_2 K_2+\tfrac{\alpha_1 H_3^{(b)}}{K_1 K_2}+\alpha_3 H_1 K_1 K_2 . \tag{27}$$

We observe from equation (27) that there are two options to determine the optimal integral values of $K_1$ and $K_2$ as shown below.
Option (1): Equation (27) can be written as

$$\zeta^{(1)}(K_1,K_2)=\tfrac{\alpha_1 H_2}{K_1}+\alpha_2 H_1 K_1+\frac{H_3^{(b)}(\frac{\alpha_1}{K_1}+\alpha_2)}{K_2}+\alpha_3(H_1 K_1+H_2)K_2 .$$

To minimize $\zeta^{(1)}(K_1,K_2)$ is equivalent to separately minimize

$$\phi_2^{(1)}(K_1,K_2)\equiv\frac{H_3^{(b)}(\frac{\alpha_1}{K_1}+\alpha_2)}{K_2}+\alpha_3(H_1 K_1+H_2)K_2 , \tag{28}$$

and

$$\phi_1^{(1)}(K_1)\equiv\tfrac{\alpha_1 H_2}{K_1}+\alpha_2 H_1 K_1 . \tag{29}$$

The validity of the equivalence is based on the following two-step minimization procedure.
Step (1): Because $\zeta^{(1)}(K_1,K_2)=\phi_1^{(1)}(K_1)+\phi_2^{(1)}(K_1,K_2)$, it is partially minimized by minimizing $\phi_1^{(1)}(K_1)$. As a result, the optimal integral value of $K_1$, denoted by $K_1^{(1)*}$ and given by expression (32) is obtained.
Step (2): Because $K_1^{(1)*}$ is fixed, to minimize $\zeta^{(1)}(K_1^{(1)*},K_2)$ is equivalent to minimize $\phi_2^{(1)}(K_1^{(1)*},K_2)$. As a result, a local optimal integral value of $K_2$, denoted by $K_2^{(1)*}$ and given by expression (33), and a local minimum, namely $\zeta^{(1)}(K_1^{(1)*},K_2^{(1)*})$ are obtained.
Hence, the joint total relevant cost per year can be minimized by first choosing $K_1=K_1^{(1)*}$ and next $K_2=K_2^{(1)*}\equiv K_2(K_1^{(1)*})$ such that

$$\phi_1^{(1)}(K_1)<\phi_1^{(1)}(K_1-1) \quad\text{and}\quad \phi_1^{(1)}(K_1)\le\phi_1^{(1)}(K_1+1) , \tag{30}$$

and

$$\phi_2^{(1)}(K_1^{(1)*},K_2)<\phi_2^{(1)}(K_1^{(1)*},K_2-1) \quad\text{and}\quad \phi_2^{(1)}(K_1^{(1)*},K_2)\le\phi_2^{(1)}(K_1^{(1)*},K_2+1) . \tag{31}$$

Two closed-form expressions, derived in the Appendix, for determining the optimal integral values of $K_1$ and $K_2$ are denoted and given by

$$K_1^{(1)*}=\left\lfloor\sqrt{\frac{\alpha_1 H_2}{\alpha_2 H_1}+0.25}+0.5\right\rfloor , \tag{32}$$

and

$$K_2^{(1)*} = \left\lfloor \sqrt{\frac{H_3^{(b)}(\frac{\alpha_1}{K_1^{(1)*}} + \alpha_2)}{\alpha_3(H_1 K_1^{(1)*} + H_2)} + 0.25} + 0.5 \right\rfloor , \quad (33)$$

where $\lfloor x \rfloor$ is the largest integer $\leq x$.

Option (2): Equation (27) can also be written as

$$\zeta^{(2)}(K_1, K_2) = \frac{\alpha_2 H_3^{(b)}}{K_2} + \alpha_3 H_2 K_2 + \frac{\alpha_1 (H_2 + \frac{H_3^{(b)}}{K_2})}{K_1} + H_1(\alpha_2 + \alpha_3 K_2) K_1 .$$

To minimize $\zeta^{(2)}(K_1, K_2)$ is equivalent to separately minimize

$$\phi_2^{(2)}(K_1, K_2) \equiv \frac{\alpha_1 (H_2 + \frac{H_3^{(b)}}{K_2})}{K_1} + H_1(\alpha_2 + \alpha_3 K_2) K_1 ,$$

and

$$\phi_1^{(2)}(K_2) \equiv \frac{\alpha_2 H_3^{(b)}}{K_2} + \alpha_3 H_2 K_2 .$$

Similarly, the joint total relevant cost per year can be minimized by first choosing $K_2 = K_2^{(2)*}$ and next $K_1 = K_1^{(2)*} \equiv K_1(K_2^{(2)*})$ determined by

$$K_2^{(2)*} = \left\lfloor \sqrt{\frac{\alpha_2 H_3^{(b)}}{\alpha_3 H_2} + 0.25} + 0.5 \right\rfloor , \quad (34)$$

and

$$K_1^{(2)*} = \left\lfloor \sqrt{\frac{\alpha_1 (H_2 + \frac{H_3^{(b)}}{K_2^{(2)*}})}{H_1(\alpha_2 + \alpha_3 K_2^{(2)*})} + 0.25} + 0.5 \right\rfloor . \quad (35)$$

Both options must be evaluated for a problem (see the numerical example in Section 6). However, Option (1), evaluating in the order of $K_1$ and $K_2$, might dominate Option (2), evaluating in the order of $K_2$ and $K_1$, when the holding costs decrease from upstream to downstream firms. A formal analysis is required to confirm this conjecture.

### 3.1 Deduction of Leung's (2010a) model without inspection

Suppose that for $i = 1, 2$ and all $j$; $\chi_{ij} = 1$ and $A_{ij} = B_{ij} = C_{ij} = 0$. Then we obtain the results shown in Subsection 3.1 of Leung (2010a).

Suppose that for $i = 1, 2$ and all $j$; $\chi_{ij} = 0$ and $A_{ij} = B_{ij} = C_{ij} = 0$. Then we obtain the results shown in Subsection 3.2 of Leung (2010a).

### 3.2 Deduction of Leung's (2010b) model without shortages

Suppose that for all *j*, $b_j = \infty$. Then $H_3^{(b)}$ becomes $H_3 \equiv \sum_{j=1}^{J_3} D_{3j} h_{3j} + G_2$. Then, we obtain the results shown in Section 3 of Leung (2010b).

## 4. The global minimum solution

It is apparent from the term in equation (26), namely $H_3^{(b)} = \sum_{j=1}^{J_3} \frac{D_{3j} b_j h_{3j}}{b_j + h_{3j}} - G_2$ that it will be optimal to incur some backorders towards the end of an order cycle if neither $h_{3j} = \infty$ nor $b_j = \infty$ occurs.

This brief checking is also valid for any *n*-stage $(n = 2,\ 3, \cdots)$ single/multi-firm supply chain with/without lot streaming and with complete backorders. However, when both a linear and fixed backorder costs are considered, the checking of global minimum is not so obvious, see Sphicas (2006).

## 5. Expressions for sharing the coordination benefits

Recall that the basic cycle time and the associated integer multipliers in a decentralized supply chain are denoted by $\tau_n$ and $\lambda_{n-1}, \cdots, \lambda_2, \lambda_1$ together with $\lambda_n \equiv 1$, respectively. Then equation (20) can be written as

$$TC(\tau_3, \mu_j) = \frac{(H_3^{(b)} - G_2)\tau_3}{2} + \frac{S_{3J}}{\tau_3} + \frac{1}{2\tau_3} \sum_{j=1}^{J_3} D_{3j}(b_j + h_{3j}) \left( \mu_j - \frac{h_{3j}\tau_3}{b_j + h_{3j}} \right)^2, \tag{36}$$

which, on applying the perfect squares method to the first two terms, yields the economic order interval and backordering intervals for each retailer in stage 3 given by

$$\tau_3^* = \sqrt{\frac{2S_{3J}}{H_3^{(b)} - G_2}}, \tag{37}$$

$$\mu_j^* = \frac{h_{3j}\tau_3^*}{b_j + h_{3j}}, \tag{38}$$

and the resulting minimum total relevant cost per year given by

$$TC_3^* \equiv TC(\tau_3^*, \mu_j^*) = \sqrt{2S_{3J}(H_3^{(b)} - G_2)}. \tag{39}$$

Assume that the demand for the item with which each distributor in stage 2 is faced is a stream of $\tau_3^* D_{3j}$ units of demand at fixed intervals of $\tau_3^*$ year. Given these streams of demand, Rosenblatt and Lee (1985, p. 389) showed that each distributor's economic production interval should be some integer multiple of $\tau_3^*$. As a result, equation (19) can be written as

$$TC(\lambda_2) = \lambda_2 \left[ \frac{(H_2 - G_1)\tau_3^*}{2} \right] + \frac{1}{\lambda_2} \left( \frac{S_{2J} + A_{2J}}{\tau_3^*} \right) + \frac{G_2 \tau_3^*}{2} + \frac{B_{2J}}{\tau_3^*} + C_{2J} . \quad (40)$$

Hence, the total relevant cost in stage 2 per year can be minimized by choosing $\lambda_2 = \lambda_2^*$ such that

$$TC(\lambda_2) < TC(\lambda_2 - 1) \quad \text{and} \quad TC(\lambda_2) \le TC(\lambda_2 + 1) ,$$

which, on following the derivation given in the Appendix, yields a closed-form expression for determining the optimal integral value of $\lambda_2$ given by

$$\lambda_2^* = \left\lfloor \sqrt{\frac{2(S_{2J} + A_{2J})}{(H_2 - G_1)(\tau_3^*)^2} + 0.25} + 0.5 \right\rfloor . \quad (41)$$

Similarly, equation (18) can be written as

$$TC(\lambda_1) = \lambda_1 \left( \frac{H_1 \lambda_2^* \tau_3^*}{2} \right) + \frac{1}{\lambda_1} \left( \frac{S_{1J} + A_{1J}}{\lambda_2^* \tau_3^*} \right) + \frac{G_1 \lambda_2^* \tau_3^*}{2} + \frac{B_{1J}}{\lambda_2^* \tau_3^*} + C_{1J} , \quad (42)$$

which can be minimized by choosing $\lambda_1 = \lambda_1^*$ given by

$$\lambda_1^* = \left\lfloor \sqrt{\frac{2(S_{1J} + A_{1J})}{H_1 (\lambda_2^* \tau_3^*)^2} + 0.25} + 0.5 \right\rfloor . \quad (43)$$

We readily deduce from equations (36) to (43) the expressions for $n \; (= 2, 3, 4, \cdots)$ stages given by

$$\tau_n^* = \sqrt{\frac{2S_{nJ}}{H_n^{(b)} - G_{n-1}}} , \quad (44)$$

$$\mu_j^* = \frac{h_{nj} \tau_n^*}{b_j + h_{nj}} , \quad (45)$$

$$\lambda_n^* \equiv 1 \quad \text{and} \quad \lambda_i^* = \left\lfloor \sqrt{\frac{2(S_{iJ} + A_{iJ})}{(H_i - G_{i-1}) \left( \tau_n^* \prod_{k=i+1}^{n} \lambda_k^* \right)^2} + 0.25} + 0.5 \right\rfloor \quad \text{for } i = n-1, \cdots, 1 , \quad (46)$$

$$TC_n^* \equiv TC(\tau_n^*, \mu_j^*) = \sqrt{2S_{nJ} (H_n^{(b)} - G_{n-1})} , \quad (47)$$

and

$$TC_i^* \equiv TC(\lambda_i^*) = \frac{(H_i - G_{i-1})\tau_n^* \prod_{k=i}^n \lambda_k^*}{2} + \frac{G_i \tau_n^* \prod_{k=i+1}^n \lambda_k^*}{2} + \frac{S_{iJ} + A_{iJ}}{\tau_n^* \prod_{k=i}^n \lambda_k^*} + \frac{B_{iJ}}{\tau_n^* \prod_{k=i+1}^n \lambda_k^*} + C_{iJ} \quad \text{for } i = n-1, \cdots, 1 . \quad (48)$$

The judicious scheme for allocating the coordination benefits, originated from Goyal (1976), is explicitly expressed as follows:

$$\text{Share}_i = \text{Total saving} \times \frac{TC_i^*}{\sum_{i=1}^n TC_i^*} = (\sum_{i=1}^n TC_i^* - JTC_n^*) \times \frac{TC_i^*}{\sum_{i=1}^n TC_i^*}, \quad (49)$$

where $JTC_n^* \equiv JTC^\circ(K_1^*, K_2^*, \cdots, K_{n-1}^*)$. Hence, the total relevant cost, after sharing the benefits, in stage $i$ per year is denoted and given by

$$TC_i^\circ = TC_i^* - \text{Share}_i = JTC_n^* \times \frac{TC_i^*}{\sum_{i=1}^n TC_i^*} . \quad (50)$$

In addition, the percentages of cost reduction in each stage and the entire supply chain are the same because $\frac{TC_i^* - TC_i^\circ}{TC_i^*} = \frac{\text{Share}_i}{TC_i^*} = \frac{\text{Total saving}}{\sum_{i=1}^n TC_i^*}$, and total saving and $\sum_{i=1}^n TC_i^*$ are constants.

