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Applications and Theory of Analytic Hierarchy Process

Decision Making for Strategic Decisions

Edited by Fabio De Felice,
Thomas L. Saaty and Antonella Petrillo

APPLICATIONS AND THEORY OF ANALYTIC HIERARCHY PROCESS - DECISION MAKING FOR STRATEGIC DECISIONS

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Contributors

Ivana Ognjanovic, Ramo Šendelj, Clemens Blattert, Boštjan Gomišček, Paulo António Rodrigues Pereira, Sandra Xavier, Tomasz Stypka, Agnieszka Flaga-Maryańczyk, Jacek Schnotale, Karmen Pažek, Claudio Garuti, Valerio A. P. Salomon, Claudemir Tramarico, Fernando Marins, Elio Padoano, Giovanni Longo, Cristian Giacomini, Alice Lunardi, Antonella Petrillo, Fabio De Felice, Domenico Falcone, Rabah Medjoudj, Djamil Aissani, Fairouz Iberraken, Emmanuel Olateju Oyatoye, Adedotun Odulana

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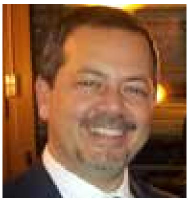
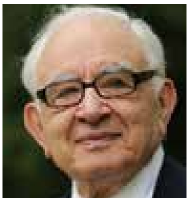


Fabio De Felice is a Professor at the University of Cassino and Southern Lazio, Italy, where he received his PhD in Mechanical Engineering. His current research focuses on multi-criteria decision-making analysis (with emphasis on AHP and ANP) and industrial, project and supply chain management. Currently, he serves as a member of Scientific Advisory Committee of International Symposium on the Analytic Hierarchy Process (ISAHP). He is the founder of AHP Academy that promotes the diffusion of the culture and methodologies of Decision Making, with particular reference to those based on Analytic Hierarchy Process. He is a member of the editorial boards of several international organizations and journals and has authored/co-authored numerous articles in the areas of decision science and business management.



Thomas L. Saaty is the Distinguished University Professor at the University of Pittsburgh. Previously, he worked for the U.S. Government agencies and government-sponsored companies and he was also a professor at the University of Pennsylvania. Prof. Saaty developed the Analytic Hierarchy Process (AHP) for decision-making and its generalization to feedback, the Analytic Network Process (ANP). He published 43 books and more than 300 papers. His latest books are: Group Decision Making: Drawing out and Reconciling Differences: Problem Solving & Decision Making; The Brain: Unraveling the Mystery of How It Works; Creative Thinking and Problem Solving; The Neural Network Process (NNP).

Antonella Petrillo is a researcher at the Department of Engineering of the University of Naples Parthenope, Italy. She received her PhD in Mechanical Engineering from University of Cassino. Her research interests include multi-criteria decision analysis, industrial plant, logistics and safety. She serves as an Associate Editor for the International Journal of the Analytic Hierarchy Process. She is a member of AHP Academy and a member of several editorial boards.

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Preface

We make important decisions every day, simple choices and hard choices. Our lives are the sum of our decisions, whether in business or in personal spheres. Often, when we decide is just as important as what we decide. Deciding too quickly can be hazardous; delaying too long can mean missed opportunities. In any case it is important to decide. Decision making is fundamental to furthering our goal of survival and ensuring the quality of our life. To be a person is to be a *decision maker.*

This book is about making decisions the natural way which we call the *Analytic Hierarchy Process (AHP).* It involves assumptions about what people do with their biological equipment. They should not need to steep themselves for long in technical training to organize their thinking and discover what judgments they hold. They should be able to approach a decision problem by posing and answering the right kind of questions.

The Analytic Hierarchy Process (AHP), described in several of our earlier works and now widely used in decision making, is a theory that depends on values and judgments of individuals and groups. It is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology.

This book presents some application examples of Analytic Hierarchy. It contains original research and application chapters from different perspectives, and covers different areas such as supply chain, environmental engineering, safety and social issues.

In detail, **Chapter 1** presents AHP applications to solve two real supply chain management problems faced by Brazilian companies: one problem regarding resource allocation (RA) in the automotive industry and another one regarding supply selection (SS) in a chemical corporation.

Chapter 2 "An Analytical Hierarchy Process to Decision Making in Human Blood, Cells, and Tissue Banks" offers an application of AHP to the production of blood and presents a case study that could be interpreted as applicable to other situations in these organizations. A case study on the application of the Analytic Hierarchy Process (AHP) to assess agri-environmental measures of the Rural Development Programme (RDP 2007-2013) in Slovenia is presented in **Chapter 3**. The issue of environmental management is analyzed in **Chapter 4** with particular attention to 3 case studies: the first one concerning the selection of the best municipal solid waste disposal system, the second one regarding the assessment of the tap and bottled water consumption on the environment, and the last one on the selection of the heat pump for the individual home. In **Chapter 5**, the authors analize two aspects: a model for maintenance policy selection based on the AHP methodology and a model to determine the importance of sustainability factors for employee suggestion systems. A strategic decision model, based on AHP, in the transport sector, concerning the reconfiguration of the railway infrastructure of the seaport of Trieste is presented in **Chapter 6**. In **Chapter 7** authors propose a novel approach to ensure safety in emergency conditions in industrial plants considering the presence of dangerous equipment and human errors. The proposed idea aims to integrate the Human Reliability Analysis (HRA) and the Failure Mode and Effects Analysis (FMEA).

The topic is extended in **Chapter 8** where the authors develop a perceived comprehensive disaster Risk Index in three Chilean Cities. In **Chapter 9** we shift our attention to identify stakeholders' decision criteria using a meta-heuristic approach and AHP. **Chapter 10** presents an analysis on evaluation of growth simulators for forest management in terms of functionality and software structure using AHP. The problem of measuring closeness in weighted environments (decision-making environments) is developed in **Chapter 11**. The relevance of this article is related to having a dependable cardinal measure of distance in weighted environments. **Chapter 12** provides an AHP Method with BOCR Merits to Analyze the Outcomes of Business Electricity Sustainability. Finally, **Chapter 13** addresses how AHP model developed for contractor selection can be implemented on the computer to get the right ratings using some existing computer software.

This book is intended to be a useful resource for anyone who deals with decision making problems. Furthermore, we hope that this book will provide useful resources, techniques and methods for further research on Analytic Hierarchy Process.

As editors of this book, we would like to thank the authors who accepted to contribute with their invaluable research as well as the referees who reviewed these papers for their effort, time and invaluable suggestions. Our special thanks to Ms. Ana Pantar, Publishing Process Manager, for her precious support and her team for this opportunity to serve as guest editors.

Fabio De Felice
University of Cassino and Southern Lazi,
Cassino, Italy

Thomas L. Saaty
University of Pittsburgh,
PA, USA

Antonella Petrillo
University of Naples Parthenope,
Naples, Italy

Chapter 1

Analytic Hierarchy Process Applied to Supply Chain Management

Valerio Antonio Pamplona Salomon,
Claudemir Leif Tramarico and
Fernando Augusto Silva Marins

Additional information is available at the end of the chapter

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Abstract

Resource allocation (RA) and supplier selection (SS) are two major decision problems regarding supply chain management (SCM). A supply chain manager may solve these problems by considering a single criterion, for instance, costs, customer satisfaction, or delivery time. Applying analytic hierarchy process (AHP), the supply chain manager may combine such criteria to enhance a compromised solution. This chapter presents AHP applications to solve two real SCM problems faced by Brazilian companies: one problem regarding the RA in the automotive industry and another one to SS in a chemical corporation.

Keywords: analytic hierarchy process, ranking reversal, resource allocation, supplier selection, supply chain management

1. Introduction

Supply chain is the "global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash" [1]. Therefore, many decision problems make up the supply chain management (SCM). Resource allocation (RA) and supplier selection (SS) are two major decision problems regarding SCM. A supply chain manager may solve these problems by considering a single criterion, for instance, costs, customer satisfaction, or delivery time. Applying Analytic Hierarchy Process (AHP), the supply chain manager may combine such criteria to enhance a compromised solution.

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Foundations of AHP came back from the 1970s [2]. Originally, AHP consisted in hierarchy structuring, relative measurement (pairwise comparisons between criteria and between alternatives), and distributive synthesis (priorities are normalized, i.e., they sum equal to one).

One great advance in AHP practice is the “absolute measurement”, also known as “ratings” [3]. In absolute measurement, alternatives are compared with standard levels, instead of pairwise compared. Relative measurement has been most applied than ratings, even with software packages including ratings [4, 5]. Since in relative measurement alternatives must be pairwise compared, their number must be less than or equal to nine, that is, “seven, plus or minus two” [6]. In absolute measurement there is no bound for the set of alternatives. Another advantage from using ratings is the opportunity to avoid biases. With alternatives being compared with each other, two by two (relative measurement), some historical trends could be kept in mind. Comparing alternatives with a standard (absolute measurement) seems to provide a less partial or unbiased measurement.

Another advance for original AHP comes with the “ideal synthesis” [7]. With ideal synthesis, priorities are not normally distributed. That is, the sum of priority vectors components will not be equal to one. In this mode, the highest priority regarding each criterion will be equal to one. Normalizing priorities creates a dependency among priorities. However, if an old alternative is deleted or if a new one is inserted normalized priorities can lead to illegitimate changes in the rank of alternatives, known as rank reversal (RR). RR was firstly associated with AHP in preliminary studies by Professor Valerie Belton at University of Cambridge [8].

This chapter presents AHP applications to solve SCM problems. Two real cases from Brazilian companies are presented, one case regarding to RA in the automotive industry and another one to SS in a chemical corporation. In both cases, AHP was applied with absolute measurement. However, in the first case, the normal synthesis was adopted; in the second case, ideal synthesis was applied. The first conclusion from these cases is that for RA, normal synthesis maybe proper than ideal synthesis; conversely, for SS, ideal synthesis maybe more indicated.

2. Ranking reversal and synthesis mode

To illustrate the concept of RR, let us consider a decision of project selection by a company. The decision criteria are Benefits (B), Opportunities (O) and Risks (R). After pairwise comparisons, the priorities for the criteria (B, O and R) are, respectively, 73%, 19%, and 8%. Project X will be the selected one, due its highest overall priority (**Table 1**).

Project	Benefits (73%)	Opportunities (19%)	Risks (8%)	Overall
X	0.540	0.185	0.149	0.442
Y	0.348	0.659	0.691	0.434
Z	0.112	0.156	0.160	0.124

Table 1. Priorities for Projects X, Y, and Z (normal synthesis).

Let us now consider that the supplier responsible for Project Z unexpectedly discontinues its operations. So, this alternative must be deleted of the decision. Then, surprisingly, overall priority of Project Y becomes higher than Project X's (**Table 2**).

Project	Benefits (73%)	Opportunities (19%)	Risks (8%)	Overall
X	0.600	0.250	0.167	0.499
Y	0.400	0.75	0.833	0.501

Table 2. Priorities for Projects X and Y (normal synthesis).

With the same set of criteria and alternatives, but with ideal synthesis, overall priority of Project X will be higher than Project Y's, considering Project Z (**Table 3**), or not (**Table 4**).

Project	Benefits (73%)	Opportunities (19%)	Risks (8%)	Overall
X	1	0.281	0.215	0.801
Y	0.643	1	1	0.740
Z	0.207	0.237	0.232	0.215

Table 3. Priorities for Projects X, Y, and Z (ideal synthesis).

Project	Benefits (73%)	Opportunities (19%)	Risks (8%)	Overall
X	1	0.281	0.215	0.801
Y	0.643	1	1	0.740

Table 4. Priorities for Projects X and Y (ideal synthesis).

As presented in **Tables 1–4**, when one alternative is pulled out from the decision, ideal synthesis preserves ranks; conversely, normal synthesis reverses ranks. RR also may occur when new alternatives are inserted, or even when the set of criteria is changed. Matter of fact, absolute measurement and ideal synthesis always preserve ranks [9]. However, it is important to note that RR can be legitimate. That is, RR has already occurred. Two examples of real world decisions with RR are the United States Presidential Election, in 2000, and the Election of Host City of the 2016 Summer Olympics, in 2009.

The United States Presidential Election, in 2000, was quite controversial. The main contesters were Al Gore, George W. Bush, and Ralph Nader (**Table 5**).

Contester	Party	Electoral votes	Popular votes
Al Gore	Democratic	266	48.9%
George W. Bush	Republican	271	47.9%
Ralph Nader	Green	0	2.7%

Table 5. United States presidential election 2000.

Bush won with 271 electoral votes against 266 votes for Gore. It was the only fourth time, in 54 presidential elections, that the electoral vote winner failed to win also by popular vote. However, this is not an RR situation, because the set of alternatives was unchanged. An RR could have happened if Nader had quit. That is, most of Nader's popular votes could go to Gore, in a case of Nader deletion from **Table 5**. For this reason, Nader was accused of spoil the Gore presidency [10].

During the 121st International Olympic Committee Session, Rio de Janeiro was selected as the host city of the 2016 Summer Olympics. Chicago, Madrid, and Tokyo were the other applicant cities (**Table 6**). On the first round, Madrid had more votes, Rio was the second, Tokyo was the third, and Chicago, with fewer votes, was eliminated. From the second round, Rio had more votes, then, an RR occurred, and, for the first time, South America will host the Summer Olympics.

City	Round 1	Round 2	Round 3
Chicago	19.1%		
Madrid	29.8%	30.5%	32.6%
Rio de Janeiro	27.7%	48.4%	67.4%
Tokyo	23.4%	21.1%	

Table 6. Votes for host city of Summer Olympics 2016.

Depending on the type of measurement and synthesis, ranks can be preserved or reversed with AHP. Nevertheless, the main discussion is the legitimacy of RR for the decision. For instance, RR may be avoided for a president election. After all, it is not only a pair of persons (the nominee for president and the running mate) who are being elected. With the candidate, also his ideas, political orientation (conservationist or reformist, etc.), and a whole party is being selected for a four-year term. For this reason, in countries like Brazil, a two round election is adopted for presidential elections.

In another instance, for the selection of the host city for a major event, RR can be acceptable. At first, it may sound strange: X is preferred among X, Y and Z, but Y is preferred between X and Y. What happened? Who preferred Z also preferred Y than Z. In this case, RR will be legitimate. Since, AHP is a method that allows RR, its application than will be proper than other methods which not allow RR.

In Sections 3 and 4, two SCM problems are presented. For the first one, RR will not be a problem: the normal synthesis is adopted. In the second case, RR must be avoided: the ideal synthesis is adopted.

3. AHP applied to SCM in an automobile plant

Supply chain is a network of supplier-customer companies connected by information and production flows, among other flows. For instance, a supply chain for an automobile production, beyond the car maker, or car assembler, may include auto parts manufacturers (Tiers 1 and 2 Suppliers), raw material providers, logistics providers, car dealers, and, as end customer, the car owner (**Figure 1**).

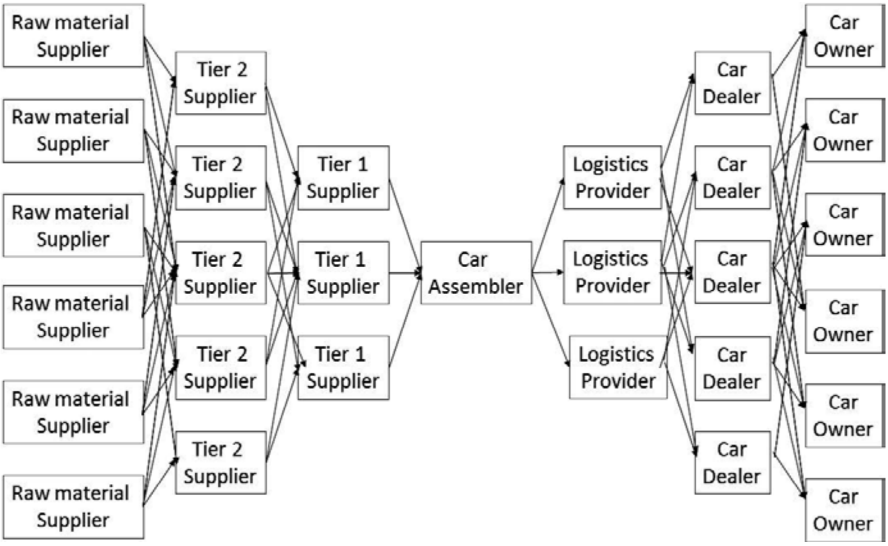

Figure 1. Automobile supply chain.

Let us consider a Brazilian manufacturer of vehicle frames, also known as chassis. This manufacturer has four plants (two in Brazil, one in Mexico, and a new one in Argentina) to closer supply its customers. These plants act as Tier 1 Suppliers for major car assemblers. In all these plants, the multiple source policy is adopted. That is, purchased items are provided eventually by more than one supplier. This policy has the main advantages of supplier competition and operational flexibility [11].

Blanking is the main process in the chassis production. Blank dies are specialized tools purchased in large lots to attend annual demands. The decision making is decentralized: buyers from each plant select suppliers for local requirements. Due to multiple supplier policy, a lot is often distributed in more than one supplier. Then, this is a resource allocation (RA) problem.

Suppliers are usually selected for a lot considering two main attributes: payment conditions and supplier loading. Usually, suppliers offering best payment conditions are selected. However, if a supplier has too many orders, then this supplier will be sidestepped. The distribution of a lot among suppliers is all done by a single buyer.

In one of the Brazilian plants, the Production Manager decides to apply the AHP, considering his team expertise to a new purchase of blank dies. The production management team, composed of three engineers, including the Production Manager, listed twelve more attributes desired for a supplier:

- Capability, that is, supplier's know-how.
- Certification of the management system, according to international standard.
- Quality, based on engineering tolerance.
- Reliability, based on expected lifetime.
- Services, post-sale technical support provided by suppliers.
- Post-sales costs, differently charged by suppliers for post-sales support.
- Flexibility, based on the supplier's skills to change product specifications or lot size in orders.
- Reaction, that is, supplier's speed to incorporate these changes.
- Sub-suppliers, that is, suppliers of the supplier.
- Price truthful (does the die worth the charged price?).

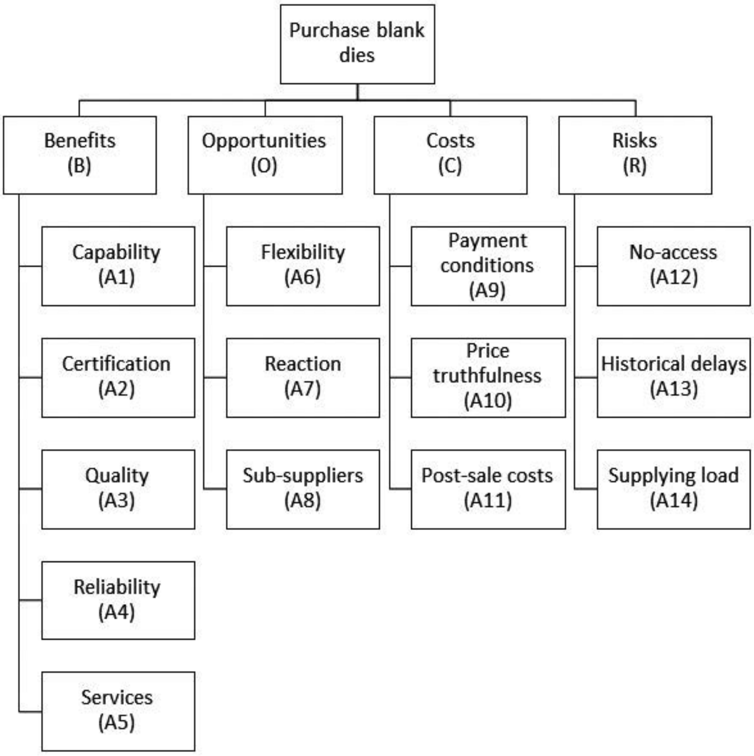

Figure 2. Hierarchy of attributes to prioritize suppliers of blank dies.

- Risk of the no-access supplier, on time, when a need for support emerges.
- Historical delays from previous deliveries.

The fourteen attributes (the new twelve plus the old two) were grouped based on the Benefits-Opportunities-Costs-Risks (BOCR) model [12], resulting in a hierarchy for the set of attributes (**Figure 2**).

The Production Manager decided that each major aspect of BOCR should equally contribute for the decision. Therefore, the overall priorities for Benefits, Opportunities, Costs, and Risks were set in 25% each. Every member of the production management team made pairwise comparisons between attributes inside the aspects (**Table 7**).

Attribute	A1	A2	A3	A4	A5
Capability (A1)	1	7	1	1	3
Certification (A2)	1/7	1	1/7	1/7	1/7
Quality (A3)	1	7	1	1	1
Reliability (A4)	1	7	1	1	3
Services (A5)	1	1/7	1	1/3	1

Table 7. Pairwise comparisons for attributes on benefits according to one member of production management team.

Comparisons made by every engineer were individually aggregated, by geometrical mean, since they are willing their preferences for the same organization [13]. This procedure results in an aggregated comparisons matrix (**Table 8**).

Attribute	A1	A2	A3	A4	A5	Priority
Capability (A1)	1	$(392)^{1/3}$	$(6)^{1/3}$	$(1/6)^{1/3}$	$(6)^{1/3}$	26%
Certification (A2)	$(1/392)^{1/3}$	1	$(1/280)^{1/3}$	$(1/567)^{1/3}$	$(315)^{1/3}$	3%
Quality (A3)	$(1/6)^{1/3}$	$(280)^{1/3}$	1	$(1/15)^{1/3}$	$(6/5)^{1/3}$	17%
Reliability (A4)	$(6)^{1/3}$	$(567)^{1/3}$	$(15)^{1/3}$	1	$(8/3)^{1/3}$	35%
Services (A5)	$(1/6)^{1/3}$	$(315)^{1/3}$	$(5/6)^{1/3}$	$(3/8)^{1/3}$	1	19%

Table 8. Pairwise comparisons for attributes on benefits aggregated to all member of production management team.

The local priorities for all attributes can be obtained normalizing the right eigenvector for the aggregated comparison matrices. The overall priorities for the attributes are obtained weighting local priorities by 25% (**Table 9**).

Attribute	Overall priority
Capability (A1)	7%
Certification (A2)	1%
Quality (A3)	4%
Reliability (A4)	8%
Services (A5)	5%
Flexibility (A6)	6%
Reaction (A7)	13%
Sub-suppliers (A8)	6%
Payment conditions (A9)	17%
Price truthfulness (A10)	4%
Post-sale costs (A11)	4%
No-access (A12)	2%
Historical delays (A13)	5%
Supplying load (A14)	18%

Table 9. Overall priorities of attributes for suppliers of blank dies.

The production management team prioritized six potential suppliers with ratings, that is, relative measurement, by consensus. They prioritized the suppliers rating them in a 0–1 linear scale (**Table 10**). For Certification (A2), the priority value was binary: 1, when the supplier had a certified management system, or 0, otherwise.

Supplier	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14
S1	0.8	1	0.7	0.8	0.8	0.8	0.9	0.9	0.6	0.6	0.7	0.8	0.9	0.9
S2	0.7	0	0.8	0.7	0.8	0.9	0.7	0.8	0.7	0.8	0.8	0.8	0.7	0.8
S3	1	1	0.9	0.9	0.9	0.7	1	1	0.5	0.5	0.7	0.7	0.7	0.9
S4	0.8	0	0.9	0.9	0.8	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.8
S5	0.7	1	0.8	0.85	0.9	0.8	0.6	0.8	0.3	0.3	0.8	0.9	0.8	0.7
S6	0.5	0	0.6	0.6	0.6	0.5	0.2	0.6	1	1	0.5	0.2	0.5	0.5

Table 10. Rated suppliers of blank dies.

S5 was the most expensive supplier (A9 = 0.3) and S6 was the cheapest one (A9 = 1). However, S6 will be not be selected, since it was relatively overloaded (A14 = 0.5). Usually, a buyer makes this decision. Sometimes, buyers make unpredictable decisions for production management.

Then, Production Manager decides to go on with AHP application. Next step is normalizing priorities for each attribute. Then, normalized priorities need to be weighted by criteria priorities (**Table 9**). This way, a decision matrix brings local priorities for each aspect (BOCR) and overall priorities (**Table 11**).

Supplier	Benefits (25%)	Opportunities (25%)	Costs (25%)	Risks (25%)	Overall
S1	17.4%	19.7%	15.4%	19.6%	18.0%
S2	15.1%	17.3%	18.3%	17.1%	17.0%
S3	20.4%	20.9%	13.3%	18.5%	18.3%
S4	17.4%	18.5%	20.4%	18.2%	18.6%
S5	17.9%	15.5%	9.4%	16.2%	14.7%
S6	11.7%	8.0%	23.2%	10.4%	13.3%

Table 11. Local and overall priorities for suppliers of blank dies.

Production Manager decided to delete Suppliers 5 and 6 for the next supplying of blank dies. Then, the lot will be equally divided in four suppliers (S1–S4). The overall priorities for suppliers will change from (18.0%, 17.0%, 18.3%, 18.6%, 14.7%, 13.3%) to (25%, 25%, 25%, 25%). This is not a case of ranking reversal. If S5 and S6 were deleted in **Tables 10** and **11**, overall priorities will be (25.0%, 23.7%, 25.3%, 26.0%). Therefore, AHP application supported the Production Manager decision.

Production Manager, finally, communicates the decision to procurement management. The new role for buyers will be only to contact suppliers and purchase the blank dies. After all, production will be the user of the blank dies in their processes, not the buyers. No contest emerged, and the company was confident that select suppliers not only based in costs and risks, but also considering benefits and opportunities would be a better decision.

4. AHP applied to SCM by a chemical corporation

Outsourcing is an increased business practice. Instead of directly providing to customers, suppliers may contract third-party companies to perform non-core activities. Functions often outsourced include accounting, human resources, and marketing [14]. Logistics of finish goods to resellers is 100% outsourced by a chemical corporation in Brazil. That is, Third-Party Logistics (3PL) providers transport all items produced in the Brazilian plants to distribution centers. Land transport is the dominant mode of transport, and there are three 3PL providers. When a plant requires a new transportation, from the corporate office, located in Sao Paulo City, one of four buyers selects a 3PL provider. There is no structured method to select 3PL providers. Then, the Supply Chain Manager decided to apply AHP to select a 3PL for a new transportation order.

Desired attributes for a 3PL provider include [15, 16]:

- Costs.
- Financial performance.
- Geographical location.
- Information technology.
- Operations performance.
- Quality.
- Responsiveness.
- Risks.
- Workforce.

The SCM team grouped 27 attributes, relevant for 3PL of the chemical corporation, in a BOCR model (**Figure 3**).The fourteen attributes regarding to Benefits were grouped as structural benefits or technological benefits.

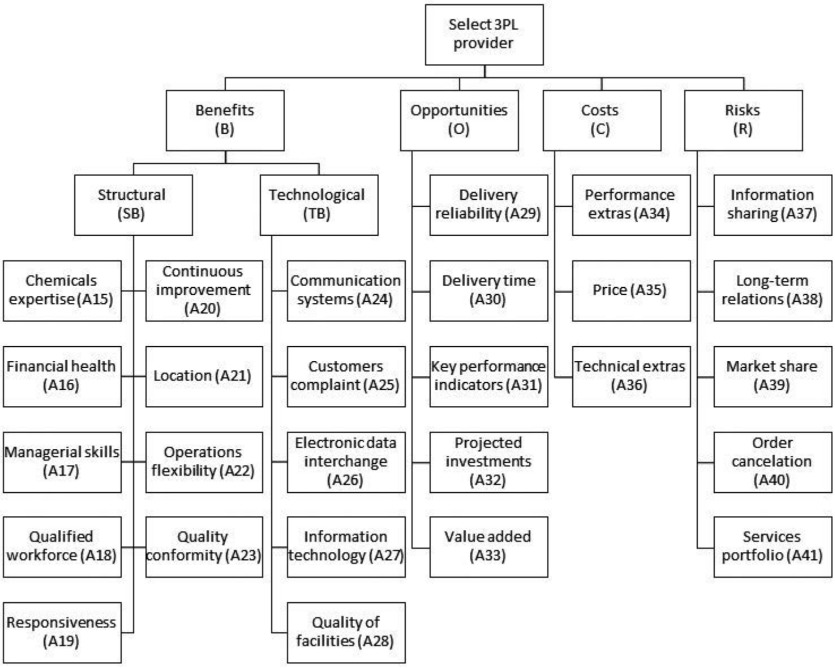

Figure 3. Hierarchy of attributes for third-party logistics provider.

As in the previous case of blank dies supplier selection, the chemical corporation's SCM team decided that each major aspect of BOCR should equally contribute for the decision. Then, the overall priorities for Benefits, Opportunities, Costs, and Risks are also 25% each. Every member of SCM, including the Supply Chain Manager, compared the attributes inside the aspects. They input their judgments in an AHP web-based software. This software enables comparison values with two decimal points, as 2.33 (**Table 12**).

Costs	A34	A35	A36
Performance extras (A34)	1	2.33	0.70
Price (A35)	1/2.33	1	0.40
Technical extras (A36)	1/0.70	1/0.40	1

Table 12. Pairwise comparisons for attributes on benefits according to one member of supply chain management team.

Comparisons made by every SCM member were individually aggregated, by geometrical mean, resulting in aggregated comparison matrices, which resulted in the local priorities for the attributes (**Table 13**).

Costs	A34	A35	A36	Local priority
Performance extras (A34)	1	$(0.122)^{1/5}$	$(0.233)^{1/5}$	25.9%
Price (A35)	$(1/0.122)^{1/5}$	1	$(2.238)^{1/5}$	39.8%
Technical extras (A36)	$(1/0.233)^{1/5}$	$(1/2.238)^{1/5}$	1	34.3%

Table 13. Pairwise comparisons for attributes on costs aggregated to all member of supply chain management team.

The local priorities for all attributes can be obtained normalizing the right eigenvector for the aggregated comparisons matrices. The overall priorities for the attributes A29–A41 are obtained weighting local priorities by 25%; for A15–A28, local priorities must be weighted by 12.5%, since local priorities for structural benefits and technological benefits are 50% each (**Table 14**).

Attribute	Overall priority
Chemicals expertise (A15)	1.0%
Financial health (A16)	1.9%
Managerial skills (A17)	1.6%
Qualified workforce (A18)	1.4%
Responsiveness (A19)	1.7%
Continuous improvement (A20)	1.7%
Location (A21)	1.2%
Operations flexibility (A22)	1.2%

Attribute	Overall priority
Quality conformity (A23)	0.8%
Communication systems (A24)	2.7%
Customers complaint (A25)	2.7%
Electronic data interchange (A26)	2.1%
Information technology (A27)	2.1%
Quality of facilities (A28)	2.9%
Delivery reliability (A29)	5.8%
Delivery time (A30)	5.4%
Key performance indicators (A31)	3.6%
Projected investments (A32)	3.9%
Value added (A33)	6.3%
Performance extras (A34)	6.5%
Price (A35)	9.9%
Technical extras (A36)	8.6%
Information sharing (A37)	4.3%
Long-term relations (A38)	4.9%
Market share (A39)	5.1%
Order cancellation (A40)	6.3%
Services portfolio (A41)	4.4%

Table 14. Overall priorities of attributes for 3PL providers.

In this case, AHP must be applied with absolute measurement and ideal synthesis, since RR is not desired. The rating of 3PL providers will be based on a five-level scale from Poor to Excellent performance (**Table 15**).

Level	L1	L2	L3	L4	L5	L6	Priority
Excellent (L1)	1	2	3	5	7	9	1
Between excellent and very good (L2)	1/2	1	3	4	7	8	0.75
Very good (L3)	1/3	1/3	1	5	6	8	0.49
Between very good and good (L4)	1/5	1/4	1/5	1	6	8	0.25
Good (L5)	1/7	1/7	1/6	1/6	1	3	0.10
Poor (L6)	1/9	1/8	1/8	1/8	1/3	1	0.06

Table 15. Levels of performance [16].

By consensus, the SCM team rated three 3PL providers, for every attribute (**Table 16**).

3PL provider	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28
S7	L1	L2	L4	L2	L1	L3	L2	L2	L1	L4	L5	L2	L2	L4
S8	L1	L4	L1	L3	L3	L2	L3	L3	L2	L3	L3	L3	L3	L5
S9	L1	L2	L2	L3	L4	L4	L1	L4	L3	L2	L3	L3	L1	L6

Table 16. Rated 3PL providers according to benefits.

Local priorities regarding every criterion are obtained with the priorities of levels L1–L6. Overall priorities for 3PL providers (**Table 17**) are obtained weighting local priorities by the priorities of attributes.

3PL provider	Benefits	Opportunities	Costs	Risks	Overall
S7	0.55	0.75	0.25	0.54	0.52
S8	0.51	0.49	0.56	0.7	0.57
S9	0.55	0.42	0.53	0.65	0.54

Table 17. Local and overall priorities for 3PL provider.

Overall priorities for 3PL providers indicate medium performances for the suppliers. SP8, SP9 and SP7 are almost tied with respective overall priorities equal to 0.57, 0.54 and 0.52. However, these priorities were obtained with balanced priorities for the major aspects of BOCR model.