More benefits have to be allocated to retailers so as to convince them of their coordination when $TC_n^\circ > TC_n^{**}$, where $TC_n^{**} \equiv \sum_{j=1}^{J_n} \sqrt{2S_{nj}D_{nj}h_{nj}(\frac{b_j}{b_j + h_j})}$ = the minimum total relevant cost of all retailers based on the EOQ model with complete backorders penalized by a linear shortage cost (see, e.g. Moore *et al.* 1993, pp. 338-344). Even if $TC_n^\circ \le TC_n^{**}$, additional benefits should be allocated to the retailers to enhance their interests in coordination. The reason is that if the retailers insist on employing their respective EOQ cycle times, then clearly the corresponding total relevant cost of all firms in stage $i\ (= 1, \cdots, n-1)$ denoted by $TC_i^+$ is higher than $TC_i^*$ which in turn is higher than $TC_i^\circ$, i.e. $TC_i^+ \ge TC_i^* \ge TC_i^\circ\ (i = 1, \cdots, n-1)$. As a result, the retailers are crucial to realize the coordination.

Because we consider a non-serial supply chain (where each stage has more than one firm, but a serial supply chain has only one firm), not necessarily tree-like, a reasonable scheme is explicitly proposed as follows:

$$\text{Adjusted Share}_i = \begin{cases} [\text{Share}_i - \chi(TC_n^\circ - TC_n^{**})(\frac{J_i}{\sum_{i=1}^{n-1} J_i})](1 - \frac{J_i}{\sum_{i=1}^{n-1} J_i}) & \text{for } i = 1, \cdots, n-1, \\ \text{Share}_n + \sum_{i=1}^{n-1} \chi(TC_n^\circ - TC_n^{**})(\frac{J_i}{\sum_{i=1}^{n-1} J_i}) + \sum_{i=1}^{n-1} [\text{Share}_i - \chi(TC_n^\circ - TC_n^{**})(\frac{J_i}{\sum_{i=1}^{n-1} J_i})](\frac{J_i}{\sum_{i=1}^{n-1} J_i}) & \text{for } i = n, \end{cases} \quad (51)$$

where $\chi = \begin{cases} 0 & \text{if } TC_n^\circ \le TC_n^{**}, \\ 1 & \text{if } TC_n^\circ > TC_n^{**}. \end{cases}$ Obviously, if $(TC_n^\circ - TC_n^{**}) > \sum_{i=1}^{n-1} \text{Share}_i$, then no coordination exists.

The rationale behind equation (51) is that we compensate, if applicable, the retailers for the increased cost of $(TC_n^\circ - TC_n^{**} > 0)$, and share additional coordination benefits to them, in proportion to the number of firms in each of the upstream stages. In addition, equation (51) is simplified to

$$\text{Adjusted Share}_i = \begin{cases} \text{Share}_i(1-\frac{J_i}{\sum_{i=1}^{n-1} J_i}) - \chi(TC_n^{\circ} - TC_n^{**})(\frac{J_i}{\sum_{i=1}^{n-1} J_i})(1-\frac{J_i}{\sum_{i=1}^{n-1} J_i}) & \text{for } i = 1,\cdots,n-1, \\ \text{Share}_n + \sum_{i=1}^{n-1} \text{Share}_i(\frac{J_i}{\sum_{i=1}^{n-1} J_i}) + \sum_{i=1}^{n-1} \chi(TC_n^{\circ} - TC_n^{**})(\frac{J_i}{\sum_{i=1}^{n-1} J_i})(1-\frac{J_i}{\sum_{i=1}^{n-1} J_i}) & \text{for } i = n. \end{cases} \quad (52)$$

Hence, the total relevant costs, after adjusting the shares of the benefits, in stage $i$ per year are denoted and given by

$$TC_i^{\circ\circ} = TC_i^* - \text{ Adjusted Share}_i \quad \text{for } i = 1,\cdots,n, \quad (53)$$

and the adjusted percentages of cost reduction are given by $\frac{TC_i^* - TC_i^{\circ\circ}}{TC_i^*}$ $(i = 1,\cdots,n)$ or $\frac{TC_n^{**} - TC_n^{\circ\circ}}{TC_n^{**}}$ if $\chi = 1$.

## 6. A numerical example

(A 3-stage multi-firm centralized/decentralized supply chain, with/without lot streaming, with/without linear backorder costs, and with inspections)
Suppose that an item has almost the same characteristics as those on page 905 of Leung (2010b) as follows:

Two suppliers $(i = 1; j = 1, 2)$:

$\chi_{11} = 0$, $D_{11} = 100{,}000$ units per year, $P_{11} = 300{,}000$ units per year, $g_{11} = \$0.08$ per unit per year, $h_{11} = \$0.8$ per unit per year, $S_{11} = \$600$ per setup, $A_{11} = \$30$ per setup, $B_{11} = \$3$ per delivery, $C_{11} = \$0.0005$ per unit, $\chi_{12} = 1$, $D_{12}$ = 80,000, $P_{12}$ = 160,000, $g_{12}$ = 0.09, $h_{12}$ = 0.75, $S_{12}$ = 550, $A_{12} = 50$, $B_{12} = 4$, $C_{12} = 0.0007$.

Four manufacturers $(i = 2; j = 1,\cdots,4)$:

$\chi_{21} = 1$, $D_{21} = 70{,}000$, $P_{21} = 140{,}000$, $g_{21} = 0.83$, $h_{21} = 2$, $S_{21} = 300$, $A_{21} = 50$, $B_{21} = 8$, $C_{21} = 0.001$;
$\chi_{22} = 0$, $D_{22} = 50{,}000$, $P_{22} = 150{,}000$, $g_{22} = 0.81$, $h_{22} = 2.1$, $S_{22} = 310$, $A_{22} = 45$, $B_{22} = 7$, $C_{22} = 0.0009$;
$\chi_{23} = 0$, $D_{23} = 40{,}000$, $P_{23} = 160{,}000$, $g_{23} = 0.79$, $h_{23} = 1.8$, $S_{23} = 305$, $A_{23} = 48$, $B_{23} = 7.5$, $C_{23} = 0.0012$;
$\chi_{24} = 1$, $D_{24} = 20{,}000$, $P_{24} = 100{,}000$, $g_{24} = 0.85$, $h_{24} = 2.2$, $S_{24} = 285$, $A_{24} = 60$, $B_{24} = 9.5$, $C_{24} = 0.0015$.

Six retailers $(i = 3; j = 1,\cdots,6)$:

$D_{31} = 40{,}000$, $b_1 = \$3.5$ per unit per year, $h_{31} = 5$, $S_{31} = \$50$ per order; $D_{32} = 30{,}000$, $b_2 = 5.3$, $h_{32} = 5.1$, $S_{32} = 48$;

$D_{33} = 20{,}000$ , $b_3 = 4.8$ , $h_{33} = 4.8$ , $S_{33} = 51$ ; $D_{34} = 35{,}000$ , $b_4 = 5.3$ , $h_{34} = 4.9$ , $S_{34} = 52$ ; $D_{35} = 45{,}000$ , $b_5 = 5.2$ , $h_{35} = \infty$ , $S_{35} = 50$ ; $D_{36} = 10{,}000$ , $b_6 = \infty$ , $h_{36} = 5$ , $S_{36} = 49$ .

Table 1 shows the optimal results of the integrated approach, obtained using designations (2) to (13), and equations (18) to (20), (24) to (26) and (32) to (35). Detailed calculations to reach Table 1 are given in the Appendix. Thus, each of the two suppliers fixes a setup every 41.67 days, each of the four manufacturers fixes a setup every 41.67 days and each of the six retailers places an order every 13.89 days, coupled with the respective backordering times: 8.17, 6.81, 6.95, 6.67, 13.89 and 0 days.

Note that the yearly cost saving, compared with no shortages, is 8.20% $(= \frac{69{,}719.47 - 63{,}999.43}{69{,}719.47})$, where the figure \$69,719.47 is obtained from the last column of Table 1 in Leung (2010b). The comparison is feasible because the assignments of $b_5 = 5.2$ and $h_{35} = \infty$ (causing all negative inventory) has the same cost effect as $b_5 = \infty$ and $h_{35} = 5.2$ (all positive inventory) on retailer 5.

| Stage | Integer multiplier | Cycle time (year) | Cycle time (days) | Yearly cost (\$) |
|---|---|---|---|---|
| Suppliers | 1 | 0.11415 | 41.67 | 13,337.04 |
| Manufacturers | 3 | 0.11415 | 41.67 | 31,716.19 |
| Retailers | – | 0.03805 | 13.89 | 18,946.20 |
| Entire supply chain | – | – | – | 63,999.43 |

Table 1. Results for the centralized model

When the ordering decision is governed by the adjacent downstream stage, Table 2 shows the optimal results of the independent approach, obtained using equations (44), (46) to (48) with $n = 3$ . Table 3 shows the results after sharing the coordination benefits, obtained using equations (49) and (50). Detailed calculations to reach Tables 2 and 3 are also given in the Appendix.

| Stage | Integer multiplier | Cycle time (year) | Cycle time (days) | $TC_i^*$ (\$ per year) |
|---|---|---|---|---|
| Suppliers | 1 | 0.09636 | 35.16 | 14,955.80 |
| Manufacturers | 3 | 0.09636 | 35.16 | 31,283.07 |
| Retailers | – | 0.03212 | 11.72 | 18,677.85 |
| Entire supply chain | – | – | – | 64,916.72 |

Table 2. Results for the decentralized model

| Stage | Yearly saving (\$) or penalty (–\$) | Share (\$ per year) | $TC_i^{\circ}$ (\$ per year) | Yearly cost reduction (%) |
|---|---|---|---|---|
| Suppliers | 1618.76 | 211.33 | 14,744.47 | 1.41 |
| Manufacturers | –433.12 | 442.04 | 30,841.03 | 1.41 |
| Retailers | −268.35 | 263.92 | 18,413.93 | 1.41 |
| Entire supply chain | 917.29 | 917.29 | 63,999.43 | 1.41 |

Table 3. Results after sharing the coordination benefits

Table 3 shows that the centralized replenishment policy increases the costs of the four manufacturers and six retailers, while decreases the cost of the two suppliers. According to Goyal's (1976) saving-sharing scheme, the increased costs of the manufacturers and retailers must be covered so as to motivate them to adopt the centralized replenishment policy, and the total yearly saving of \$917.29 is shared to assure equal yearly cost reduction of 1.41% through all three stages or the entire chain.

Because $18,413.93 = TC_3^{\circ} > TC_3^{**} = 17,913.57$, we have $\chi = 1$. Table 4 shows the adjusted results, obtained using equations (52) and (53), and indicates that the retailers' yearly cost reduction increases from 1.41% to 4.56% (which is rather significant), and the suppliers' and manufacturers' yearly cost reductions are *at least* ($\frac{TC_i^{+} - TC_i^{\circ\circ}}{TC_i^{+}} \geq \frac{TC_i^{*} - TC_i^{\circ\circ}}{TC_i^{*}}$ because $TC_i^{+} \geq TC_i^{*} \geq TC_i^{\circ}$, $i = 1,\ 2$) 0.20% and 0.12%, respectively. However, if the retailers regard 0.49% as the relevant comparison figure and as insignificant, all the coordination benefit may be allocated to them, and hence this figure becomes 0.85% $(= \frac{17,913.57 - 17,826.42 + 29.70 + 36.16}{17,913.57})$. If they consider 0.85% insignificant, negotiation between all the upstream stages and the retailers is the last resort.

| **Stage** | **Adjusted share (\$ per year)** | $TC_i^{\circ\circ}$ **(\$ per year)** | **Adjusted yearly cost reduction (%)** |
|---|---|---|---|
| Suppliers | 29.70 | 14,926.10 | 0.20 |
| Manufacturers | 36.16 | 31,246.91 | 0.12 |
| Retailers | 851.43 | 17,826.42 | 4.56 (or 0.49) |
| Entire supply chain | 917.29 | 63,999.43 | 1.41 |

Table 4. Results after adjusting the shares of the coordination benefits

The final remark for this example is that we need not assume that, for instance, supplier 1 supplies manufacturers 1 and 2, and supplier 2 supplies manufacturers 3 and 4. The mild condition for a non-serial supply chain is to satisfy the equality: $\sum_{j=1}^{J_1} D_{1j} = \sum_{j=1}^{J_2} D_{2j} = \sum_{j=1}^{J_3} D_{3j}$.

## 7. Conclusions and future research

The main contribution of the chapter to the literature is threefold: First, we establish the $n$-stage $(n = 2,\ 3,\ 4, \cdots)$ model, which is more pragmatic than that of Leung (2010b), by including Assumption (13). Secondly, we derive expressions for sharing the coordination benefits based on Goyal's (1976) scheme, and on a further sharing scheme. Thirdly, we deduce and solve such special models as Leung (2009a, 2010a,b).

The limitation of our model manifest in the numerical example is that the number of suppliers in Stage 1 is arbitrarily assigned. Concerning the issue of "How many suppliers are best?", we can refer to Berger *et al.* (2004), and Ruiz-Torres and Mahmoodi (2006, 2007) to decide the optimal number of suppliers at the very beginning.

Three ready extensions of our model that warrant future research endeavors in this field are: First, following the evolution of three-stage multi-firm supply chains shown in Section 3, we can readily formulate and algebraically analyze the integrated model of a four- or higher-stage multi-firm supply chain. In addition, a remark relating to determining optimal integral values of $K$'s is as follows: To be more specific, letting $n = 4$, we have *at most* 6 (= 3×2×1) options to determine the optimal values of $K_1$, $K_2$ and $K_3$ (see Leung 2009a, 2010a,b). However, Option (1), evaluating in the order of $K_1$, $K_2$ and $K_3$, might dominate other options when the holding costs decrease from upstream to downstream firms. Although this conjecture is confirmed by the numerical example in this chapter and those in Leung (2010a,b), a formal analysis is still necessary.

Secondly, using complete and perfect squares, we can solve the integrated model of a $n$-stage multi-firm supply chain either for an equal-cycle-time, or an integer multiplier at each stage, with not only a linear (see Leung 2010a) but also a fixed shortage cost for either the complete, or a fixed ratio partial backordering allowed for some/all downstream firms (i.e. retailers), and with lot streaming allowed for some/all upstream firms (i.e. suppliers, manufacturers and assemblers).

Thirdly, severity of green issues gives rise to consider integrated deteriorating production-inventory models incorporating the factor of environmental consciousness such as Yu *at al.* (2008), Chung and Wee (2008), and Wee and Chung (2009). Rework, a means to reduce waste disposal, is examined in Chiu *et al.* (2006) or Leung (2009b) who derived the optimal expressions for an EPQ model with complete backorders, a random proportion of defectives, and an immediate imperfect rework process while Cárdenas-Barrón (2008) derived those for an EPQ model with no shortages, a fixed proportion of defectives, and an immediate or a $N$-cycle perfect rework process. Reuse, another means to reduce waste disposal, is investigated in El Saadany and Jaber (2008), and Jaber and Rosen (2008). Incorporating rework or reuse in our model will be a challenging piece of future research.

***Appendix***

***A1. Derivation of equations (32) and (33)***

Substituting equation (29) in the two conditions of (30) yields the following inequality

$$K_1(K_1 - 1) < \tfrac{\alpha_1 H_2}{\alpha_2 H_1} < K_1(K_1 + 1) .$$

We can derive a closed-form expression concerning the optimal integer $K_1^{(1)*}$ as follows:

$$K_1(K_1 - 1) + 0.25 < \tfrac{\alpha_1 H_2}{\alpha_2 H_1} + 0.25 < K_1(K_1 + 1) + 0.25$$

$$\Leftrightarrow (K_1 - 0.5)^2 < \tfrac{\alpha_1 H_2}{\alpha_2 H_1} + 0.25 < (K_1 + 0.5)^2$$

$$\Leftrightarrow K_1 - 0.5 < \sqrt{\tfrac{\alpha_1 H_2}{\alpha_2 H_1} + 0.25} < K_1 + 0.5$$

$$\Leftrightarrow \sqrt{\tfrac{\alpha_1 H_2}{\alpha_2 H_1} + 0.25} - 0.5 \le K_1 < \sqrt{\tfrac{\alpha_1 H_2}{\alpha_2 H_1} + 0.25} + 0.5 .$$

From the last inequality, we can deduce that the optimal integer $K_1^{(1)*}$ is represented by expression (32). In an analogous manner, the optimal integer $K_2^{(1)*}$ represented by expression (33) is derived.

### *A2. Detailed calculations for the numerical example*

Designations (2) to (13) give

$$\varphi_{11} = \tfrac{1}{3}\,,\ \varphi_{12} = 0.5\,,\ \varphi_{21} = 0.5\,,\ \varphi_{22} = \tfrac{1}{3}\,,\ \varphi_{23} = 0.25\,,\ \varphi_{24} = 0.2\,,$$

$$\alpha_1 = 1150 + 80 = 1230\,,\ \alpha_2 = 1200 + 203 + 7 = 1410\,,\ \alpha_3 = 300 + 32 = 332\,,$$

$$\beta_3 = 50 + 56 + 70 + 45 + 48 + 30 = 299\,,$$

$$G_0 \equiv 0\,,\ G_1 = -100{,}000(0.8) + 80{,}000(0.75)(\tfrac{1}{3} - \tfrac{2}{3}) = -100{,}000\,,$$

$$G_2 = 70{,}000(2)(0.5 - 0.5) - 50{,}000(2.1) - 40{,}000(1.8) + 20{,}000(2.2)(0.2 - 0.8) = -203{,}400\,,$$

$$H_1 = 100{,}000(\tfrac{1}{3} \times 0.88 + 0.8) + 80{,}000(0.5 \times 0.09 + 0.5 \times 0.75) = 142{,}933.33\,,$$

$$\begin{aligned}H_2 &= 70{,}000(0.5\times 0.83 + 0.5\times 2) + 50{,}000(\tfrac{1}{3}\times 2.91 + 2.1) + 40{,}000(0.25\times 2.59 + 1.8) + 20{,}000(0.2\times 0.85 + 0.8\times 2.2)\\ &\quad - 100{,}000 = 99{,}050 + 153{,}500 + 97{,}900 + 38{,}600 - 100{,}000 = 289{,}050,\end{aligned}$$

$$H_3^{(b)} = \frac{40{,}000(3.5)(5)}{3.5+5} + \frac{30{,}000(5.3)(5.1)}{5.3+5.1} + \frac{20{,}000(4.8)(4.8)}{4.8+4.8} + \frac{35{,}000(5.3)(4.9)}{5.3+4.9} + 45{,}000(5.2) + 10{,}000(5) - 203{,}400 = 378{,}036.84\,.$$

Equations (32), (33) and (26) give

$$K_1^{(1)*} = \left\lfloor \sqrt{\frac{1230(289{,}050)}{1410(142{,}933.33)} + 0.25} + 0.5 \right\rfloor = \lfloor 1.92 \rfloor = 1\,,$$

$$K_2^{(1)*} = \left\lfloor \sqrt{\frac{378{,}036.84(\frac{1230}{1} + 1410)}{332(142{,}933.33\times 1 + 289{,}050)} + 0.25} + 0.5 \right\rfloor = \lfloor 3.18 \rfloor = 3\,,$$

$$JTC^{\circ}(1,\ 3) = \sqrt{2(\tfrac{1230}{3} + \tfrac{1410}{3} + 332)(142{,}933.33\times 3 + 289{,}050\times 3 + 378{,}036.84)} + 299$$

$$= \sqrt{2(1212)(1{,}673{,}986.83)} + 299 = \$63{,}999.42 \ \text{ per year.}$$

Equations (34), (35) and (26) give

$$K_2^{(2)*} = \left\lfloor \sqrt{\frac{1410(378{,}036.84)}{332(289{,}050)} + 0.25} + 0.5 \right\rfloor = \lfloor 2.91 \rfloor = 2\,,$$

$$K_1^{(2)*} = \left\lfloor \sqrt{\frac{1230(289{,}050 + \frac{378{,}036.84}{2})}{142{,}933.33(1410 + 332\times 2)} + 0.25} + 0.5 \right\rfloor = \lfloor 1.99 \rfloor = 1\,,$$

$$JTC^{\circ}(1,\ 2) = \sqrt{2(\tfrac{1230}{2} + \tfrac{1410}{2} + 332)(142{,}933.33\times 2 + 289{,}050\times 2 + 378{,}036.84)} + 299$$

$$= \sqrt{2(1652)(1{,}242{,}003.50)} + 299 = \$64{,}358.19 \ \text{ per year.}$$

Hence, the optimal integral values of $K_1$ and $K_2$ are 1 and 3, and equations (24) and (25) give the optimal basic cycle time and backordering times:

$$T_3^* \equiv T^\circ(1,\ 3) = \sqrt{\tfrac{2(1212)}{1{,}673{,}986.83}} = 0.03805 \text{ year} \cong 13.89 \text{ days},$$

$$t_1^* \equiv t_1^\circ(1,\ 3) = \tfrac{5(0.03805)}{3.5+5} = 0.02238 \text{ year} \cong 8.17 \text{ days},$$
$$t_2^* \equiv t_2^\circ(1,\ 3) = \tfrac{5.1(0.03805)}{5.3+5.1} = 0.01866 \text{ year} \cong 6.81 \text{ days},$$

$$t_3^* \equiv t_3^\circ(1,\ 3) = \tfrac{4.8(0.03805)}{4.8+4.8} = 0.01903 \text{ year} \cong 6.95 \text{ days},$$
$$t_4^* \equiv t_4^\circ(1,\ 3) = \tfrac{4.9(0.03805)}{5.3+4.9} = 0.01828 \text{ year} \cong 6.67 \text{ days},$$

$$t_5^* \equiv t_5^\circ(1,\ 3) = 0.03805 \text{ year} \cong 13.89 \text{ days (all backorders)},$$

$$t_6^* \equiv t_6^\circ(1,\ 3) = 0 \text{ (no backorders)}.$$

The three yearly costs are obtained using equations (18) to (20) as follows:

$$\sum_{j=1}^{2} TC_{1j} = \tfrac{142{,}933.33(1)(3)(0.03805)}{2} - \tfrac{100{,}000(3)(0.03805)}{2} + \tfrac{1150+80}{1(3)(0.03805)} + \tfrac{7}{3(0.03805)} + 50 = \$13{,}337.04 \text{ per year},$$

$$\sum_{j=1}^{4} TC_{2j} = \tfrac{(289{,}050+100{,}000)(3)(0.03805)}{2} - \tfrac{203{,}400(0.03805)}{2} + \tfrac{1200+203}{3(0.03805)} + \tfrac{32}{0.03805} + 249 = \$31{,}716.19 \text{ per year},$$

$$\sum_{j=1}^{6} TC_{3j} = \tfrac{(378{,}036.84+203{,}400)(0.03805)}{2} + \tfrac{300}{0.03805} = \$18{,}946.20 \text{ per year}.$$

In particular, the optimal solution to the model based on the equal-cycle-time coordination mechanism is as follows:

$$JTC^\circ(1,\ 1) = \sqrt{2(1230+1410+332)(142{,}933.33+289{,}050+378{,}036.84)} + 299$$

$$= \sqrt{2(2972)(810{,}020.17)} + 299 \quad = \$69{,}687.47 \text{ per year},$$

which is 8.89% $(= \tfrac{69{,}687.47-63{,}999.42}{63{,}999.42})$ higher than $JTC_3^* \equiv JTC^\circ(1,\ 3)$,

$$T^\circ(1,\ 1) = \sqrt{\tfrac{2(2972)}{810{,}020.17}} = 0.08566 \text{ year} \cong 31.27 \text{ days}.$$

When the ordering decision is governed by the adjacent downstream stage, equations (44) and (46) with $n = 3$ give

$$\tau_3^* = \sqrt{\frac{2(300)}{378,036.84+203,400}} = 0.03212 \text{ year} \cong 11.72 \text{ days},$$

$$\lambda_2^* = \left\lfloor \sqrt{\frac{2(1200+203)}{(289,050+100,000)(0.03212)^2} + 0.25} + 0.5 \right\rfloor = \lfloor 3.19 \rfloor = 3,$$

$$\lambda_1^* = \left\lfloor \sqrt{\frac{2(1150+80)}{142,933.33(3\times 0.03212)^2} + 0.25} + 0.5 \right\rfloor = \lfloor 1.95 \rfloor = 1.$$

The three yearly costs are obtained using equations (47) and (48) with $n = 3$ as follows:

$$TC_3^* = \sqrt{2(300)(378,036.84+203,400)} = \$18,677.85 \text{ per year},$$

$$TC_2^* = \frac{(289,050+100,000)(3)(0.03212)}{2} - \frac{203,400(0.03212)}{2} + \frac{1200+203}{3(0.03212)} + \frac{32}{0.03212} + 249 = \$31,283.07 \text{ per year},$$

$$TC_1^* = \frac{142,933.33(1)(3)(0.03212)}{2} - \frac{100,000(3)(0.03212)}{2} + \frac{1150+80}{1(3)(0.03212)} + \frac{7}{3(0.03212)} + 50 = \$14,955.80 \text{ per year}.$$

The results for the decentralized model are summarized in Table 2, and the results after sharing the coordination benefits are summarized in Table 3, in which columns 3 and 4 are obtained using equations (49) and (50), respectively.

## 8. References

Banerjee, A., 1986. A joint economic-lot-size model for purchaser and vendor. Decision Sciences 17 (3), 292-311.

Ben-Daya, M., Al-Nassar, A., 2008. An integrated inventory production system in a three-layer supply chain. Production Planning and Control 19 (2), 97-104.

Ben-Daya, M., Darwish, M., Ertogral, K., 2008. The joint economic lot sizing problem: review and extensions. European Journal of Operational Research 185 (2), 726-742.

Berger, P.D., Gerstenfeld, A., Zeng, Z.A., 2004. How many suppliers are best? A decision-analysis approach. Omega 32 (1), 9-15.

Bhatnagar, R., Chandra, P., Goyal, S.K., 1993. Models for multi-plant coordination. European Journal of Operational Research 67 (2), 141-160.

Cárdenas-Barrón, L.E., 2001. The economic production quantity (EPQ) with shortage derived algebraically. International Journal of Production Economics 70 (3), 289-292.

Cárdenas-Barrón, L.E., 2007. Optimal inventory decisions in a multi-stage multi-customer supply chain: a note. Transportation Research Part E: Logistics and Transportation Review 43 (5), 647-654.

Cárdenas-Barrón, L.E., 2008. Optimal manufacturing batch size with rework in a single-stage production system: a simple derivation. Computers and Industrial Engineering 55 (4), 758-765.

Cha, B.C., Moon, I.K., Park, J.H., 2008. The joint replenishment and delivery scheduling of the one-warehouse, *n*-retailer system. Transportation Research Part E: Logistics and Transportation Review 44 (5), 720-730.

Chan, C.K., Kingsman, B.G., 2007. Coordination in a single-vendor multi-buyer supply chain by synchronizing delivery and production cycles. Transportation Research Part E: Logistics and Transportation Review 43 (2), 90-111.

Chiou, C.C., Yao, M.J., Tsai, J.T., 2007. A mutually beneficial coordination mechanism for a one-supplier multi-retailers supply chain. International Journal of Production Economics 108 (1-2), 314-328.

Chiu, Y.S.P., Lin, H.D., Cheng, F.T., 2006. Technical note: Optimal production lot sizing with backlogging, random defective rate, and rework derived without derivatives. Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture 220 (9), 1559-1563.