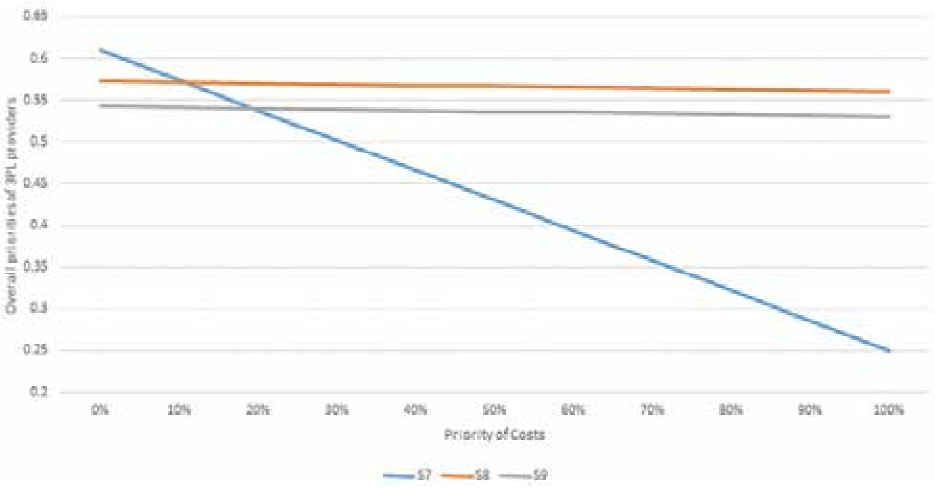

Figure 4. Sensitivity analysis of 3PL providers' overall priorities to priority of costs.

The current Brazilian scenario, with economic recession, suggests unbalances favoring Costs and Risks. Then, after sensitivity analysis (**Figure 4**), SP8, SP9 and SP7 were prioritized in this order. That is, when available SP8 will be chosen as 3PL provider; SP7 will provide 3PL only when both SP8 and SP9 were not available.

The SCM team validated the results. The experts considered the AHP based model as applicable in practice. Besides the results are considered adequate, the steps of AHP were perceived as a better practice for supplier selection to logistics.

5. Conclusions

This chapter presents two applications of AHP to SCM. In both applications, absolute measurement was adopted instead of the original relative measurement. That is, in both applications the set of criteria was larger than usual AHP applications. With absolute measurement pairwise comparisons between suppliers are not necessary. This way, the effort for the AHP application is reduced. However, this is not the main reason for absolute measurement, in both cases. In the case of RA by an automobile plant, there was feeling that the decision must be impartial. That is, pairwise comparing Supplier S1 with S2 may invoke past deficiencies already overcome.

Another reason for absolute measurement, only for the SS by a chemical corporation, is the avoiding of RR. That is, for a problem of SS, RR seemed not justifiable. If Supplier S8 is preferred than S7 and S9, it must be preferred without S7 or S9 in the decision, and even if other Suppliers S10, S11, S12, …, all worst then S7 were inserted in the decision. Concluding: there is no space for RR in SS. For that reason, AHP must be applied to SS with absolute measurement and ideal synthesis.

On the other hand, adding new suppliers in an RA problem may change previous priorities of older suppliers. This way, RR can be legitimate for this problem. Then normal synthesis, and also, relative measurement, seems to be proper procedures for AHP application to RA.

It is important to state that this chapter presents some highlights based on only two cases. Obviously, more examples and real cases must be studied to generalize our conclusions. Perhaps the main contribution of this work is presenting that there are different ways to solve a problem. The way a problem is solved defines a decision, which may be irreversible, as the selection of a supplier to a specific order.

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Author details

Valerio Antonio Pamplona Salomon*, Claudemir Leif Tramarico and
Fernando Augusto Silva Marins

*Address all correspondence to: salomon@feg.unesp.br

Sao Paulo State University, Guaratingueta, Brazil

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An Analytical Hierarchy Process to Decision Making in Human Blood, Cells, and Tissue Banks

Paulo Pereira and Sandra Xavier

Additional information is available at the end of the chapter

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Abstract

The decisions are critical in transfusion and transplantation principally because they could affect directly and indirectly the post-transfusion and post-transplantation safety. However, the blood, cells, and tissues banks should not be uniquely centered in the satisfaction of receptor (patient) requirements. All the decisions affecting the sustainability of the organization should also be considered. Despite not to be systematically used in these banks, the analytical hierarchy process could be useful for the improvement in the reliability of the decisions. This chapter reviews the basics of the analytical hierarchy process applied to the production of blood, cells, and tissues, and presents a case study that could be interpreted as applicable to other situations in these organizations.

Keywords: AHP, Clinical decision, Comparisons, Decision making, Priorities, Ratings, Sustainability

1. Introduction

The decisions of blood, cells, and tissues banks, referred to as banks, are usually complex, considering the risk of failure during the collection, production, storage, and distribution of the blood, cells, and tissues. Differently from hospitals, where most of the clinical decisions are performed by physicians (an important and noncontrolled source of uncertainty), the clinical decisions in banks are taken according to what is required by the law or algorithms (a minor and controlled source of uncertainty). Decisions related to the specifications of products, such as based on laboratory quality control results, should happen using reliable methodologies to assure an acceptable risk associated with the post-transfusion or post-transplantation

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safety [1, 2]. Clearly, critical decisions could not consider uniquely the safety of the receptor of blood, cells, or tissues. Some other variables are also significant to the selection of an individual product or service. Examples are the impact in the budget, which could be decisive in choosing of products or services satisfying the technical specifications. Unreliable decisions are happening from technical levels to the top management. Failures in decisions could contribute seriously to unsuccessful goals, such as the example of improper validation of an individual product is the cause of a receptor's infection.

The role of the decision maker is critical for the successful implementation of a methodology to the acceptance of new products or services. The decision must be carefully achieved. Erroneously, it could find that all the available information could be useful to contribute to accurate decisions. However, this is inappropriate since a larger quantity of information does not signify more substantial impact in the decision making (most of the information is nonsignificant). The decision maker identifies what is the critical information to a certain decision. This was already defined by Deming in the Pareto principles or "80-20 rule." This policy considers that approximately 80% of the effects come from 20% of the causes [3]. It is closely related to the cause-effect diagram, allowing an easier identification of the primary sources of a particular effect. The effect in the context of this chapter is the decision goal.

A methodology that is recognized in the industry and services is the analytical hierarchy process (AHP). However, it is not systematically applied in banks. Following this model, the goal is identified together with the criterion and subcriterion, stakeholders, and alternative actions. The options per criterion should be selected according to the considered priorities, usually ranked in a matrix table involving criteria and subcriteria [4, 5].

Frequently, banks are focused exclusively on the customer (donor and receptor). However, current management systems [6] consider it must not be uniquely centered in customer but also in all relevant interested parties (stakeholders). ISO 9000 defines stakeholder as the "person or organization that can affect, be affected by, or perceive itself to be affected by a decision or activity" (entry 3.2.3 of [7]). In the European banks, stakeholders are also the State (usually in the name of a regulatory agency) and the European Commission (the European banks must fulfill a set of directives transposed to the national law), manufacturers and suppliers including certification and accreditation providers

Despite ISO 9001 model is applied systematically to European banks, the use of decision-making models is not uniform and even rarely discussed. ISO 9001 is focused on the continuous satisfaction of the stakeholders. However, the management procedures are not standardized. The (AHP) is a recognized procedure that could be valuable to assure successful decision making. The use of this approach could also be helpful when setting the objective per process, such as when defining the target's criteria. Alternatives to the goal are considered. The AHP requires that the information related to the decision methodology is organized in a hierarchy tree using judgments to determine the ranking of the applied criteria. Banks staff easily recognize the major decisions critically related to the sustainability of the organization, such as:

1. Selection of a screening test to validate blood and tissues donations (e.g., an antihepatitis C virus immunoassay);
2. Formulating a successful marketing strategy to blood donation (e.g., growth in the number of donors from 1700 to 2000 during one year);
3. Selection of a metrology policy (e.g., to assure testing and calibration of all the monitoring and measurement equipment);
4. Choice of a statistical process control method to the monitoring of blood components production (e.g., a method based on variables and attributes charts, and capability indexes);
5. Selection of a strategy to decrease the cost of production (e.g., reduce the cost of red blood cells concentrates from €30.00 to €25.00 per component); and
6. Choosing a leader of an establishment or department (e.g., selection of a director of the bank).

This chapter briefly discusses the AHP theoretical approach applied to the banks. As an example, it uses an AHP methodology to the selection of a clinical chemistry laboratory test. Currently, the recommend methods to select a lab test are not related to AHP. Commonly, they are primarily focused on technical requirements, and in a second phase to the cost of reagent per result. However, there are other critical variables, such as reliability of the results, and the cost also has some components that are not considered. This example verifies if the application of the AHP approach could significantly improve the decision-making correctness. Although this is a unique case, the principles considered are generic.

2. Research methods

2.1. The AHP in the blood and transplantation scope

Hypothetically, the application of the AHP decreases significantly the risk of failure related to decisions. The judgment plays a crucial role in an AHP approach when considered in transfusion and transplantation. The judgments are required principally when standard practices are not required, i.e., when the law or standards are not considered. Some critical requirements are standardized in this scope, to assure that the products have normalized specifications to guarantee necessarily successfully transfusions or transplantations. This is also common to others industries where the production must fulfill a set of specifications usually coming from the law. Nonetheless, not all essential requirements are standardized, such as some regarding the management or even technical requirements closely related to the post-transfusion and post-transplantation safety. For example, testing and calibration methods, and quality control of laboratory tests. The staff must be skilled in judging the differentiated factors accurately to prevent biased conclusions in these examples.

The AHP methodology identifies the decision separated into phases according to the priorities. Four steps are considered [5]:

Stage 1 - Goal and knowledge: Determination of the goal to satisfy a questioned problem and selection of the knowledge needed to accomplish the objective.

Stage 2 - Decision hierarchy: Ranking the decision hierarchy from the decision goal (top), through intermediate stages, to a set of alternatives (bottom).

Stage 3 - Pairwise comparison: Conception of a set of pairwise comparison matrices where each variable is compared to upper level with the variables of the next lower level, this comparison allows the classification of criterion.

Stage 4 - Ranking the priorities: Use of the previous comparison to determine the degree of priority of each of the variables in the level below. The determination should be repeated to next level(s). An overall rating orders the classification of variables identifying the highest ranked variable.

2.2. Goal and knowledge

The banks define goals from top to bottom levels. The bottom level is related to the production processes, measured using a key performance indicator (KPI) such as the fulfillment of blood components specifications. Intermediate levels are related to the major goals such as the number of tissues produced per year. The top level is linked principally to goals regarding costumer's satisfaction.

The goals should be well-defined. It is a risky practice to establish a goal based on subjectivity. Therefore, it is determined based on empirical data (evidence-based using objective evidence) (entry 3.8.3 of [7]). Some nontechnical goals are typically not considered in banks, for example, the financial viability.

For a successful implementation of the goals, the selection and adequate training of the decision makers are required. The staff must show proper skills acquired through academic and practice. This also does not systematically happens in the bank's management scope. Considering a worst case where the managers at different levels of organization regularly do not demonstrate adequate skills, the use of AHP is useless (this is applied to any other management tool). Accordingly, the banks managers require a long-term training monitored by advisors.

2.3. Decision hierarchy and pairwise comparison matrices

Sometimes, the decision hierarchy is complex in these banks, impacting negatively the decision-making part. The decision hierarchy must be reviewed in this case. It is considered a structure, commonly designed in a hierarchy tree diagram. The criteria to reach the goal are divided into classes, for example, training, cost, and reliability. These classes are selected following the Pareto principle. If the classes do not have a significant contribution to the "correct" judgment, the final decision will be critically affected. The alternatives to the goal are represented in lower classes and are classified using the preceding criteria. The hierarchy tree complexity depends on the nature of the problem. For example, the selection of a new laboratory test requires a simpler tree when compared to the selection of a new production method for a certain blood component. The bank applies the criteria (and subcriteria when applied) unequally, grading according to the contribution to the decision. This ranking is based on several inputs such as data, experience, expertise, consulting, and judgments. Again, the use of subjectivity is erroneous and even nonconforming (entry 2.3.6 of [7]).The construction of the tree requires leadership and the engagement of people to permit an adequate design. One more time, the staff, including the leader or leaders, must have an appropriate matrix of competencies. It is a challenge to identify the leaders of decision making based on AHP. The criteria should be correctly defined. However, the team can revise when it is demonstrated that they are not useful for the decision making [8, 9].

The pairwise comparison matrix is suited to identify the relative importance of a criterion over another to rank the priorities. For example, the reliability and cost are classified differently according to their importance to the decision. This chapter considers the numerical scale in **Table 1**. This table is adapted from (**Table 1** of [5]). Further information about matrix operations can be found elsewhere [10].

Scale	Level of importance	Description
1	Equal	Equal contribution to the goal
3	Moderate	Somewhat advantage to one variable over another according to the knowledge and judgment applied
5	Strong	Strong advantage to one variable over another according to the knowledge and judgment applied
7	Very strong	Very strong advantage to one variable over another according to the knowledge and judgment applied with evidenced supremacy based in empirical data
9	Extreme	The advantage to one variable over another is related at the highest confident level of supremacy based in empirical data

Table 1. Numerical scale to be used in pairwise comparison matrixes.

AHP contemplate priorities as the contribution of the hierarchy variables to the goal using relative metrics, for example, test A and test B in decision making to a new laboratory test. The sum of the relative results is equal to one (synonymous of goal property). The metrics should be analyzed considering the weight per variable compared to the weight of another paired variable. For example, if test A = 0.426 and test B = 0.143, test A has around three times the test B weight, therefore, test A is a primary candidate to be selected. Accordingly, "weight" is similar to priority level. Simple hierarchy scenarios could be easily computed in a spreadsheet software. However, complex problems require a dedicated software since the correct estimation of priorities is an arduous task in this scenario [9]. Additional information about decision hierarchy and pairwise comparison could be found elsewhere [11-13].

3. Case study

3.1. Goal

In blood, cells, and tissues banks, the intended use of the reported results is primarily the validation of blood components, cells, and tissues. Test validation methodology is related to the residual risk (entry 2.29 of [14]) of the reaction/infection post-transfusion or post-transplantation. Consequently, the error measured must be lower or equal to the maximum allowable error, mostly recognized as the allowable total analytical error (TEa) [15]. This allowable error is the error that could be associated with the true result (*in vivo* result) without affecting the clinical decision.

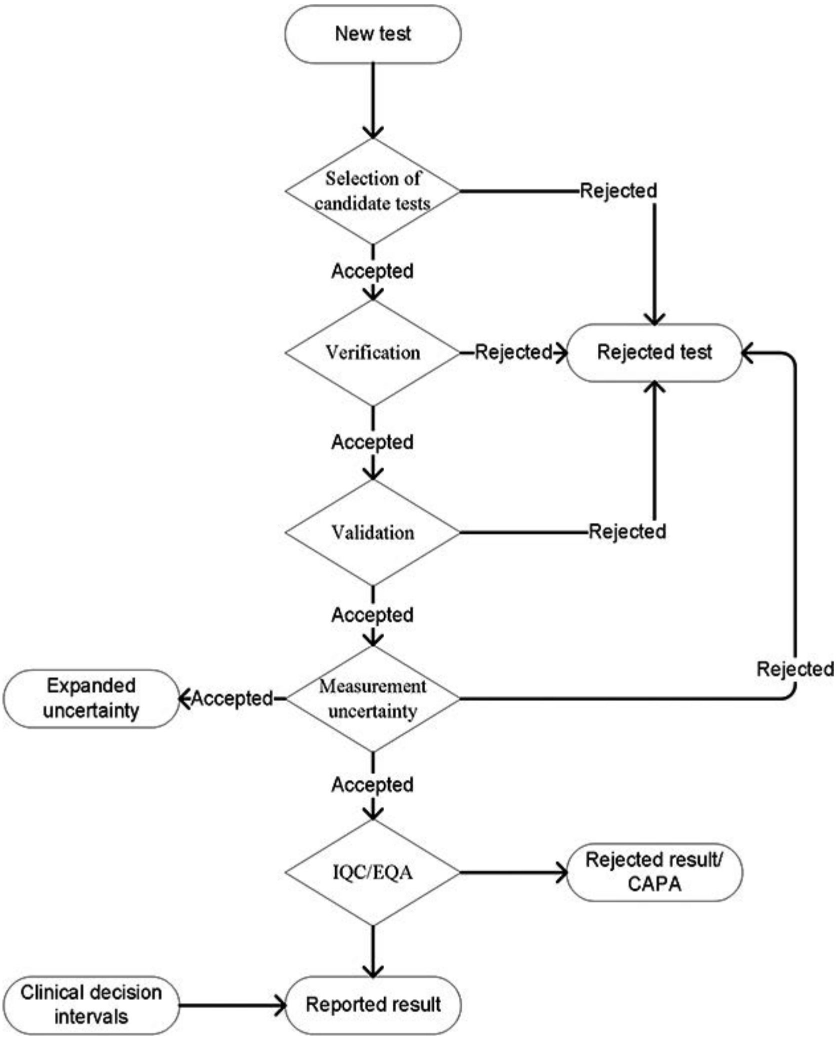

Figure 1. A flowchart to decide about of new test in a medical laboratory according to ISO 15189.

The case considers a hypothetical selection of a new laboratory test (goal). Let us consider a hematology test to the measurement of the hemoglobin (Hb) (the example could be applied similarly to any other medical laboratory test). It is chosen that three different laboratory tests are to be evaluated using the AHP. The candidate tests (alternatives) have the same photometric method.

The APH methodology differs from ISO 15189 requirements [16], intended to the accreditation of medical laboratory tests or methods. This standard aims to assure that reported results (*in vivo* results plus error) are nonsignificantly different from the *in vivo* result (true result). **Figure 1** illustrates the ISO 15189 technical requirements related to the control of the error in the results. The first step in the flowchart (entry 5.5.1.1 of [16]) is intended to decide what test or tests can be selected. The second step (entry 5.5.1.2 of [16]) is to verify if the claimed error is lower or equal to the allowable error. Tests with an error higher than the allowable limit in the bank's laboratory are rejected, despite being approved to be used in the European Union (note: manufacturers and medical laboratory specifications could not be the same). The thirds step is the validation (entry 5.5.1.3 of [16]). The lab measures the error in a representative sampling of the donors. It is compared to the allowable error. This phase is intended to verify in the laboratory conditions and with representative samples if the validation condition is acceptable. So, only tests with an estimated error lower or equal than the allowable error are accepted [20]. The fourth step is the determination of the expanded measurement uncertainty U (entry 5.5.1.4 of [16]). The approach used is commonly empirical and is expressed as follows: $U = k(u_c)$, where k is a constant related to the degrees of freedom v_{eff} (equal to the number of measurements minus one in this evaluation), and u_c is the combined standard uncertainty. In this case, the u_c is computed using an empirical mathematical model: $\sqrt{(u_b^2 + s_{\mathrm{Rw}}^2}$, whre u_b is the standard uncertainty of bias and s_{Rw} is the within-laboratory reproducibility standard deviation. ISO 15189 requires the U to be verified against an acceptable uncertainty interval. From the clinical point of view, the measurement uncertainty and the total analytical error concepts could be viewed as similar. The uncertainty approach (entry Annex A of [17]) is not systematically used in medical laboratories [18], different from the error approach. So, this step is like a second validation stage using the same data but with a different metrology concept. Since the purpose of the error validation and the measurement uncertainty validation are close, the AHP example considers uniquely the test validation. Further details about the estimation of measurement uncertainty are available elsewhere [17, 19]. The fifth and last step is the internal quality control (IQC) and external quality assessment (EQA) (also known as proficiency testing). Different from the validation and the measurement uncertainty models where the outcomes are primary verified before the test is used in routine, the IQC verifies the allowable error in daily runs (number of samples tested in 1 day) and it is used not to accept or reject a test but to accept or reject test results. This is a source to classify the test's reliability, i.e., the capacity to produce conforming results. The EQA has a different role, and it is used to compare the results in a group of laboratories using data arising from the same control sample. Since the EQA results are affected by the heterogeneity of the results from different laboratories, they are not considered in the AHP case. Further details about quality control schemes are available elsewhere [20].

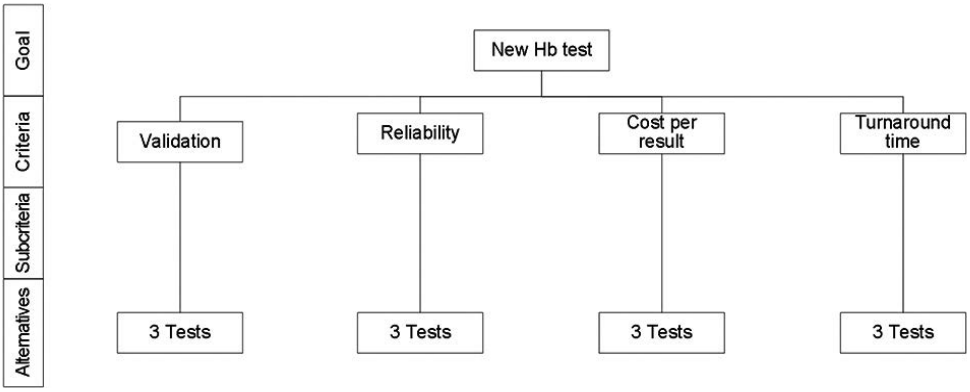

Figure 2. Hierarchical tree to the selection of a new Hb test.

The hierarchical tree of criterion is illustrated in **Figure 2**. It represents the hierarchy tree to select the Hb test. This example is a simple case. The criteria considered four variables: validation, reliability, cost per result, and turnaround time. It does not consider any subcriteria. There are three alternatives (candidates) to choose the new Hb test: test A, test B, and test C.

3.2. Pairwise comparisons matrices

A pairwise comparisons matrix is used to a paired comparison among the criteria. The fraction of a criterion over another is elaborated according to the scale in **Table 1**. It is based primarily on the relevance of each one to the post-transfusion and post-transplantation safety considering the impact of turnaround time in the production of blood components, cells, and tissues and the sustainability of the organization. This matrix is done by skilled personnel concerning the interest of parties, focused on the receptor (patient) satisfaction.

3.2.1. Criteria x criteria matrix

The matrix of criteria x matrix pondered is denoted by:

$$\begin{array}{r|cccc|} & \text{Validation} & \text{Reliability} & \text{Cost per test} & \text{Turnaround time} \\ \text{Validation} & 1/1 & 5/1 & 3/1 & 5/1 \\ \text{Reliability} & 1/5 & 1/1 & 1/3 & 1/3 \\ \text{Cost per test} & 1/3 & 3/1 & 1/1 & 3/1 \\ \text{Turnaround time} & 1/5 & 3/1 & 1/3 & 1/1 \end{array} = \begin{array}{r|cccc|} & \text{Validation} & \text{Reliability} & \text{Cost per test} & \text{Turnaround time} \\ \text{Validation} & 1 & 5 & 3 & 5 \\ \text{Reliability} & 0.200 & 1 & 0.333 & 0.333 \\ \text{Cost per test} & 0.333 & 3 & 1 & 3 \\ \text{Turnaround time} & 0.200 & 3 & 0.333 & 1 \end{array}$$

To normalize the matrix, each entry is calculated dividing each one by the sum to the associated column (e.g., the component of the first column and second row of the preceding matrix, 0.200/(1 + 0.200 + 0.333 + 0.200) = 0.115), as follows:

$$\begin{array}{r|cccc|} & \text{Validation} & \text{Reliability} & \text{Cost per test} & \text{Turnaround time} \\ \text{Validation} & 0.577 & 0.417 & 0.643 & 0.536 \\ \text{Reliability} & 0.115 & 0.083 & 0.071 & 0.036 \\ \text{Cost per test} & 0.192 & 0.250 & 0.214 & 0.321 \\ \text{Turnaround time} & 0.115 & 0.250 & 0.071 & 0.107 \end{array}$$

The weight of criteria could be determined using the elements per row of the previous matrix. It uses the geometric mean of each matrix row to calculate the weight of a particular component. The geometric mean of a set of numbers$\{x_i\}_{i=1}^{N}$ is $\left(\prod_{i=1}^{N} x_i\right)^{1/N}$. It is calculated in Microsoft® Excel® 2016 (Microsoft Corporation, Microsoft Redmond Campus, Redmond, WA, USA) using the function =GEOMEAN(number1,[number2],…). The weight for validation, reliability, cost per test, and turnaround time is 0.536, 0.070, 0.240, and 0.122, respectively.

3.2.2. Criteria

3.2.2.1. Validation

3.2.2.1.1. Experimental procedures

Most of the statistical tools require a parametric distribution. Therefore, the laboratorian confirms the normality of the data distribution, such as the existence of outliers. The D'Agostino-Pearson K^2 normality test 21 verifies the normality of the samplings distribution. Since the p-value is equal or higher than 0.05, the normality distribution is not rejected: $p_{testA} = 0.4085$, $p_{testB} = 0.4090$, and $p_{testC} = 0.4678$. The outliers are tested using the p-value which is also equal or higher than 0.05 to the Grubbs double-sided [22]. Complementary, the Generalized Extreme Studentized Deviate (ESD) tests [23] for the area and Tukey's test [24] also does not identify outliers. The p-value is interpreted as the chance of a sample in this sampling to be an outlier and is not significant at the 0.05 significance level.

The validation follows a suitable protocol divided into two phases: preliminary phase and final phase [25]. The preliminary phase is intended to verify if random and systematic error components are conforming using simple approaches. These methods require the use of results in repeatability conditions (entry 2.20 of [26]), i.e., the within-run/nonsignificant variance of uncertainty sources, allowing the laboratorian to verify if there are significant causes of error previously identified using this tools. For example, during the transport of equipment or installation, incorrect use of mathematical models, power supply failure, wrong room temperature, and lack of personnel skills due to short experience. When detected as nonconforming types of error, the laboratorian avoids wasting time and resources/cost with more complex approaches (final phase).

The carry-over, interference, and recovery should be uniquely determined in the primary phase, differently from the standard deviation measurement. Their determination in the final stage is erroneous implying a waste of cost. For example, the cause of the estimation of a nonconforming reproducibility standard deviation or bias could be the carry-over of reagent. In this case, a correction is mandatory, and carry-over and reproducibility standard deviation must be reevaluated.

Carry-over determines the standard deviation increase from one sample to another sample. Carry-over could be caused by hardware failure, such as pipette malfunction. A clinically nonsignificant carry-over is the one where three times the standard deviation of the low concentration samples tested after a low concentration sample is less than the difference of the results' average of high concentration samples tested after low concentration samples, and the results' average of low concentration samples tested after low concentration samples. A low concentration sample is commonly a saline solution. Carry-over is computed using the model $\bar{x}_{high-low}$ - $\bar{x}_{low-low} < s_{low\text{-}low}$, where $\bar{x}_{high-low}$ is the average of the difference between two consecutive samples, first with higher concentration and the second with low concentration, $\bar{x}_{low-low}$ is the average of the difference between two consecutive samples, both with low concentration, and $s_{low\text{-}low}$ is the standard deviation of the results of samples with low concentration [27]. If the difference for the three tests is lower than the $s_{low\text{-}low}$, the carry-over is classified as clinically irrelevant, as a result of test A: 0.08 < 0.12 g/dL, test B: 0.11 < 0.13 g/dL, and test C: 0.09 < 0.12 g/dL.

Interference verifies bias caused by an external component or property of the sample. It is tested a human sample added with a small volume of a pure solvent such as a saline solution. It is prepared a second solution of the same human sample but added with the same volume of the suspected interference material. These solutions are prepared to three different human samples. Each sample is tested in triplicate. For each sample the bias is computed using the difference between the result's average of sample added with interferer and result's average of sample combined with a solvent. The interference is equal to the average of the samples' bias. The interference to not be clinically significant must be equal or lower than the allowable total error. Consequently, $\bar{x}_{\mathrm{int}}-\bar{x}_{\mathrm{dil}}\leq \mathrm{TE}_a$, where $\bar{x}_{\mathrm{int}}$ is the average of the samples with interferent, and $\bar{x}_{\mathrm{dil}}$ is the average of the samples without interferent [28]. The differences of the candidate outcomes are test A = 2%, test B = 2%, and test C = 3%, all equal or lower than 7%. Note that the TEa is available in tables for most of the medical laboratory tests, available elsewhere [29, 30]. Therefore, the error caused by interference is clinically nonsignificant. Simply, the interference test is a bias estimate in an unusual condition. Further information about carry-over and interference can be found elsewhere [31].

Recovery study confirms if any analytical bias occurs using a simple and low-cost approach. It validates the bias using two different concentration samples considering a linear regression of outcomes. Bias magnitude increases as the concentration of analyte rises. The preparation of the samples is identical to the interference model. However, the samples must have different concentrations. Usually, it is used as supplied in the test kit and a dilution of the same standard. The dilution should not be higher than 10% to assure a lower dilution of the original sample matrix, to ensure no other significant sources of analytical bias. The recovery is calculated for each sample by dividing the difference between the sample with addition and the diluted sample by the additional volume. Then, the average of the recoveries of two samples is determined. The proportional error is calculated as follows: $\bar{x}_{high-conc} - \bar{x}_{\text{low-conc}} / \Delta * 100 \leq \text{TE}_a$, where $\bar{x}_{high-conc}$ is the average of the results of the high concentration samples, $\bar{x}_{\text{low-conc}}$ is the average of the results of the low concentration samples, and Δ is the expected difference [21]. The differences of the candidates are: test A = 3%, test B = 2%, and test C = 3%, all equal or lower than 7%. Further information about recovery study can be found elsewhere [25].

The next preliminary phase test is the repeatability standard deviation s_r, which measures the random error in repeatability conditions. Westgard et al. [15] recommend a minimum of 20 replicate tests. The sample used to determine standard deviation and bias should be equal or close to the clinical decision value. High- or low-value samples should not be considered since the estimates are clinically not significant. The laboratorian should be considered using the risk of outliers (entry 4 of [32]) to control the chance of unrealistic measurements due to the use of erroneous data. A rule of thumb in statistics is to assume a normal distribution when sampling is equal or higher than 30. Note, when the distribution is unknown, and the data is less than 30, a nonparametric test is used. The criteria for acceptable performance requires it should be equal to a quarter or less of the TE_a (see **Table 1**). It is not used as a final estimator of random error as its result is unrealistic since it is not affected by the long-term sources of imprecision. The clinical decision value of Hb tests is assumed to be 12 g/dL and the sample tested close to the value. It is computed using the following model $s_r \leq 0.25 * \text{TE}_a$ [21]. The result for the three tests is $s_{\text{r(testA)}} = 0.12$ g/dL, $s_{\text{r(testB)}} = 0.12$ g/dL, and $s_{\text{r(testC)}} = 0.14$ g/dL. Considering the $\text{TE}_a = 7\%$, all the results should be equal or lower than 0.25*(12*0.07) = 0.8 g/dL to be accepted. Thus, the repeatability is classified as clinically nonsignificant in all the candidates.

After reporting that the claimed requirements in primary phase are fulfilled, the final stage of validation follows. In this phase, the detection limit is determined to check if the manufacturer's estimated lowest concentration of the analyte is acceptable, i.e., to verify if the standard deviation of the functional sensitivity is equal or lower than the test's standard deviation under reproducibility conditions. It uses the standard kit with a concentration equal to the claimed functional sensitivity. If the functional sensitivity is higher, it means the standard deviation is clinically significant, for which a higher concentration should be evaluated. In this case, the linearity (reportable range) is not verified, for which the reported manufacturer studies are accepted. The functional sensitivity is measured using the model $s_{\text{fs}} \leq s_{\text{Rw}}$. The candidates results are $s_{\text{(fs(testA))}} = 0.11$ g/dL, $s_{\text{fs(testB)}} = 0.14$ g/dL, and $s_{\text{fs(testC)}} = 0.15$ g/dL. All the results are equal or lower than the s_{Rw} (see the next paragraph). Further details on the evaluation of detection limit could be found in [33].

The reproducibility standard deviation s_{Rw} is the next final phase determination. All the other measurements and graphics in this stage are determined with MedCalc® software (Medcalc Software bvba, Ostend, Belgium). It expresses more realistic results due to use long-term data.

CLSI EP15-A3 requires using, at least, two samples with different concentrations. The samples are tested for at least 5 days with five replicates per daily run. If 5 days does not cover the primary imprecision sources, the period should be extended. The standard deviation is calculated by pooling the repeatability standard deviation s_r and the intermediate standard deviation s_I from between-runs. s_r and s_I are combined using the square root of the sum of the squares. The candidate tests results are $s_{Rw(testA)} = 0.19$ g/dL, $s_{Rw(testB)} = 0.21$ g/dL, and $s_{Rw(testC)} = 0.24$ g/dL, or $CV_{Rw(testA)} = 1.6\%$, $CV_{Rw(testB)} = 1.8\%$, and $CV_{Rw(testC)} = 2.0\%$. All the results are equal or lower to the TEa (7%). Further information about reproducibility standard deviation can be found elsewhere [34, 35].

Bias is determined using a comparison of paired results, where a number of samples n with different concentrations is measured in the candidate and the comparative or reference test obtaining n pairs of results (x, y). The comparison permits principally to calculate the regression equation (the case considers a linear regression) for two tests. This equation allows to correct the results of the evaluation test, transforming y in x. After the correction, the bias is determined on the clinical decision value(s). The sample is tested and replicated (minimum duplicate) during, at least, 5 days. The pair of results considers x (independent or explanatory variable) as the outcome of the reference test and y the result of the evaluation test (dependent variable). x and y are determined using the average of the replicates. The data should be displayed in the comparison plot such as in the difference plot:

a) The comparison plot reveals the interceptions of x and y results. This could indicate a simple linear regression or a constant or proportional biased regression. For easy understanding, let us consider the linear regression. It requires the calculation of the slope b and y-intercept a of the line of best fit, being $y = \mathrm{a} + \mathrm{b} \bullet \mathrm{x}$. Accordingly, $x = (y - a)/b$, and bias equal to $(y - a)/b - x$. Note that in this equation x is assumed as the closest to the trueness, and $(y - x)/b$ as the corrected y, statistically identified as x, but is equivalent to x+residual systematic error. This chapter uses the Deming regression due to its robustness to outliers and to consider the random error also in the reference test [36]. **Figure 3** displays the regression between the candidate tests and a reference test. The results are significantly close due to the previous correction using the regression equation. It is shown that principally the tests A and C have nonsignificantly biased results. Test B apparently seems to have some significantly biased results. However, the regression equations in all the tests suggest significantly nonbiased estimates, since the slope is nearly one and the y-intercept is close to zero.

b) The difference plot shows the bias per pair of results (bias plotted on the y-axis, and the comparator/reference results on the x-axis). In a best case, all the points are in the zero line (unbiased results). A large dispersion of points suggests that y results are significantly biased. **Figure 4** indicates the bias percentage. It is around ±1.5% in tests A and C and around ±6% in test D.