Chung, C.J., Wee, H.M., 2007. Optimizing the economic lot size of a three-stage supply chain with backordered derived without derivatives. European Journal of Operational Research 183 (2), 933-943.

Chung, C.J., Wee, H.M., 2008. Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain. International Journal of Production Economics 113 (2), 528-545.

El Saadany, A.M.A., Jaber, M.Y., 2008. The EOQ repair and waste disposal model with switching costs. Computers and Industrial Engineering 55 (1), 219-233.

Goyal, S.K., 1976. An integrated inventory model for a single supplier single customer problem. International Journal of Production Research 15 (1), 107-111.

Goyal, S.K., 1988. "A joint economic-lot-size model for purchaser and vendor": a comment. Decision Sciences 19 (1), 236-241.

Goyal, S.K., Gupta, Y.P., 1989. Integrated inventory models: the buyer-vendor coordination. European Journal of Operational Research 41 (3), 261-269.

Goyal, S.K., Deshmukh, S.G., 1992. Integrated procurement-production systems: a review. European Journal of Operational Research 62 (1), 1-10.

Grubbström, R.W., 1995. Modeling production opportunities: an historical overview. International Journal of Production Economics 41 (1-3), 1-14.

Grubbström, R.W., Erdem, A., 1999. The EOQ with backlogging derived without derivatives. International Journal of Production Economics 59 (1-3), 529-530.

Hill, R.M., 1997. The single-vendor single-buyer integrated production-inventory model with a generalized policy. European Journal of Operational Research 97 (3), 493-499.

Jaber, M.Y., Rosen, M.A., 2008. The economic order quantity repair and waste disposal model with entropy cost. European Journal of Operational Research 188 (1), 109-120.

Joglekar, P.N., 1988. Comments on "A quantity discount pricing model to increase vendor profits". Management Science 34 (11), 1391-1398.

Khouja, M., 2003. Optimizing inventory decisions in a multi-stage multi-customer supply chain. Transportation Research Part E: Logistics and Transportation Review 39 (3), 193-208.

Leng, M.M., Parlar, M., 2009a. Lead-time reduction in a two-level supply chain: non-cooperative equilibria vs. coordination with a profit-sharing contract. International Journal of Production Economics. 118 (2), 521-544.

Leng, M.M., Parlar, M., 2009b. Allocation of cost savings in a three-level supply chain with demand information sharing: a cooperative game approach. Operations Research 57 (1), 200-213.

Leng, M.M., Zhu, A., 2009. Side-payment contracts in two-person non-zero supply chain games: review, discussion and applications. European Journal of Operational Research 196 (2), 600-618.

Leung, K.N.F., 2008a. Technical note: A use of the complete squares method to solve and analyze a quadratic objective function with two decision variables exemplified via a deterministic inventory model with a mixture of backorders and lost sales. International Journal of Production Economics 113 (1), 275-281.

Leung, K.N.F., 2008b. Using the complete squares method to analyze a lot size model when the quantity backordered and the quantity received are both uncertain. European Journal of Operational Research 187 (1), 19-30.

Leung, K.N.F., 2009a. A technical note on "Optimizing inventory decisions in a multi-stage multi-customer supply chain". Transportation Research Part E: Logistics and Transportation Review 45 (4), 572-582.

Leung, K.N.F., 2009b. A technical note on "Optimal production lot sizing with backlogging, random defective rate, and rework derived without derivatives". Proceedings of the Institution of Mechanical Engineers Part B: Journal of Engineering Manufacture 223 (8), 1081-1084.

Leung, K.N.F., 2010a. An integrated production-inventory system in a multi-stage multi-firm supply chain. Transportation Research Part E: Logistics and Transportation Review 46 (1), 32-48.

Leung, K.N.F., 2010b. A generalized algebraic model for optimizing inventory decisions in a centralized or decentralized multi-stage multi-firm supply chain. Transportation Research Part E: Logistics and Transportation Review 46 (6), 896-912.

Lu, L., 1995. A one-vendor multi-buyer integrated inventory model. European Journal of Operational Research 81 (2), 312-323.

Maloni, M.J., Benton, W.C., 1997. Supply chain partnerships: opportunities for operations research. European Journal of Operational Research 101 (3), 419-429.

Moore L.J., Lee S.M., Taylor B.W., 1993. Management Science. Allyn and Bacon, Boston.

Rosenblatt, M.J., Lee, H.L., 1985. Improving profitability with quantity discounts under fixed demand. IIE Transactions 17 (4), 388-395.

Ruiz-Torres, A.J., Mahmoodi, F., 2006. A supplier allocation model considering delivery failure, maintenance and supplier cycle costs. International Journal of Production Economics 103 (2), 755-766.

Ruiz-Torres, A.J., Mahmoodi, F., 2007. The optimal number of suppliers considering the costs of individual supplier failure. Omega 35 (1), 104-115.

Sarmah, S.P., Acharya, D., Goyal, S.K., 2006. Buyer vendor coordination models in supply chain management. European Journal of Operational Research 175 (1), 1-15.

Seliaman, M.E., Ahmad, A.R., 2009. A generalized algebraic model for optimizing inventory decisions in a multi-stage complex supply chain. Transportation Research Part E: Logistics and Transportation Review 45 (3), 409-418.

Silver E.A., Pyke D.F., Peterson, R., 1998. Inventory Management and Production Planning and Scheduling (3rd Edition). Wiley, New York.

Sphicas, G.P., 2006. EOQ and EPQ with linear and fixed backorder costs: Two cases identified and models analyzed without calculus. International Journal of Production Economics 100 (1), 59-64.
Sucky, E., 2005. Inventory management in supply chains: a bargaining problem. International Journal of Production Economics 93-94 (1-6), 253-262.
Wee, H.M., Chung, C.J., 2007. A note on the economic lot size of the integrated vendor-buyer inventory system derived without derivatives. European Journal of Operational Research 177 (2), 1289-1293.
Wee, H.M., Chung, C.J., 2009. Optimizing replenishment policy for an integrated production inventory deteriorating model considering green component-value design and remanufacturing. International Journal of Production Research 47 (5), 1343-1368.
Wu, K.S., Ouyang, L.Y., 2003. An integrated single-vendor single-buyer inventory system with shortage derived algebraically. Production Planning and Control 14 (6), 555-561.
Yang, P.C., Wee, H.M., 2002. The economic lot size of the integrated vendor-buyer inventory system derived without derivatives. Optimal Control Applications and Methods 23 (3), 163-169.
Yu, C.P.J., Wee, H.M., Wang, K.J., 2008. Supply chain partnership for three-echelon deteriorating inventory model. Journal of Industrial and Management Optimization 4 (4), 827-842.

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# Life Cycle Costing, a View of Potential Applications: from Cost Management Tool to Eco-Efficiency Measurement

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## 1. Introduction

In the field of modern production contexts, the complexity of processes combined with an increasingly dynamic competitive environment has created, in business management, the need to monitor and analyze, in terms of generation costs, not only the internal production phase but all stages both upstream and downstream in order to minimize the total cost of the product throughout the entire life cycle.

The approach of life-cycle cost analysis was used primarily as a tool to support investment decisions and complex projects in the field of defence, transportation, the construction sector and other applications where cost constitutes the strategic analysis of cost components of a project throughout its useful life.

The analysis methodology of Life Cycle Costing (LCC) concerns the estimate of the cost in monetary terms, originated in all phases of the life of a work, i.e. construction, operation, maintenance and eventual disposal / recovery. The aim is to minimize the combined costs associated with each phase of the life cycle, appropriately discounted, thus providing economic benefits to both the producer and the end user.

Life Cycle Costing (LCC) is a tool used in consolidated management accounting (Horngren, 2003, Atkinson et al., 2002), which aims to achieve a reduction in carbon dioxide. Whole life cost. This identifies, with reference to the system, the functional activities within the appropriate stages of design, production, use and disposal of waste, and appropriates a cost (Fabricky Blanchard, 1991) in order to clarify the causal relationship between resulting architecture of product design alternatives and cost estimates of fees, which will probably be supported by the various actors within the economic life of the product [Fixson, 2004].

Life Cycle Costing is an analytical tool and method which belongs to the set of life cycle approach. Traditionally, LCC was used to support purchasing decisions of products or capital equipment involving a large outlay of financial resources (Huppes et al., 2005). In the definition provided by Rebitzer & Hunkeler (2005) LCC incorporates all costs, both internal and external, associated with the life cycle of a product, and are directly related to one or more actors in the supply chain.

In recent years, the spread of life cycle thinking within business planning and management has led to an evolution of LCC methodology by extending the scope of integrated analysis of the three pillars comprising sustainable development - economic, environmental and social – in a financial representation.

Analysis of different applications undertaken in recent years identifies three types of Life Cycle Costing, for separate purposes and methods of application: Business LCC, Environmental LCC and Social LCC.

Business LCC, or traditional LCC, is commonly used as a method of cost analysis and business decision support in procurement and investment. Cost categories and principles that are to be followed in the measurement procedure need to be established in advance, and the functional unit is represented by just one product.

Environmental LCC in the product or system under study is usually less complex and the functional unit is chosen according to international standards as specified by ISO 14040 (i.e. $1m^2$ of floor). Unlike the traditional LCC, it is not used as a tool for procurement decisions or control, but to analyze the environmental and economic impact of a product or system. The cost estimate is obviously simpler than what occurs in the traditional LCC approach and is usually characterized by a static (steady state). In Environmental LCC, the integration of the instrument in Life Cycle Assessment is one of the fundamental aspects.

The Social LCC is the third component of the measure of sustainable development, in addition to the LCA and Environmental LCC (Hunkeler et al., 2006). The goal is to allow the organization to conduct its business in a responsible manner by providing information on potential social impacts caused to individuals by the product during its life cycle.

The analysis of social impacts, as is the case for environmental LCC, takes into account both the internal and external costs. Internal costs are those that the various actors involved during the lifecycle of a product must support, such as production costs or the costs of use; while the external costs, also called externalities, are related to the effects of monetized environmental and social impacts generated by a given product. These costs are usually not directly borne by the consumer or derived from making or using the product, but affect the entire community indiscriminately.

The following chapter will highlight the main applications of Life Cycle Costing methodology, both as a tool for minimizing business costs for a project or a product and as an essential component of sustainability-oriented life cycle management. In the final section, we will see a short description of the possible application of LCC for the construction of eco-efficiency indicators

## 2. Business life cycle costing

The issue of life cycle costing arrives in the context of at least two aspects: one related to the development of new products, the other in the evaluation of strategic investments (Ciroth, 2003).

The first refers to the application of Life Cycle Costing to identify, measure and evaluate the costs associated with the entire life cycle of a new product, especially in the case of complex and durable products. The second concerns the application of LCC as a tool for comparative analysis of long-term investment projects and in managing the cost of a new product.

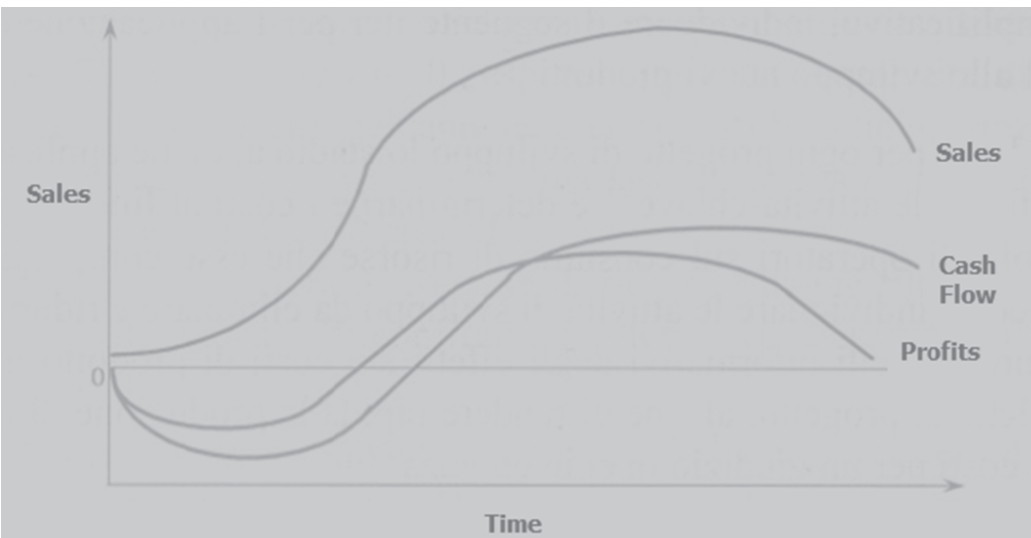
The application of LCC in the management of the product can be seen from two distinct perspectives:

1. From the economic perspective of a producer, to support management in planning and managing the product throughout its life cycle;
2. From the economic perspective of a customer, or as an aid in the purchasing stage aimed at determining the total cost for the entire life cycle.

From the perspective of the producer, calculations consist of the estimation of the costs of design, engineering, industrialization and production of a new product and in the analysis of these costs throughout the life cycle (Asiedu & Gu, 1998).

Once the life cycle duration of the product has been identified and individual cost elements produced in the various stages has been identified and measured, a detailed analysis can highlight the relationships between the individual cost items of each phase.