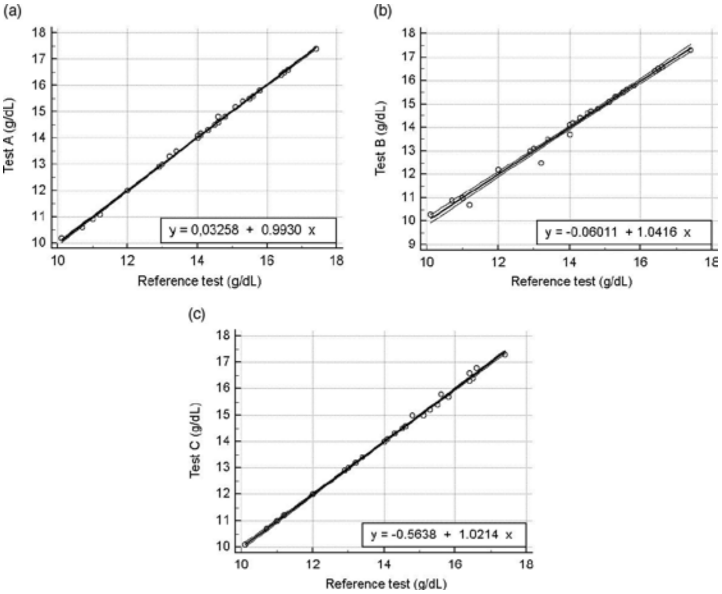

Figure 3. Scattergram, the regression line, and 95% confidence interval for the three candidate tests in MedCalc® software. The input data in the graphics is corrected according to the regression equations.

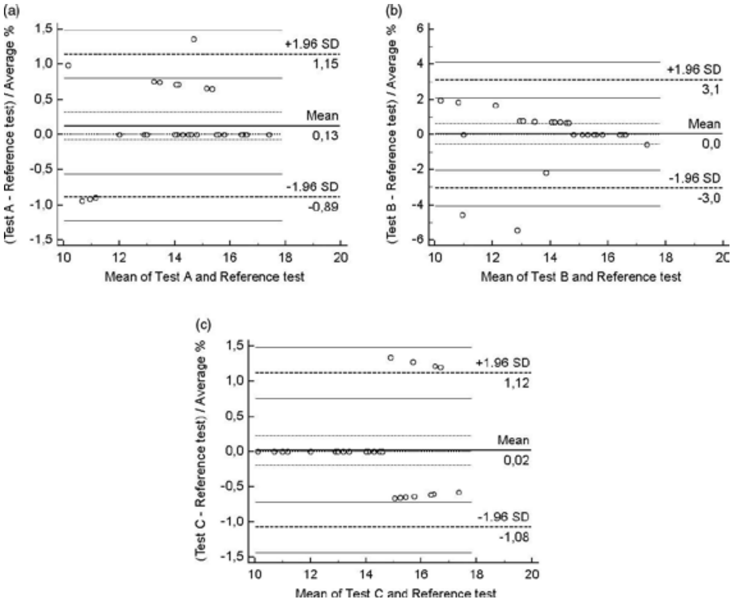

Figure 4. Bland-Altman plot for the three candidate tests (corrected input data) (MedCalc® software).

The correlation coefficient r is a measurement of the relationship between the two variables. It should be understood as the level of association between x and y. A perfect correlation result is one, in practice, if r is equal or higher than 0.99, the estimations of b and a are considered as reliable. In this case, it is recommended to determine simple linear regression statistics and calculate bias in the clinical decision value(s). If r is less than 0.99, the laboratorian should collect extra data increasing the concentration range. In this second case, bias should be estimated at the mean of the data from t-test statistics. The correlation coefficient should not be used as an outcome to validate a test, due to the bias effect to be omitted. For example, the laboratorian could watch in the graph a proportional bias but the r to be equal to 0.99.The coefficient of correlation of tests A, B, and C is $r_{\text{testA}} = 0.9993$, $r_{\text{testB}} = 0.9948$, and $r_{\text{testC}} = 0.9979$, significantly close to one [25].

The bias is determined to each of the tests in the decision value, 12 g/dL, i.e., the difference between the average of the test results and an accepted reference value. The sample chosen per test is the one which is the closest to the decision value. If there are more than one sample, it is preferred the worst case. The tests' results were previously corrected. Thus, $b_{\text{testA}} = 12\text{-}12 = 0$ g/dL (0%), $b_{\text{testB}} = 12.2\text{-}12\text{=}0.2$ g/dL (1.7%), and $b_{\text{testC}} = 12\text{-}12 = 0$ g/dL (0%).

Finally, the total analytical error (TAE) [37] is determined to verify the acceptability of the total error in novel test results. It is computed according to the model: $\text{TAE}=b+z \bullet s_{\text{Rw}}$., where b is the analytical bias, z is the coverage factor, which is related to the level of confidence chosen. For the approximate level of confidence of 95%, z is commonly established as $z= 1.65$ or $z = 1.96$, respectively, for a one-sided or a two-sided estimate. Alternatively, z could be determined easily in Excel® (Microsoft®, Redmond, Washington, USA) using the function =TINV(probability;deg_freedom). For a 95% confidence, the probability is equal to the difference between 1 and 0.95. Consequently, the criterion for acceptable performance is TAE ≤ TEa. The tests' TAE is as follows: $\text{TAE}_{\text{testA}}$: 0% + 1.95*1.61% = 3.1%; $\text{TAE}_{\text{testB}}$: 1.67% + 1.95*1.75% = 5.1%; and $\text{TAE}_{\text{testC}}$: 0% + 1.95*2.00% = 3.9%. All the tests satisfy the claimed TEa [14]. The sigma level is used to classify the TAE in an equation where it is related to the TEa: TEa% - b%/CV%, where CV is the coefficient of variation. Thus, $\text{Sigma}_{\text{testA}}$: (7%-0%)/1.61% = 4.4, $\text{Sigma}_{\text{testB}}$: (7%-1.67%)/ 1.75% = 3, and $\text{Sigma}_{\text{testC}}$: (7%-0%)/2.00% = 3.5. The test performance is classified as follows:

1. 6-sigma is classified as "world class quality";
2. 5-sigma as the goal related to quality improvement;
3. 4-sigma as the typical sigma level in industry; and
4. 3-sigma as the minimum acceptable quality level.

This case uses the TAE as the validation criterion. However, the sigma level could be employed alternatively. Detailed information about sigma level are available elsewhere [38].

These set of models differ according to different sources. CLSI harmonizes these models and is commonly the primary reference [39]. It is considered that tests with nonconforming TAE are rejected and are not included in the comparison matrices.

3.2.2.1.2. Scale

Tests with the same TAE should be classified as equal (to one). When tests have different results, the test with the lowest TAE rank is classified with one, and the other tests are categorized using the rule of three (cross-multiplication), i.e., $a/b = c/x \Leftrightarrow x = b*c/a$. Note that the TAE is ranked according to its statistical significance, i.e., it is assumed that the lower the result is, closer to the *in vivo* will be the *in vitro* results. Then, it is calculated as the difference between x and the highest value of the scale. The result is the closest to the scale value. Next, the metrics are applied to the next test. **Figure 5(a)** displays the primary pairwise comparisons matrix of validation and **Figure 6(a)** shows the normalized matrix and scores. Thus, in test A and test B, $x = 3.1\%*9/5.1\% = 5.5$, and $9\text{-}x = 3.5$. Therefore, the value of scale is equal to three. So, in test B and test A, $x = 1/3$.

a. Validation

$$\begin{array}{c|ccc} & \text{Test A} & \text{Test B} & \text{Test C} \\ \hline \text{Test A} & 1/1 & 3/1 & 3/1 \\ \text{Test B} & 1/3 & 1/1 & 1/3 \\ \text{Test C} & 1/3 & 3/1 & 1/1 \end{array}$$

b. Reliability

$$\begin{array}{c|ccc} & \text{Test A} & \text{Test B} & \text{Test C} \\ \hline \text{Test A} & 1/1 & 1/1 & 3/1 \\ \text{Test B} & 1/1 & 1/1 & 3/1 \\ \text{Test C} & 1/3 & 1/3 & 1/1 \end{array}$$

c. Cost per test

$$\begin{array}{c|ccc} & \text{Test A} & \text{Test B} & \text{Test C} \\ \hline \text{Test A} & 1/1 & 7/1 & 5/1 \\ \text{Test B} & 1/7 & 1/1 & /3 \\ \text{Test C} & 1/5 & 3/1 & 1/1 \end{array}$$

d. Turnaround time

$$\begin{array}{c|ccc} & \text{Test A} & \text{Test B} & \text{Test C} \\ \hline \text{Test A} & 1/1 & 1/1 & 1/1 \\ \text{Test B} & 1/1 & 1/1 & 1/1 \\ \text{Test C} & 1/1 & 1/1 & 1/1 \end{array}$$

Figure 5. Pairwise comparisons between tests and criterion.

a. Validation

$$\begin{array}{c|ccc|c} & \text{Test A} & \text{Test B} & \text{Test C} & \text{Scores} \\ \hline \text{Test A} & 0.600 & 0.429 & 0.692 & 0.563 \\ \text{Test B} & 0.200 & 0.143 & 0.077 & 0.130 \\ \text{Test C} & 0.200 & 0.429 & 0.231 & 0.270 \end{array}$$

b. Reliability

$$\begin{array}{c|ccc|c} & \text{Test A} & \text{Test B} & \text{Test C} & \text{Scores} \\ \hline \text{Test A} & 0.429 & 0.429 & 0.429 & 0.429 \\ \text{Test B} & 0.429 & 0.429 & 0.429 & 0.429 \\ \text{Test C} & 0.143 & 0.143 & 0.143 & 0.143 \end{array}$$

c. Cost per test

$$\begin{array}{c|ccc|c} & \text{Test A} & \text{Test B} & \text{Test C} & \text{Scores} \\ \hline \text{Test A} & 0.745 & 0.636 & 0.790 & 0.721 \\ \text{Test B} & 0.106 & 0.091 & 0.053 & 0.080 \\ \text{Test C} & 0.149 & 0.273 & 0.158 & 0.186 \end{array}$$

d. Turnaround time

$$\begin{array}{c|ccc|c} & \text{Test A} & \text{Test B} & \text{Test C} & \text{Scores} \\ \hline \text{Test A} & 0.333 & 0.333 & 0.333 & 0.333 \\ \text{Test B} & 0.333 & 0.333 & 0.333 & 0.333 \\ \text{Test C} & 0.333 & 0.333 & 0.333 & 0.333 \end{array}$$

Figure 6. Normalizes matrix and scores of pairwise comparisons between tests and criterion.

3.2.3. Reliability

A reliable test is the one that has a low risk to produce nonconforming results, i.e., internal quality control results that are rejected by a simple rule or multirules in a Levey-Jennings chart. Unreliable tests are a primary cause of waste in the budget. For example, if one analytical run is rejected, the repetition of that rule means that the cost per test in the new run will be twice. The reliability is determined considering the percentage of internal quality control results during five consecutive analytical runs. The result is the percentage of the division of the accepted runs by the total number of runs. Tests A and B have five approved runs, and test C has one rejected run. In the previous criterion, the rank is determined using the rule of three. The ratios to reliability are presented in **Figure 5(b)**, and **Figure 6(b)** shows that test A and test B are equally reliable, and tests A and B have a somewhat advantage to test C. Tests A and B have five accepted runs while test C has one rejected series. Accordingly, $x = (4/5)*9/(5/5) = 7.2$, and $9\text{-}x = 1.8$. Like 1.8 is closest to three, it is assumed as the value of the scale.

3.2.4. Cost per result

The cost of each reported result is 20c, 50c, and 80c to test A, test B, and test C, respectively. This cost is uniquely related to the price of the reagent. The cost is sometimes the only criterion in decision making, which is erroneous. For example, a less expensive cost per result in an unreliable test will critically increase the cost because the rejected run will require at least a new run/new series of samples tested. The value of scale is determined using the previous criterion. **Figure 5(c)** and **Figure 6(c)** show that there is a significant difference between the costs, principally between the price of tests A and B. Using the mathematical expression, $x = 20c*9/80c = 2.3$, and $9\text{-}x = 6.7$. So, seven is the closest value of scale to the fraction (test A, text B). For test A and test C, $x = 20c*9/50c = 3.6$, and $9\text{-}x = 5.4$. Therefore, five is selected as the closest value of scale. For test B and test C, $x = 50c*9/80c = 5.6$, and $9\text{-}x = 3.4$. Then, three is the closest value.

3.2.5. Turnaround time

Turnaround time is the period that a test requires to provide the results. This is critical for the efficiency principally related to blood components acceptance and in emergency cases, such as those happening in blood and transplantation fields. A bank defines the maximum turnaround time, i.e., the time that does not affect the production of components, cells, and tissues, or uniquely reported results. So, it is needed to know if the turnaround time is equal or lower than the maximum period allowed.

The turnaround time is equal or less than 90 minutes in this study. Test A and test C time are 60 minutes, and test B is 50 minutes, for what all the ratios are equal to one. If one of the tests has a turnaround time higher than 90 minutes, the rule of three should be applied. Shorter turnaround times could be understood as an opportunity to review to enable a faster production. The fraction and outcome are displayed in **Figure 5(d)** and **Figure 6(d)**, respectively.

3.3. Overall scores

The overall rating for each alternative requires the calculation of the matrix product of two arrays. The outcome is an array with the equal number of rows as array1 and the same number of columns as array2. It is determined in Excel® spreadsheet using the function =MMULT(array1,array2). In the case, array 1 is the elements of matrix table and array 2 is the weight of criteria (see Section 3.2.1). The overall score determines the test with the highest score take from a matrix using the scores presented in:

$$\begin{array}{l|cccc|c} & \text{Validation} & \text{Reliability} & \text{Cost per test} & \text{Turnaround time} & \text{Overall scores} \\ \text{Test A} & 0.563 & 0.429 & 0.721 & 0.333 & 0.545 \\ \text{Test B} & 0.130 & 0.429 & 0.080 & 0.333 & 0.160 \\ \text{Test C} & 0.270 & 0.143 & 0.186 & 0.333 & 0.240 \end{array}$$

Test A is the one with the highest score, for what it is the selected test. The result is due to its highest scores in the validation and cost per test. Comparing the overall scores with the standard test validation, it permits to classify different tests with same or close (acceptable) TAE. Therefore, the use of the AHP in decision making to a new test (or another decision, namely, technical decisions) is a more complete approach, since it contemplates other important criteria related to the goal. If the decision making considers uniquely part of the significant criteria, for instance, the validation and cost per test in the example, there is the chance to select an unreliable test. The present case could even be more complex, for instance, considering the TAE and sigma level as subcriteria of criterion validation.

4. Conclusion

In summary, the AHP provides a logical framework to determine the benefits of each alternative. In this context, discussing costs together with benefits does not bring biased estimations/answers. The case study could be inferred to a wide range of decisions in the bank, principally when dealing with specifications. The AHP demonstrates to improve the accuracy of the decision making in the study. In the example if decision making does not use the AHP methodology, the decision is biased. The incorrect decision could be demonstrated in the long term (due to reliability), on the bank's budget (due to cost per test), or on the costumers' satisfaction (due to turnaround time) in general decision making to new lab tests. The AHP application could be viewed as a complement or an extension to part of the decision approaches currently used in the banks.

Author details

Paulo Pereira[1*] and Sandra Xavier[2]

*Address all correspondence to: paulo.pereira@ipst.min-saude.pt

1 Quality Management Department, Portuguese Institute of Blood and Transplantation, Lisbon, Portugal

2 School of Health, Polytechnical Institute of Beja, Beja, Portugal

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Chapter 3

A Case Study on the Application of the Analytic Hierarchy Process (AHP) to Assess Agri-Environmental Measures of the Rural Development Programme (RDP 2007–2013) in Slovenia

Monica Huehner, Črtomir Rozman and
Karmen Pažek

Additional information is available at the end of the chapter

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Abstract

The reform of the Common Agricultural Policy (CAP) in 2003 focused mainly on the economic and environmental challenges. The Rural Development Programme 2007–2013, hereafter RDP, being implemented in Slovenia is therefore aiming at promoting proposed activities that help to improve the rural areas. Agri-environmental measures (AEMs) encourage farmers to make an environmental commitment for a period of at least 5 years aiming at preserving the environment and maintaining the countryside. Because of practising environmental friendly production methods, the farmers might be encountered with more costs and reduction of yield. Therefore, payments are made as compensation. Concentrating only on one of the four pillars of the RDP, "Improvement of environment and the countryside", this paper attempts to assess the Slovenian agri-environmental measures with the help of the multicriteria decision analysis, that is, analytic hierarchy process (AHP) and its supporting software Expert Choice™. In the presented case study, three main criteria and their attributes were determined. With the help of experts (questionnaires), data were collected, which made the assessment possible. The results show that organic fruit, vine and horticultural production are seen as the most important AEM. This is specific for the Republic of Slovenia because of its large amount of area designated as least favoured areas (LFA) that are not suitable for arable farming.

Keywords: agri-environmental measures, rural development programme, multicriteria decision method, analytic hierarchy process, Expert Choice™

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1. Introduction

For a long time, agriculture was marked by intensive production practices, which meant that the massive use of mineral fertilisers and pesticides was indispensable to achieve high yields. This led to the deterioration of the environmental conditions [1]. The pollution of soils and ground water was the result, biodiversity dwindled [2]. The Slovene agriculture is not an exception. The resources in Slovenia are already limited because of unfavourable natural conditions. More than 75% of the Slovene territory lies in the less favoured areas (LFA), where agricultural practice is limited by natural factors. More than half of the Slovene territory is covered by forests. Also, 90% of the entire Slovene territory is classified as rural, with 57.2% of its inhabitants living there [3]. Of the 57.2% inhabitants in the rural areas, only 6% are engaged in agriculture [4]. Agriculture has a potential of making a great contribution to the economic development in the rural areas. The emphasis in today's agricultural policies, therefore, has to be on sustainable agricultural production, which can be practised and maintained when the following three main features are fulfiled [3,5]:

- Social acceptability
- Environmental reliability
- Economic feasibility

Sustainable agricultural production is strongly linked to the environmental aspect. Many countries or regions in the world have therefore adopted environmental programmes to slowly suit the changing agricultural production methods and to counter climatic change. While a couple of years ago environmental protection was a fashion, today, it has become a strong and indispensable philosophy being followed in all aspects of life. The research on the role of environmental attitudes towards the participation in the next generation of agriculture conservation programmes was already going on in the USA in 1999 [6]. Ho et al. [7] point the importance of the Environmental Technology Centre of the Murdoch University in Australia with training and research programmes on renewable energy in the context of environmentally sound technologies. Zbinden and Lee [8] state that since 1997, Costa Rica's Payments for Environmental Services Programme has provided payments to more than 4400 farmers and forest owners for reforestation, forest conservation and sustainable forest management activities. The idea of a Danube River Basin environmental programme was born in Sofia in 1991, and the programme was started in 1992 as described by Nachtnebel [9]. Nachtnebel [9] points out that the Danube River Basin environmental programme provides for joint actions of the 10 Danubian countries to assist integrated environmental management in the basin. Environmental programmes are not only limited to the agriculture but are also found in the industrial sector. Abaza [10] argued that the structural adjustment programmes of the World Bank in the 1990s, packages of economic reforms specifically designed to enhance the recovery of economies in crises, were urged to address environmental issues. Abaza elaborates further that efficient management of natural resources is essential for sustainable development and poverty alleviation. To promote and support sustainable agriculture in its member states, the European Union introduced a Common Agricultural Policy (CAP) [11]. Within the scope of

CAP and to be able to successfully integrate the environmental aspect, agri-environmental measures (hereafter AEM) were compiled as part of the second pillar of the Slovenian rural development programme (RDP) aiming at improving the environment and the rural areas. AEM are now compulsory for all EU member states. Each EU member state has its own RDP especially compiled to suit their circumstances and special conditions. Petersen [12] from the European Environment Agency gathered information on the countries preparing to access the European Union using questionnaires and information from the responsible national ministries. He used this data for his exposition with the main focus on agri-environmental programmes of the candidate countries. AEM enable payments to farmers who voluntarily take up environmental commitment for at least five years. In these 5 years, they commit themselves to use environmental friendly production methods (RDP 2007–2013). The emphasis is on the right balance between competitive agricultural production and the respect of nature and the environment. Furthermore, awareness of sustainable production with focus on regenerative use of the available natural resources has to be roused [13]. AEM also ensures agricultural production that suits the needs of consumers and protects their health. Through these measures, the standard of living in the countryside is expected to be improved.

An ex ante evaluation carried out by the Biotechnical Faculty of the University of Ljubljana together with the Danish Orbicon in September 2006 using the Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis was to help reveal loopholes and faults in the draft for the RDP. In the evaluation, the need for a hierarchical structure of the objectives was mentioned several times in order to clearly determine the main objective and the subobjectives [14].

Cunder analysed the role of rural development policy in environmental and land management in Slovenia based on a desk research [15–17] using the legislative documents like the Common Agricultural Policy Reform from the EU and the document on the analysis of the accession of Slovenia and its agriculture into the EU in 2004. No modelling was done in all these cases. At this point, in the decision-making process, the analyst should consider a multicriteria (objective) decision analysis approach (hereinafter MCDA), which combines different mathematically based methods—the most commonly known approaches are the utility theory and the analytical hierarchical process [18–20]. Multicriteria analysis (MCA), also known as multicriteria decision analysis (MCDA), is an umbrella term for a number of decision-making techniques. As the name implies, MCDA makes it possible to tackle "problems" with many different conflicting criteria. According to the Department for Communities and Local Government in London [21], their role is to deal with the difficulties that human decision-makers have been shown to have in handling large amounts of complex information in a consistent way. In agriculture, decisions to be made are complex, mostly consisting not only of a single criterion but multiple criteria as in the implementation of the AEM. Thus, many criteria determine or influence the optimum decision. For such complex decision-making procedures, the traditional mathematical programming, especially linear programming, is therefore not adequate for modelling them [22]. Also, just determining strengths, weaknesses, opportunities and threats does not analyse the problem being assessed thoroughly enough. The relations and interactions of the criteria are not determined.

Besides for making decisions, some scientists [23–25] have used MCDA methods also as assessment tools. Ferrarini et al. [26] used MCA to assess and compare municipal performance in environmental quality and sustainability in the province of Reggio Emilia in Italy. Gómez-Limón et al. [27] also made use of MCA to analyse input usage in agriculture and the way it affects the environment. Hellstrand [28] found MCA useful to survey the sustainability effects of increasing concentrate intensity in Swedish milk production. Solomon and Hughey [29] proposed a MCA decision support tool for international environmental policy issues on the example of emissions control in the international aviation sector. Crete Tsoutsos et al. [30] showed how sustainable energy planning can be done by MCA. The analysis of air pollution [31] and soil pollution [32] in an urban area in Serbia was done by Nikolić et al. using MCA. For improving strategic environmental assessment of water programmes in Brazil, MCA was also taken by Garfì et al. [58]. In Malaysia, Al-Hadu et al. [33] showed how useful MCA is for environmental management. Payraudeau and Gregoire [34] modelled pesticides transfer to surface water with MCA.

One of the most common methods of MCA is analytical hierarchical process (AHP). AHP has found its use in a few branches of the agricultural field for more than two decades, though not extensively. It has since been very attractive and useful for water management engineers. Pillai and Rasu [35] used this method for ranking irrigation management alternatives in an Indian region in order to increase the effectiveness of the irrigation system, which was underutilised. Tiwari et al. [36] used AHP to develop a framework for environmental-economic decision making that includes the environmental and economic sustainability criteria, and local people's preferences in the context of a lowland irrigated agriculture system in Thailand. The method was also relevant for Ni and Li [37], who used it for the assessment of soil erosion in terms of land use structure changes. Tran et al. [38] used AHP to prioritize future renewals of irrigation and drainage assets in the La Khe irrigation scheme in North Vietnam; Srdjevic and Medeiros [39] also demonstrated the use of AHP for the assessment of water management plans. Braunschweig and Becker [40] showed how AHP could be used in international agriculture to choose research priorities. Pažek et al. [18] used AHP for evaluation of business alternatives on organic farms. Liu et al. [5] made an assessment of how sustainable a high-yield agro ecosystem in Huantai County, China, was. In Iran, Rezaei-Moghaddam and Karami [41] used AHP for the evaluation of sustainable agricultural development models. Ziolkowska [42] used AHP in combination with cost-effectiveness analysis for the evaluation of the AEM and analysis of the economic aspects to support the decision-making process of the Polish government. In the same year, Ziolkowska [43] also combined AHP and linear programming to estimate the importance of AEM with respect to the environmental objectives and calculate an objective orientated budget allocation for AEM. Ziolowska also used the AHP to investigate/evaluate the importance of AEM from the regional perspective in Poland. Mortazavi et al. [44] showed how AHP can successfully be used for prioritizing agricultural research projects. Vindis et al. [45] also used AHP to perform a further evaluation of energy crops for biogas production.

The aim of this paper is therefore a further attempt to show how multicriteria decision models can be successfully applied in the assessment of agricultural problems, the main focus being on the assessment of AEM in Slovenia. The paper is organised as follows: first, we present the methodology and describe the AHP model, and this is followed by the main results. The main findings conclude this article.

2. Materials and methodology

The assessment in this paper is based on one of the most used multicriteria decision methods (hereafter MCDM), the AHP. As recommended by Saaty [46], Meixner and Haas [47], the paper is organised as follows:

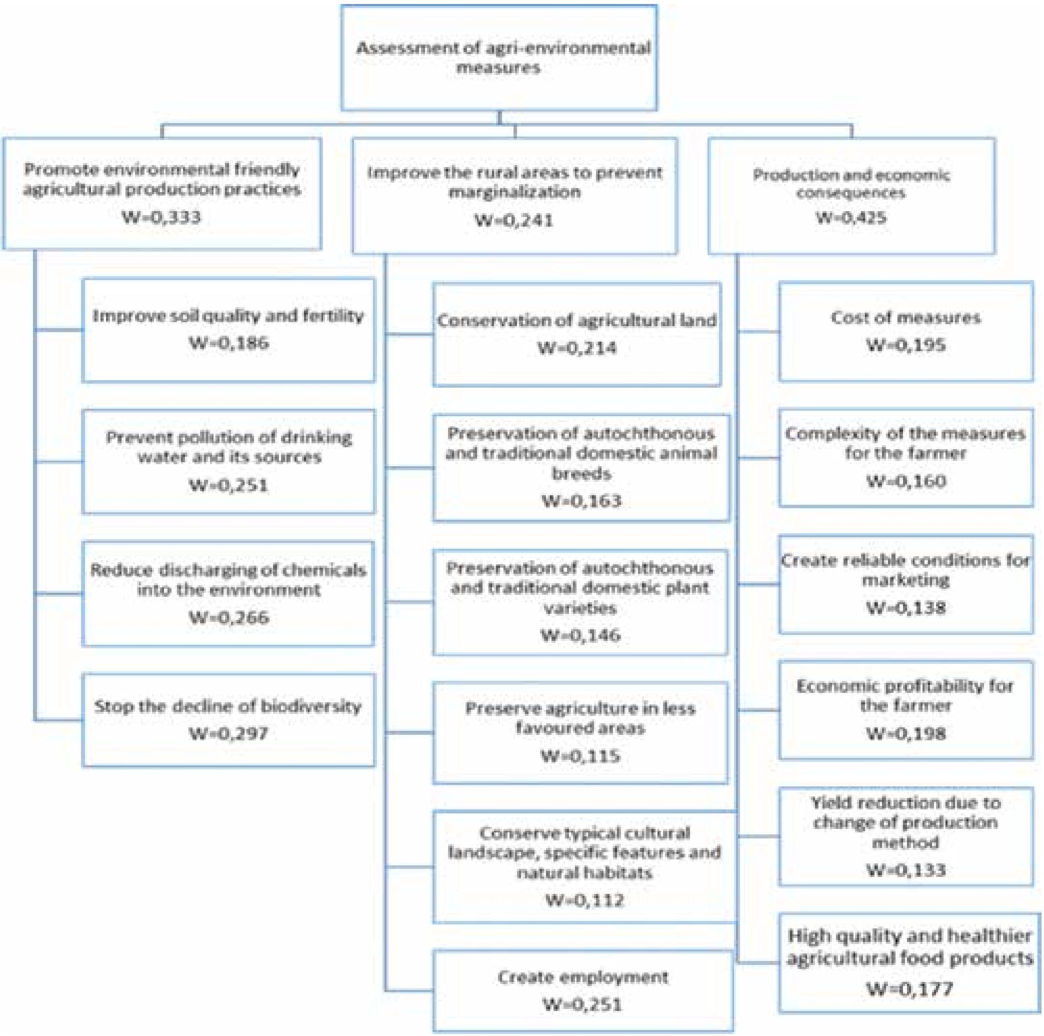


Figure 1. Aggregated weights based on group judgements.

Step 1: The main goal, subgoals (attributes), criteria, people involved and/or affected and their objectives and the means of reaching the goal were identified and formulated.

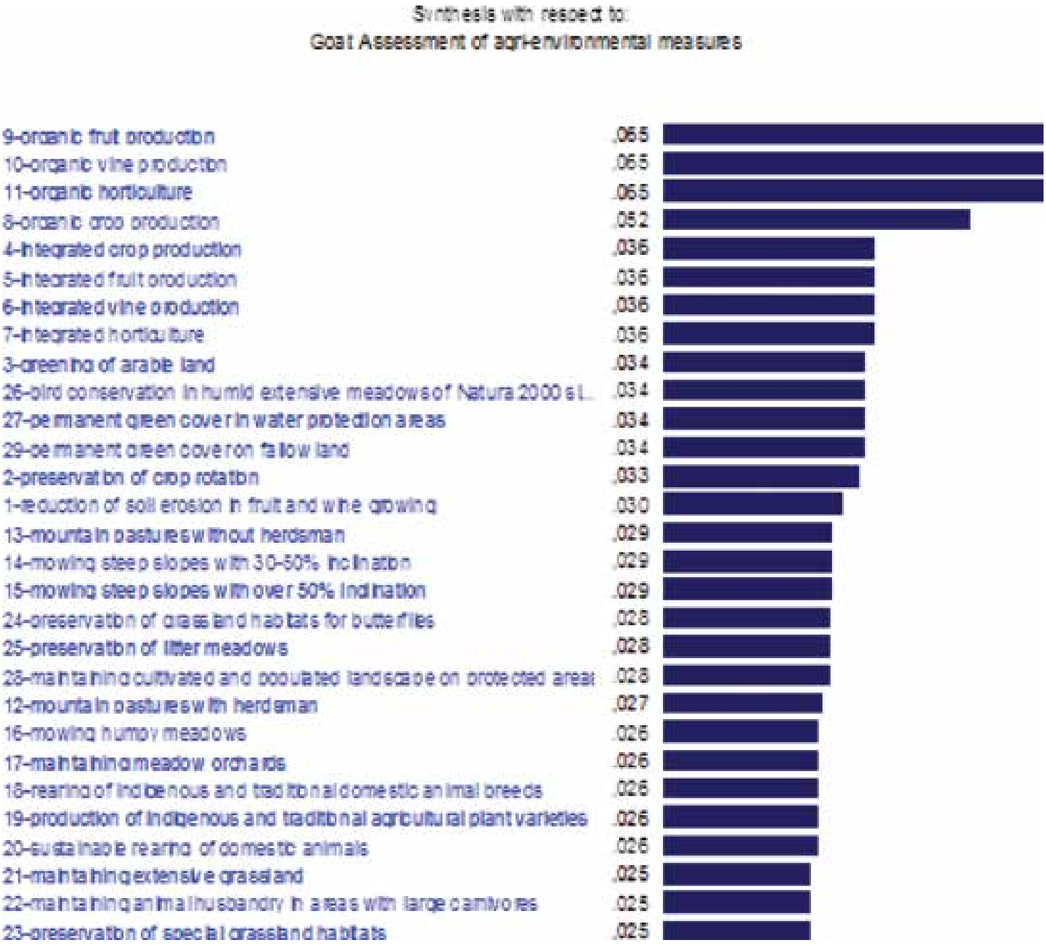


Figure 2. Synthesis with respect to goal (group judgements).

Step 2: The models in AHP were built by decomposing the complex main goal into smaller less complex sub-goals, factors that affect the subgoals and ending with the outcome of the strategies [46,48]. This led to a hierarchical structure (**Figure 1**) with criteria, attributes and alternatives [48,49]. The concrete measures to fulfil the defined objectives to finally reach the main goal, 29 of them in this case compiled by the state, are at the bottom of the hierarchy.

Step 3: To determine the interrelations in the hierarchy, pairwise comparisons of the parameters at each level of the hierarchy were done with respect to the element immediately above them. Through pairwise comparison of the elements at each level of the hierarchy and within the hierarchical levels, weights were determined (**Figure 2**), which help to show the correlations within the structure [49]. AHP allows comparisons using real measurements (quantitative judgement) or a scale created by Saaty which expresses the degree of preference, importance or likelihood (qualitative judgement) [18,46].

Step 4: Aggregation of the priorities to have a ranking of the alternatives was carried out. This was done by determining the ratings of the alternatives with respect to each criterion and then adding up these ratings for all criteria.

Step 5: Control of consistency was done by determining the consistency index, CI that is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

where $\lambda_{\max}$ is the eigenvalue of the matrix and n the size of the matrix. A consistency index of up to 10% is tolerable. A slight deviation of the consistency index from 10% is not a problem. A large deviation means that the judgements are not optimal and have to be improved.

The attributes/criteria and alternatives included in the hierarchy (**Figure 1**) were extracted from the agri-environmental measures of the RDP of the Republic of Slovenia. Each EU member state has its own RDP especially compiled to suit its circumstances and special conditions.

The hierarchical structure consists of four levels with the main goal, "Assessment of agri-environmental measures" as the first level. The second level has three subgoals (•) and the third level a different number of subgoals (-) for each subgoal, as shown in **Figure 1**:

- Promote environmental friendly agricultural practices: sustainable and careful use of agricultural resources is the main focus in this subgoal.
  - Soil quality and fertility will be improved by reducing soil erosion, loss of humus and loss of nutrients through leaching [50].
  - Agri-environmental measures aim at reducing the contamination of groundwater and drinking water sources through chemicals discharged into the environment during agricultural production.
  - According to Latacz-Lohmann and Hodge [51], there has been an exaggerated and uncontrolled use of chemical fertilizers and pesticides in the past. As a result, considerable decline of biodiversity was observed among other negative consequences. The agri-environmental measures aim at reducing this destructive practice.
- Improve the rural areas to prevent marginalisation: Because of lack of income in the rural areas there has been a significant amount of rural exodus, people moving to areas of industrial concentration and into bigger towns [52]. With this subobjective, there is hope that the rural exodus might be reduced or even reversed to a certain degree.
  - Conservation of agricultural land implies minimal soil disturbance, permanent soil cover and crop rotation.

  - Unique traditional and indigenous domestic animal breeds are mostly well known for their toughness and resistance against aggressive animal diseases. So the main aim here is to retain this valuable genetic material. Genetic diversity will help reduce loss in times of drought and epidemics.
  - Climatic change has evoked unreliable weather conditions. The growing seasons are threatened by these unpredictable weather conditions. Traditional and indigenous plant varieties contribute to a greater diversity of crop plants that can be utilised for agricultural food production. They are a valuable genetic source towards food security since many can grow under harsh conditions. Their constituents are usually highly nutritious or medically effective. Preservation of a high agro-biodiversity is one of the important goals towards sustainable agricultural production.
  - Less favoured areas already have the problem that agricultural land is limited and the conditions for agricultural production are not favourable. The little space that is available has to be used gently/carefully to avoid deterioration. Traditional and indigenous domestic animal breeds and plant varieties could play a role to make these areas usable for agricultural purposes [53].
  - The landscape has to preferably be kept in its natural state so that many animals, big and small, have their ideal habitat. This means for example that grasslands have to be maintained to avoid bush encroachment.
  - Job creation is vital to make the rural areas an attractive place to live. This might help to attract many people out of the industrial/urban areas back to the rural areas.

- Production and economic consequences: With farmers investing in the rural areas, new jobs will be created. If the rural areas are made attractive enough with the appropriate infrastructure, even young farmers will find it worth settling in the rural areas [54].
  - Costs of measures play a major role as to whether they are successfully implemented until the end of the given period.
  - Successful implementation of the agri-environmental measures also depends on how complex they are for the farmers. Too complex measures will be wrongly put into practice, which leads to the wrong outcome as the intended.
  - To be able to get the produce from the rural areas on the markets, reliable channels for marketing have to be created.
  - If there is economic profitability for the farmers through implementation of the measures, the farmers might not give up farming. They might also not leave rural areas and migrate to urban areas [55].
  - The farmers will probably encounter yield reduction if they changed the method of production to suit the demand for more biologically produced foodstuff. Their products are healthier and of a higher quality. They produce less but will be able to sell their products at higher prices.

The fourth and last level at the bottom of the hierarchy has 29 measures that are very specific for Slovenia.

After determining the hierarchy, questionnaires were sent to five experts involved in the preparation and evaluation of agriculture environmental subsidies payment system, on who made pairwise comparisons at each level of the hierarchy. These pairwise comparisons were used to assess the agri-environmental measures. For assessment, the individual judgements obtained from questionnaires were turned into comparison matrices for each expert. Since this decision procedure is considered as a group decision, the decision values from the individual experts have to be aggregated to one matrix. This can be done by aggregating the values of the individual pairwise comparisons at each level of the hierarchy or by first calculating the priority weights for each individual expert at each level of the hierarchy and then aggregating these priority weights. In both cases, the aggregation is done by building the geometric mean as recommended by Saaty and Vargas [49] and Meixner and Haas [47]. The geometric mean (G) is obtained by calculating the *n-th* root of the product of the individual expert values:

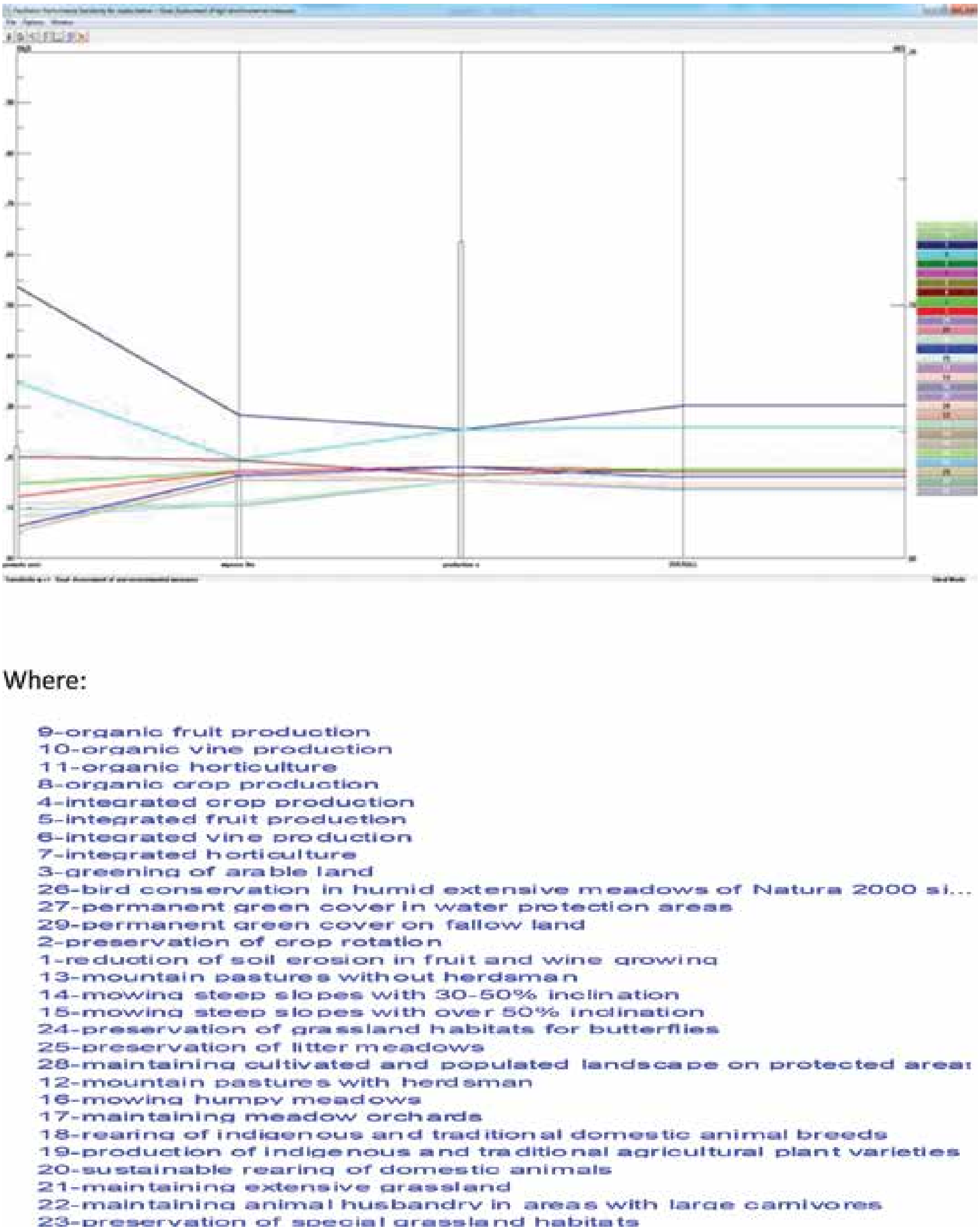
$$G = \sqrt[n]{x_1 x_2 \ldots x_n}$$

where x represents each expert and n is the total number of experts. The results in this paper were obtained by aggregating the values of the individual pairwise comparisons at each level of the hierarchy. The values of the aggregated matrices were fed into the software programme Expert Choice™, which was programmed to implement AHP. Expert Choice™ calculated the criteria, subcriteria and alternative weights with respect to importance and the consistency index.

3. Results and discussion

The alternative priority weights with respect to the goal were calculated. The bigger the weight is, the more the measure is considered as important. Ranking the calculated priority weights with respect to the goal gave an insight into which AEM is considered important. Some rankings have more than one AEM, which indicates that the AEM for the particular ranking are considered to have the same importance. Weights of criteria show that production and economic consequences (0.425) are considered to make the most substantial influence on the assessment of AEM, followed by promotion of environmental friendly agricultural practices (0.333); improvement of rural areas to prevent their marginalization (0.241) is on third place. All three criteria are an integral part of the efforts towards improving the rural areas and the environment because they address different aspects of these efforts. The aggregated weights for the criteria and subcriteria of the group model are shown in **Figure 1**.

Further, the control of consistency was done by controlling the consistency index (CI) calculated by expert choice. The CI of 0 shows that the assessment results are consistent. The overall results (priorities) for each AE measure are shown in **Figure 2**.



Where:

9-organic fruit production
10-organic vine production
11-organic horticulture
8-organic crop production
4-integrated crop production
5-integrated fruit production
6-integrated vine production
7-integrated horticulture
3-greening of arable land
26-bird conservation in humid extensive meadows of Natura 2000 si...
27-permanent green cover in water protection areas
29-permanent green cover on fallow land
2-preservation of crop rotation
1-reduction of soil erosion in fruit and wine growing
13-mountain pastures without herdsman
14-mowing steep slopes with 30-50% inclination
15-mowing steep slopes with over 50% inclination
24-preservation of grassland habitats for butterflies
25-preservation of litter meadows
28-maintaining cultivated and populated landscape on protected area:
12-mountain pastures with herdsman
16-mowing humpy meadows
17-maintaining meadow orchards
18-rearing of indigenous and traditional domestic animal breeds
19-production of indigenous and traditional agricultural plant varieties
20-sustainable rearing of domestic animals
21-maintaining extensive grassland
22-maintaining animal husbandry in areas with large carnivores
23-preservation of special grassland habitats

Figure 3. Sensitivity analysis with an increased weight of production criteria.

The ranking shows that organic and integrated agricultural production practices make the best contribution to promote sustainable agriculture and protect the environment (**Figure 3**).

Permanent green cover on fallow land and greening of arable land are measures that contribute to reducing soil erosion and improving soil quality and fertility. Permanent green cover in water protection areas is vital to prevent the pollution of drinking water and its sources. Also considered as important is bird conservation in humid extensive meadows of Natura 2000 sites, which contributes to stopping the decline of biodiversity. Preserving and maintaining extensive meadows of Natura 2000 sites will not only secure natural habitats for birds, but also for other indigenous wild animals and plants. Almost equally important to promote environmental friendly agricultural production practices are stopping the decline of biodiversity, reduction in discharging chemicals into the environment and preventing pollution of drinking water and its sources. Improvement of the rural areas is best achieved by creating employment. Conservation of agricultural land is also an important factor to prevent the marginalisation of the countryside.

Stopping the decline of agricultural biodiversity through rearing of indigenous and traditional domestic animal breeds and production of indigenous and traditional agricultural plant varieties is also considered as important. These are key measures towards sustainable agricultural production and food security.

The importance of AEM for the individual criteria and attributes can be shown by synthesizing their priority weights at each node of the hierarchy levels. These values are seen in **Figure 3**. The sensitivity analysis, a test of the reaction of the agri-environmental measures to a change of the priority weight of the objectives, shows no significant changes in the overall ranking of importance of the measures.

By varying the priority weight of each objective, making it most important as shown in **Figure 3**, a slight change in the importance of the agri-environmental measures is only visible for each objective. **Figure 2** shows the highest overall performance in organic production. Integrated crop production, greening of arable land, and preservation of crop rotation are the next important measures.

The criteria weights are 33.3% for promoting environmental friendly agricultural practices, 24.1% for improving the rural areas to prevent marginalisation and 42.5% for production and economic consequences. The organic fruit and vine production and organic horticulture are the most important measures with 6.5% each, followed by organic crop production with 5.2%, integrated crop, fruit, vine production and integrated horticulture with 3.6% each. Bird conservation in humid extensive meadows of Natura 2000 sites, permanent green cover in water protection areas, and on fallow land and greening of arable land got 3.4% each. The preservation of crop rotation was allocated a weight of 3.3% and reduction of soil erosion in fruit and wine growing 3.0%. By changing the priority weight of the criteria: promote environmental friendly agricultural practices to 49.0%, organic fruit and vine production, organic horticulture kept their leading position as most important measures but their weights increased to 7.5% each, followed by organic crop production which also got a bigger weight of 5.6%; integrated crop, fruit, vine production and integrated horticulture each got 3.7%, a weight bigger than in primary assessment. Bird conservation in humid extensive meadows of Natura 2000 sites and permanent green cover in water protection areas and on fallow land each has a weight of 3.6%. Greening of arable land went down to 3.3%, whereas the preservation of crop rotation reduced to 3.1% and reduction of soil erosion in fruit and wine growing to 2.6%.

By changing the weight and priority of the objective: improve the rural areas to prevent marginalisation to 49.0%, the ranking of the measures still stayed the same. Organic fruit and vine production, organic horticulture kept their leading position as most important measures, followed by organic crop production with 4.8%; integrated crop, fruit, vine production and integrated horticulture kept their weights of 3.7%. Bird conservation in humid extensive meadows of Natura 2000 sites, permanent green cover in water protection areas and on fallow land, greening of arable land and preservation of crop rotation each got a weight of 3.4%, reduction of soil erosion in fruit and wine growing 3.1%.

By changing the weight and priority of the objective: production and economic consequences to 49.0%, the there was no significant change in the weights of the measures compared to Figure 6. Organic fruit and vine production, organic horticulture kept their leading position as most important measures with weights of 6.4% each, followed by organic crop production with 5.2%; integrated crop, fruit, vine production and integrated horticulture kept their weights of 3.6% each. Bird conservation in humid extensive meadows of Natura 2000 sites, permanent green cover in water protection areas and on fallow land show weights of 3.4% each, greening of arable land 3.5%, the preservation of crop rotation each 3.4% and reduction of soil erosion in fruit and wine growing 3.1%.

However, the organic fruit production is seen as the most important agri-environmental measure is specific for Slovenia because of its geographical features. Vrišer [56] states that in the census of the agricultural sector made in 2000, the proportion of Slovenia’s total surface area of plains and low hills amounts to 36.4%, on which 54.5% of the utilised agricultural area is found, whereas on the karst regions that occupy about 25.3% of the total surface area, there is only 17.5% of utilised agricultural area, and in the high mountains (10.8%), only 3.5%. Vrišer also noted that 2.6% of the agricultural area was used for fruit production. In 2006, Sušnik et al. [57] still noted that fruit is grown on 2–3% of all agricultural land in Slovenia. This shows no increase in the fruit-growing area.

Despite limitations (particularly in the field of data acquisition), we found that the approach full field our expectations in the field of AEM assessment. The methodology results in precise AEM ranking with respect to defined criteria priorities. Furthermore, the group approach and priorities aggregation enable inclusion of the large number of experts relevant for the analysis.

4. Conclusion

The attempt in this paper was to show how AHP can successfully be employed in agriculture by assessing the role of agri-environmental measures to improve agriculture and the countryside. The goal, criteria and their attributes were compiled by the government of Slovenia. Arranging them in a hierarchy helped to analyse their interactions within the hierarchy and with respect to the main goal. The correct implementation of the necessary steps in AHP results in very comprehensive data, which can be used to verify the goal. Very decisive for the data to be representative is its collection either by questionnaires, brain storming or discussions. Since the AHP process mostly involves a group of experts, stake holders or other persons affected, the collected data have to be compressed by building the geometric mean. In this example, it was successfully done. Though it is time consuming, it is the best way to take the different opinions involved in the assessment procedure into consideration. Compressing the data is necessary to be able to feed the information into the computer software programme Expert Choice™.

Instead of just using SWOT, a form of MCDA could have therefore been successfully used to evaluate the AEM. AHP could have combined different interests, expertise and opinions of all the government institutions involved. The employment of Expert Choice™ could have delivered reliable information. The results obtained in the assessment clearly show that organic and integrated production methods are seen to contribute most to achieving the set environmental goals and enhancing sustainable agricultural production. At the same time, measures that contribute to stopping the decline of biodiversity and preventing contamination of drinking water and its sources are also seen as an integral part of agricultural activities. However, the results generated by AHP do not end debates on further action regarding environmental friendly agricultural practices and policy. They are a good basis for further discussion.

Author details

Monica Huehner, Črtomir Rozman and Karmen Pažek*

*Address all correspondence to: karmen.pazek@um.si

Faculty of Agriculture and Life Science, University of Maribor, Maribor, Slovenia

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Application of the AHP Method in Environmental Engineering: Three Case Studies

Tomasz Stypka, Agnieszka Flaga-Maryańczyk and
Jacek Schnotale

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Abstract

The chapter presents the application of the Analytic Hierarchy Process (AHP) method in the field of environmental management. The work shows how to use the results of environmental engineering tools or models as an input for the AHP method. Three case studies are presented: selection of the best municipal solid waste disposal system, assessment of the tap and bottled water consumption on the environment, and selection of the heat pump for the individual home. In the first case study, the AHP analysis was required to assess the environmental impact of waste disposal system. This was done by the use of Integrated Waste Management model (IWM-1), which delivered results aggregated, at the next step, into Life Cycle Analysis (LCA) categories. The obtained results were used in the AHP analysis to choose the best scheme for the waste disposal system. In the second case study, the AHP method was used to evaluate different patterns of water drinking. Obtained results help decision makers in assessing regional and individual environmental impact if the drinking pattern changes. Selected evaluation criteria were solid waste stream, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. The third case study presents the method of heat pump selection. The environmental performance criteria were developed using the criteria of the ecolabeling program. All three case studies are based on real data.

Keywords: AHP, MSWM model, sustainable development, ecolabeling, heat pumps

1. Introduction

The Analytic Hierarchy Process (AHP) method turns up to be a useful and dominant method for solving the whole spectrum of multicriteria problems [1]. It is the most popular among

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European, Asian, and American researchers in all environmental areas with the exception of air quality and its popularity is growing in time [1]. At present, it is often integrated with other tools of decision making such as Quality Function Development (QFD), meta-heuristics, SWOT analysis, mathematical programming, and Data Envelopment Analysis (DEA) [2].

The full potential of the AHP in solving the environmental problems can be unveiled when the method is combined with the environmental tools. The environmental tools are used to develop and measure many criteria of the analyzed systems performance which are used as an input for the AHP analysis. Such tools can also help in the proper designing of the criteria hierarchy. The presented case studies show such an integrated approach where environmental tools—ecolabeling programs, Life Cycle Analysis (LCA) software or Eco-indicator 99 H/A points—are used to measure the environmental impact and deliver input information for the AHP analysis. These tools can also help build the proper structure of the hierarchy of criteria.

The first case study shows how the AHP method can be combined with the LCA waste disposal model to help select the best municipal solid waste system. Two systems, one based on incineration and the other based on landfilling, are compared. Because one of the evaluation criteria is an environmental performance, the professional solid waste management tool called Integrated Waste Management model (IWM-1) was used to calculate this environmental impact. Because the IWM-1 results are too detailed for the AHP, they, in the next step, had to be integrated into Life Cycle Analysis (LCA) impact categories. For the final integration, the AHP method was applied. The Web-HIPRE software (http://hipre.aalto.fi/) was used to conduct the analysis. Finally, the presented sensitivity analysis showed the confidence of the obtained results and pointed out the most important assumptions of the whole analysis.

The second case study shows how the AHP method combined with eco-indicators can be used to help develop municipal policy toward drinking tap and bottled water. So popular bottled water is expensive for individuals and causes problems for the environment and waste disposal communities. The goal of the project is to measure this burden to help municipality develop rational policy in this area. The impacts of drinking tap water and bottled water are estimated using criteria such as waste stream reaching landfills, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. The developed criteria are integrated using the AHP method, which allowed developing graphs that can be used by the decision makers to estimate results and to make appropriate proposals on policy actions toward bottled water drinkers.

The third case study shows how to select the heat pump for a house. Generally, the selection is conducted by professionals with limited attention to the personal needs of the user, or it is made by the user with limited attention to technical details. The presented AHP method combined with the ecolabeling program solves this problem. It can be used by a non-professional to help professionally select a heat pump. The critical problem of proper criteria selection was solved with the help of the "Nordic Swan" ecolabeling program. Because sometimes costs are separated from the criteria hierarchy, the option with the Cost-Benefit Analysis (CBA) of the same heat pumps is also conducted. In this case, the AHP method is used to calculate the integrated benefit of each heat pump while the cost was calculated using the Net Present Value (NPV) indicator.

All three case studies are described in more details in Refs. [3–5].

2. Comparative analysis of municipal solid waste systems: Cracow case study

There is a need to develop, master, and implement a simple, but reliable tool that would help the decision makers select the Municipal Solid Waste Management (MSWM) system. There are number of mathematical municipal solid waste models that might be used to solve the problem, where the objective function is the cost of waste disposal. The environmental elements (the recycling schemes) have appeared in the models beginning in the 1980s [6, 7]. Also there is a group of models, which include the environmental factors in the form of constrains of the economic models [8]. Some of the models are based on the concept of Life Cycle Analysis (LCA) while other focus only on different environmental elements such as traffic or noise [8] or CO_2 emissions from waste delivering vehicles [9]. The review of different models can be found in Refs. [10–12], but so far no model fits fully the decision makers' expectations.

Probably the group of models which, in the best way, reflects the idea of sustainable development is a group of Life Cycle Analysis (LCA) models. The examples of such models are the US-EPA [13], WISARD [14], MIMES/Waste [15], ORWARE [16], ISWM tool Canada, LCA-IWM [17] and Integrated Waste Model (IWM) [14]. IWM (Integrated Waste Model) was first published in 1995 as an IWM-1 (in form of an Excel spreadsheet). IWM-2 was developed to improve certain aspects of IWM-1 and to make the model more global by including new set of data. IWM-1 was rather a European development [18]. IWM-2 was published in more user-friendly SQL-Database environment, which unfortunately is less transparent hence less useful for in-depth analysis. The authors chose IWM-1 model considering it to be transparent, flexible and simple.

The results of IWM-1 model are numerous and detailed, which makes them not convenient for the inexperienced decision makers, who are interested in the clear and simple answer which MSWM system is the best. To help with this issue, the authors integrated IWM-1 results using the LCA impact categories and later, implementing simple, but sound multiobjective AHP method. Described methodology allowed to compare two MSWM systems for the city of Cracow, Poland (population: 742,000).

2.1. Description of the compared MSWM systems

The authors compared two MSWM systems. The real system applied in Cracow, Poland, in year 2001, based on the landfill as the main option of waste disposal (called "system A"), and the hypothetical system based on the assumption that the waste recycling is improved and the main way of rest-waste disposal is incineration. This was the planned system for Cracow at that time. In the analysis, this system is called "system B." The case study is based on real data. The information regarding waste and systems' description was cited after Kopacz [19].

The key data for the MSWM analysis are the amount and composition of waste. Waste input data, the same for system A and system B, divided into categories required by the IWM-1 model presents (**Table 1**).

Amount (t/year)	**Household waste composition (wt.%)**								
	Paper	**Glass**	**Metal**		**Plastic**		**Textiles**	**Organics**	**Other**
169,346	19.9	7.8	2.9		14.4		6.1	36.2	12.7
			Ferrous	Non-Fe	Film	Rigid			
			65	35	44	56			
Amount (t/year)	**Commercial waste composition (wt.%)**								
	Paper	**Glass**	**Metal**		**Plastic**		**Textiles**	**Organics**	**Other**
107,806	45.0	5.0	4.1		12.0		1.0	30.0	2.9
			Ferrous	Non-Fe	Film	Rigid			
			60	40	80	20			

Table 1. Composition of different parts of Municipal Solid Waste in analyzed Cracow case.

In system A, landfilling is the main disposal method and there are also 150 recycling material banks for metal, polyethylene terephthalate (PET) bottles, paper and glass. Additionally to the system of recycling banks, there is a system of "bring and earn" collection points and the composting facility with the throughput of 6000 tons per year. A number of charity organizations run the system of collection points for the textile waste.

In system B, the annual throughput of 200,000 tons of waste is assumed for the incinerator. The incinerator generates only electricity with the 20% efficiency. Contrary to the real Cracow plans, the waste heat recovery is not modeled because IWM-1 model does not have such an option. This blurs the final results, but in reality the incinerator generates the heat for the municipal district heating system, substituting the waste heat from the power plants. If the city decides to utilize the heat from the incinerator, the power plants have the problem of "what to do" with their by-product, hence the environmental benefits of incinerator's waste heat utilization are problematic. Additionally, in system B, the number of collection banks is increased up to 450, and thanks to the increase of public awareness, the amount of recyclables collected in each bank is increased by 25%. System B assumes the development of the recycling program. Material Recovery Facility ready to handle 20,000 tons of recyclables along with two composting facilities for 6000 and 9000 tons of green waste is commissioned. Also, in some parts of the town, the "wet" and "dry" waste collection systems are introduced.

As a result of those changes, the amount and quality of waste disposed at the landfill change significantly. The exact results, for both systems, calculated using IWM-1 model are presented in **Table 2**. In system B, the amount of waste disposed at the landfill is reduced by five times (from 247 ktons in system A to 49 ktons in system B). Also in system B, the diversion from landfill is eight times higher than in system A, and the amount of recyclables is increased more than twice. The economic and environmental results of the two systems are also very different.

Final solid waste	**System A**	**System B**
Non-hazardous (kt)	246.98	48.67
Hazardous (kt)	0.39	6.57
Total weight (kt)	247.37	55.24
Total volume (m^3)	160,590	44,410
Materials recovery rate		
Average	17%	36%
Paper	25%	54%
Glass	6%	20%
Metal Fe	40%	56%
Metal non-Fe	15%	21%
Plastic film	4%	5%
Plastic rigid	1%	22%
Textiles	6%	11%
Organic recovery rate	1%	4%
Overall recovery rate	10%	22%
Diversion from landfill	10%	80%
Secondary materials (kt/year)		
Paper	20.77	44.09
Glass	1.12	3.66
Metal Fe	2.36	3.25
Metal non-Fe	0.53	0.74
Plastic film	0.92	1.10
Plastic rigid	0.14	3.65
Textiles	0.71	1.25
Compost	1.02	3.58
Total	27.56	61.33

Table 2. Streams of waste and recovered materials for analyzed scenarios.

2.2. Integration method of the IWM-1 results

The IWM-1 model delivers results estimating the air emissions of 22 compounds and emission of 23 compounds into water. Additionally, the basic statistical and economical data about the systems' performance are also presented. This is a lot of detailed information not useful for the decision makers and has to be combined before implementation. The proposed integration method is based on impact assessment of LCA. To calculate these indicators, the authors used the methodology described in detail in Refs. [20–22]. The general assumption was to estimate the maximum possible number of LCA categories, which could be calculated based on the IWM-1 results. **Table 3** presents the list of the selected categories.

Impact categories	Characterization factor	Unit
Baseline categories		
Depletion of abiotic resources	Abiotic depletion potential (ADP)	kg (antimony eq.)
Climate change	Global warming potential (GWP 100)	kg (carbon dioxide eq.)
Human toxicity	Human toxicity potential (HTP 100)	kg (1,4-dichlorobenzene eq.)
Ecotoxicity: fresh water aquatic ecotoxicity	Freshwater aquatic ecotoxicity potential (FAETP 100)	kg (1,4-dichlorobenzene eq.)
Ecotoxicity: terrestrial ecotoxicity	Terrestrial ecotoxicity potential (TETP 100)	kg (1,4-dichlorobenzene eq.)
Photo-oxidant formation	Photochemical ozone creation potential (POCP)	kg (ethylene eq.)
Acidification	Acidification potential (AP)	kg (SO_2 eq.)
Eutrophication	Eutrophication potential (EP)	kg (PO_4^{3-} eq.)
Stratospheric ozone depletion	Ozone depletion potential (ODP steady state)	kg (CFC-11 eq.)
Land competition	Land use	m^2 year
Other impact categories		
Odor malodorous air	Reciprocal of odor threshold value (1/OTV)	m^3 (air)

Table 3. Selected categories of the life cycle impact assessment.

Indicators for the different impact categories were selected based on the literature [23]. Unfortunately, not all recommended impact categories can be directly calculated from the IWM-1 result table. The obtained results are presented in **Table 4**. More detailed environmental analysis of the results can be found in reference [3].

The results show that, based on landfilling, system A is superior when the following criteria were analyzed: abiotic depletion, human toxicity, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, acidification and eutrophication. The second scenario, system B, with advanced waste sorting and incineration, turned out to be better in categories of energy consumption, climate change, photochemical smog creation and odor creation.

		System A	System B
Energy balance	GJ th	−102,500	−702,530
Depletion of abiotic resources	kg (antimony eq.)	−8.77E + 00	1.12E + 02
Climate change	kg CO_2 eq.	2.68E + 08	2.11E + 08
Human toxicity	kg (1,4-dichlorobenzene eq.)	3.67E + 05	3.49E + 08
Fresh water aquatic ecotoxicity	kg (1,4-dichlorobenzene eq.)	−7.19E + 04	−3.01E + 05
Terrestrial ecotoxicity	kg (1,4-dichlorobenzene eq.)	−1.89E + 02	3.65E + 05
Photo-oxidant formation	kg (ethylene eq.)	6.19E + 04	−2.51E + 04
Acidification	kg (SO_2 eq.)	4.81E + 04	2.21E + 05
Eutrophication	kg (PO_4^{3-} eq.)	1.36E + 04	1.34E + 03
Odor malodorous air	m^3	1.07E + 13	−9.83E + 11
Land competition	m^2 yr	7.49E + 05	2.07E + 05
Cost	1000 euro	20586.23	37298.27

Table 4. Results of the Integrated Waste Management model (IWM-1) analysis.

The obtained aggregated results still do not give a straight answer about the superiority of one specific system. There are many categories, measured by different units, and the analyzed systems fulfill various criteria in varying degree. Some of the categories are measured using the same units, but even in this case, the comparison between the different categories is impossible. For example, human toxicity, freshwater aquatic ecotoxicity and terrestrial ecotoxicity are all measured by 1,4-dichlorobenzene eq. in 100 years perspective. Even in this case, comparison among these categories is possible only when using the impact ratios.

The final evaluation of the analyzed scenarios was made using the AHP method.

2.3. Multicriteria analysis of the Cracow MSW systems

The authors used Analytic Hierarchy Process (AHP) as a method of further analysis with software prepared by Helsinki University of Technology [24]. Prepared hierarchy of criteria and assigned ratings are presented in **Figure 1**. Criteria were developed based on IWM-1 analysis and the ratings were assigned arbitrarily by the authors based on their experience. The goal of the model was to find the most sustainable solution and the selected hierarchy of criteria reflected this approach. The authors represented the whole spectrum of expertise in environmental engineering, environmental management and waste handling. The final ratings were reached at some point in the joined discussion.

Figure 2 presents the final results of the analysis. The graph shows that system B is better evaluated than system A. The overall score of system A is 0.362 and system B is 0.638. This means that system B is almost two times better than system A and, in other words, meets all the expectations in 64%. System B is superior to system A, thanks to significantly better environmental performance. The more detailed comparison of the environmental performance of the two MSW systems is presented in **Figure 3**. System B is more friendly toward all three components of the environment: water, soil and air. It is superior to system A in all subcategories of air and water criteria. The environmental superiority of system B in subcategory "soil protection" is not so dominant. System B is better only in "land use" sub-criterion, but because this sub-criterion is so important, the total evaluation of system B in subcategory of "soil protection" is better than the performance of system A.

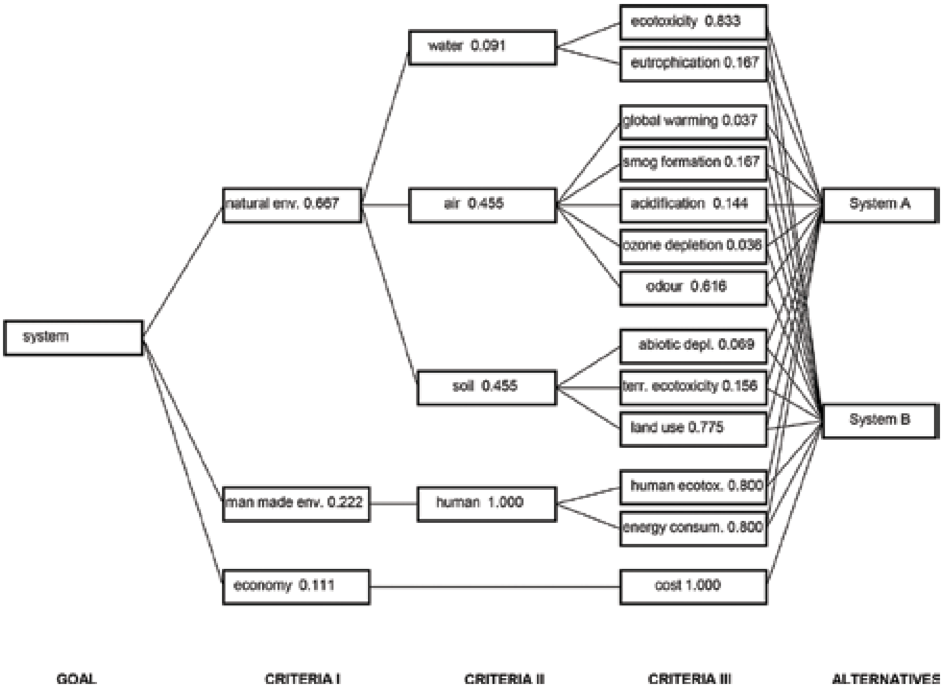


Figure 1. Objective hierarchy and ratings for the Cracow analysis.