The decisions taken during planning and design can have an impact on the costs incurred in subsequent phases. An example can be durable consumer goods, such as appliances: the choice between different technological solutions in the design phase can strongly influence the efficiency of the product and thus reduce or increase its usage cost. Efficiency measures the relation between outputs from and inputs to a process, the higher the output for a given input, or the lower the input for a given output, the more efficient is an activity, product, or




| | | | | |
|---|---|---|---|---|
| **Marketing stage** | Introduction | Growth | Maturity | Decline or revitalization |
| **Strategic Objective** | Sales growth | Sales growth | Profits | Cash flow or Profits |
| **Projecting stage / Production** | Planning / Development | Planning / Development | Production / Logistics | Production / Logistics, Planning / Development |
| **Level of cost:** | | | | |
| R&D - product | High | Medium | Medium | Low or Medium |
| R&D - process | Medium | High | High | Low or Medium |
| Advertising | Medium | High | Medium | Low or Medium |
| Plant and Equipment | Low | High | Medium | Low |

Source: Vitali, 2004 (adapted from Susman, 1995)

Fig. 1. The life cycle of a product

business (Burritt & Saka 2006). The traditional cost accounting systems tend to focus on the production phase, underestimating the importance of cost information relating to upstream and downstream stages. An integrated view of the different phases of the lifecycle, however, show that the maximization of value added does not depend strictly on cost minimization or revenue maximization at each stage.
Following the product throughout its life cycle ensures a useful flow of information to all business functions regarding the elements that determine the success of a product, allowing them to react promptly and effectively to resolve any weaknesses. From this perspective, Life Cycle Costing moves from a mere trend costing instrument to assuming a key role in the support strategies and decisions of business management.
From the perspective of the customer, the LCC aspect of the concept of Total Cost of Ownership (TCO) is defined as a philosophy of cost calculation aimed at determining the total cost of purchase, possession and use of a particular product (Ellram, 1995). This philosophy recognizes that the purchase price represents only one component of the total cost of a product throughout its useful life and can be applied both to the process of purchasing goods and as a capital investment tool by organisations (Ellram & Sifred, 1998).
TCO, compared to traditional methods of cost analysis of the life cycle, has some distinctive features: the range of costs considered is wider considering the cost of the first purchase. Moreover, while LCC considers only the costs as quantifiable monetary values, TCO also extends to the costs associated with the low quality of a product and related services, and all the opportunity costs associated with such low quality (Pitzalis, 2003b).
A survey of consumers conducted in the 1970's by Hutton and Wilkie found that consumers who make buying decisions using the LCC approach could lead to a reduction in the consumption of energy equal to a saving of $ 4 billion annually (Hutton and Wilkie, 1980).
The use of LCC in the procurement phase is also desirable from the economic perspective of the buyer. Taking Italy as an example, we find that the volume of public spending of Public Administration represents 17% of the Gross Domestic Product (GDP), compared to 18% on average in the EU, and 15% in the USA (Iraldo et al. 2008).
A survey conducted by ICLEI - Local Governments for Sustainability - in 2007 on behalf of the European Commission, shows how the use of LCC during purchasing would allow, for certain types of products, financial savings as well as offering significant environmental benefits.

## 3. The product lifecycle and Life Cycle Assessment (LCA)

In recent years, different methodologies have been developed as a direct response to increasing environmental threats, in order to study and evaluate the environmental impacts associated with a product. The need to develop operational and technical management tools in this area is gained as a result of a more environmental focus and mounting pressure from external partners of the undertaking, who increasingly request guarantees regarding the environmental compatibility of products. In order to address these challenges, environmental considerations need to be integrated into a number of different types of decisions made both by business, individuals, and public administrations and policymakers (Nilsson and Eckerberg, 2007) This has prompted companies, scientific institutions and standardisation bodies (national and international) to study, develop and progressively refine methodologies that would respond to the needs of public authorities, business partners, consumers and, more generally, by all stakeholders of an organisation.

The first problem we find in the definition of methodological tools of environmental assessment is the correct measurement of the impacts as related to a product. It is known that a product passes through different stages during its lifetime: from the initial manufacture through the process of production, consumption throughout the use of the product, and finally the "death" (and disposal) with the exhaustion of its function. During each of these stages, the product has a number of impacts on the environment. The significance of these impacts may vary depending on the stage of the lifecycle that is treated; if the study of the impact, for example, is limited to a single phase, the outcome could be misleading. The main tool, available to scholars to conduct an examination congruent with the requirements mentioned, is the method known as "Life Cycle Assessment". This tool, developed to overcome these potential drawbacks, has as its focal point the performance analysis of systems, applied to assess the potential environmental impacts and resources used throughout a product's lifecycle, i.e., from raw material acquisition, via production and use phases, to waste management (ISO, 2006a).
This approach is also defined as "cradle to grave". The comprehensive scope of LCA is useful in order to avoid problem-shifting, for example, from one phase of the life-cycle to another, from one region to another, or from one environmental problem to another (Finnveden et al 2009).
LCA-methodology and the term was first coined during a SETAC (Society of Environmental Toxicology and Chemistry) conference in 1990 in Vermont (USA), and is defined as "an objective process of evaluation of environmental burdens associated with a product (...) through identifying and quantifying energy and materials used and waste released into the environment, to assess the impact of these uses of energy and materials and releases into the environment and to evaluate and implement environmental improvement opportunities. The assessment includes the entire lifecycle of the product (...), including extraction and processing of raw materials, manufacture, transport, distribution, use, reuse, recycling and final disposal" ( SETAC, 1993).
The first LCA studies were undertaken in the late sixties and covered some aspects of the life cycle of materials and products, to highlight issues such as energy efficiency, consumption of raw materials and waste disposal. Starting from these early experiences, there has been a gradual spread of use of such means, promoted by the positive results that first applications produced. Simultaneously, however, there were obvious limits to this methodology due, mainly, to the non-comparability of results, owing to the development with different approaches and methodologies [Baldo, 2000]. To fill this gap, in the 1990s, efforts were made by standardisation bodies at national and international levels, aiming to rationalize and harmonize the references in this field.
The development of LCA methodology culminated in the codification of a family of standards, ISO 14040 (Environmental Management - Life cycle assessment), published in 1997. Today the ISO 14040 constitutes the most important reference for the dissemination of these methodologies. The provision recognizes the LCA tool utility in identifying opportunities for improving the environmental aspects of product in the various stages of the lifecycle, in identifying the most appropriate indicators for measuring the environmental performance, guiding the design of new products/processes in order to minimise its environmental impact and strategic planning in support of businesses and policy maker (ISO, 1996). In this logic, LCA is also used as the basis of scientific information communication strategies of organisations, that is, in the definition of instruments that can

be used for this purpose, such as those assertions of type II (environmental product declarations) or of type I (eco-labelling programmes). The European ecolabel, for example, utilises LCA for processing of ecological criteria and environmental product statements are to be assured by the results of a life cycle analysis, according to the specifications in ISO 14025.

There exists a wealth of data and methods for LCA throughout the world today, with government bodies and international organisations recognising that there is an increasing need for guidance on what to use. The UNEP/SETAC Life Cycle Initiative is an example of one of the international activities underway to disseminate life cycle approaches throughout the world, with a focus on developing countries (UNEP 2002). The life cycle initiative and other related life cycle activities, such as the International Reference Life Cycle Data System (ILCD) (European Commission 2008) are instrumental in expanding LCA approaches and in supporting the increasing understanding and application of life cycle assessments. In this way, the expansion of LCA is an approach based on expanding the usefulness of LCA whilst not increasing the complexity of the LCA, thereby decreasing it's value.

According to ISO, LCA is a technique for assessing the environmental aspects and potential impacts throughout the life cycle of a product or process or service, which is divided into four phases (see the figure 2):

1. Setting the goals and boundaries of the system (goal and scope definition - ISO 14041)
2. Data collection (inventory analysis - ISO 14041);
3. Environmental impact assessment (impact assessment - ISO 14042);
4. Interpretation of results and improvement (improvement analysis - ISO 14043).

The 4 phases of LCA should not be seen as a fixed sequence or standard of methodological steps, but rather as a cycle of iterations, with frequent changes and revisions of the contents of each, as each phase is interdependent with others.

1) The first stage indicates clearly and coherently the planned application, the reasons why the LCA is developed, the intended use of the results and the intended audience of the study. In particular, in defining the scope of the study, certain elements must be clearly

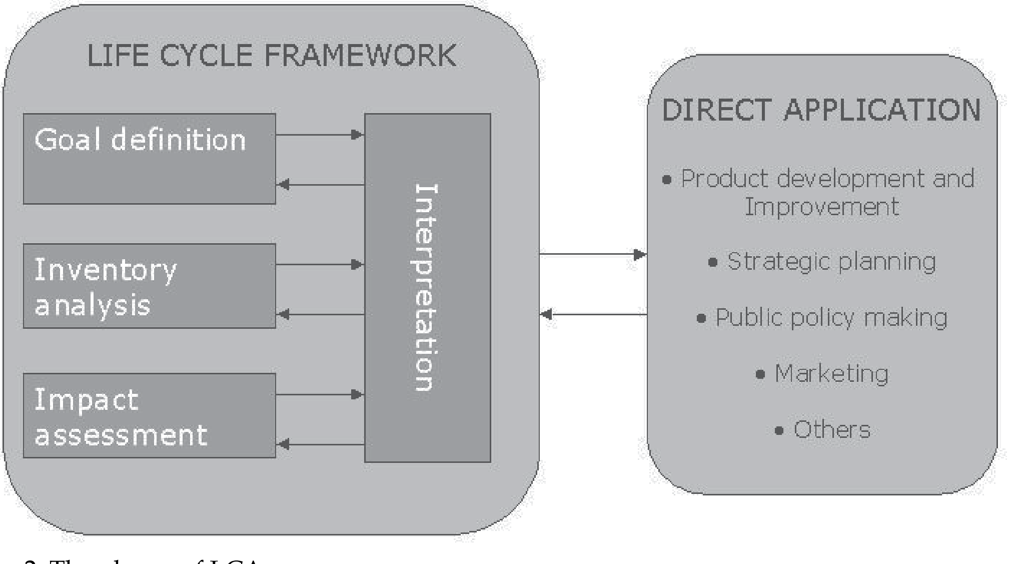



Fig. 2. The phases of LCA

described and taken into account, including: the functions of the product system (or systems product in the case of comparative studies, as LCA can be used to compare the alternative products or processes); the functional unit; the system of the product (defined in the standard as "the set of elementary units of the combined process with regard to the matter and energy, pursuing one or more defined function"); the types of impacts, methodologies for evaluating the impact and the subsequent interpretation to be used; the quality requirements of initial data, etc.

Within this phase, a fundamental step is the definition of the functional unit, whose purpose is to provide a reference in which to bind the inflows and outflows (defined as inflows of matter or energy that enters a process unit consisting of raw materials or products, and outflow matter or energy that leaves a unit process, formed from raw materials, intermediate products, products, emissions or waste), as we assume that the measures and evaluations are conducted according to the provision of the system under consideration. In other words, the system covered by the study is the product, defined not so much by its physical characteristics, as in its function, i.e. in the service that it provides (European Environmental Agency, 1998). If the function performed by the painting of a steel artifact, for example, is the protection of atmospheric corrosion, the functional unit could be defined as the unit of area protected to a predetermined period of time.

Another key step in conducting a LCA study is the definition of borders of the system studied, namely the identification of individual operations (units) that make up the process and their inputs and outputs, which must be included in the study. All transactions, or "process units", within the confines of the system are interrelated: they receive their input from the unit "upstream" while their output constitutes the inputs of “downstream” units, according to the outline of the process studied.

The criteria used to define the boundaries must always be identified and justified in order to clearly spell out the scope of the study.

2) The successive step in the undertaking of LCA’s is the lifecycle inventory phase (LCI). This phase involves collecting data and calculation procedures that enable the quantification of the types of interaction that the system has with the environment; these interactions may cover the use of resources and emissions in the air, the releases into water or soil associated with the system-product (Frankl, Rubik, 2000). The process of how to conduct an analysis is iterative in nature: inventory or data collection allows an increased level of knowledge of the system and, consequently, new data requirements may emerge or new requirements or limitations concerning data already collected may be identified. All this may entail a change to collection procedures and methodologies for calculation, in order to maintain a study coherent with objectives and allow, then, the achievement of a consistent audit. A review of the purpose or scope of the study may also be demanded by the emergence of problems related to the non-availability of required information. In relation to the latter issue, it should be noted that recent years have been characterised by a strong development of commercial and public databases both in the private and public domain. National or regional databases, which evolved from publicly funded projects, provide inventory data on a variety of products and basic services that are needed in every LCA, such as raw materials, electricity generation, transport processes, and waste services as well as sometimes complex products (Finnveden et al. 2009). In the private sector, as understanding grew of the increasing importance that the LCA tool has in environmental strategies of enterprises, and in public sector entities, in order to support enterprises in its application. This development

of databases started a process of elaboration which today is available for companies interested in experimenting with LCA methodology on its processes/products. With regard to Europe, it is appropriate to highlight the efforts made by Joint Research Center (JCR) of the European Commission in the development of a database "network", the international lifecycle database, and a relative Handbook (manual), with the objective of making data available to the user via web information from databases from diverse sectors, collected in the field. The UNEP/SETAC Life Cycle Initiative along with the ILCD are focusing on addressing inventory data, among other issues, by building on the currently existing achievements and approaches in increasing consistency and quality assurance. Both UNEP and the European Commission have recognised these tools as an opportunity to spread the LCA methodology to all Community companies, providing technical and scientific reliability and data quality.
The data collected during the inventory phase relates to natural resources and energy use, emissions into the atmosphere and bodies of water, in addition to solid waste. These resource inputs consumed and output of emissions into the environment are attributable to all operations included in the life cycle of the product being investigated.
Clearly, the quality of the data collected with a view to the completion of the inventory strongly determines the significance of the findings of the study. In LCA studies, therefore, it is desirable to use the highest possible percentage of (so-called) specific data — which refer exactly to the system in question or to one "technologically equivalent" (i.e. with sources of energy, raw materials, process phases and similar structures). A strength of inventories carried out within the LCA is represented, in particular, by the methodology of measuring energy consumption that calculates not only the share of energy directly consumed at every stage of the production system, but also the indirect share of energy needed to produce fuels and electricity that normally feed industrial processes and whose values vary from country to country depending on the level of efficiency associated with different modes of production and transformation of energy. Table 1 shows what can be the differences between national energy mix of various Nations.

| Nation | Hydro | Nuclear | Fossil fuels and waste | Other renewable sources |
|---|---|---|---|---|
| Austria | 67.6 | - | 29.2 | 3.22 |
| France | 17.11 | 75.6 | 6.49 | 0,72 |
| Germany | 5.28 | 25.51 | 61.95 | 7.26 |
| Japan | 9.81 | 24.91 | 64.86 | 0.42 |
| Italy | 18.07 | - | 79.21 | 2.72 |
| Norway | 98.71 | - | 0.84 | 0.45 |
| Spain | 9.99 | 15.61 | 64.4 | 10 |
| Switzerland | 68.17 | 28.04 | 3,76 | 0.03 |
| UK | 1,71 | 17,22 | 79,4 | 1,67 |
| USA | 7.26 | 19.11 | 72.6 | 1.03 |

Source: (International Energy Agency, 2007)

Table 1. Mix % of primary combustible sources used to generate electric energy in various countries

These differences lead to consequences for the calculation of the energy consumption of a "product" that systems using LCA techniques can measure. Because a production process can generate, along with the core product, different co-products or by-products, the need arises to define rules to assign each a share of output production, and consumption impacts associated with transactions underway. Such allocation criteria, defined as allocation methods, can be traced back to two main groupings, as follows:

- allocation on the basis of physical magnitudes: is the proportional distribution of environmental burdens on the basis of a physical parameter, such as mass, volume, energy, etc;
- economic allocation: consisting of the distribution of environmental burdens in proportion to the economic value of co-products or by-products. This method, which is not based on any physical parameter, can be applied however only in cases where the physical allocation is not easily applicable.

3) The inventory phase follows that of the impact assessment lifecycle during which environmental effects generated by the system under study are analysed. In other words, this phase is intended to assess the potential environmental impacts caused by processes, products or activities of the study, using the information gathered in the inventory. Every environmental impact can also be associated with one or more environmental effect and the performer of the study has the choice of the level of detail and the impacts to be assessed, in coherence with the objectives and the scope as defined in the first phase of the study. Environmental effects, on the other hand, can be divided according to the level of action: global, regional or local (Baldo, 2000).

Considering the subjective elements that characterize this phase (which evaluate the categories of environmental effects), it is appropriate to bring clarity and transparency with the assumptions that underlie their choices.

Among the categories of impacts more typically used in this phase of the LCA are the following:

- greenhouse;
- acidification;
- eutrophication;
- stratospheric ozone ducting;
- photochemical smog;
- land.

The ISO 14042 provides for two stages of analysis of impacts, the first, which is required, consists of three sequential tasks:

- selecting categories of impacts to consider and related indicators (acidification ⇒ SO2, greenhouse ⇒ CO2, eutrophication NO3, ozone depletion ⇒ CFC11, etc.);
- assigning inventory results to the selected impact categories (classification);
- calculation of the indicators of each category of impact (e.g. GWP, etc.) (characterization);

The second, optional stage, is divided by:

- comparison between calculated indicators and benchmarks (standardisation);
- determining the importance of individual environmental effects (weighting).

Classification consists of the organizing of inventory values of all emissions, gaseous, liquid and solid, caused directly and indirectly by the operations in question, by associating them to the various categories of impact. The characterization, on the other hand, allows the

determination in quantitative terms of the contribution of individual emissions, calculated using the ratios of characterization of each pollutant found in the scientific literature (e.g. IPPC Intergovernmental Panel on Climate Change; WMO World Meteorological Organisation; etc.).
The optional stages (standardisation and weighting) determine to aggregate the results of the various categories of impact in a single index, e.g. expressed with a score, to assess the environmental impact of the studied system as a whole, these methods, however, display a high level of subjectivity and, therefore, do not enjoy unanimous consensus in the international scientific community.
4) during the last phase of life cycle analysis, interpretive, the results of previous phases are summarized, analyzed, tested and discussed in consideration with the objectives of the study, to reach findings and recommendations to address and improve the environmental performance of the system-product analyzed. This stage has, therefore, the purpose of presenting, clearly and completely, the results of the previous phases, in support of decision-making processes and the planning of improvements. The aims and purposes defined in the initial phase are shaped into actions that are planned following this period of the interpretation of results. On the other hand, this phase may involve a review of some fundamentals of the study (scope, nature and quality of the data collected), taking account of the need to achieve the defined objective.
Whilst LCA does enable a comprehensive assessment and considers attributes or aspects of the natural environment, human health, resources and can inform consumer and policy decisions on environmental issues, decision makers must also take into account other sustainability aspects. In order to provide information for decision makers, it has been argued that there is a growing need to expand the ISO LCA framework for sustainability assessment by considering broader externalities, broader interrelations and different application/user needs with often conflicting requirements (Jeswani *et al.,* 2010).
In this sense the combination of common data and models and the synergies that exist between LCA and LCC offer additional advantages of their combined use (Udo et al., 2004).
The main difference that emerges between LCA and LCC is the traditional perspective that guides the use of each methodology. LCC adopts traditional perspectives of the life cycle of their "producer" or "customer." The objective is to minimize the overall costs of a product or investment to optimize the use of economic resources and increase customer satisfaction.
The goal of LCA, instead, is to identify and quantify the environmental burdens related to a product over the life cycle.
There are many purposes and diverse motives for which an LCA study may be undertaken, the main reasons may include:

1. The creation of an information system that supports the system's management, resource consumption, emissions and related environmental effects;
2. The identification of critical points in the production cycle or product life cycle to identify areas for improvement;
3. To compare the environmental burdens associated with alternative products or processes, in the selection of suppliers and choices of integration / vertical disintegration;
4. The orientation of the design of new products / processes, so as to minimize environmental impacts;
5. Provision of scientific support for external communication and consumer information.

## 4. LCC as a tool for evaluating multiannual investments.

The Logic of Life Cycle Costing can be applied even if the object of analysis is not the product but a long-term investment project. In particular, LCC lends itself well to comparative assessments of complex investments, such as investment in capital equipment or in the building & construction sector.

From this perspective, the National Institute of Standards and Technology has defined LCC as the sum of discounted total costs of the design, implementation, maintenance and end of a project over a given period of time.

According to this definition we can distinguish three fundamental components of cost within the life cycle:

1. Cost responsibility of the work / investment to be undertaken;
2. The period of time within which the costs occur;
3. The discount rate used to discount future costs at time t0.

The LCC of alternative projects can therefore be seen as the sum of initial investment (I), the present value of replacement costs (R), energy costs (E), and maintenance costs (M), minus the present value of salvage (S) which can be either the sales value at the end of the period or the residual value.

$$LCC = I + R + E + M - S$$

The first component of LCC is of course the cost. There are different categories of cost that must be considered during the lifetime of a project, ranging from the initial cost of investment to the purchase cost of installation or the costs of building a structure, management costs, costs of maintenance and repair and replacement costs.

The following table shows by way of example the main cost components to consider for each category in the application of LCC methodology in the building industry.

Cost elements that occur throughout the life cycle of the project must be added to the residual value or the net value of the investment after the LCC study period. This value consists of several elements, of both a positive and negative nature. For example, there may be the possibility that parts or components of a particular product/project have a high market demand and can be located at an economically advantageous rate. The negative component concerns issues such as disposal costs of waste resulting from the work. In the case of a production line, these costs vary depending on the presence of hazardous substances or the possibility of disassembly and shipment for the recovery of individual components.

The second element of LCC methodology is the time or the time period within which the costs generated by a project must be considered. In evaluating investments, we can split the analysis time in two phases: the first includes the design and implementation of the project, the second phase concerns the operation and eventual disposal. Usually, in order to simplify the analysis, the entire design, construction and generated costs, are understood as the original time unit.

The last component is represented by the discount rate used for discounting cash flows generated over the time period. The discount rate can be defined as the interest rate that reflects the value of the investor's money over time. Two discount rates can be distinguished: the discount rate and the actual rate. The difference being that the real discount rate considers the effect of changing prices, and thus the purchasing power of money, during the period considered.

| Initial cost of Investment | Management costs | Repair and maintenance costs | Substitution costs |
|---|---|---|---|
| Management of construction | Fuel for heating | Heat production plants | Heat production plants |
| Acquisition of land | Consumption of electric energy | Wastewater collection and water distribution system | Wastewater collection and water distribution system |
| Site survey | Consumption of water | Property insurance | Property insurance |
| Design | Wastewater | Windows and external walls | Windows and external walls |
| Acquisition of primary materials and construction | Management and disposal of waste | Interior finishes (floors, walls etc) | Interior finishes (floors, walls etc) |
| Facilities and technical equipment | Insurance | Fire protection systems | Fire protection systems |
| Indirect administrative costs | Renting and housing costs | Lighting system | Lighting system |
| …. | ….. | ….. | |

Table 2. Main cost components

The phase of identification and estimation of cost components is certainly the most critical phase, as it determines the accuracy and validity of the entire analysis. In fact, estimates are made in the initial phase of a project, or when the degree of knowledge of the cost magnitudes may still only be approximate. This can result in failing to achieve the desired objectives, and therefore undertaking an ineffective LCC (or failing to choose an alternative project with lower costs). The main reasons as to why an LCC may represent an ineffective analysis are:

- omission of data;
- lack of a systematic structure analysis;
- misinterpretation of data;
- improper use of analysis and estimation techniques;
- an erroneous view of the voices and cost parameters;
- a concentration of incorrect or insignificant events;
- errors in the evaluation of uncertainty;
- errors in job control.

These are the points which should act as central to obtaining the real benefit from the use of LCC methodology.

### 4.1 The integration of environmental aspects with LCC

The increased sensitivity of the market, its actors, and the various stakeholders to the role it plays in the production system to build a development model that meets the needs of current and future generations, has created a greater propensity for organizations to practice more sustainable conduct of its activities (Durairaj et al., 2002; Settani, 2006).

This move towards more sustainable conduct could enable organizations themselves to identify opportunities for cost reductions, resulting from more efficient uses of natural resources, with the end result being the reduction of the environmental impact of products and services provided (Norris, 2001).

In order to fully appreciate the benefits, both environmental and economic, that the introduction of appropriate changes in terms of product design, raw materials or processes may have, we need to incorporate business activities and waste disposal activities that are attributable to other actors interested in the life cycle of the system in question (Porter and van der Linde, 1996). In other words, the dissemination of life cycle thinking in business management systems is a prerequisite for the definition and implementation of truly sustainable actions.

In this context it is a clear reference to Life Cycle Management (LCM), that is, as an integrated approach that can assist management in managing the entire lifecycle of products or services to more sustainable patterns of production and consumption.

Life Cycle Management can be defined as a "philosophy", direct planning and administration capable of supporting management through:

1. Initial analysis in understanding the stages of the life cycle of a product or service;
2. Identifying, at each stage, the potential economic, environmental and social risks and opportunities;
3. Establishing pro-active systems in pursuing the opportunities identified and managed, or minimize the risks within LCM operational applications that have been developed (Parker, 2000; Epstein, 1996, Epstein and Roy, 1997; Shapiro, 2001), in which some management accounting tools such as Life Cycle Costing (LCC), have been integrated with systems and analytical environmental management tools, such as Life Cycle Assessment (LCA).

The integration of environmental considerations in a tool for cost management ensures that corporate decision-making is based on a growing awareness of the potential consequences in terms of costs and impacts on the environment and human

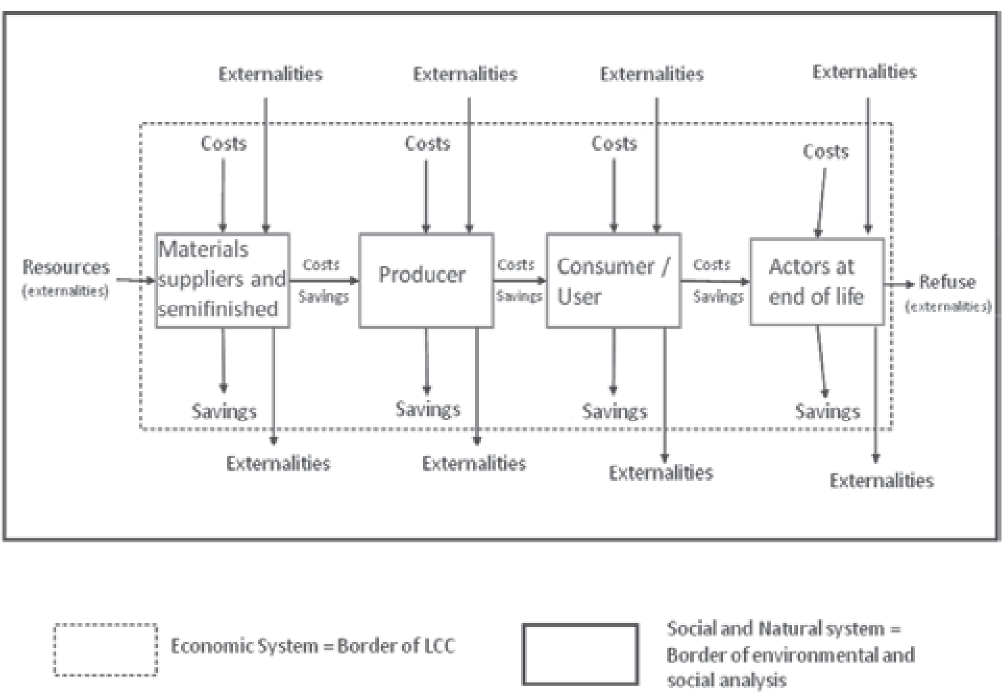
health, which occur in all stages ranging from the extraction of raw materials to waste disposal, and which relate to alternative design and production. Krozer (2008) applied life cycle costing to life cycle management with the assessment of 10 diverse products, based on the assessment of life cycle costs that accommodate demands for emission reductions. The model enabled the assessment of the costs of compliance strategies by available technologies from the past, in comparison with the costs of preventive strategies by innovative solutions in life cycles of products, which could assist companies with compliance in far-reaching emission reductions.