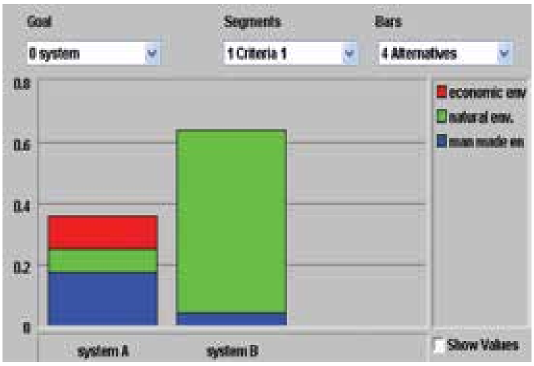
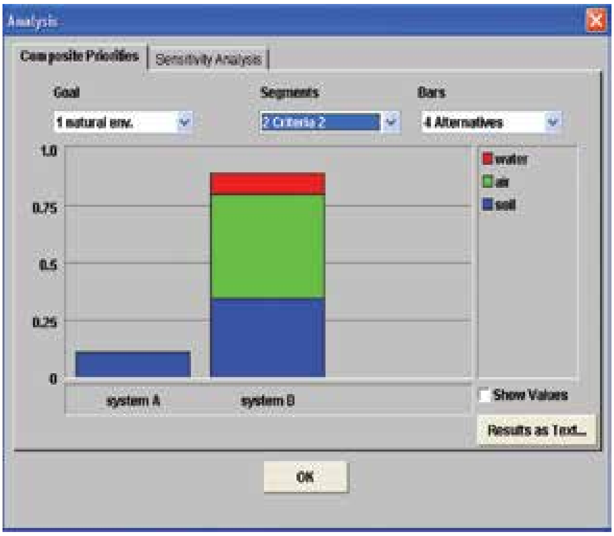

Goal: 0 system
Segments: 1 Criteria 1
Bars: 4 Alternatives

Figure 2. Results of the AHP analysis for the two Cracow MSWM scenarios (criteria 1).



Goal: 1 natural env.
Segments: 2 Criteria 2
Bars: 4 Alternatives

Figure 3. Results of the AHP analysis for the two Cracow MSWM scenarios (criteria 2).

A more detailed analysis of the obtained results allow to draw conclusion about how much the environmental performance of system B is increased by substituting the landfilling with the incineration and extension of the waste collection system. Also, the local and global environmental impacts can be distinguished [3].

The AHP analysis gives very clear answer that system B is superior to system A. Such a simple answer is expected by the decision makers, but the AHP analysis combined with the IWM-1 model also gives more detailed results justifying its overall score which can be useful in further analysis.

2.4. Sensitivity analysis and conclusions

The sensitivity analysis is trying to give answer to the question: how much the obtained results change if there is a change in the input values? The final outcome of the AHP analysis depends on the assumed hierarchy of goals, on the assigned relative weights of the goals and on the performance of the analyzed alternatives, but the performance of the analyzed systems has far more limited impact on the final result. If only two options are compared, it is important if the performance in each category is superior, but not the level of this superiority.

The reason why system B performs better than system A is its significantly better performance in the category "impact on the natural environment." The performance in the AHP analysis is a product of relative weight of the category and estimated physical performance. The relative weight of this category was assumed to be equal to 0.67, but the sensitivity analysis indicates that if this weight is 0.48, both analyzed scenarios will be estimated as equally good (**Figure 4**). If the weight for the natural environment equals 0.48, the other two weights should be in the same proportion to each other, and have the values 0.347 for the impact on the manmade environment and 0.173 for the economic performance. Also, the analysis shows that if the importance of the economic criterion increases from the present ratio 0.11 to 0.30, this will result in making the two analyzed systems equally good (**Figure 5**). The threefold increase of the economic criterion weight is not likely, but possible. The increased rating of the "manmade environment" from the present 0.22 to 0.47 will result in equalizing of the two systems performance. To change the ranks of analyzed scenarios, the weights have to change significantly. It is up to the decision makers to decide whether such a significant change of weights is possible.

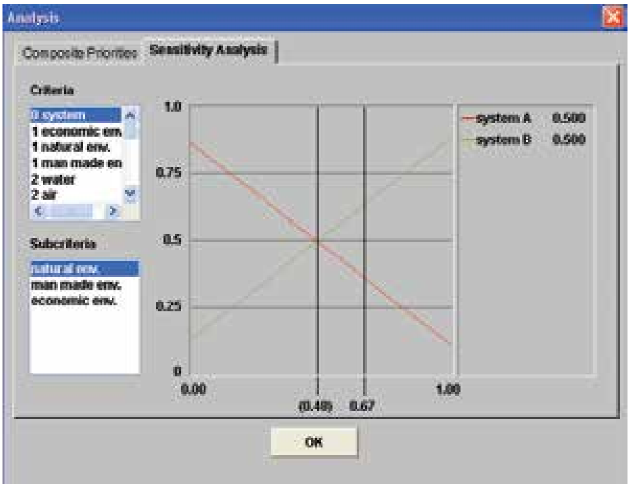


Figure 4. Sensitivity analysis: the relative weight of the category "impact on the natural environment."

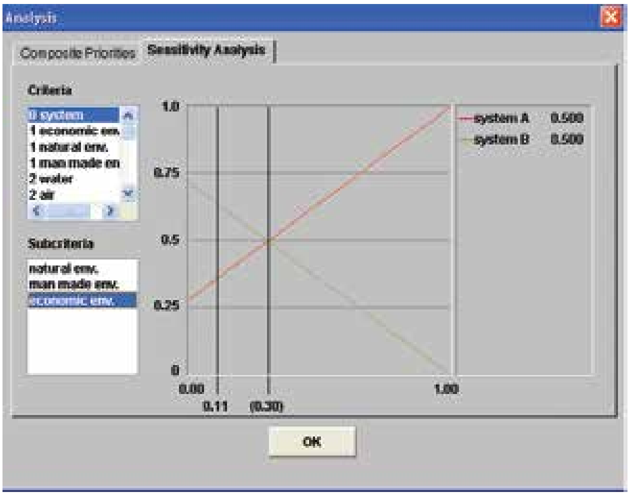


Figure 5. Sensitivity analysis: the relative weight of the category "economic performance."

Changing the weights of all components of the environment (water, air and soil) will change the final evaluation score, but will not change the rating of the systems' impact on the natural environment since all ratings' impact on the natural environment of the system B is better than those of the system A.

No change of water or air criteria ratings can change the two systems' performance in the subcategory "impact on water" and "impact on air" (**Figure 6**). In subcategory "impact on soil," changing the ratings of all subcategories can result in the switch of superiority of the two systems in the category "impact on soil," but the changes have to be substantial (**Figure 7**).

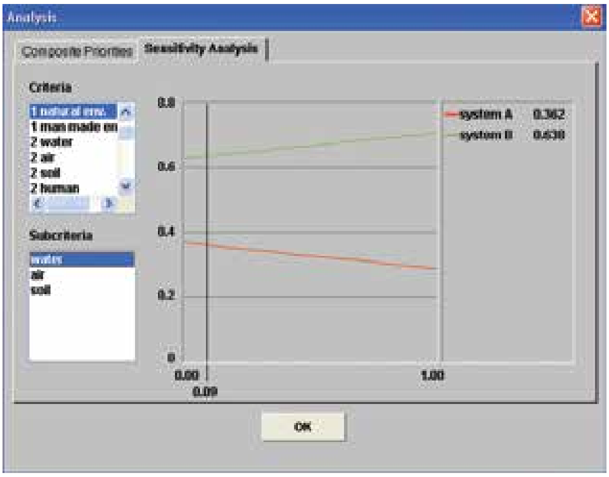


Figure 6. Sensitivity analysis: the relative weight of the subcategory "impact on water."

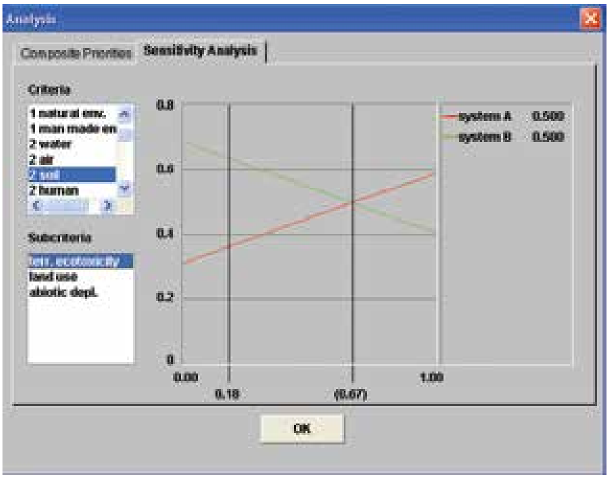


Figure 7. Sensitivity analysis: the relative weight of the subcategory "impact on soil."

Generally, the sensitivity analysis shows that the biggest impact on the final score have the weights assigned at the top level of hierarchy (natural environment, manmade environment, economic impact) and the weights assigned to category "impact on soil."

The AHP method combined with the IWM-1 model allowed the broad and thorough comparison of two different waste disposal systems. In this case, the system based on incineration looks like a better solution and shows superior environmental performance. This good environmental performance is the result of "avoided emissions," thanks to material and energy recovery. The economic performance of the traditional landfilling system is better than the performance of system based on incineration. The overall evaluation shows that the city should build the incinerator and implement advanced recycling programs. These conclusions are in tune with the common trends and regulations. Thanks to the integration of the AHP and IWM-1, the obtained results are clear and detailed simultaneously. This is a quality very much sought by the decision makers.

3. Drinking water consumption in Cracow: an assessment from sustainable development perspective

In this case, the AHP method is used to assess, from a sustainable development perspective, the current consumption model for drinking water in Cracow. It assesses the economic consequences for the average city resident who decides to drink bottled water. The total energy demand for the production, distribution and consumption of bottled water is estimated and is compared to the household energy consumption.

The healthy lifestyle trends and the lack of trust in the quality of tap water result in mass consumption of bottled water. The problem is particularly significant in rich cities, which are visited by large numbers of tourists and also in academic cities, populated by young people who are trend setters, like Cracow. Such a behavior also has consequences from the sustainable development perspective.

The general goal of this case study is to develop a tool for the municipal decision makers to measure the efficiency of policy toward bottled water drinkers.

The environmental impact for the current water consumption model in Cracow is estimated by summing the waste reaching landfills, energy consumption, carbon dioxide emission, and Eco-indicator 99 H/A points. These estimates were calculated based on the data in the reviewed literature revised for the actual quantities of consumed bottled water and bottle recycling levels in Cracow. The potential environmental savings for the city related to an annual reduction of one liter of bottled water consumed by an average resident is also calculated. The different water consumption scenarios are assessed using the AHP to see how compliant they are with sustainable development.

The concept of sustainable development can be considered on three levels: ecological, social and economic. However, a problem arises with how to measure sustainable development for such an activity when the negative effects on an economic and ecological level are partially compensated for on a social level. Russel [25] suggests that energy-intensity and material-intensity of comparable products or processes serve as sustainability indicators. Life-cycle assessment (LCA) is a tool which enables an assessment of material and energy intensity of tap and bottled water preparation as well as an assessment of the impact on an ecological level. In this case, the authors tried to quantify how much bottled water is drunk in Cracow and then using American and Swiss LCA analysis, assess the actual environmental costs of such consumption for the city and its residents. Thanks to LCA, it is also possible to estimate how the environment and economy will change if an average resident reduces his/her consumption of bottled water by one liter annually. A total assessment method is also presented from the perspective of sustainable development for each of the water consumption scenarios. For the total assessment, the multicriteria AHP was used.

3.1. Economic consequences for the present water consumption model

An average Polish citizen drinks 72.4 liters of bottled mineral water annually [26]. Since most people who drink bottled water have a secondary or university education and reside in cities [27], it can be assumed that a resident in Cracow annually drinks 80 liters of bottled water.

A survey of water prices carried out in one of the supermarkets in Cracow showed that bottled water is about 500 times more expensive than tap water. Considering that a person should drink 1.5 liters of water daily, a resident of Cracow drinks approximately 548 liters of water annually, of which bottled water amounts to at least 80 liters (15%). Consequently, a resident of Cracow pays between 53 zloty and 24.22 zloty annually for bottled water whilst the remaining 85% of water drunk costs just 1.60 zloty.

3.2. The effect of bottled water consumption on the natural environment

One of the main burdens on the natural environment associated with the consumption of bottled water is its energy-intensity and the waste produced. Currently 95% of the bottled water sold in the USA and over 90% in Poland is in bottles manufactured from PET [28].

Energy is required for PET and bottle manufacture, water treatment, transportation of bottled water, chilling the water, and maintaining it at low temperature. The energy demand for bottle production depends on bottle size. For a one liter bottle weighing 38 grams, about 4 MJ of energy is required [28]. The energy required for the treatment of drinking water depends on the technology and the degree of pollution. For example, ultraviolet disinfection requires only 10 kWh/million liters, but the energy required for reverse osmosis can reach up to 1600 kWh/million liters or more as in the case of sea water desalination [29].

The transportation's energy demand depends on two factors: distance and means of transport. The vehicles used in Poland have a medium energy demand between 3.5 and 6.8 J/(kg km) [29]. **Table 5** shows the total estimated energy demand for bottled water [28].

In this analysis, the energy requirements for the long-distance transportation of water through the pipeline or from deep boreholes have not been taken into account. It is assumed that water is first treated and then poured into plastic PET bottles, capped, labeled, and packed in a bottling plant. Then it is distributed into shops and chilled before consumption. Based on these assumptions, the total energy required for bottled water varies between 5.6 and 10.2 MJ/liter. For comparison, tap water requires on average 0.005 MJ/liter for treatment and distribution [29]. This means consumption of bottled water is between one and two thousand times more energy intensive compared to that of tap water.

Stage	Energy demand (MJ_{th})	Percentage
Manufacture of plastic PET bottle	4	39–71%
Water treatment	0.0001–0.02	0–0.3%
Bottling and labeling	0.01	0–0.1%
Transport—dependent on distance and type	1.4–5.8	25–57%
Chilling	0.2–0.4	3–9%
Total	5.6–10.2	100%

Table 5. Total energy demand for the production and consumption of one liter of bottled water.

3.3. Waste

It is estimated that between 100,000 and 150,000 tons of PET packaging is manufactured in Poland annually [28]. Some of it is recycled, but most ends up in a landfill. According to the estimates of Organizacja Odzysku REKOPOL (Warszawa) (REKOPOL Recovery Organisation S.A. Warsaw) currently about 40,000 tons of PET waste is collected annually [30]. Other sources estimate that 28% of plastic PET bottles are recycled in Poland [31]. In 2010, 73% of packaging waste was recycled in some form in Cracow [32]. Based on these data, one can assume that the average resident of Cracow, drinking 80 liters of bottled water in 1.5 liter bottles annually, uses 53 bottles of which 39 bottles are recycled whilst the remaining 14 end up in a landfill occupying 0.019 m^3 (density of compressed plastic PET bottles is 44 kg/m^3 [33] and an average bottle weighs 60 grams). For the whole of Cracow, this means 14,000 m^3 of waste being sent to landfill annually.

3.4. Adapting LCA analysis for the consumption of bottled water in Cracow

To more accurately assess the effect of drinking water consumption on the environment in Cracow, two reports on a similar subject were studied: an LCA report on drinking water systems in the state of Oregon, USA [34] and a similar report for the water supply for Swiss regions [35]. In the reports, various drinking water supply scenarios were analyzed ranging from unboiled tap water to bottled water transported over long distances. Taken into account were various types of packaging (tap water, bidons, bottles), transportation (different sizes of vehicles, shipping), consumption (boiled, unboiled, chilled) and packaging waste disposal policy. Forty-eight different scenarios were analyzed in the American report and 19 in the Swiss report. It was eventually decided that the conditions in Cracow were best reflected by the scenarios in the Swiss report.

Scenario		**Unit indicators**		**Data for Cracow**	
		Energy consumption	**Greenhouse gas emissions**	**Energy consumption**	**Greenhouse gas emissions**
Description	**Abbreviation**	$\frac{MJ_{eq.}}{l_{water}}$	$\frac{kg\ CO_{2\ eq.}}{l_{water}}$	$\frac{GJ_{eq.}}{year}$	$\frac{kg\ CO_{2\ eq.}}{year}$
Water from a municipal water supply network, unchilled	Kr.4	0.014	4.06E–04	5631	168
Water from a water supply network, boiled in an electric kettle	Kr.6	1.07	1.65E–02	442,991	6831
Bottled water, transported 50 km, still, unchilled, plastic PET bottle	But.4	4.35	1.78E–01	1,800,944	73,694
Bottled water, transported 200 km, carbonated, unchilled, plastic PET bottle	But.5	4.38	1.98E–01	1,813,365	81,974
Bottled water, transported 1000 km, still, unchilled, plastic PET bottle	But.9	8.34	4.25E–01	3,452,845	175,954

Table 6. Energy consumption and greenhouse gas (GHG) emissions for different water consumption scenarios for Cracow.

This report envisages nine tap water supply scenarios, out of which four assume water consumed directly from the tap, without chilling or carbonation. The differences between these scenarios are related to the source of the water and consequently to its treatment. The scenarios cover water from abstraction intakes typical for Switzerland (Kr.1), Europe (Kr.2), Swiss rural areas (Kr.3) and Swiss urban areas (Kr.4). In Cracow, each abstraction intake uses different water treatment technology [36]. They all have coagulation, sedimentation and disinfection stages. Since surface water is the source for both Zurich and Cracow, i.e., water having similar parameters, it can be assumed that the water treatment processes have a similar burden on the natural environment in both cities. As for bottled water, the Swiss report assumes 10 scenarios depending on the location where the water is produced (Switzerland, Europe), vehicle transportation distance (from 50 to 1000 km), the distribution method to the households (from 0 to 10 km by delivery van), the type of water (carbonated, still), drinking temperature (chilled, not chilled), packaging (1.5 liter PET, 18.9 liter demijohn for recycling, 1 liter glass bottle for recycling). The But.5 scenario seems to be a good choice for the water consumption model for Cracow. Based on unit indicators estimated in the Swiss report and assuming that 756,186 residents drink 1.5 liters of water daily, the annual consumption of primary energy and greenhouse gas emissions has been estimated (see **Table 6**).

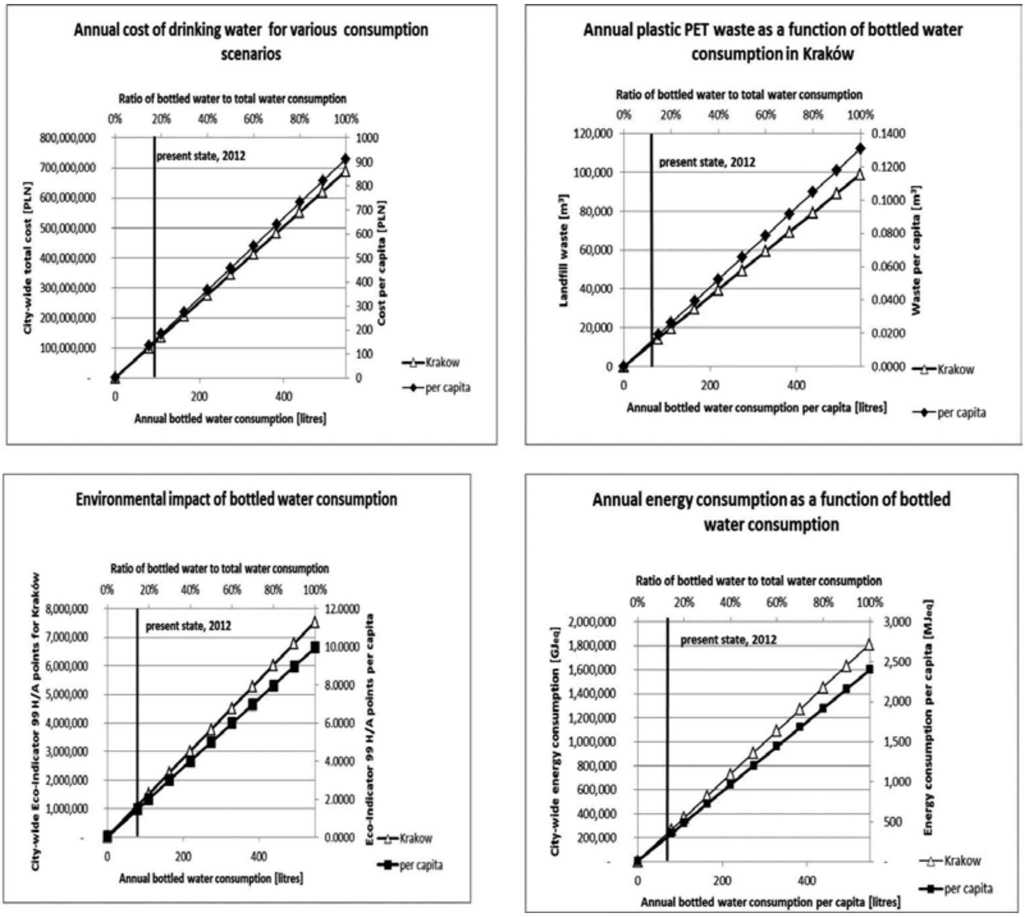


Figure 8. Economic and environmental impact for different drinking water consumption scenarios in Cracow.

Table 6 shows that the environmental impact depends on the water consumption scenario.

In reality, water consumption in Cracow is a mixture of scenarios. About 15% of water (80 liters annually) is drunk as bottled water, which approximately corresponds to scenario But. 5, whilst the remainder is drunk as tap water which corresponds to scenario Kr.4 or Kr.6. Using scenarios Kr.4 and But.5 as the base, the impacts of the intermediate scenarios on the environment were estimated. The results are shown in **Figure 8**.

Figure 8 shows the environmental impact of different bottled water scenarios. If the bottled water consumption increases, all the environmental impact parameters increase very sharply. These charts can be helpful in estimating the expected impacts when changes to the water consumption model are made. The impact of reducing consumption of bottled water by one liter on the global environment and the city was also estimated. These estimates are both city-wide and for one resident. The results are shown in **Table 7**.

Table 7 shows, for example, that the municipal policy which reduces the bottled water consumption by one litter per person results in 3202 GJ energy savings and saves 181 m^3 of the landfill's space. The impact on the environment is measured using Eco-indicator 99 H/A points. Eco-indicator 99 H/A points are used primarily to compare different scenarios and 1000 points have been defined as the annual environmental load of an average European citizen. It is estimated that the impact on the environment is 3.93×10^{-5} points when consuming 1 liter of tap water. However, for bottled water it is 463 times greater at 1.82×10^{-2} points.

	Reduction in bottled water consumption	**Energy consumption**	**CO_2 emission**	**Cost**	**Volume of waste**	**Environmental impact**
	Liters	MJ eq	kg CO_2 eq.	PLN	m^3	Eco-indicator 99 H/A points
For 1 resident	1	4.366	0.198	1.66	0.0002	0.0182
For Cracow	756,183	3,301,797	149,417	1,257,711	181	13,733

Table 7. Environmental impact of a one liter reduction in the consumption of bottled water.

3.5. Evaluation of the water consumption model in Cracow from a sustainable development perspective

The evaluation of individual water consumption models, from a sustainable development perspective, requires an analysis of these models with consideration to their effect on society, the natural environment and economic impact [37, 38]. The next stage is to work out the individual criteria and select the comparison method. The AHP is one of the universal comparison methods which can be used to compare products or processes from a sustainable development perspective [39].

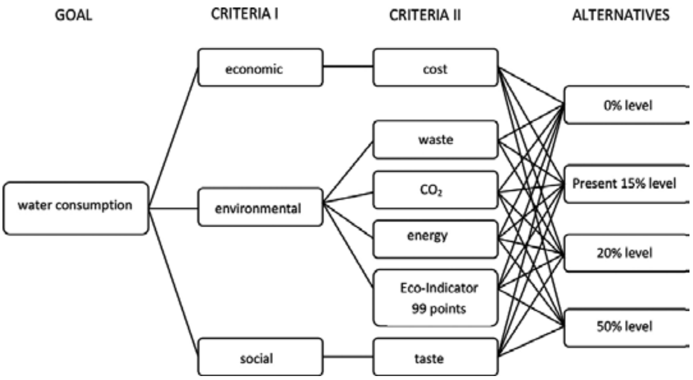


Figure 9. Hierarchical tree of criteria for AHP analysis.

In the case of water consumption in Cracow, four potential scenarios were considered by the authors of the report [4], each differing in the percentage of bottled water of the total water consumed. Scenarios where bottled water constituted, 0%, 15%, 20% and 50% of the water drunk were analyzed. On the basis of the available criteria, a hierarchical tree of criteria (**Figure 9**) was constructed and using the described method earlier, the degree of compliance with individual criteria for each scenario was evaluated (**Table 8**). Minimum and maximum values in each category were assigned to the scenario where bottled water consumption was 0 and 100%, respectively. As a social criterion, the taste of water was assigned between 0 and 10 points. The same satisfaction level from drinking water was assigned to all scenarios since in reality both professionals and amateurs find it difficult to distinguish the source the water originates from [28]. The authors of the article assigned the weightings to individual criterion in accordance with the AHP procedure, comparing individual criteria pair-wise. The process of assigning was the result of experts' discussion. The Web-HIPRE application supplied by the Helsinki University of Technology was used for analyses [24].

Criteria	Unit	Scenarios analyzed (% of bottled water consumed)				Minimum	Maximum
		0%	15%	20%	50%		
Energy consumption	MJ eq/capita	7.45	356.00	485.57	1 202.75	7.45	2398.05
GHG emissions	kg CO_2/capita	0.22	16.03	21.86	54.31	0.22	108.41
Waste	m^3/capita	0.00	0.02	0.03	0.07	0.00	0.13
Cost	PLN/capita	1.88	134.94	184.00	457.19	1.88	912.50
Environmental impact	Eco-indicator 99 H/A points	0.02	1.47	2.01	4.99	0.02	9.96
Taste	points	5.00	5.00	5.00	5.00	0.00	10.00

Table 8. Degree of compliance for individual criterion for various water consumption scenarios.

Table 9 and **Figure 10** show the results for the AHP analysis.

Criteria	Weightings for level ll criteria	Analyzed scenarios (% of bottled water consumed)			
		0%	15%	20%	50%
Waste	0.22	1	0.854	0.800	0.500
CO_2 emissions	0.09	1	0.854	0.799	0.500
Energy consumption	0.08	1	0.854	0.800	0.500
Environmental impact	0.62	1	0.854	0.800	0.500
Criteria	**Weightings for level I criteria**				
Economic	0.250	0.250	0.213	0.200	0.120
Environmental	0.655	0.655	0.559	0.524	0.327
Social	0.095	0.048	0.048	0.048	0.048
Total		**0.953**	**0.820**	**0.772**	**0.495**

Table 9. AHP scores for the drinking water problem in Cracow according to sustainable development criteria.

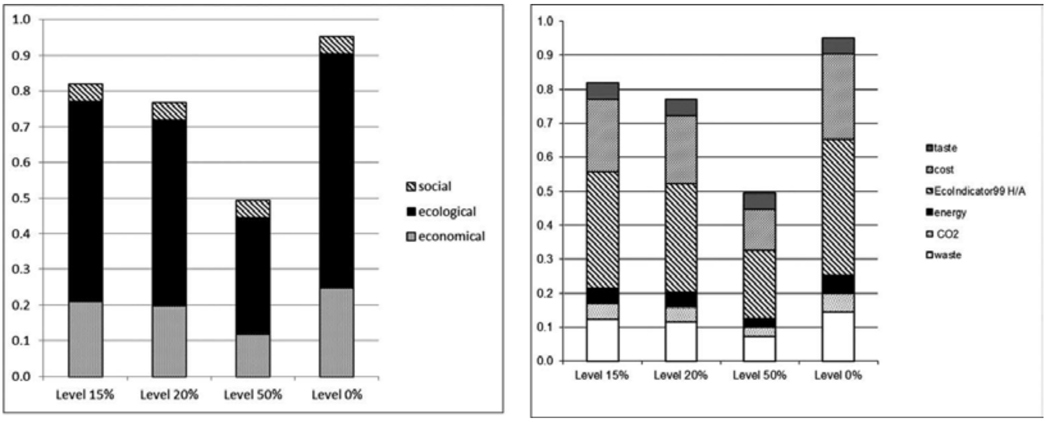


Figure 10. AHP scores for the drinking water problem in Cracow according to sustainable development criteria.

In accordance with the accepted procedure, the scenario which assumes drinking only unboiled tap water has an overall score of 0.953 where the maximum score is 1. This is almost a perfect solution. However, the scenario where 50% of water drunk comes from plastic PET bottles scores 0.495. A sensitivity analysis shows that when the weightings are changed, the overall score for the individual scenarios also changes, but their relative ranking remains unchanged [4]. The current water consumption scenario for Cracow has an overall score of 0.820 and is 14% worse than the best scenario from the sustainable development perspective.

The environmental impact, particularly when measured using Eco-indicator 99 H/A points is the most important criterion for Level I.

It is obvious that drinking safe tap water and not bottled water is superior to the person's economy and to the environment. The conducted AHP analysis shows measurably the size of this superiority. It also shows how much progress can be achieved in the city if tap water drinking becomes more common. This is particularly important in town such as Cracow which plans to organize big social events such as the World Youth Day in 2016 or the Olympic Games in the future. Thanks to the AHP, the impact of water drinking pattern is precisely measured in all selected criteria. This allows individuals and decision makers to compare the results of very different municipal policies. For example, the energy savings obtained, thanks to municipal program of building insulation, can be compared with the results of the bottled water consumption reduction program. The results of the conducted analysis can be used by the decision makers to estimate results and to make appropriate proposals on policy actions toward bottled water drinkers.

4. Developing environmentally sound selection method for heating appliances using ecolabeling and Analytic Hierarchy Process

This case study presents an assessment of heating appliances prepared on the basis of the AHP multicriteria evaluation method. The main problem with appliances' selection is that the consumers do not know which parameters of the equipment are important and, on the other hand, the professionals do not know the individual preferences of the consumers. The authors propose to design the hierarchy of criteria utilizing the concept of sustainable development and the criteria originating from ecolabeling programs [40, 41]. Integrating ecolabeling criteria into the AHP process is a similar concept as developing integrated AHP or combining AHP with other tools of environmental assessment [42].

The case study presents application of all three stages of AHP method for the real heat pump selection. The first stage, design of the evaluation criteria hierarchy, is carried out following the concept of sustainable development, and the criteria of the European Union ecolabeling program. The second stage of analysis assigns the weights of different criteria; this part is done based on the authors' knowledge and experience. The last stage of the AHP method—the evaluation of the analyzed heat pumps combined with the sensitivity analysis of the assumed weights—is also presented and discussed.

4.1. Ecolabeling as a basis for a criteria selection

The idea of ecolabeling [40, 41] originates from the assumption that consumers are looking for environment-friendly products. On the other hand, producers knowing the consumers' preferences are ready to deliver such products if products' quality is objectively confirmed. To allow such objective quality check, the independent certifying organizations set up very specific criteria, unique for specific groups of products. The producers can voluntarily apply for an ecolabel presenting their products for certification. If the products meet the criteria, and the producer pays the fee, he is allowed to display the ecolabel sign on the product for a certain period of time. The certifying organization undertakes the responsibility to start a campaign supporting the product. Both ways, there is a hope for the favorable consumers' response.

The example of four European ecolabels is given in **Figure 11**.

Figure 11. Examples of European ecolabels.

Ecolabeling criteria do not include the economical aspects of product's usage; however, since these features are critical for the consumers, the economical criteria have to be included into the decision process. Because economical criteria tend to dominate the whole analytical process, they are introduced into the decision process in a very careful way. Haas [43] proposes to analyze the products' benefits without the economic criteria and then include them into the analysis, separately.

4.2. Heat pumps ecolabeling criteria

The EU Commission decision issued on November 9, 2007, with the later amendments [44] specifies the ecological criteria for the European ecolabel program for heat pumps powered by gas, electricity and heat (max. power 100 kW). According to the European Community Regulation No 1980/2000, to obtain the ecolabel, a heat pump must meet all environmental criteria set out in the Annex to this decision.

The criteria's objective is to limit the environmental impact of the production, operation and subsequent decommissioning of heat pumps. The criteria include:

- efficiency of heating and/or cooling of buildings
- reduction of the environmental impact during heating and/or cooling of buildings
- reduction or prevention of the risks to the environment/human health due to the use of hazardous substances
- proper transfer of information to customers and fitters on efficient operation of the heat pump

There are nine important elements identified in the ecolabeling document, which decide whether an ecolabel is granted to a heat pump. The list of those criteria with their brief descriptions is presented in the following section.