Since a significant proportion of costs and environmental loads are determined - although not yet supported by any of the actors operating along the life cycle - from choices made at the design phase as part of the LCM concept of LCC, it is essential in supporting product development to balance the demands of reducing costs with those of better environmental performance. Thus, the costs and environmental burdens are considered not only within the corporate boundaries, but affect, in a holistic perspective, processes and operators upstream and downstream along the supply chain (Hunkeler and Rebitzer, 2003).

As previously described, Life Cycle Costing (LCC) in its traditional sense is not configured as an instrument of environmental accounting. However, to be usefully employed in LCM as the economic counterpart of an extended type of Life Cycle Assessment, it should be based on systematic analysis, complementary and consistent with the corresponding environmental assessment (Rebitzer and Hunkeler, 2003) - which is usually an LCA-type Life Cycle Costing (LCC LCA-type) (Huppes, 2004). Consequently, we can actually obtain synergies from contextual implementation of LCA and LCC, should the system boundaries, functional unit and key assumptions be aligned between the two methodologies.

Life Cycle Assessment is, therefore, necessarily function-oriented and focuses on a system whose boundaries are wider than those considered in traditional LCC. The key element is the identification of the functional unit intended as a measure of performance of the system under study, which concerns all the environmental burdens (in terms of input and output) resulting from the inventory phase. By function-oriented, we mean that LCC must analyze the processes both upstream and downstream with respect to a given function, regardless of the location or time in which they occur. In the context of LCM, LCC must take into account different economic and environmental demands that characterize the different actors and processes along the supply chain in order to quantify the impact in terms of cost, related to emissions and consumption of natural resources. In this way it could allow for the linking of environmental issues, business strategies and operational processes, considering the costs and environmental impacts that occur beyond organizational boundaries, in relevant stages along the supply chain (Hunkeler and Rebitzer, 2003).

The following figure shows the conceptual framework of Life Cycle Costing, based on the life cycle of the physical product, and the relationship with LCA.




Source: adapted from Rebitzer and Hunkeler 2005

Fig. 3. The conceptual framework of LCC

There is a clear distinction between the economic system considered in LCC, and the natural system considered in LCA, to the exclusion of the external cost or externality from the calculation of the total cost. Traditional LCC considers all costs and revenues attributable to the different actors in the supply chain, while the external costs, which represent the effects of monetized environmental impacts, are not directly charged by individual actors and consequently are outside the economic system.

In an ideal economic system, all externalities, both environmental and social, should be completely covered by the mechanisms of taxation and subsidy, and, therefore, there is no need for systematic analysis on the environmental components, as comprehensive cost analysis along the full life cycle is able to achieve full integration of all three founding aspects of LCM (economic, environmental and social) in a monetary representation.

In order for LCA and LCC to be integrated, it is also necessary that the latter approach is characterized by a static (steady state).

Since the application of the discount rate to future cash flows is intended primarily to take into account uncertainty about the manifestation of the costs themselves (Ciroth, 2003), a probability distribution could be used as an alternative (Emblemsvåg, 2001), or a “scenario analysis” (Hellweg et al., 2003).

Entering the process of costing in LCC, the focus must be on the flows of environmental costs that are generated to produce a single functional unit during its whole life cycle. The range of costs to be considered are very broad, ranging from direct costs to explicit and hidden costs. According to one of the most popular classifications developed by the US-EPA (Environmental Protection Agency), it is possible to distinguish the environmental costs in terms of the ease of measurement and level of integration of the business system of cost evaluation. In addition to the distinction between external costs and internal costs already described above, the EPA distinguishes four categories of costs incurred directly by an organization:

- Conventional costs;
- Potentially hidden costs;
- Contingent costs;
- Image costs.

Conventional costs are those typical of business accounting systems, such as labor costs or the costs of plant and equipment. Although these costs are typically not environmental, the effects can have a significant environmental perspective such as increasing energy efficiency or a reduction of waste processing.

Potentially hidden costs are divided into upfront, regulatory, voluntary and back-end costs. The first are those that occur before a production process and relate, for example, to the design, qualification of suppliers, and analysis of a site. These costs, if they are classified as indirect costs or costs in R & D, can be easily "forgotten" by managers and analysts in the assessments of the costs of system operation. The regulatory concern is the cost necessary for compliance with environmental legislation, such as the cost of sampling and analysis of pollutants, those for waste management, training, insurance, etc. The volunteer costs are those incurred by the organization to go beyond regulatory compliance, for example costs of auditing and qualification of suppliers, implementation of environmental management systems, etc. The back-end costs are costs that are not subject to corporate accounting as they occur at a more or less defined period in the future. They include, for example, operating costs, post-mortem of a landfill or the cost of investigation into a site that is no longer used.

Contingent costs can be defined as quotas for future costs of risk management, or costs in which the event is uncertain. Think of any future legal actions or sanctions that may be imposed on the organization for failure to comply with regulatory requirements. These are costs that must be respected and whose probability of occurrence must be determined.

The image cost is the direct cost of a more difficult environmental determination. The environmental value of the image of an organization may include the value of corporate welfare, reduction of regulatory pressure, customer loyalty, and while the cost report may cover the loss of customers and suppliers as a result of environmental performance, it is not an excellent measure.

The costs of conventional and hidden costs can potentially be determined by the accounting process of Activity-based Environmental Cost Assignment: once the environmental activities within the corporate boundaries have been identified, direct and indirect costs will be allocated according to a criterion of causality, measured by the resource drivers, and a differential approach, in this way working on a reclassification to arrive at the same destination (for example, distinguishing between costs of prevention, monitoring costs, costs of internal accountability and external liability costs) (Hansen and Mowen, 2003). With the procedure of Full Environmental Costing, costs associated with quotas in the event of future production processes and their products can also be considered (Krewze and Newell, 1994).

The physical flows of matter and energy measured by an LCA can provide useful information for; the identification of internal costs with environmental implications (EPA, 1995); the drivers most capable of the appropriate allocation of direct costs, associated with flows of matter and energy (Orbach et al., 2003); and processes for allocating these costs to the functional unit chosen for analysis. Furthermore, identification of these flows allows for the construction of complex indices

capable of measuring the environmental load or the impact of a product or service, complementing the information provided by the analysis of environmental costs.

The inclusion of external costs in LCC analysis has several proposed approaches. There are numerous authors who have advanced methodologies for the calculation of external costs (Rebitzer and Hunkeler, 2003, Lazzari and Levizzari, 2000; Shapiro, 2001), but the limitations of these methods are still evident, especially the difficulty calculating estimates of complex monetary phenomena which incorporate the different forms of pollution and their effects.

Some authors propose to consider only the internal environmental costs because domestic representation of environmental load (Borghini and Vicini, 1997), and complementary monetary information determine at least one physical or environmental impact.

### 4.2 Integrating LCC with social aspects

While the integration of the economic impact and environmental impact generated by a product over its life cycle is at a fairly advanced stage, the development of life cycle approaches to assess the social impact of a product is still at the embryonic stage.

Reconstruction of the range of social impacts, both positive and negative, on the various stakeholders, relating to the design, implementation and use of a product is a somewhat difficult operation, while the identification of impact categories and aggregation through quantitative indicators seems almost impossible.

Within the scientific debate, we can distinguish different methodological approaches, amongst the most interesting are social life cycle assessment and the social life cycle impact assessment.

The first, developed by Hunkeler (2006), is a proposal to quantify the social impact of a product in which the key element is the total hours worked. The developed methodology incorporates the basic steps of the LCA and provides a quantitative tool for comparing the social impact of products, offering itself as a complement to Environmental LCAs and LCC for an integrated measure of sustainability.

A distinctive feature is certainly geographical: that in both LCC and LCA, costs or environmental impacts during the life cycle of a product irrespective of the geographical, or rather the connotation, is not as important except for the determination of the energy mix in the country where the project took place.

The societal LCA, and in general all life cycle approaches that seek to take account of social impacts, are site-specific, i.e. the geographical significance is important for calculating key indicators such as those related to health care, housing, or education.

The methodology proposed by Hunkeler includes five main phases:

1. Data collection for each unit process and geographically specific (inventory analysis);
2. Calculation, of each of the major geographic areas, hours worked per unit processes;
3. Calculation of the range of work crossing the inventory data analysis and distribution of unit labour process, and geographical location of points 1 and 2;
4. Estimation of regional characterization factors for each category of social impact;
5. The social LCA result of using the intersection of the data referred to in paragraphs 3 and 4.

The Societal LCA focuses exclusively on one category of stakeholders: employees. As previously anticipated the units are hours worked, a value that lends itself easily to currency conversion. The impacts identified are 4 categories: health care, housing, education and needs (necessities). The characterization factors represent an estimate of hours required in each geographic area to purchase units of each impact category. The entire analysis result indicates the contribution of the functional unit of each purchase of "social need".

Assuming that the social impact can be measured by hundreds of indicators which are difficult to be clustered and have an important local connotation, Hunkeler proposes a "geographically specific" methodology. It is a highly complementary method to both LCA and LCC - in terms of system boundaries of the functional unit - which summarizes the impact of the life cycle in a few quantitative indicators. This element of strength is also the cause of its greatest weakness, in fact, over-simplification of the method has resulted in using the number of hours worked as the sole determinant of 'social', connecting only the wellbeing of people to the wealth generated from their salary.

This differs to the diverse approach used by Dreyer et al. (2006) in outlining the main features that must be incorporated in a Social Life Cycle Impact Assessment. While keeping the basic stages of life cycle assessment, the tool is not intended as an immediately integrated measure with the others to complete the life cycle view of sustainability of a product, but intends to build, using a two-layer system of indicators, a social identity map of the product formed by the sum of individual social profiles of the companies involved in each stage of the life cycle. These profiles are characterized by social effects generated on three main stakeholders (employees, local community and society), from activities to develop the product. Hours worked are determined via a share factor methodology, with the total combined hours worked by each actor to produce a functional unit.

Unlike societal LCA, in this method the hours worked are used exclusively as a weighting factor, and impact indicators are more complex and heterogeneous, being of both a qualitative and quantitative nature, aiming to provide a measure of the level of "protection and promotion of human dignity and welfare."

The system of indicators for measuring social impacts are built on international standards like the Universal Declaration on Human Rights and ILO Conventions and Recommendations, and on major national and local regulations. The latter aspect points to the previous approach, such as the geographic component being relevant to an analysis of the social impact of a good or a service.
However, the complete definition of the methodology of the Social LCIA is still under development, although some impact categories and indicators have been tested successfully in different organizations. It is therefore necessary for further research and trials to overcome those limitations of using a qualitative approach - which makes the model difficult to integrate with other life cycle tools, whilst avoiding an over-simplification, which would diminish its effectiveness.

### 4.3 LCC as a measure of eco-efficiency

To achieve sustainability there is no universal approach, but there exist different methods and concepts that can be used to guide society toward more sustainable patterns of production and consumption. One of these is certainly the concept of eco-efficiency, which combines two of the three pillars of sustainability: the economic and environmental. As defined by the World Business Council for Sustainable Development (2004) eco-efficiency is achieved through the provision of goods and services at a competitive price that satisfies human needs by increasing the quality of life, and progressively reducing ecological impacts of the use of resources throughout their entire life cycle at a rate in line with the estimated capacity of the Earth. It has been argued that for eco-efficiency measures to be calculated, and to add corporate value, it is essential that conventional accounting and financial management applications are integrate with natural science (physical) measures (Schaltegger et al., 2000).
The WBCSD has identified seven elements that an organization can use to increase their eco-efficiency: a reduction in the use of materials and energy, a reduced dispersion of toxic substances, an increased use of recyclable materials, maximising the use of renewable energy, the extension of product durability and increasing the intensity of services.
Acquiring information on eco-efficiency of a product or process not only provides useful information to management regarding the company's performance, but may be subject to communication processes aimed at strengthening dialogue with stakeholders, which can potentially improve a company or products' image. De Simone and Popp (2000), have classified the possible benefits of eco-efficiency into five categories:

- Reduced operating costs due to poor environmental performance (eg. Electricity consumption);
- Possible reduction in future costs due to poor environmental performance (eg. Legal penalties or lost profits related to forced interruption of production);
- Reducing costs of financial capital;
- Increased market share and improving market opportunities;
- Strengthening brand and corporate image.

Measuring eco-efficiency is based on the construction of indicators capable of linking economic and environmental components. There are numerous methods for calculating the basis of components chosen for the construction of the indicator. Since eco-efficiency concepts go beyond corporate boundaries, we require the use of data that is representative of the entire life cycle.