4.2.1. Coefficient of performance (COP)

The coefficient of performance (COP) is a ratio of generated heating power Q_k, to input power L (electricity or gas) for a particular source and output temperature. The minimal efficiency of an electrically powered heat pump working in a heating mode in a brine/water system must not be lower than 4.3 (internal unit input/output temperatures = 30°C/35°C) or 3.50 (internal unit input/output temperatures = 40°C/45°C).

4.2.2. Primary energy ratio (PER)

Additionally, the primary energy ratio (PER) for a brine/water system has to exceed 1.72 (internal unit input/output temperatures = 30°C/35°C) or 1.40 (internal unit input/output temperatures = 40°C/45°C), while for a combi unit (with a cooling function), the minimal value of a PER ratio should be 1.2.

Due to the fact that both PER and COP are linearly related, only one (COP) was included into the AHP analysis.

4.2.3. Global warming potential (GWP)

The global warming potential (GWP) coefficient was introduced to describe the impact of refrigerant on a global climate. In case of heat pumps, GWP coefficient shows how much the used refrigerant increases the global warming, if compared to carbon dioxide. The GWP coefficient for carbon dioxide is assumed 1 and the lifespan of the analysis is 100 years. According to the EU commission (decision 2007/742/WE [42]), the refrigerants' GWP coefficient cannot exceed 2000 in a 100 years lifespan.

4.2.4. Noise

Following the ecolabeling requirements for heat pumps, a noise level has to be measured according to the standard ENV-12 102, and the results, in dB(A), have to be presented in the product information document.

4.2.5. Heavy metals and flame retardants

Cadmium, lead, mercury, chromium (VI) or flame retardants polybrominated biphenyl (PBB) or polybrominated diphenyl ether (PBDE) cannot be used in heat pump units or heat pump systems. The acceptable limits of these substances are precisely set in the commission document 2005/618/WE. The concentration levels of these substances have to be certified.

4.2.6. Personnel training

Heat pump manufacturers are responsible for personnel training in the European Union countries, where the pumps are sold. The training should focus on proper pump sizing and installation as well as to provide assistance during filling up the documents. The heat pump manufacturer's declaration about the training and its place is required.

4.2.7. Documents

Heat pump manufacturers have to deliver a complete user's manual with the equipment. The manual has to provide information on installation, maintenance and operation of the heat pump. All these documents have to comply with the standard EN 378:2000 and all later amendments.

4.2.8. Spare parts

The heat pump manufacturer guarantees that the spare parts will be available for 10 years, starting from the date of purchase. The manufacturer should also specify how this requirement is going to be met.

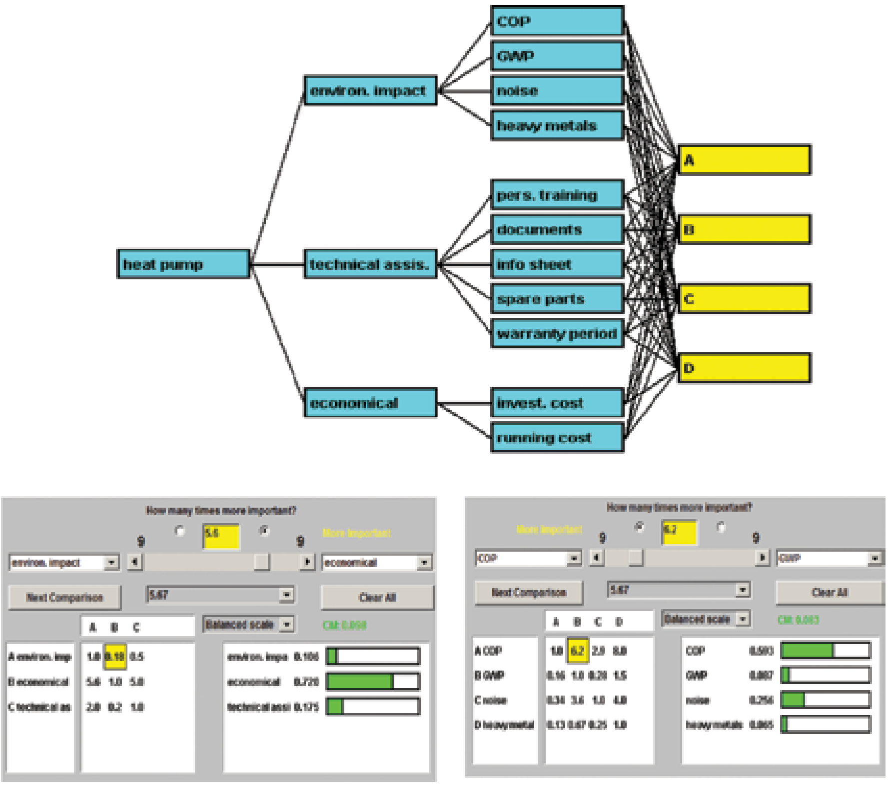
4.2.9. Information sheet

The heat pump manufacturer guarantees that a blank information sheet is available at the location, where the heat pump is sold. This is to guarantee the minimal level of consumer's assistance. Fitters should have an access to a filled up "information sheet" for fitters. Additionally, manufacturers should provide fitters with special tools, computer software and assistance, to allow them to calculate the following working parameters of the heat pump installation: seasonal energy efficiency ratio (EER), seasonal coefficient of performance (COP) or yearly carbon dioxide emission.

4.3. Construction of the objective hierarchy

Ecolabeling criteria were only used as a basis for selection of the final objective hierarchy. To help determine the weights of the final subcriteria, they were grouped into three categories/objectives. These categories were selected according to the sustainable development requirements. The final goal of the selection was divided into three categories: "impact on natural environment," user friendliness called "technical assistance" and "economical" criterion. Introduction of the economical criterion, next to others, follows the concept of sustainable development, but can lead to serious distortion in weights assignment, and further on, to false results. Because the analysis is usually carried out by professionals or by the heat pump users, the authors assumed that the risk of such problem is minimal.

If one does not want to include the economic criteria into the AHP analysis directly, there is an option to make the AHP analysis without the economic criterion and to include it separately later in form of the cost-benefit analysis. This option is also presented at the end of this case study.



environ. impact ○ 5.6 ● economical

5.67

CR: 0.058

	A	B	C
A environ. imp	1.0	0.18	0.5
B economical	5.6	1.0	5.0
C technical as	2.0	0.2	1.0

environ. impa	0.106
economical	0.720
technical assi	0.175

COP ● 6.2 ○ GWP

5.67

CR: 0.083

	A	B	C	D
A COP	1.0	6.2	2.9	8.0
B GWP	0.16	1.0	0.28	1.5
C noise	0.34	3.6	1.0	4.0
D heavy metal	0.13	0.67	0.25	1.0

COP	0.593
GWP	0.087
noise	0.256
heavy metals	0.065

Figure 12. Objective hierarchy for heat pumps analysis and exemplary calculation of weights.

Figure 12 presents the objective hierarchy and examples of weights calculation created by the authors. The hierarchy and weights were developed by the authors and the group of students who participated in the research pretending to be a potential heat pump user. The final weights used in the analysis were the result of the whole group discussion.

4.4. Evaluation of heat pumps with the selected criteria

The analysis comprised the heat pumps used for heating of a single family house, with a water storage tank and the power of approx. 10 kW; with no cooling capacity. Four actually manufactured heat pumps were selected and marked A, B, C and D. The information about the heat pumps performance was delivered by the manufacturers' representatives.

The performance of the heat pumps and the acceptable range for each category are presented in **Table 10**.

	Heat pump						
Criteria	**C**	**A**	**D**	**B**	**Min. rating**	**Max. rating**	**Unit**
Spare parts	10	20	20	10	0	20	years
Global Warming Potential (GWP)	1610	1890	1610	1610	0	2000	–
Coefficient of performance (COP)	4.4	4.3	4.3	4.4	2.5	5.5	–
Personnel training	1	1	0	0	0	1	Yes/No (1/0)
Information sheet	1	1	1	1	0	1	Yes/No (1/0)
Noise	51	46	47	47	20	60	db(A)
Heavy metals and flame retardants	0	0	1	0	0	1	Yes/No (1/0)
Documents	1	1	1	1	0	1	Yes/No (1/0)
Warranty period	3	2	2	2	2	3	years
Investment cost	6068	5228	8210	5659	2380	9523	Euro
Running cost	13,885	9309	9309	13,885	7142	14,285	Euro/15 years

Table 10. Heat pump parameters and the acceptable range of values.

4.5. Analysis of the AHP-HIPRE results

The results of the AHP-HIPRE analysis are presented in **Tables 11** and **12**. The final result for each heat pump consists of sum of partial results, presented in **Table 12**, multiplied by relative weights at levels I and II. The final results have also been presented in a graphical form by HIPRE software in **Figures 13** and **14**.

Level I°	**Weights at the level I°**	**Results at the level I°**			
		A	**B**	**C**	**D**
Environmental impact	0.106	0.055	0.058	0.057	0.063
Economical	0.720	0.450	0.302	0.271	0.225
Technical assistance	0.175	0.132	0.069	0.153	0.090
	Final results	**0.638**	**0.429**	**0.481**	**0.379**

Table 11. Weights, partial results from the first level of analysis and the final results.

The analysis indicates that the heat pump A is the best choice (**Figure 13**). Remaining heat pumps received similar scores; if compared with the heat pump A, they were lower by one-third. The second was the heat pump C, and then heat pumps B and D.

Criteria at level II°	**Weights at level II°**	**Results at level II°**			
		A	**B**	**C**	**D**
Coefficient of performance	0.593	0.825	0.847	0.847	0.825
Global Warming Potential	0.087	0.054	0.192	0.192	0.192
Noise	0.256	0.109	0.101	0.070	0.101
Heavy metals and flame retardants	0.065	0	0	0	1
Personnel training	0.240	1	0	1	0
Documents	0.225	1	1	1	1
Information sheet	0.047	1	1	1	1
Spare parts	0.246	1	0.5	0.5	1
Warranty period	0.241	0	0	1	0
Investment cost	0.750	0.601	0.541	0.484	0.185
Running cost	0.250	0.697	0.056	0.056	0.697

Table 12. Weights and results at the second level of analysis.

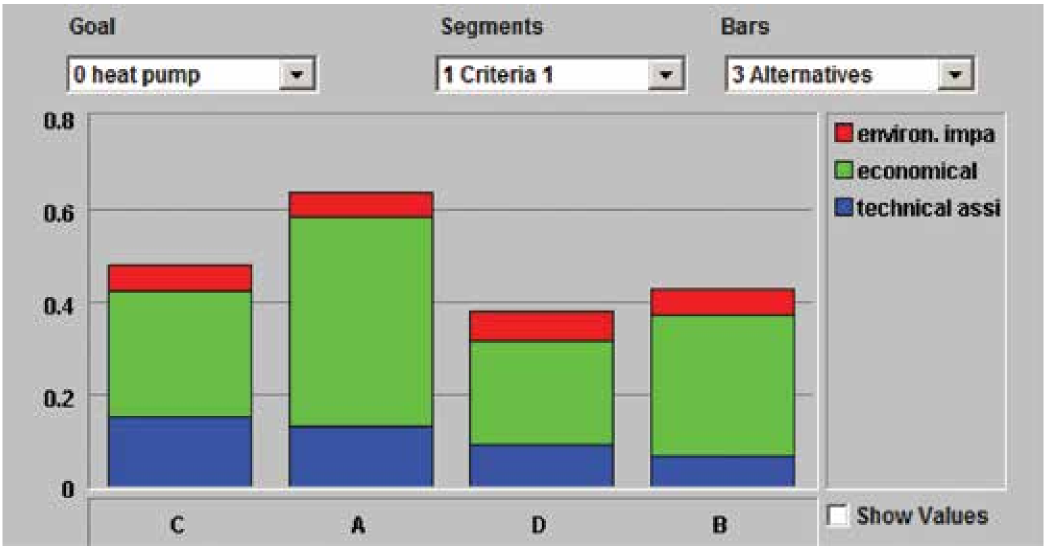

Goal: 0 heat pump
Segments: 1 Criteria 1
Bars: 3 Alternatives
☐ Show Values

Figure 13. Comparison of the heat pumps performance at level I of evaluation.

The high score of the heat pump A is a result of a superior economic performance, mainly a low “investment cost.” The final score of the heat pump A is also improved by a high score in the category “technical assistance,” mainly “personnel training” and “spare parts.” The heat pump C was equally well evaluated in the category “technical assistance” and had an extremely long “warranty period” (**Figure 14**). Mainly due to this long “warranty period,” the heat pump C is the second in the ratings. A low evaluation score of the heat pump D results from a high "investment cost."

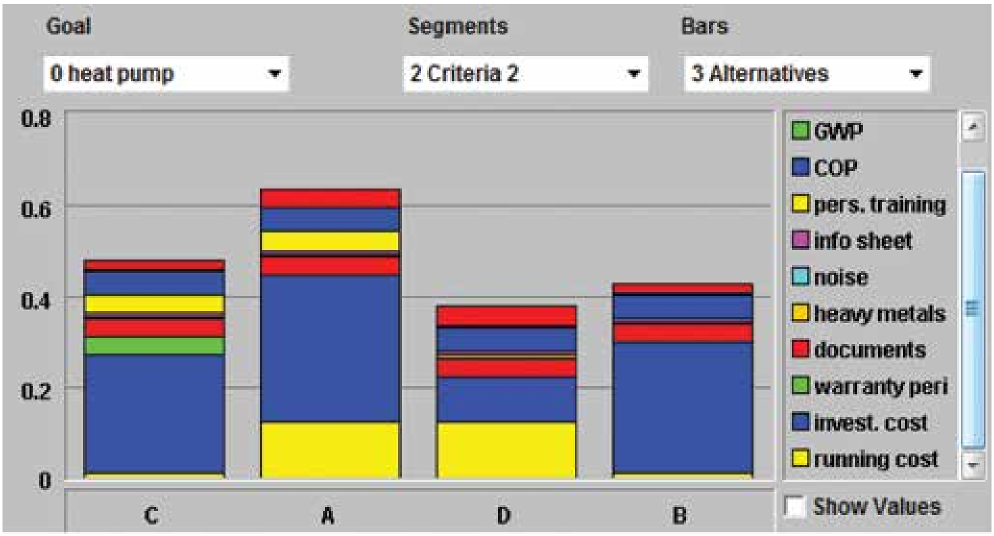

Goal: 0 heat pump
Segments: 2 Criteria 2
Bars: 3 Alternatives

Figure 14. Comparison of the heat pumps performance at level II of evaluation.

4.6. Cost-Benefit Analysis

Another way to compare the costs and performance of the analyzed heat pumps is to use the Cost-Benefit Analysis (CBA) [45]. This can be done by separate calculations of the benefits of each heat pump, and then by graphical comparison with the calculated costs.

The cost of each heat pump was calculated as an Net Present Value (NPV) indicator. The costs include the investment cost (**Table 10**) and running costs for the entire 15-year long period. The NPV was calculated using the nominal prices, with the assumption that the energy cost increases 6% per year and the discount rate is 8%.

The benefits for each heat pump were calculated using the AHP method. This time the economic criteria were removed from the criteria hierarchy. All other criteria and performance parameters remained the same as in a previous analysis. The CBA results are presented in **Figure 15**.

The graph clearly indicates that the heat pump A as the best solution. The pump shows the highest benefit-to-costs ratio graphically displayed as the slope of the ray from the origin to the point representing each heat pump. The slope is the highest for the heat pump A, which means the highest value (unit benefit). The heat pump C offers slightly higher benefits, but at significantly higher costs. The cost of heat pumps C, D and B is almost the same, but substantially differ in delivered benefits.

The results of the Cost-Benefit Analysis (CBA) are the same as calculated using the multicriteria AHP analysis. The CBA results are self-explanatory and almost intuitive, but because in the CBA method all the benefits are aggregated into one parameter called "benefit," the detailed analysis of the results is more difficult.

Combining the professional knowledge of the people who set the ecolabeling standards with the potential of AHP method allows the lay person understand the detailed and professional analysis of different appliances.

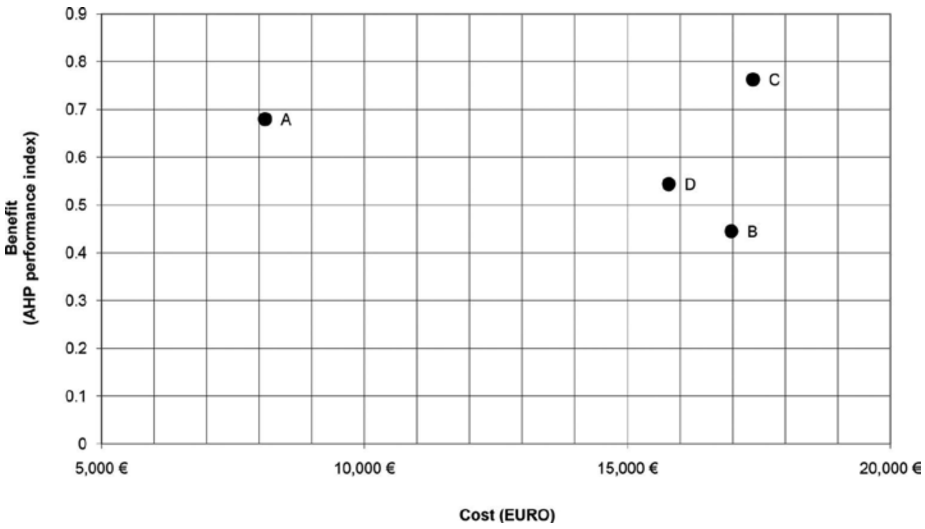


Figure 15. CBA for the analyzed heat pumps.

5. Conclusions

The AHP method is very useful in solving the whole spectrum of real environmental problems and can help choosing more sustainable solutions. The reliability of the obtained results can be increased if during the construction of goal hierarchy or collection of data, special engineering tools are also applied. Such approach can help ease most of the criticisms that there is no theoretical basis for constructing the AHP criteria hierarchy or, that there is no objective criteria which can help in the process of weights assignment. Three presented case studies show how this integration can be carried out.

In the first case study, the two-stage data collection and aggregation is carried out. First, the IWM-1 model was used to calculate the emissions to air, water and soil from each analyzed system. Second, these emissions were aggregated into LCA categories which were finally used as an input data for the AHP analysis. As a result, one obtains a clear and simultaneously detailed evaluation of the compared waste disposal systems. This is a quality very much sought by the decision makers.

In the second case study, Eco-indicator 99 H/A points were used to assess among others the environmental impact of water drinking pattern. The conducted AHP analysis shows measurably the environmental superiority of tap water drinking. It also shows how much progress can be achieved in the city if tap water drinking becomes more common. Such information can be an important guideline for a city management. Using AHP integrated with other environmental engineering tools allows comparison and evaluation of very different city policies.

The third case study presents the methodology of heat pump selection using the AHP method in connection with the ecolabeling program criteria. Through this combination, the selection can be carried out by non-professionals, and the selection is adjusted to the individual needs of the final consumer.

All three case studies show the flexibility and versatility of the AHP method which can be used and serve different customers: professionals, non-professionals and managers.

Acronyms.

AHP	Analytic Hierarchy Process
CBA	Cost-Benefit Analysis
COP	Coefficient of performance
DEA	Data envelopment analysis
GHG	Greenhouse gas
EER	Energy efficiency ratio
GWP	Global warming potential
IWM-1	Integrated Waste Management model
LCA	Life cycle analysis
MSWM	Municipal Solid Waste Management
ORWARE	ORganic WAste REsearch
PBB	Polybrominated biphenyl
PBDE	Polybrominated diphenyl ether
PER	Primary energy ratio
PET	Polyethylene terephthalate
QFD	Quality function development
SQL	Structured query language
SWOT	Strengths, weaknesses, opportunities and threats analysis
US-EPA	Environmental Protection Agency
Web-HIPRE	HIerarchical PREference analysis in the World Wide Web

Author details

Tomasz Stypka*, Agnieszka Flaga-Maryańczyk and Jacek Schnotale

*Address all correspondence to: agnieszkaflaga@poczta.onet.pl

Cracow University of Technology, Cracow, Poland

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Chapter 5

Analytic Hierarchy Process Application in Different Organisational Settings

Damjan Maletič, Flevy Lasrado, Matjaž Maletič and
Boštjan Gomišček

Additional information is available at the end of the chapter

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Abstract

Purpose – The purpose of this paper is to apply AHP in two case settings which include (i) evaluation/selection of maintenance policy (ii) sustainability factors of employee suggestion schemes.

Methodology/Approach – The paper adopts a case study approach of selecting most appropriate maintenance policy and prioritizing factors for employee suggestion system. Several steps of the AHP method are used in both case settings to illustrate the application of the AHP method.

Findings – This paper proposes (i) a framework for maintenance policy selection based on the AHP methodology and (ii) a framework to determine the importance of sustainability factors for employee suggestion schemes. The results of the first case setting suggest that total quality maintenance is the most suitable approach for a paper machine. In the second case setting, the findings suggest that five sustainability factors can be modelled according to their importance.

Originality/Value – The paper contributes firstly to the literature by providing a framework for decision-making process regarding the maintenance policy selection. In addition, this paper utilizes an exponentially weighted moving average (EWMA) chart for performing a consistency test and a sensitivity analysis. Secondly, the paper proposes a framework to model the sustainability factors of employee suggestion scheme according to their importance level.

Keywords: Analytical hierarchy process, decision-making, maintenance policy, sensitivity analysis, employee suggestion scheme

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1. Introduction

The analytic hierarchy process (AHP) is widely used in multi-criteria decision-making tool for tackling multi-attribute decision-making problems in real situations [1]. It represents a powerful technique for solving complicated and unstructured problems that may have interactions and correlations among different objectives and goals [2]. The AHP helps the decision makers to organise the critical aspects of a problem into a hierarchical structure similar to a family tree [3]. It is based on experts' judgements through pairwise comparisons. Experts are interviewed and pairwise comparison judgements are applied to pairs of homogenous criteria, eventually generating the overall priorities for ranking the alternatives [1].

AHP gained substantial attention as a possible solution to the decision-making problems in different organisational areas, for example, the selection of maintenance policy or factors of employee suggestion schemes which will be more deeply illustrated in the following section. However, this method can also be utilised in many other fields. For example, in the study [4], the fuzzy AHP was employed to prioritise and select a suitable organisational structure. The AHP method has been widely used in the decision-making problems that involve multiple criteria in multiple levels [5] as well. The method helps to decompose their decision problem into hierarchy of factors, each of which can be analysed independently and once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them one to another, two at a time, with respect to their impact on an element above them in the hierarchy [6]. AHP method is used to measure the importance of these factors.

Moreover, this technique allows for the search of relative importance placed on product attributes and attribute levels of the analysed complex goods [7]. To make the pairwise comparisons, we need a scale of numbers that indicate how many times a more important or dominant element over another element was, with respect to the criterion or property, with respect to which they are, compared [8].

In this chapter two case studies are presented: first, empirical case study will be utilised to evaluate and select the most appropriate maintenance approach; the second one, based on expert opinion will present a possibility to formalise the importance levels for the importance of factors of sustainability of employee suggestion schemes.

2. Literature review

2.1. Review of maintenance approaches

Different maintenance approaches (i.e. strategies and concepts, methodology or philosophy) have been developed in the last few decades.

The development of maintenance approaches are discussed by many authors [9–13]. Failure-based maintenance (FBM) prescribes activation of maintenance in the event of failure [10]. No action is taken to detect or to prevent failure [14]. Maintenance is carried out only after a breakdown. This approach is only appropriate in a case where customer demand exceeds supply and profit margins are large. However, increasing global competition, small profit margins, safety awareness and strict environmental regulations are changing the environment that most companies are facing today. In this regard, more emphasis is being placed on developing maintenance concepts [15]. However, it is always possible that a failure is allowed to occur. This depends on the existence of secondary damage, redundancy and the ease to repair. Waeyenbergh and Pintelon [13] suggest that one should determine the economic feasibility in order to evaluate the technical feasibility of FBM for a critical component or a non-critical component.

Preventive maintenance (PM) is comprised of maintenance activities that are undertaken after a specified period of time or amount of equipment used [16]. Therefore, traditional preventive maintenance models are using policies such as age replacement and block replacement [17]. One of the disadvantages of the PM is that PM is only suitable when the standard deviation of the failure population is small [18]. This means that if the distributions have a small standard deviation, they are usually a candidate for PM and in such cases PM is economical. Another shortcoming of PM is the lack of decision support systems and insufficient historical data [14, 19].

Condition-based maintenance (CBM) is a maintenance strategy that monitors the actual condition of the asset to decide what maintenance needs to be done [20]. CBM is defined as the preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Using a condition monitoring (CM) system, the machine condition is assessed by the current and historical measurements of one or more of relevant CM parameters [21]. Vibration-based maintenance (VBM) is the most frequently used technique under the CBM approach. By an efficient use of VBM policy, which means utilisation of the information provided by vibration monitoring system for planning and performing maintenance actions, the machine can be run until just before failure as defined by the monitored parameter reaching a predetermined unacceptable value [21]. Al-Najjar [22] indicated that the implementation of VBM policy provides possibilities for obtaining early indications of alterations of machine-state.

Al-Najjar [9] proposed a strategy called total quality maintenance (TQMain), which sustains not only machinery but also the essential elements constituting a manufacturing process, such as production/operation, environmental conditions, quality, personnel, and methods. TQMain was defined by Al-Najjar [23] as a means for monitoring and controlling deviations in a process, working conditions, product quality and production cost, and for detecting damage causes and their developing mechanisms and potential failures in order to interfere (when it is possible) to 'stop' or reduce machine deterioration rate before the production process and product characteristics are intolerably affected and to perform the required action to restore the machine/process or a particular part of it to as good as new. Further, Al-Najjar and Alsyouf [24] also presented what characterises TQMain and distinguish it from other maintenance concepts (e.g. reliability-centred maintenance (RCM), total productive maintenance (TPM)). They highlighted that TQMain supports the use of a common database, continuous improvement, implementation of CBM such as VBM, and it is based on intensive use of real-time data acquisition and analysis to detect reasons behind deviations in product quality and machine condition.

Reliability-centred maintenance was first introduced by the aircraft industry of the United States in 1978 [25]. There have also been several improvements to the traditional RCM methodology (e.g. RCM2). Moubray's book [11] is a key reference. RCM can, among other things, improve system availability and reliability, reduce the amount of preventive maintenance, unplanned corrective maintenance and increase safety. These are all important aspects for organisation in order to sustain in a competitive environment [26]. RCM aims to increase the asset's lifetime and create a more efficient and effective maintenance [27]. But, Al-Najjar [22] pointed out that RCM cannot completely exploit the use of condition monitoring (CM) techniques, and the progress of damage cannot be monitored until just before a failure. Further, Pintelon and Parodi [27] described that available statistical data used in RCM are insufficient or inaccurate, and that there is a lack of insight in the equipment degradation process (failure mechanisms) and the physical environment (e.g. corrosive or dusty environment) is overlooked. There have been already attempts to combine RCM and AHP in the maintenance domain—for example, development of a hybrid model for trunk road network maintenance prioritisation. The proposed hybrid model was used to establish failure diagnostic and multi-criteria decision making, respectively [28].

Total productive maintenance (TPM) is a methodology originating from Japan to support its lean manufacturing system, since dependable and effective equipment are essential prerequisite for implementing lean manufacturing initiatives in any organisation [29]. To do so, the overall equipment effectiveness (OEE), which is defined as the product of availability, speed and quality performance, is used to assess the reached level [13]. Nakajima [30], a major contributor of TPM, has defined TPM as an innovative approach to maintenance that optimises equipment effectiveness, eliminates breakdowns and promotes autonomous maintenance by operators. The definition of TPM includes five major elements [31]:

1. overall equipment effectiveness maximisation;
2. a thorough system of preventive maintenance for the equipment's whole life span;
3. implementation by various departments (engineering, production, maintenance, etc.);
4. total employee involvement from top management to the workers on the floor; and
5. motivation management through small group activities and teamwork.

Though the concept of TPM is simple and obvious, there are some reported limitations. First, TPM does not provide clear rules to decide which basic maintenance policy will be used, and second, calculation of the OEE is not really a complete analysis. Cost and profits are not taken into account, and therefore it is not a comprehensive measure [13]. Moreover, TPM also requires changing the organisational culture, what is not easily to accomplish. In this regard, Tsang and Chan [32] indicated that those organisations that will not change their culture will not be successful in implementing TPM. A study regarding application of AHP in the implementation of TPM decision making in manufacturing organisations was performed by Ahuja and Singh [33].

2.2. Review of employee suggestion system factors

The existing research aptly identifies the enablers to the employee suggestion schemes. Buech et al. [34] note that researchers trying to ascertain which factors affect employees to submit suggestions focus on three main streams of research. The first considers work environment, the second focuses on the features of the scheme, weighs the influence of feedback about suggestions against management support of the system as well as rewards for successful suggestions and the third deals with the characteristics of the individuals. Carrier [35] reports that the majority of researchers consider organisational creativity to be fostered through the personal characteristics and motivation of creative individuals while the other group of researchers turned their attention to context and organizational factors. Axtell et al. [36] argue that different sets of variables influence these two stages of employee suggestion system process, i.e. the creative and the implementation phases. So, it is evident that the drivers that trigger the suggestion scheme comprise individual, organisational and contextual variables. Moreover, the innovation process is a complex phenomenon and many variables have roles to play in determining its process [37]. Amabile et al. [38] also contend that the organisational context can impede or support the generation of ideas. Everyone has ideas all the time, not all are creative, nor do they all lead to innovation [39]. Therefore, creativity needs to be nurtured to turn into valuable suggestions. A list of variables emerging from the literature that hint as the indicators are: Top Management Support, Supervisor Encouragement, Coworker Support, Organisational Encouragement, Support for innovation, Communication Evaluation, Awareness, Resources, Rewards, Training, Effective System, Feedback, Implementation of Ideas, Empowerment, Job Factors, Expertise, Self-Efficacy and Individual Characteristics, Teamwork, Employee Participation, Job Control, Organisational Impediments and the Competition, Employee Confidence, Sense of Security, Commitment and Accountability, Improvement in Process, Customer Satisfaction, Product Quality, New Revenue, Cost Saving, Employee Satisfaction.

3. Application of AHP in two organisational settings

First, in an empirical case study for selecting the most appropriate maintenance policy AHP was utilised aiming to evaluate and select the most appropriate maintenance approach. The case study was conducted at a Slovenian paper mill company.

Secondly, an expert opinion study was conducted in the context of UAE organisations using suggestion systems to formalise the importance levels for sustainability of employee suggestion system factors. The illustration of AHP for these two case instances is discussed in the next sections.

3.1. Case study 1: an AHP-based framework for maintenance policy selection

The method proposed for selecting the most appropriate maintenance approach is based on a hierarchical model composed of a set of criterion and sub-criterion. AHP method is demonstrated by the following case study from the paper industry. One of the Slovenian paper mill companies is the subject of the case study in this research. It could be argued that maintenance is highly crucial for this company, since production process in this company is running 24/7. Equipment life, equipment availability and equipment condition is very important in order to ensure smooth running of a paper machine, and provide on-time delivery at low prices. As such, the objective of this case study is to identify the most appropriate maintenance policy concerning the above mentioned objectives.

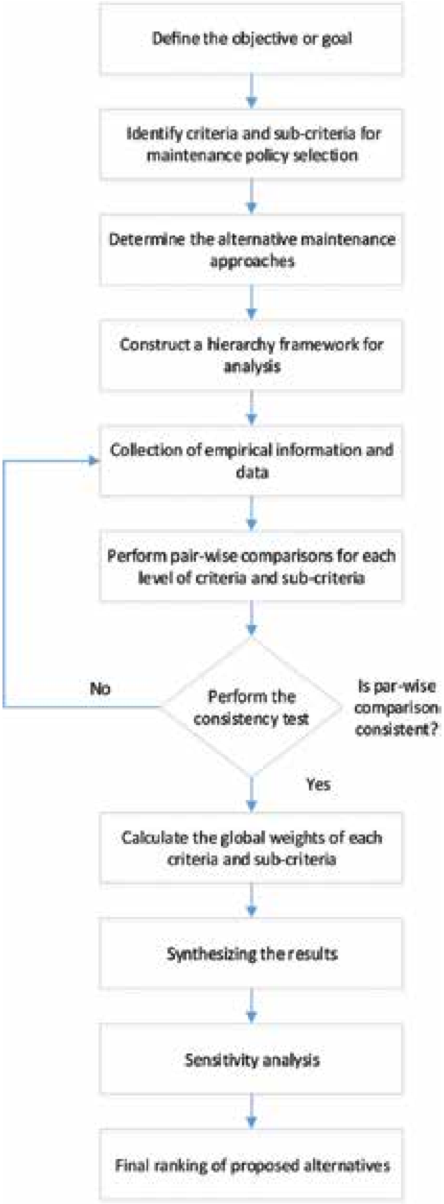


Figure 1. Steps for conducting an AHP study.

In order to select the most appropriate maintenance policy for the paper machine, this research paper uses the AHP methodology. Based on the guidelines proposed by Saaty [8], an AHP framework was developed for facilitating the study. In this regard, Saaty [8] proposed four steps to make a decision in an organised way:

1. define the problem and determine the kind of knowledge sought,

2. structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives),

3. construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it,

4. use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority and

5. continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

Using these guidelines, an AHP framework was established for facilitating the study. **Figure 1** shows a flow chart involving various steps to conduct the AHP study.

Step 1: *Define the objective or goal*

The objective or goal of this study is to assess and select the most appropriate maintenance approach/policy for a paper machine.