The method developed for the definition of the key interpretation for the Environmental Product Declaration (EPD) Steen et al. (2004) used Life Cycle Costing to build an index capable of measuring the eco-efficiency of a product throughout the entire life cycle.

$$\text{Eco-efficiency} = 1 - (\text{EDC} / \text{LCC})$$

The index constructed by the authors is the ratio between the costs of environmental damage (Environmental Damage cost EDC) and the total cost of the product throughout the entire life cycle, and is expressed as a percentage value (the value 100% indicates, for example, that a product does not produce harmful impacts on the environment).
The EDC is a monetary measure of environmental load units (ELU Environmental Load Unit) generated from the production of a product with respect to impact categories similar to those used in LCA studies: emissions of greenhouse gases, acidifying gases, disrupting ozone gases, photochemical smog precursors, non-renewable energy resource consumption and emissions of substances that contribute to inadequate oxygen amounts in water.
One study by the CPM (Centre for the Environmental Assessment of Products and Material System) has verified the validity and enforceability of the index as a measure of eco-efficiency by comparing two versions of the electric motor HXR500, with or without the ACS800 frequency converter, produced by the Swiss-Swedish multinational ABB (Lyrstedt, 2005).
The measure of the eco-efficiency index showed that the combination of the electric motor with the converter ACS800 enhances the economic value of the asset while reducing its environmental impact.

| | **Scenario 1** *(HXR500)* | **Scenario 2** *(HXR500 e ACS800)* |
|---|---|---|
| *Life Cycle Costs* | 40501 sek | 21615 sek |
| *Environmental Damage Costs* | 7800 sek | 3922 sek |
| ***Eco-efficiency Index*** | ***81%*** | ***82%*** |

Table 3. Eco-efficiency measure of the ACS800 Converter

## 5. Conclusions

The overview given in this chapter has shown how life cycle costing is a very flexible tool that supports the various actors in the economic arena in the new challenge of sustainability. The capacity of life cycle costing to estimate environmental burdens in financial values, by integrating economic and environmental information of physical evidence, has been largely demonstrated, however, some doubts and uncertainties remain concerning the approach to be used.
Furthermore, recent contributions from the literature on the integration of social impact studies on the life cycle of a product demonstrate there is much room for development. While we are still in the early stages on the side of methodological approaches, it is desirable that in the future there be more trials in order to find a perfect blend between simplification and efficiency.
The social component in the life cycle approach is certainly the most complex element in working towards a tool capable of integrating the three elements of sustainable development. Connecting elements should be sought with other lines of research that have potential synergies. For example, the theme of intangible assets and measures of corporate social capital could be a possible area of development with a view to analysing the contribution of intangible resources of the entire lifecycle of a product.

The use of LCC as a tool-oriented sustainability approach should be analysed also in terms of communication to the consumer. The growing sensitivity of the buyer, be it professional or personal, highlights that market demand is growing for clear information about environmental and social impacts related to a product or service. The perspective could be that LCC provides a condensed function that is able to actually make consumers aware of the sustainability of their choices, economically, environmentally and socially.

## 6. Reference

Artto, K.A. (1994): Life Cycle Cost Concept and Methodologies. Journal of Cost Management, 8 (3, Fall) : 28-32.

Asiedu Y., Gu P., (1998): Product life cycle cost analysis: state of the art review. International Journal of Product Research, 36 (4) : 836 - 908.

Atkinson A.A., Banker R.D., Kaplan R.S., Young S.H., (1998): Management Accounting. Una prospettiva fondata sulle attività. 2nd edition. ISEDI, Torino.

Baldo G.L. (2000): LCA: a tool for energetic and environmental analysis. IPAServizi Editore, Milan.

Baker D., (1996): Environmental Accounting's Conflicts and Dilemmas. Management Accounting, CIMA, 74 (9) : 46 – 48.

Bartolomeo M., Bennett M., Bouma J. J., Heydkamp P., James P., Wolters T., (2000): Environmental management accounting in Europe: current practice and future potential. The European Accounting Review, 9 (1) : 31 – 52.

Bianchi M., (1997): Fare i conti con l'ambiente conviene. Impresa Ambiente, 1/97: 35-40.

Burritt R., Saka C., (2006) Environmental management accounting applications and eco-efficiency: case studies from Japan Journal of Cleaner Production 14 (2006) 1262 - 1275

Ciroth A. (2003), Data Consistency for LCC Data. Draft Discussion Paper of SETAC Working Group on Life Cycle Costing. Janaury 2003.

Cooper R., Slagmulder R., (1998): Cost Management Beyond the Boundaries of the Firm. Management Accounting, 79 (9) : 18 – 20.

De Simone L., Popp F. (2000): Eco-efficiency: the business link to sustainable development, The MIT Press, Cambridge

Drury D.H., McWatters C. S., (1998): Management Accounting Paradigms in Transition. Journal of Cost Management, 12 (3) : 32 – 40.

Dreyer L.C., Haushild M.Z., Schierbeck J. (2006): A Framework for Social Life Cycle Impact Assessment The International Journal of Life Cycle Assessment, 11 (2) : 88 – 97.

Durairaj S. K., Ong S. K., Tan R. B. H., Nee A. Y. C., (2002) : Evaluation of Life Cycle Cost Analysis Methodologies. Corporate Environmental Strategy, 9 (1) : 30 – 39.

Ellram L.M. (1995) "Activity Based Costing and Total Cost of Ownership: A crictical Linkage". Journal of Cost Management, Winter pp. 22-30

Ellram L.M. e Sifred S.P. (1998), "Total Cost of Ownership. A key Concept in Strategic Cost Management Decisions", in Journal of Business Logistics, Vol 19, n.1 pp. 55-84.

Emblemsvåg J. (2001), Activity-Based Life-Cycle Costing. Managerial Auditing Journal, 16 (1) :17–27.

EPA (1995), An Introduction to Environmental Accounting as a Business Management Tool: Key Concepts and Terms. www.epa.gov

Epstein M. J., (1996): Improving Environmental Management with Full Environmental Cost Accounting. Environmental Quality Management, Autumn : 11-22.

Epstein M. J., Roy M-J, (1997): Environmental Management to Improve Corporate Profitability. Journal of Cost Management, 11 (6) : 26 – 34.

Fabricky, W. J. and Blanchard, B. S. (1991) Life Cycle Cost and Economic Analysis, Prentice Hall, New Jersey

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., (2009) Recent developments in Life Cycle Assessment. Journal of Environmental Management, 91, 1-21

Frankl, P. and F. Rubik (eds.) (2000), 'Life Cycle assessments in Industry and Business, Adoption Patterns, Applications and Implications', Berlin, Heidelberg, New York: Springer.

Hellweg S., Hofstetter T. B., Hungerbühler, (2003) : Discounting and the Environment. The International Journal of Life Cycle Assessment, 8 (1) : 8 – 18.

Horvath A., (2003): Life-Cycle Environmental and Economic Assessment of using recycled materials for asphalt pavements. Technical Report. University of California Transportation Center (UCTC).

Hunkeler D., (2006): Societal LCA Methodology and a Case Study The International Journal of Life Cycle Assessment, 11 (6) : 371 – 382.

Hunkeler D., Rebitzer G., (2003): Life Cycle Costing - Paving the Road to Sustainable Development? The International Journal of Life Cycle Assessment, 8 (2) : 109 – 110.

Huppes, (2004), Life Cycle Costing and Life Cycle Assessment in Management Accounting for Sustainability. Presented at the EMAN Conference "Sustainability Accounting and Reporting", March 4-5th 2004, Lueneburg, Germany.

Huppes G., van Rooijen M., Kleijn R., Heijungs R., de Koning A., van Oers L., (2004): Life Cycle Costing and the environment. Report of a Project Commissioned by The Ministry of VROM-DGM.

Hutton R. B., Wilkie W. L.(1980) Life Cycle Cost: A New Form of Consumer Information; The Journal of Consumer Research, Vol. 6, No. 4. (Mar., 1980), pp. 349-360.

Iraldo, F., Melis, M., Testa, F., (2007): L'attuale sviluppo del Green Public Procurement; Economia delle Fonti di Energia e dell'Ambiente 1, pp. 1-8

ISO, 2006. ISO 14040 International Standard. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organisation for Standardization, Geneva, Switzerland.

Jeswani, H.K. Azapagic, A., Schepelmann, P., and Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches. Journal of Cleaner Production, 18, 120-127.

Kreuze, J.G. and G.E. Newell (1994), ABC and Life-Cycle Costing for Environmental Expenditures: The combination gives companies a more accurate snapshot. Management Accounting, 75 (8) : 38-42

Krozer, Y. (2008) Life cycle costings for innovations in product chains. Journal of Cleaner Production 16: 310-321.

Lazzari S., Levizzari A., (2000): Life Cycle Costing as a New Tool Matching Economical and Environmental Evaluations: The Experience on a Real Case Study. SAE Technical Paper 2000-01-1466.

Letmathe P., Doost R. K., (2000): Environmental cost accounting and auditing. Managerial Auditing Journal, 15 (8) : 424 - 430.

Lyrstedt F. (2005) "Measuring eco-efficiency by a LCC/LCA ratio, an evaluation of its applicability" Master of Science Thesis in the Master Degree Programme: International Project Management, Chalmers University of Technology Sweden.

Nilsson M, Eckerberg K (Eds.), 2007,Environmental policy integration in practice: Shaping institutions for learning, (Earthscan, London)

Norris G.A., (2001): Integrating Life Cycle Costing Analysis and Life Cycle Assessment. The International Journal of Life Cycle Assessment, 6(2), 118 – 120.
Orbach T., Liedtke C., (2003): Resource-efficiency accounting. In Bennett M., Bouma J. J., Wolters (eds): Environmental Management Accounting: informational and institutional developments. Kluwer Academic Publishers, London.
Pitzalis A. (2003a) "La logica del Life Cycle Costing" in Strumenti per l'Analisi dei Costi , Vitali P. (a cura di) Giappichelli, Torino
Pitzalis A. (2003b) "Il Total Cost of Ownership" in Strumenti per l'Analisi dei Costi , Vitali P. (a cura di) Giappichelli, Torino
Porter M., van der Linde C., (1996): Green and Competitive: Ending the stalemate. In Welford R., Starkey R. (eds.): The Earthscan Reader in Business and the Environment. Earthscan Pubblications.
Ranaganathan J., Ditz D., (1996): Environmental Accounting: a tool for better management. Management Accounting, CIMA, 74 (2) : 38 – 40.
Rebitzer G., (2002), Integrating Life Cycle Costing and Life Cycle Assessment for Managing Costs and Environmental Impacts in Supply Chains. In: Seuring S., Goldbach M. (editors): Cost Management in Supply Chains. Heidelberg: Physica-Verlag.
Rebitzer G., Hunkeler D. (2003): Life Cycle Costing in LCM: Ambition, Opportunities and Limitations. The International Journal of Life Cycle Assessment, 8 (5) : 253 – 256.
Rebitzer G., Hunkeler D. (2005): The future of Life Cycle Assessment. The International Journal of Life Cycle Assessment, 10 (5) : 305 – 308.
Rebitzer G., Seuring (2003), Methodology and Application Of Life Cycle Costing. The International Journal of Life Cycle Assessment, 8 (2) : 110 – 111.
Saur K., Donato G., Cobas Flores E., Frankl P., Astrup Jensen A., Kituyi E., Lee K. M., Swarr T., Tawfic M., Tukker A., Schaltegger S, Burritt RL. Contemporary environmental accounting issues, concepts and practice. Sheffield, UK: Greenleaf Publishing; 2000
Schmidt W.P., (2003): Life Cycle Costing in Design for the Environment. The International Journal of Life Cycle Assessment, 8 (3) : 167 – 174.
Settani E. (2006): LCA-type Life Cycle Costing: note metodologiche ed applicazione alla produzione di energia ed al recupero di materia. www.ambientediritto.it
Shapiro K. G., (2001): Incorporating Costs in LCA. The International Journal of Life Cycle Assessment, 6(2), 121- 123.
Sten B., Garling A., Imrell A. M., Sanne K., (2004): Development of interpretation keys for environmental product declaration (EPD), Chalmers, ABB, Azo Nobel, Sweden.
Susman G.I. (1995) "Product Life Cycle Management", in Brinker B. (editor), Handbook of Cost Management, Warren, Gorham & Lamont, Boston
Udo de Haes H, Heijungs R, Suh S, Huppes G. Three strategies to overcome the limitations of life-cycle assessment. Journal of Industrial Ecology 2004;8(3):19–32.
United Nations Environment Programme, 2002. Life Cycle Initiative homepage,
<http://lcinitiative.unep.fr/default.asp?site=lcinit&page_id=15CFD910-956F-457D-BD0D-3EF35AB93D60>
Vogtländer J. G., Bijma A., Brezet H. C., (2002): Communicating the eco-efficiency of products and services by means of the eco-costs/value model. Journal of Cleaner Production, 10 (1) : 57 – 67.
Weidema B.P., (2006): The Integration of Economic and Social Aspects In Societal Life Cycle Impact Assessment The International Journal of Life Cycle Assessment, 11 Special Issue 1: 89 – 96.
Weitz, K. A., J. K. Smith and J. L. Warren (1994): Developing a Decision Support Tool for Life Cycle Cost Assessment. Total Quality Environmental Management (Autumn): 23-36.

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The purpose of supply chain management is to make production system manage production process, improve customer satisfaction and reduce total work cost. With indubitable significance, supply chain management attracts extensive attention from businesses and academic scholars. Many important research findings and results had been achieved. Research work of supply chain management involves all activities and processes including planning, coordination, operation, control and optimization of the whole supply chain system. This book presents a collection of recent contributions of new methods and innovative ideas from the worldwide researchers. It is aimed at providing a helpful reference of new ideas, original results and practical experiences regarding this highly up-to-date field for researchers, scientists, engineers and students interested in supply chain management.

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