Step 2: *Identify criteria and sub-criteria for maintenance policy selection*

In this step, the objective or goal of maintenance policy selection was decomposed into three criteria (equipment- and process-related measures, financial measures and health, safety and environment measures) and 12 maintenance indicators (sub-criteria) were identified from the literature so as to form a hierarchical abstraction of the problem. A literature search was conducted using the databases such as Emerald, ABI/Inform and ScienceDirect. The search was done in different combinations of keywords such as maintenance performance, maintenance indicators, maintenance costs, maintenance savings and maintenance measurement. Results of the search show different works that have dealt with topics related to these keywords [40–42]. Maintenance indicators are vital for effective support of decision making [42]. Performance measurement provides the required information to the management for effective decision making. As such, management of maintenance performance is critical for long-term economic viability of business and industry [42]. As a result of this literature search, various maintenance performance measures were identified.

Step 3: *Determine the alternative maintenance approaches*

Different maintenance approaches, i.e. strategies and concepts, methodology or philosophy, were used in this study. Briefly, they are the following:

1. failure-based maintenance,

2. preventive maintenance,
3. total productive maintenance,
4. total quality maintenance (using VBM) and
5. reliability-centred maintenance.

A more detailed description of these approaches was presented in the literature review section.

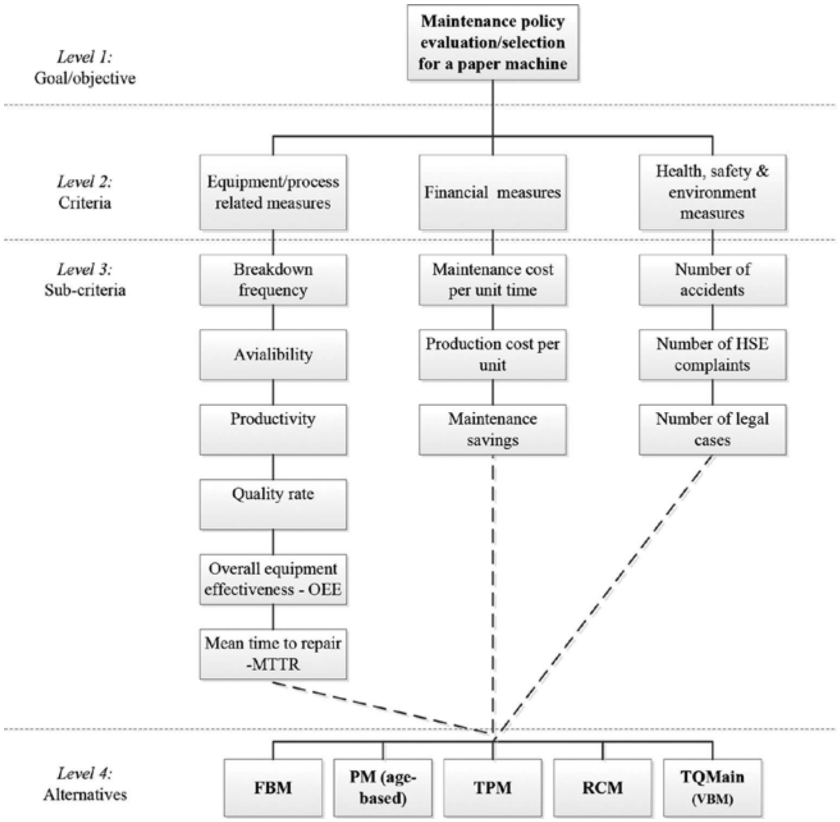


Figure 2. A hierarchy model for maintenance policy evaluation/selection.

Step 4: *Construct a hierarchy framework for analysis*

After the goal of this study had been established, relevant criteria and sub-criteria of maintenance performance measurement were identified via steps 1 and 2. These criteria and sub-criteria were then structured into a hierarchy descending from the overall objective or goal to the various stages and related sub-criteria in successive levels. The top level of the hierarchy represents the defined objective, while the second level of the hierarchy consists of three main maintenance criteria, followed by various sub-criteria (see **Figure 2**). Finally, the fourth level of the hierarchy characterises the alternative maintenance approaches/policies.

Step 5: *Collection of empirical information and data*

This step is concerned with the collection of empirical information and data through the combined judgements of the individual evaluators from industry and academia. For this purpose, a group of three evaluators were chosen for evaluating the selected criteria and sub-criteria. Two evaluators were chosen from academia having experience in the field of maintenance, and one from industry also experienced in the field of maintenance. They had sufficient knowledge, expertise and understanding of the maintenance approached used in this study.

Step 6*: Perform pairwise comparisons for each level of criteria and sub-criteria*

Once the evaluators were identified and relevant empirical information and data were collected, the next step was to determine the relative importance among the criteria and sub-criteria. Before conducting the pairwise comparison, all team members were given the instruction on how to complete the comparison. Invited evaluators were asked to carefully compare criteria of each hierarchy level by assigning relative scales in a pairwise fashion with respect to the goal of this study. Evaluators' judgements were then combined using the geometric mean approach at each hierarchy level to attain the corresponding consensus. A relational scale of real numbers from 1 to 9 was used in the ranking process (**Table 1**). The purpose of this scale is to determine how many times a more important or dominant element is prioritised over another element with respect to the criterion or property with respect to which they are compared [8].

Scale	Judgement
1	Equal importance
3	Moderate importance of one over the other
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Extreme or absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements

Table 1. Scale of relative preference for pairwise comparison.

Step 7: *Perform the consistency test*

In this step consistency test was performed. A measure of inconsistency is useful in identifying possible errors in expressing judgements as well as actual inconsistencies in the judgements themselves [2]. AHP provides a method called the consistency ratio (CR) which is used to gauge whether a criterion can be used for decision making. In the AHP the pairwise comparisons in a judgment matrix are considered to be consistent if the CR is less than 10% [1]. On the contrary if CR is bigger than 10%, possible cause should be examined. However, the standard consistency test has been critiqued by a number of authors [43–45]. For these reasons, we adopted a quality control approach for the consistency test, proposed by Karapetrovic and Rosenbloom [43]. Authors recommended that quality control of consistency can be performed using the simple Shewhart Xbar-R chart or exponentially weighted moving average (EWMA) chart. In this study, EWMA chart was used. This chart is suitable due to its possibility to identify small shifts in the consistency index (CI). CI can be calculated using the following equation: $\mathrm{CI} = \lambda_{\max} - n/n - 1$, where '$n$' is the number of criteria or sub-criteria of each level and $\lambda_{\max}$ is the biggest eigenvector in the matrix. In place of dividing each CI by the 'random index', we used an approach to plot the average values for CI (taking into consideration all decision makers) into EWMA chart (**Figure 3**). For this purpose, a free software environment for statistical computing and graphics *R* was applied using the QCC (an *R* package for quality control charting and statistical process control) package. We used a default value of smoothing parameter (λ), which was set at 0.2 in the aforementioned *R* package. **Figure 3** shows that all EWMA values were within the defined control limits. This means that decision makers were consistent.

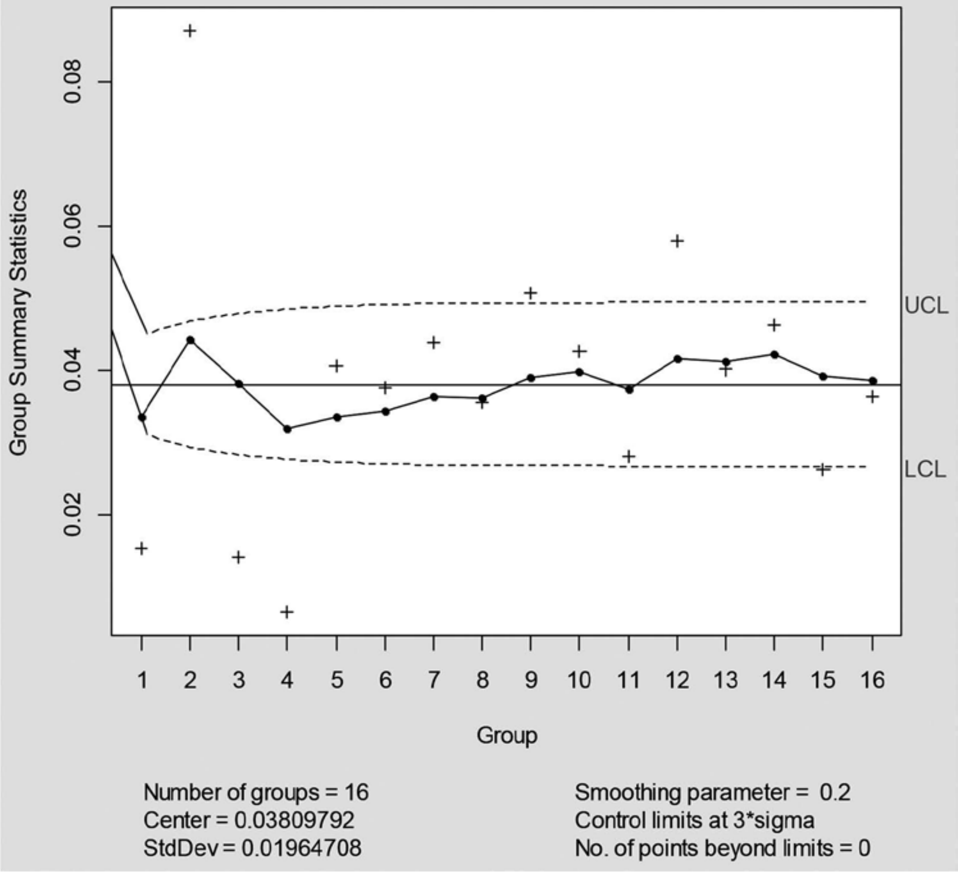


Figure 3. EWMA control chart—average CIs.

Hierarchy level	Criteria	Local weights		Global weights	
		Weights	Ranking	Weights	Ranking
Level 2	*With respect to maintenance performance measures*				
	Equipment/process related measures	0.530	1	0.530	1
	Financial measures	0.270	2	0.270	2
	Health, safety and environment measures	0.199	3	0.199	3
Level 3	*With respect to equipment/process related measures*				
	Breakdown frequency	0.076	5	0.040	9
	Availability	0.181	3	0.096	5
	Productivity	0.183	2	0.097	4
	Quality rate	0.095	4	0.050	7
	Overall equipment effectiveness—OEE	0.422	1	0.224	1
	Mean time to repair—MTTR	0.043	6	0.023	12
	With respect to financial measures				
	Maintenance cost per unit time	0.127	3	0.034	10
	Production cost per unit	0.243	2	0.066	6
	Maintenance savings	0.630	1	0.170	2
	With respect to health, safety a environment measures				
	Number of accidents	0.626	1	0.125	3
	Number of HSE complaints	0.233	2	0.046	8
	Number of legal cases	0.141	3	0.028	11

Table 2. The local and global weights.

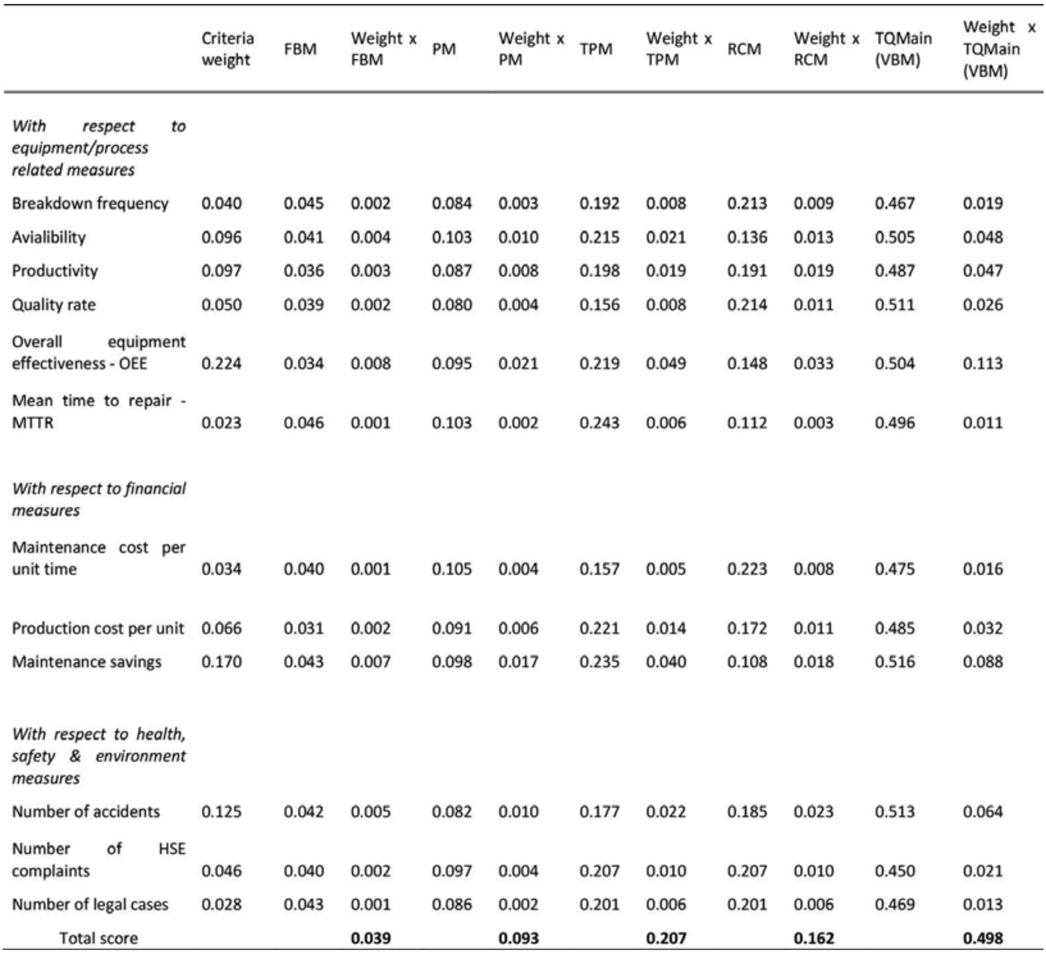
Step 8: *Calculate the global weights of each criteria and sub-criteria*

The next step comprises a calculation of local and global weights. While local weights refer to the preceding hierarchical level, the global weights take into account the highest hierarchical level [2]. The local and global weights as well as the corresponding ranks are presented in **Table 2**.

Step 9: *Synthesising the results*

In order to obtain final results, all alternatives were multiplied by the global weight of the single decision criteria. The results are presented in **Table 3**.

In **Table 3**, the global priorities are calculated for each of the alternatives. The highest value (0.498) corresponds to the TQMain, followed by TPM (0.207) and RCM (0.162). As expected the lowest value refers to the FBM.



	Criteria weight	FBM	Weight x FBM	PM	Weight x PM	TPM	Weight x TPM	RCM	Weight x RCM	TQMain (VBM)	Weight x TQMain (VBM)
With respect to equipment/process related measures											
Breakdown frequency	0.040	0.045	0.002	0.084	0.003	0.192	0.008	0.213	0.009	0.467	0.019
Avialibility	0.096	0.041	0.004	0.103	0.010	0.215	0.021	0.136	0.013	0.505	0.048
Productivity	0.097	0.036	0.003	0.087	0.008	0.198	0.019	0.191	0.019	0.487	0.047
Quality rate	0.050	0.039	0.002	0.080	0.004	0.156	0.008	0.214	0.011	0.511	0.026
Overall equipment effectiveness - OEE	0.224	0.034	0.008	0.095	0.021	0.219	0.049	0.148	0.033	0.504	0.113
Mean time to repair - MTTR	0.023	0.046	0.001	0.103	0.002	0.243	0.006	0.112	0.003	0.496	0.011
With respect to financial measures											
Maintenance cost per unit time	0.034	0.040	0.001	0.105	0.004	0.157	0.005	0.223	0.008	0.475	0.016
Production cost per unit	0.066	0.031	0.002	0.091	0.006	0.221	0.014	0.172	0.011	0.485	0.032
Maintenance savings	0.170	0.043	0.007	0.098	0.017	0.235	0.040	0.108	0.018	0.516	0.088
With respect to health, safety & environment measures											
Number of accidents	0.125	0.042	0.005	0.082	0.010	0.177	0.022	0.185	0.023	0.513	0.064
Number of HSE complaints	0.046	0.040	0.002	0.097	0.004	0.207	0.010	0.207	0.010	0.450	0.021
Number of legal cases	0.028	0.043	0.001	0.086	0.002	0.201	0.006	0.201	0.006	0.469	0.013
Total score			**0.039**		**0.093**		**0.207**		**0.162**		**0.498**

Table 3. The summarised matrix.

Step 10: *Sensitivity analysis*

In this step, a sensitivity analysis is held to show the effect of altering different parameters of the model on the choice of the maintenance policy selection. First, the current values of the model are presented. **Figure 4** demonstrates the current importance of each alternative considering all criteria used in this model. As one can see from **Figure 4**, the highest value corresponds to TQMain (49.8%). Additionally, **Figure 4** also shows the values of the weights of all three main criteria from level 2 ($C1$—equipment-/process-related measures, $C2$—financial measures and $C3$—health, safety and environment measures).

Furthermore, a series of sensitivity analysis were performed to investigate the impact of changing the priority of the criteria on the alternatives' ranking. Dynamic sensitivity of expert choice was accomplished to analyse the change in outcome caused by a change in each of the main criterion. The aim of sensitivity analysis is to explore how these changes affect the priorities of the selected alternatives. In the following three scenarios are presented. We investigated the impact of changing the priority of three main criteria on overall results. First, the criterion 'equipment-/process-related measures' was increased for approximately 25% (from 53 to 66.2). The results are presented in **Figure 5**. This figure consists of two parts. The results presented on the left side of **Figure 5** are criteria and their corresponding weights, while the right side of the figure illustrates the ranking of the alternative as expressed by importance (in percentage). The results of the sensitivity analysis showed that change (an increase of 25%) in the first criterion has no significant influence on the final ranking of the alternatives. As such, the overall rank of the final outcome remained unchanged.

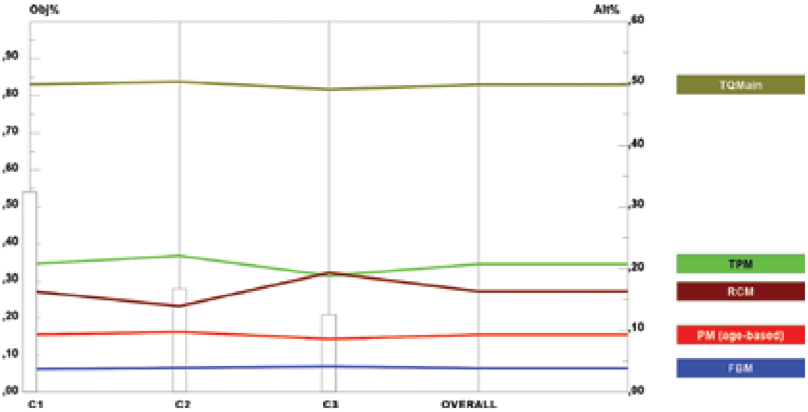


Figure 4. Sensitivity graph—the initial results with respect to the main goal.

Secondly, the criterion 'financial measures' was increased by approximately 25% (from 27 to 33.8) (**Figure 6**). Similarly as in the first case, the change in this criterion also appears to have no substantial impact on the final ranking. As can be seen from **Figure 6**, TQMain remains the best alternative.

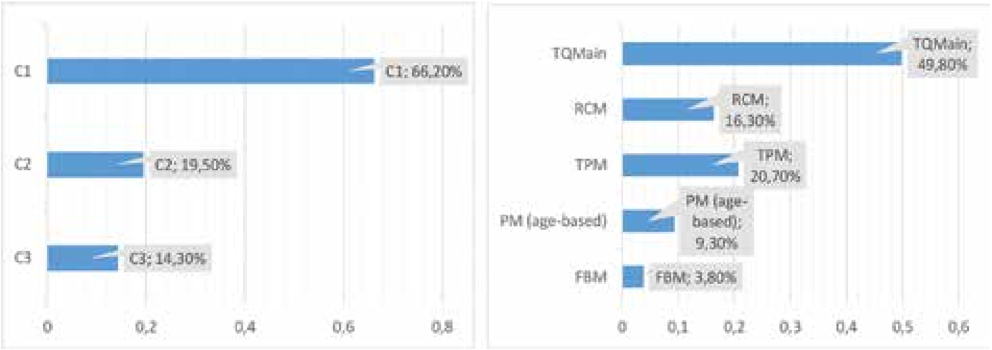


Figure 5. Scenario 1.

Finally, the last criterion 'health, safety and environment measures' was also increased by 25% (from 19.9 to 25.1), and the model was tested for the change of the final ranking. The results show (**Figure 7**) that the criterion 'health, safety and environment measures' has no major impact on the final outcome as well, and therefore TQMain remains the best alternative.

Overall, the results of the sensitivity analysis revealed that the ranks of the alternatives remained stable in all cases. Additionally, a sensitivity analysis was carried out in which main criteria were decreased by 10%. The results displayed that the model is stable also when weights are decreased. This indicates that the proposed model is stable and robust and thus appropriate for decision-making process.

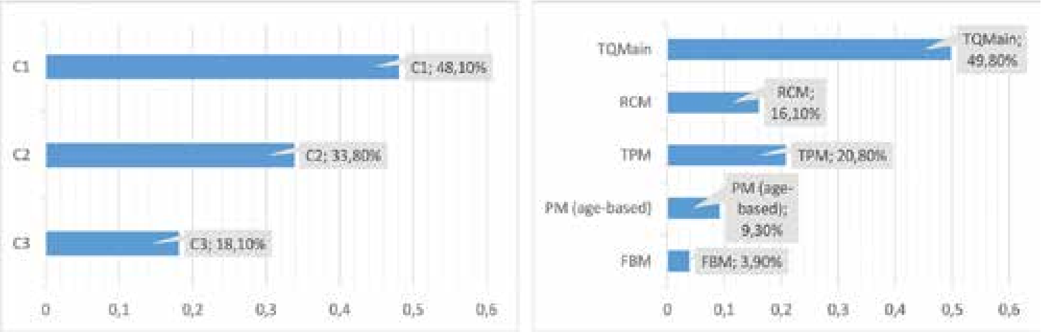


Figure 6. Scenario 2.

Figure 7. Scenario 3.

Step 11: *Final ranking of proposed alternatives*

Taking into account the results of the 9th step and the results of the sensitivity analysis, the final solution of the AHP method can be determined. Therefore, with respect to the main objective of the proposed model, TQMain was selected as the most appropriate maintenance approach (**Table 4**).

Approach	Importance	Rank
TQMain	0.498	1
TPM	0.207	2
RCM	0.162	3
PM	0.093	4
FBM	0.039	5

Table 4. Global importance of maintenance approaches.

3.2. Case study 2: prioritisation of factors for sustainability of employee suggestion schemes

Employee suggestion system (ESS) is a tool widely used by the corporations to elicit employees' creative ideas. It should elicit suggestions from employees, classify them and dispatch them to the 'experts' for evaluation. After this, the suggestion might be adopted, in which case the suggestion may well be rewarded. `Experts' are dedicated committees who evaluate the suggestions and propose them for its implementations.

Intensity of importance	Definition	Explanation
1	Equal importance	Two factors equally contribute to the objective
3	Somewhat more important	Experience and judgment slightly favour one over other
5	Much more important	Experience and judgment strongly favour one over other
7	Very much more important	Experience and judgment very strongly favour one over the other. Its importance is demonstrated in practice
9	Absolutely more important	The evidence favouring in ever the other is of the highest possible validity
2, 4, 6, 8	Intermediate-values	When compromise is needed

Employee suggestion systems create win-win situation for employers and employees alike. However, despite the many benefits of the suggestion systems, sustaining them is still a challenge for organisations. Organisations need to assess their suggestion schemes to determine their sustainability and to examine if the right conditions exist for the suggestion schemes to flourish. After all, suggestion systems can contribute to build organisations innovative capability.

The variables identified in the literature review were first subjected to a factor analysis. This enabled the emergence of five factors, namely—Leadership and Work Environment, System Effectiveness, System Capability, Organisational Encouragement and System Barriers. These five factors were considered in an AHP analysis to determine the importance levels. Expert opinion study was conducted to formalise the importance levels for the importance of factors of sustainability of employee suggestion schemes. Once the importance was identified, the initial framework was created to place the indicators in the order of their importance. An AHP expert opinion questionnaire following Saaty's [8] rating scale as reference for the expert to decide the importance of the indicators in the numerical range 1–9 or their reciprocals, i.e. 1/2–1/9 was used.

The steps for conducting the AHP analysis were briefed in the following steps:

The data were collected from three suggestion system implementers. These implementers were contacted through an email requesting their participation in this research study. The implementers had varied experience using suggestion systems, for example, 10–15 years and were active members of IdeasArabia Group. IdeasArabia Group conducts an annual conference on suggestion systems and awards the organisation and individuals for best suggestions. The data were collected in the form of semi-structured interview and after explaining the objective of the study and the application of the AHP method, from two participations. The third participant was then shown the data collected from two participants for the final judgment as to which two users opinion about the importance level of factor indicators was more appropriate for adjusting the importance level of factor indicators for pairwise comparisons or that both opinions were incorrect as per the knowledge of the third practitioner. The third user expressed satisfaction over factor importance level established by the first user and suggested that the same should be adopted in this study.

The steps for conducting the AHP analysis have been briefed in the following steps:

Reciprocal matrix: the first step is to construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it [8]. Pairwise comparisons were carried out for all factors to be considered, usually not more than seven and the matrix is completed [46].

Eigenvector: the next step is the calculation of a list of the relative weights, importance or value of the factors, which are relevant to the problem in question and this list is called an eigenvector. Eigenvector is calculated by multiplying together the entries in each row of the matrix and then taking the *n*th root of that product gives a very good approximation to the correct answer [46].

Consistency index: the consistency index for a matrix is calculated from $(\lambda_{\max} - n)/n - 1$.

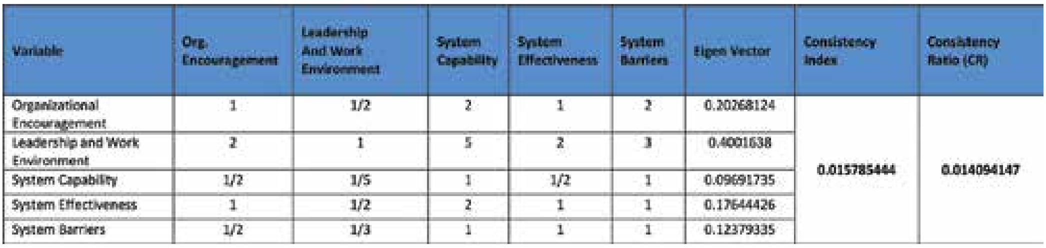
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51	1.48	1.56	1.57	1.59	

Table 5. Saaty table for calculation of consistency ratio (CR).

Consistency ratio: the final step is to calculate the consistency ratio for this set of judgments using the CI for the corresponding value from large sample of matrices of purely random judgments using **Table 5**, derived from Saaty's book, in which the upper row is the order of the random matrix and the lower is the corresponding index of consistency for random judgments [46]. CR should be less than 0.1 and if the CR is much in excess of 0.1 the judgments are untrustworthy because they are too close for comfort and to randomness and the exercise is valueless or must be repeated [46].

Indicators	**Organisational Encouragement**	**Leadership and Work Environment**	**System Capability**	**System Effectiveness**	**System Barriers**
Organisational Encouragement	1	1/2	2	1	2
Leadership and Work Environment	2	1	5	2	3
System Capability	1/2	1/5	1	1/2	1
System Effectiveness	1	1/2	2	1	1
System Barriers	1/2	1/3	1	1	

Table 6. Reciprocal matrix—overall factors.



Variable	Org. Encouragement	Leadership And Work Environment	System Capability	System Effectiveness	System Barriers	Eigen Vector	Consistency Index	Consistency Ratio (CR)
Organizational Encouragement	1	1/2	2	1	2	0.20268124	0.015785444	0.014094147
Leadership and Work Environment	2	1	5	2	3	0.4001638		
System Capability	1/2	1/5	1	1/2	1	0.09691735		
System Effectiveness	1	1/2	2	1	1	0.17644426		
System Barriers	1/2	1/3	1	1	1	0.12379335		

Table 7. AHP calculation for all sustainability factors.

Indicator	**Importance rank**
Leadership and Work Environment	1
System Capability	2
System Effectiveness	3
Organisational Encouragement	4
System Barriers	5

Table 8. Importance rank for sustainability factors.

The reciprocal matrices created for the AHP data collected through expert opinion study have been shown in **Table 6**. The calculations of the eigenvector, consistency index and consistency ratio are shown in **Table 7**. Importance ranks for factor indicators and for overall sustainability factors are depicted in **Table 8**.

As the consistency ratio resulted in < 0.1, the judgement for overall sustainability factors are perfectly consistent.

4. The overall factor importance

After the study and analysis of the reciprocal matrix and AHP calculations were done, it can be interpreted that:

- Leadership and Work Environment is slightly more important than both—System Effectiveness (2) and System Capability (2), somewhat more important than Organisational Environment (3) and much more important than System Barriers.

- System Capability is equally important to System Effectiveness (1) and slightly more important to both Organisational Encouragement (2) and System Barriers (2). However, it is slightly less important than Leadership and Work Environment (1/2).

- System Effectiveness is equally important to both System Capability (1) and Organisational Environment (1) and slightly more important to System Barriers (2). However, it is slightly less important to Leadership and Work Environment (1/2).

- Organisational Encouragement is equally important to System Barriers (1) and System Effectiveness (1). However, it is less important than System Capability (1/2) and somewhat less important to Leadership and Work Environment (1/3).

- System Barriers is equally important to Organisational Encouragement (1). However, it is slightly less important to both System Capability (1/2) and system Effectiveness (1/2) and much less important to Leadership and Work Environment (1/5).

Table 8 depicts the importance order for five sustainability factors based on the above interpretations. The Leadership and Work Environment is the more important factor when compared to the other four. The indicator System Capability stands at the next importance on rank 2, System Effectiveness at importance rank 3 and Organisational Encouragement at rank 4 and System Barriers at rank 5.

5. Discussion

This chapter discusses application of the AHP method in two different organisational settings based on two case studies.

First, AHP is applicable as an evaluation technique that eases the decision maker's task of choosing the most efficient maintenance policy. Diverse management practices can be implemented by manufacturing organisations in order to improve organisational performance by continuous improvement trough implementation of process changes [47,48]. Maintenance can be seen vital for sustainable performance of a production plant [49]. Sharma et al. [50]

concluded that development, adoption and practice of new maintenance strategies had become crucial. Selecting a suitable maintenance policy is definitely one of the essential decision-making tasks in improving the cost-effectiveness of the production systems [3,14]. Recent studies [40] indicate that appropriate maintenance can extend the life of an asset and prevent costly breakdowns that may result in lost production. The maintenance function plays a critical role in a company's ability to compete on the basis of cost, quality and delivery performance [51,52]. It appears that aim of the maintenance function is to contribute towards a company's profit, clearly bringing the need for maintenance operations to be in harmony with corporate business objectives [53]. Further, the growing importance of maintenance regarding improving company's profitability and competitiveness [54,55], strengthens the need for selecting a proper maintenance policy [56]. Therefore, using the proposed AHP framework, the criteria for maintenance policy selection can be clearly recognised and the issue can be structured systematically. More importantly, it can effectively support the decision makers in the process of selecting the most appropriate maintenance policy.

Three main criteria for the maintenance policy selection were used in this study and are as follows: equipment- and process-related measures, financial measures as well as health and safety and environment measures. Furthermore, the following sub-criteria are considered to be the most important: OEE, maintenance savings, number of accidents and productivity and availability. The latter can be explained in the context of a production process which in the paper mill is running 24/7. Therefore, used criteria play an important role, especially from the perspective of accomplishing the production goals. Based on the selected criteria as well as on the decision makers' evaluations, the TQMain was selected as the most appropriate maintenance approach. Among others, the TQMain is focused on maintaining and improving continuously the technical and economic effectiveness of the process elements [9], which were indeed important criteria in our study.

To ensure that final solution is stable and robust, we additionally applied sensitivity analysis. With Expert Choice software, AHP enables sensitivity analysis of results which is very important in practical decision making [57].

Secondly, the AHP method was applied to identify the important of each of the factors that would impact the sustainability of the suggestion scheme. This analysis resulted in placing importance ranks among the five factors. These factors are arranged in the order of their importance as below:

1. Leadership and Organisational Environment

2. System Capability

3. Organisational Encouragement

4. System Effectiveness

5. System Barriers

The most important factor is placed at the centre and the least important factor is placed at the bottom of the list. Leadership and Work Environment is the first most important factor, System

Capability is the next important factor followed by System Effectives that is placed at the next level. The Organisational Encouragement is placed at layer four and the last important factor is the System Barriers.

The success of the suggestion scheme is related to the management support, practices, commitment and their leadership [35,58]. Truly, senior management ought to demonstrate their faith in the scheme, promote and support it and encourage all managers to view it as a positive force for continuous improvement [59]. Typically, the management support is seen as crucial to the implementation of ideas. For example, while a person can be creative and generate new ideas on her/his own, the implementation of ideas typically depends upon the approval, support and resources of others, which essentially calls for different forms of management support. If employees make a lot of suggestions, then the opportunity for them to be translated into implementations is greater when there are higher levels of support. Without senior level management support the workers will not be motivated to turn in suggestions [60].

The management support is also very essential for the facilitation of communication mechanism within the organisation. Management, therefore, has a responsibility to satisfy this need for participation and create a culture which is supportive of employee involvement in the decisions that affect his or her work [61]. Thus, the leadership-employee relation is of top most importance that can help the creativity practice to grow in the organisation.

Secondly, the knowledge possessed by individual employees can only lead to a firm, competitive advantage if employees have the incentive and opportunity to share and utilize their individual knowledge in ways that benefit the organisation. Systems that capture the ideas and the capability of such system to evaluate them and provide necessary feedback and reward the employees for the suggestion are other core elements that are necessary once the top management and leadership support is obtained.

Thirdly, organisations need to nurture the system by establishing mechanisms such as team works to improve the employee participation and must ensure that the right expertise and supervision is provided to guide the employees to make their suggestions.

The benefits of the suggestions must be visible. Therefore, it is important that the suggestions result in desired outcomes so these benefits are accrued, and such systems can be sustained. Often there will be organisational impediments that may have a negative impact which are normally the barriers to creativity and this factor has least importance specially because if the systems are the result of the vision of the leadership and resources are allocated to the functioning of the system, organisation impediments have a little scope to cripple the sustainability of the suggestion system.

Each of the factors has a varied influence on the sustainability of the suggestion scheme and hence understanding the importance level identified by the AHP application of each of them would help the organisation to foster the factors accordingly for an improved performance and increase the effectiveness. Using AHP method, it is possible to identify the importance level of critical success factors and success barriers that have emerged in previous studies.

Although the suggestion systems have been around for many decades, identifying the importance level of these factors helps to get a deeper understanding of sustainability of suggestion systems in organisations. Moreover, sustainability is not just a binary state of 'sustaining' or 'not sustaining'. Therefore, it is important to study the impacts of the inhibitors and barriers of suggestion systems on its sustainability.

6. Conclusions

Managers should identify the potential benefits of maintenance policy in terms of productivity, quality and profitability. The latter is essential in order to achieve cost-effective decision making [55]. The proposed framework for the maintenance policy selection appears to enable the structured and systematic way of selecting the most appropriate maintenance policy. By upgrading the traditional AHP method with a EWMA chart for consistency test, our proposed framework for maintenance policy selection represents a valuable tool for decision makers in the field of maintenance.

The second case study showed that AHP method can be successfully applied to arbitrate the importance levels or ranks for the indicators in determining the sustainability of employee suggestion system. By using the proposed importance levels, organisations can assess the suggestion schemes for its sustainability and to recognise if the right conditions exist for the suggestion schemes to flourish.

However, we acknowledge the limitations of using the traditional AHP method. This method is often criticised because of its inability to adequately handle the uncertainty and imprecision associated with the mapping of the decision makers' perception to a crisp number [62]. Nonetheless, Karapetrovic and Rosenbloom [43] suggested that quality control approach can be used with any of the variations of AHP. Future studies could therefore consider different versions of AHP for maintenance policy selection through the lens of a quality management approach.

Author details

Damjan Maletič[1], Flevy Lasrado[2], Matjaž Maletič[1] and Boštjan Gomišček[2*]

*Address all correspondence to: BostjanGomiscek@uowdubai.ac.ae

1 Faculty of Organizational Sciences, University of Maribor, Kranj, Slovenia

2 Faculty of Business, University of Wollongong in Dubai, Dubai, UAE

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Chapter 6

AHP-Aided Evaluation of Logistic and Transport Solutions in a Seaport

Cristian Giacomini, Giovanni Longo,
Alice Lunardi and Elio Padoano

Additional information is available at the end of the chapter

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Abstract

The chapter reports on the application of the analytic hierarchy process (AHP) to a strategic decision in the transport sector, concerning the reconfiguration of the railway infrastructure of the seaport of Trieste. The proposed solutions should not only solve some technical and operational problems of the terminal, but they could allow the port to be included in the Trans-European Network-Transport Programme (TEN-T), promoted by the European Union and aimed to develop the Trans-European Networks of Transport. Accordingly, the selection of the solution with the most promising potential to satisfy the goals of the TEN-T policy is a fundamental stage of the project. The case study is an actual AHP application to an evaluation process concerning a pre-feasibility study of strategic solutions in the logistics and transport fields. Some practical aspects regarding the application of the AHP and the building of the model, when several stakeholders are involved in the decision process, are highlighted and discussed.

Keywords: Logistics, intermodal transport, railway, seaport, analytic hierarchy process (AHP)

1. Introduction

The Trans-European Network-Transport Programme (TEN-T), promoted by the European Union, is aimed to develop the Trans-European Networks of Transport, which include the major priority projects for road and combined transport, waterways and seaports, and the European network of passenger and freight trains. In this context, the North Adriatic Ports Association Studies project (NAPA) was developed, which focuses on the future develop-

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ment projects of the Northern Adriatic seaports: they are considered as fundamental points of interconnection between different transport systems. Each port has therefore conducted specific research as part of NAPA Studies. As far as the Port of Trieste is concerned, its current infrastructure, layout, and operations were deeply investigated and the bottlenecks, which could negatively affect the role of the port within the network, were identified. Several institutions and subjects are interested in the progress of the port infrastructure and consider the NAPA project an opportunity for developing concrete solutions that could redefine the place of the port in the European network. A set of technically feasible alternatives was found that encompass the reconfiguration of the railway infrastructure and operations.

Three main stakeholders are involved in the decision process: the port authority, the Italian railway infrastructure manager, and the Region Friuli Venezia Giulia. They are all interested in the development of the port but pursue different goals. On account of the complex setting, the multi-criteria evaluation of the solutions has been considered as an important stage of the overall project aimed at supporting the final decision. Indeed, multi-criteria methods give the opportunity to include in the evaluation of the project solutions several points of view and effects, some of which cannot be easily translated into economic values. The opportunity to understand the points of view of each stakeholder and involve them in the evaluation process is key features of some methodologies. On these grounds, the analytic hierarchy process (AHP), which enables a transparent process and the explicit representation of the decision-makers, was selected to support the analysis and evaluation. By involving the key stakeholders and some experts in such activities, it was possible to build a valid and useful model that allowed to select the most effective alternative with respect to the goals of TEN-T policy.

After a short presentation of the background of the NAPA project, the main aspects of the discussion and decision to be made about the Port of Trieste are introduced. In Section 4, the multi-criteria methods are presented with specific reference to strategic decisions in the transport sector and the AHP is briefly outlined. The section then describes the application of the AHP in the specific situation and the procedure that was followed to interact with the stakeholders. The results of the application are reported and discussed in the Section 5. Some practical aspects that emerged during the process are eventually highlighted in the Section 6, which precedes the conclusions.

2. Background of the project

The Port of Trieste is located in the northern Adriatic, which is a strategic position at the intersection among important maritime routes and motorways of the sea and the European corridors, Adriatic-Baltic, and Mediterranean (**Figure 1**). Therefore, it may play an important role (European gateway) for long distance traffic flows between the Far East and the markets of Central and Eastern Europe.

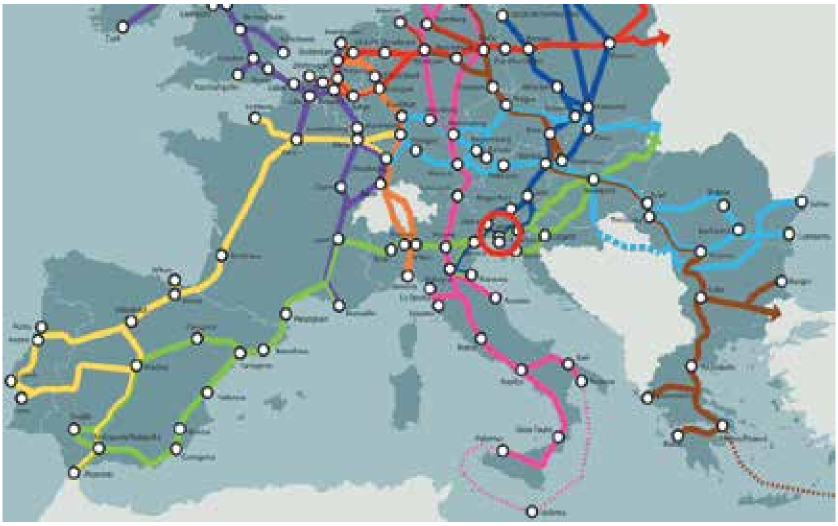

Figure 1. Map of European transport corridors.

The port already offers regular sea side and direct connections with China, the Far East, Singapore, Malaysia, Albania, Slovenia, Croatia, Greece, Turkey, Egypt, Lebanon, and Israel. From the land-side perspective, it is connected with the production areas and industrial North-East Italian and Central Europe, with different destinations, such as Germany, Austria, Czech Republic, Hungary, Switzerland, and Luxembourg, serving a very interesting economic area. In 2015, the port handled 57.12 million tonnes; therefore, it is the first port of Italy for the handling of goods in tonnes (source: port authority).

Regarding land-side infrastructure, the Port of Trieste has a long tradition in good rail connections and it is linked to the main Italian railway network through the Trieste Campo Marzio marshalling yard where all operations of train composition and de-composition are concentrated. The port is connected to Trieste Campo Marzio by means of three openings (**Figure 2**, Varco II, Varco III, Varco IV circled in red), but currently only one of them (Varco III) is in operation. Moreover, insufficient curvature radii and a critical general layout of the marshalling yard cause excessively complex and time-consuming shunting. The whole rail terminal has been identified as the main bottleneck for railway traffic increase inside and outside the port not only for the present conditions of the infrastructure, but also for its management.

The main reference document for planning and development is the Master Plan of the seaport. Starting from the analysis of the existing weaknesses and strengths, and in relation to a strategic vision and traffic increase forecasts, the Master Plan identifies a list of actions to be implemented in the port area. They include the extension/expansion of the existing facilities in the area of wharfs ("Moli") V, VI, and VII, and the realization of a new Logistic Platform, which is a modern and functional multipurpose terminal.

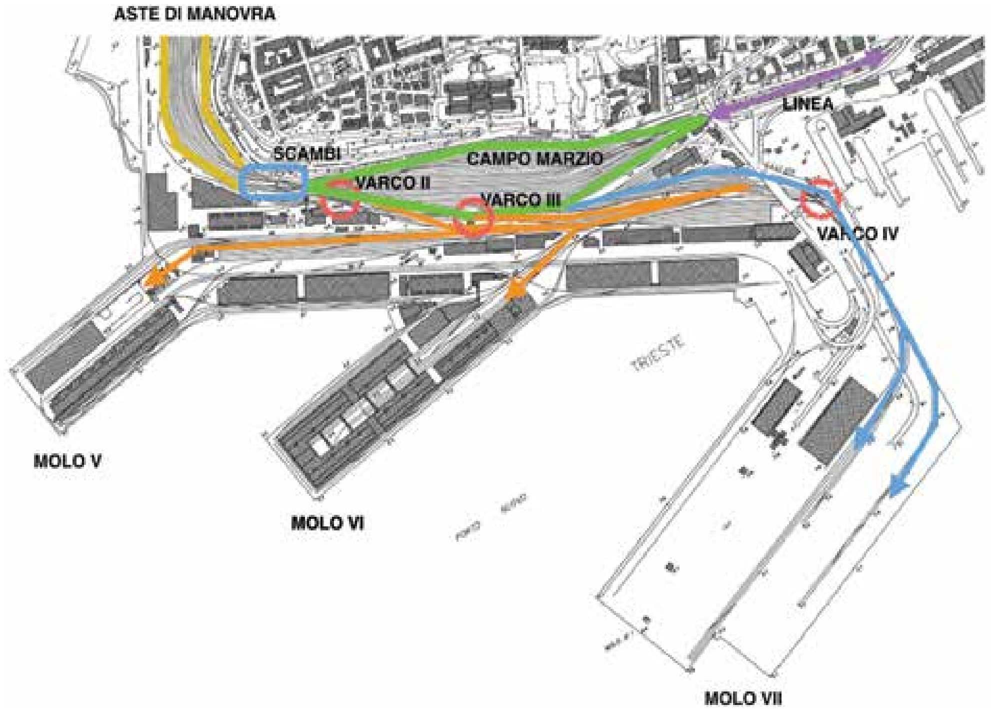

Figure 2. Layout of the seaport of Trieste.

In this context, the North Adriatic Ports Association Studies project (NAPA) was developed, which aims to support future development projects of the Northern Adriatic ports, thus contributing to the development of seaports as points of interconnection between different transport systems. In 2012, the NAPA carried out a market study on the potential handling capacity of containers in the ports of Koper, Ravenna, Rijeka, Trieste, and Venice. The five NAPA ports, in fact, intend to develop container traffic, becoming a multi-port gateway for Asian and Central and Eastern Europe economies. Each port has, therefore, conducted specific research as part of NAPA Studies. As far as the Port of Trieste is concerned, its current infrastructure, layout, and operations were deeply investigated and the bottlenecks, which could negatively affect the port's role within the network, were identified. A set of different feasible solutions was found that encompass the reconfiguration of the railway infrastructure and operations, in order to make possible the composition and movement of trains longer than those currently possible inside the port, ensuring efficiency improvement of the operational activities, particularly for containers, and, consequently, traffic increase.

These improvements are also required to meet the railway infrastructure requirements for the core network within the European Union's Regulation No. 1315/2013 [1] on “Union guidelines for the development of the trans-European transport network” (art. 39 “at least 22.5 t axle load, 100 km/h line speed and the possibility of running trains with a length of 740 m”).

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3. The decision process

Different solutions for the reconfiguration of the port infrastructure were proposed, and the main aim of the decision process was then to compare the feasible alternatives and to identify the best project for the Port of Trieste in consideration of the EU's goals and the subjects who are interested in the improvement of the facility. Three main decision-makers are involved in the decision process: the port authority, the Italian railway infrastructure manager—Rete Ferroviaria Italiana (RFI)—and the Region Friuli Venezia Giulia. They are all interested in the development of the port, but they pursue different goals.

The port authority has the primary task of defining the port strategies, planning, coordination, promotion, and control of port operations and other commercial and industrial activities in the port. The authority is also responsible for the ordinary and extraordinary maintenance of the common areas within the port and for the general services to port users. RFI has the main task to develop, manage, and maintain the railway network. It is also responsible for the commercial access and use of the infrastructure by transport companies. The Region Friuli Venezia Giulia has the competence in the regional development, transport planning, and port regulation. Accordingly, RFI may be responsible for railway design and construction, the Region for transport network planning, and the port authority for the port development.

On account of the complex setting, the evaluation of the solutions has been considered as an important stage of the overall project aimed at supporting the final decision. As stated before, the main goal of the assessment activity was to identify the best technical solution to improve the railway infrastructure both in the Port and in Campo Marzio station. Within NAPA Studies project, a team of experts has been built in order to support the analysis and evaluation process. The experts were able to estimate the performances of the alternatives against the main criteria included in the EU Regulation for this kind of interventions, and to support the decision-makers throughout the assessment.

The first step was the identification of the alternatives. In particular, three new projects were proposed and a "do minimum" alternative was also taken into consideration. In summary, the candidate solutions are the following:

> "Do minimum": The alternative refers exactly to the actual situation in which only planned maintenance activities are considered; of course, long trains cannot be composed nor circulate in the system;
>
> Alternative "650 m": The project allows the composition and circulation of trains 650 m long; it includes a new intermodal terminal between Campo Marzio yard and the Port area to be used by Molo VII container terminal; the solution was promoted by RFI;
>
> Alternative "750 m A": The project allows the composition and circulation of trains 750 m long. The composition and de-composition of longer trains is made up through a set of shunting movements of shorter trains using the existing openings; long trains cannot enter the port directly;

> Alternative "750 m B": The project allows the composition and circulation of trains 750 m long. In this case, an additional opening should be realized to allow the direct long train movement from and to Molo VII, while 650 m trains may use the other openings and reach Molo V and VI with simpler shunting operations.

The alternatives were analyzed with particular reference to the goals of TEN-T policy, and it was decided to investigate the methods that could be suitable to support the evaluation process ensuring transparency and participation. The methodological aspects and the resulting choice are discussed in the next section.

4. The methodology and the AHP model

4.1. Methodological aspects in the evaluation of transport projects

4.1.1. Generalities

The evaluation of solutions is a key activity within feasibility studies concerning transport projects. Study guidelines and regulations have traditionally focused their attention on the so-called "technical and economic feasibility"; in this context, evaluation has been based on the technical, financial, and economic contents or effects of a project, and more specifically, on economic efficiency [2]. With this respect, financial methods have been adapted and used in order to judge the economic efficiency by comparing the cost of the resources employed to produce and manage the infrastructure, and the economic benefits that could be derived from it. This evaluation approach is grounded on the assumption that it is rational to choose the solution that is the best according to one criterion: the economic advantage of the stakeholders.

A standard methodology of this kind is the cost-benefit analysis (CBA), which is focused on the welfare change of the community that bears the costs and gains the advantages of the transport infrastructure and service. CBA is widely used for infrastructure projects on account of the public expenses expected to realize and run them [3]. In the standard CBA, the capital and running financial costs and other effects (e.g., on the environment, on the community's mobility etc.) are converted into "social opportunity" costs or revenues. Different synthesis indicators, which are based on the monetization of the effects and their inter-temporal discount (e.g., the economic net present value), can be used to evaluate the economic performance of a project solution (see [4]). The methodology can clearly support the selection of the "best" alternative in a set in that the solutions can be ranked according to their economic performance.

Even if the CBA takes into account a single criterion of evaluation, the methodology aims to assess different types of outcomes, which is always appropriate to projects in the transport sector (see [5]). Indeed, some effects (e.g., the environmental costs) can be reasonably translated into monetary terms and then aggregated into a single measure of economic efficiency. Nonetheless, the methodology becomes complicated and less transparent when it comes to assessing other effects of transport infrastructures (in particular, the "intangible" ones). In addition, some criticism about the principle of welfare theory and the monetization approach, and the need to introduce different dimensions of evaluation have encouraged the use of methods that can explicitly take into consideration several evaluation criteria [6–8].

The methods of multi-criteria decision analysis (MCDA) can support decisions in which several aspects, points of view, or decision-makers are relevant. Projects of transport infrastructures have generally more than one goal to achieve which are advocated by different interest groups or stakeholders. Indeed, they are typically the subject of "strategic" decision processes that involve several participants with different roles in and power over the process and the final decision. In these multi-actor decision processes, the participants, explicitly or implicitly, promote their interests and often represent those of other subjects or groups (see, e.g., [9, 10]); in the following, the term "stakeholder" will be used to indicate subjects or groups that participate or are represented in the decision process.

According to a relevant article by Banville et al. [11], the multi-criteria methods are particularly appropriate for the introduction and the use of the stakeholder concept in supporting decisions, so that different viewpoints can be explicitly and clearly adopted. In particular, the concept of stakeholder can improve the initial stages of decision-making, namely problem analysis, identification of the alternatives and of the evaluation criteria. Different stakeholders have different perceptions of the problem that is targeted by the project, its solutions and their outcomes on the mobility system, the community, and the environment; they may appreciate such aspects from different perspectives, and therefore, the levels of importance of the evaluation criteria may vary among them. Bristow and Nellthorp [3] confirmed that MCDA can be more effective than CBA to capture and assess environmental and social impacts, while other authors [7, 12] concluded that MCDA is suitable to taking into explicit account public opinion and making a transparent and participative decision.

MCDA methods give the opportunity to include in the evaluation of the project solutions several points of view and effects, some of which are not easily converted into economic values. They have been successfully applied to decision processes concerning transport systems and are promoted within guidelines on feasibility studies (see, e.g., [13]). A good number of articles have been published that present applications of MCDA to infrastructural projects (e.g., [14–16]) and transport plans or policies (e.g., [12]). Several studies confirm the above-mentioned advantages of MCDA with respect to economic-based methods, but, in line with official guidelines, they usually suggest to carry out both analyses to have a complete picture of a project's effectiveness and efficiency (see, in particular, [7, 8]). As for ports, the studies pay particular attention to logistic and locational effects of these infrastructures and highlight the necessity to involve the port authority and users, governmental institutions, and community stakeholders in the decision process [17, 18].

Traditionally, the stress has been posed on the notion that any action performed on a transport system would involve public or private costs in exchange of benefits to the system's users or external to the system. In addition, in many cases, the decision concerns the choice of one item within a set of pre-defined alternative solutions. Accordingly, the decision process and the supporting MCDA methodology have often been applied in the framework of a "rational" decision process with the following main features:

The subjects who take part in the process have specific (and possibly stable) roles;

The process can be structured in a sequence of steps;

There is a clear distinction among decision-making, analysis and evaluation activities;

The object of the decision can be described through a set of properties or attributes that can be individually analyzed and evaluated.

Several authors have proposed guidelines for a structured application of MCDA, which should make the methodology more straightforward and, in the case of projects involving the public interest, like in the energy and transport sectors, could favor the transparency of the process (see, e.g., [15, 19]). The proposed structures or procedures can be more or less detailed but, typically, they include the following steps:

definition and structuring of the problem;

identification and development of the alternative solutions;

definition of a set of criteria for the evaluation;

identification of the stakeholders' system of preference;

evaluation of the alternatives and recommendation to the decision-maker(s).

It is commonly accepted that the MCDA process is non-linear and can be subject to several refinement cycles, in particular when several actors are involved. As previously remarked, the participants to decision processes concerning transport projects have usually different roles and decision power that can be broadly subsumed under the following categories:

actual decision-makers (who can take the final or other key decisions);

stakeholders or their representatives (who can have more or less powerful influence on decision-makers);

analysts and experts (who may be consulted to support the whole process or to provide highly technical information on specific topics).

In common practice, there is a clear distinction between the decision-makers and the subjects who support (or "aid") the decision by means of their technical or scientific expertise. Some authors, however, have made a clearer distinction between "experts," who provide technical advice on specific topics (e.g., experts who carry out mobility analysis), and analysts, who analyze, model and facilitate the decision process [20–22]. Furthermore, it has been remarked that the analyst can effectively support the decision-makers if there is an interaction with them, so that the products of the analysis (specially the models) are understood and validated.

As previously noted, decisions concerning transport projects or plans are the result of a multi-actor process in which diverse stakeholders can exercise their influence or decision power with different strength, in different stages and on different objects of the process.

For instance, a public institution can promote a project solution since the pre-feasibility study and decide to fund it, but it cannot take the final decision about its actual implementation. The clear determination of the actual objective of the decision, the involved stakeholders, and their role in the process are prerequisites to taking into account the key stakeholders' viewpoints in the application of the evaluation method, and to promoting their participation in the analysis and evaluation activities.

Some studies have indeed underscored the importance of including the stakeholders and their objectives at the beginning of the MCDA, so that it is possible to relate them to the evaluation perspectives, the criteria used in the model and their levels of importance [10, 23, 24]. Furthermore, it has been remarked that using the MCDA methods that enable to add them to the model explicitly, may improve the transparency of the whole exercise [25, 26].

In the case study discussed in this article, the analytic hierarchy process (AHP) was used because it offers some features that can facilitate the inclusion of the above-mentioned aspects in the decision aiding process. The AHP [27] has been applied since the 1980s to support the evaluation and selection of alternative project solutions or plans in the transport field. The effective hierarchical representation of a decision problem and the ability to evaluate quantitative and qualitative properties of the alternatives are just two of the most notable features of the method. Its key steps can be explained by the analyst to the decision-maker with limited effort, establishing a solid ground for the mutual understanding and validity of the evaluation process [28].

The evaluation of the alternative infrastructural solutions of the port railway system was carried out by means of an AHP model, which offered an explicit representation of the main stakeholders, the evaluation criteria, and the alternatives. The inclusion of the stakeholders in the hierarchy, which has been used in some previous studies [29], allows to take into consideration their judgments in regard to the elements of the lower level (dimensions of evaluation and criteria). The experts of the project team performed the evaluation of the alternatives' performance against the criteria. This is in line with other studies, which affirm that the experts' contribution to the decision process improves the technical soundness of the solutions and can take into account the viewpoints of the users of the transport system [30, 31]. The model and the results are discussed in the next section.

4.2. The implementation of the AHP method

4.2.1. The main features of the evaluation

The development of the NAPA project and the key role of the evaluation have been discussed in Sections 2 and 3. The evaluation stage can be conceived as a process with specific objectives, resources, and expected results. The relevant characteristics of this process are the following:

> overall goal: The project is aimed at finding a configuration of the railway infrastructure in the port that can pursue the goals of TEN-T policy;

expected output: The result of the evaluation process is the identification of the project solution that will be submitted to the EU for funding;

object of the evaluation: The candidate solutions are given and mutually exclusive (alternatives);

key stakeholders: There is a limited set of stakeholders who can exert a significant influence on the final decision (submission of the project solution);

role of experts: The project team is entitled to support the evaluation stage and provide the technical expertise to assess the performance of the project solutions.

These aspects have significant effects on the way in which the evaluation is performed and the AHP model is built. In the AHP (see, e.g., [32]), the decision problem is structured as a functional hierarchy of connected elements (or "nodes"). The overall goal was located in the top level (focus of the decision) and is broken down into elements that are used to analyze its properties, assess their importance for the decision-makers and gauge the level at which such properties are found in the available solutions (located at the bottom level). Each element of a level can be connected to one or several elements of the lower levels; stated differently, the elements connected to an upper node ("parent node") share the property represented by that node: it is then possible to judge the relative "priority" (or "importance") of the elements with respect to the property. Relative priorities can be obtained by direct rating or, as suggested by Saaty [33] and in all those cases in which direct assessment is not viable, by pairwise comparing the elements of a level against the parent node. The child nodes of a level that are connected to a parent node can be grouped into a "cluster"; the elements in a cluster should not have priorities that differ by orders of magnitude, and a cluster can contain all or only a number of the nodes of a certain level. Finally, the connected hierarchy enables to synthesize the priorities of the alternatives with respect to the overall goal.

4.2.2. The evaluation model

The hierarchy built in the case study consists of four levels (**Figure 3**):

first (top) level: overall goal of the decision;

second level: main stakeholders;

third level: criteria of evaluation;

fourth (bottom) level: alternatives.

The upmost node represents the overall goal of the evaluation process, which was stated as "Select the port project alternative that can achieve best the objectives of EU's TEN-T policy." It is worth noting that the sentence is fairly simple and contains the key aspects of the evaluation:

the evaluation is aimed at selecting a candidate in a given set of alternatives;

the evaluation solutions are evaluated on the basis of their potential to implement TEN-T policy.

The overall goal was validated by the members of the project team on the basis that it complies with the main objective to be achieved in the NAPA project. The project team identified the stakeholders that can exert major influence or power on the implementation of the project (see Section 3):

> the Regional Government of Friuli Venezia Giulia (FVG), because of its planning and control role over strategic projects in the regional territory;
>
> the Port Authority of Trieste (APT), which plans, co-ordinates, promotes, and monitors port operations;
>
> the Italian Railway infrastructure manager (RFI), which has the responsibility for the planning and management of the railway infrastructure.

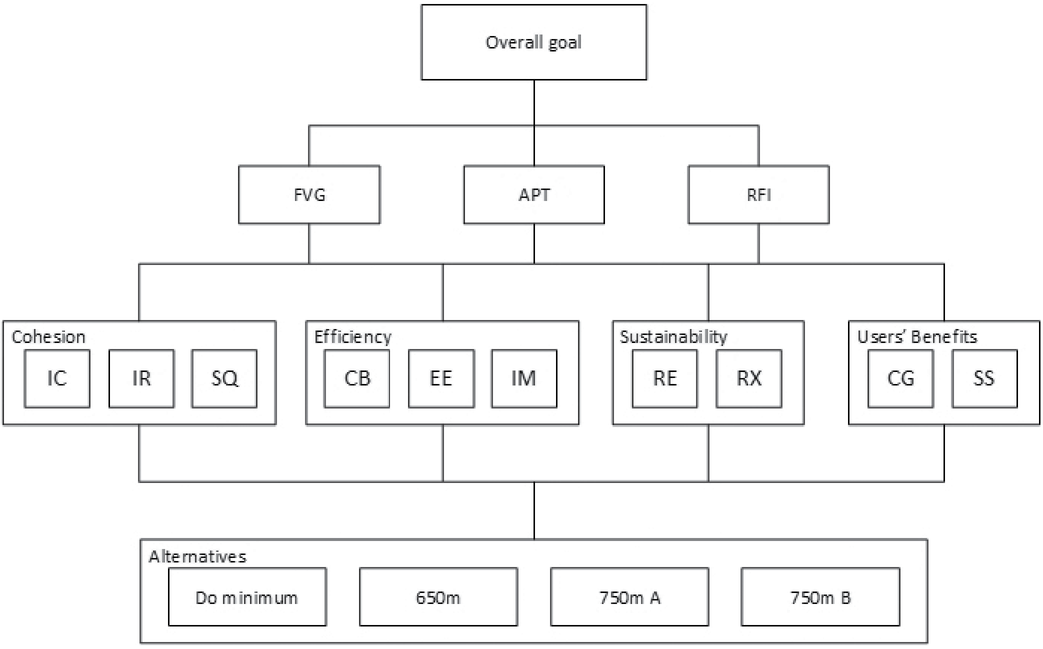

Figure 3. Hierarchical model built to support the evaluation.

These "key stakeholders" were explicitly introduced in the hierarchy, and representatives of them were interviewed to elicit the levels of importance of the criteria used in the evaluation. The explicit introduction of the stakeholders in the model is not strictly necessary to use their judgments for weighing the criteria. Nonetheless, it makes their importance or influence over the main goal more transparent, and the input of their judgments of importance, with regard to the elements of the lower levels, easier and clearer. As for the importance of the three stakeholders with respect to the overall goal, after some discussion within the project team, it was decided to assign them equal weights and analyze the sensitivity of the overall priorities to variations of their values.

The third level of the hierarchy is made up of the criteria used for the evaluation. They are grouped into four clusters that represent the four dimensions of evaluation directly related to the EU's objectives for TEN-T. It is worth remarking that TEN-T policy proposes four "categories of objectives": cohesion, efficiency, sustainability, users' benefits. Each of them is a dimension of evaluation that includes a set of "general objectives" with a common policy goal and are valid for any kind of project concerning the transport network (independently from the transport mode, location, type of action). The general objectives are then translated into "specific objectives" in light of the particular action to be carried out in a portion of the network. The categories of objectives are briefly introduced in the following points [1].

> Cohesion can be carried out through the improvement of the accessibility of all EU's regions, the reduction of quality gaps that can affect the infrastructure and a stronger interconnection of long-distance, regional, and local traffic flows.
>
> Efficiency aims at assuring the continuity of flows and the interconnection and interoperability of transport networks and promotes intermodality and economic efficiency in the production of transport service.
>
> Sustainability aims to provide a transport network that can reduce externalities, preserve sensitive areas, and reduce emissions.
>
> The users' benefits should take into consideration the needs of the users of the transport system including their safety and security.

The categories were used as clusters to group the criteria that are specific to transport projects that aim to improve the Adriatic-Baltic and Mediterranean corridors within the TEN-T network. They were selected by the project team among the criteria proposed in the "Baltic-Adriatic Core Network Corridor Study" [34] taking into account those directly connected with freight multi-modal transport. The criteria aim to evaluate the performances of a project alternative in regard to the aspects that are reported here below. It can be noted that all the criteria are aspects to be improved by means of the implementation of the project.

4.2.3. Cohesion

> Interconnection of flows (IC): The development of the interconnectivity of the transport network between long-haul sections and long-haul/short-haul sections.
>
> Standard and quality of the infrastructures (SQ): The improvement of the quality and standards of the transport infrastructure with the aim of complying with the technical requirements (for the railway transport: line speed, train length, axle load).
>
> Regional integration (IR): the development of the accessibility of European regions with particular reference to the most peripheral ones.

4.2.4. *Efficiency*

Removal of rail and road bottlenecks (CB): The reduction or removal of existing transport bottlenecks in the network or, conversely, the creation of a new bottleneck.

Intermodality (IM): The optimal integration and interconnection of different transport modes, with particular reference to the connections to ports, airports, and rail-road terminals.

Economic efficiency (EE): The promotion of economically efficient and high-quality transport and the efficient use of existing infrastructures.

4.2.5. *Sustainability*

Reduction of emissions (RE): The reduction of emissions and noise from the transport activity.

Reduction of externalities (RX): The reduction of external costs of transport and protection for environmentally sensitive areas.

4.2.6. *Users' benefits*

Congestion (CG): The reduction of congestion in the transport network.

Safety and security (SS): The enhancement of safe, secure and high-quality transport standards, for both passenger and freight.

The criteria were then presented to the representatives of the stakeholders within the project team who considered them valid in the specific context. The hierarchical structure enables to relate the set of criteria to the solutions and the key stakeholders. It can be noted (**Figure 3**) that the key stakeholders are connected to the clusters and the criteria. This feature of the model can be practically implemented by means of the supporting software tool that was chosen: SuperDecisions [35]. In this way, it is straightforward to input in the model the stakeholders' pairwise comparisons of importance:

between the clusters;

between the criteria with respect to their cluster.

The relative weight of each criterion is then the synthesis of the judgments of all three stakeholders on both clusters and criteria.

The fourth level includes the four alternative solutions that are described in Section 3, namely:

"Do minimum";

"650 m": project which allows trains 650 m long;

"750 m A": project which allows trains 750 m long, mode A;

"750 m B": project which allows trains 750 m long, mode B.

The alternatives have been analyzed by the project team's experts and they can be characterized and judged with respect to all the criteria. However, considering that the association of the criteria with specific measures of performance is not viable at this stage of the project, it was decided to elicit the alternatives' priorities by pairwise comparing them against the criteria.

The execution of the model produces the overall priority of the alternatives: it is then possible to rank them or identify the most effective. Nonetheless, it can be noted that the criteria of the model do not include a measure that accounts for the investment cost. In fact, as already remarked, the criteria represent the positive outcomes that are expected from the implementation of the solutions. As suggested by Saaty (cf. e.g., [32]), the cost of each alternative was introduced after the evaluation of the overall performance. This approach allowed the stakeholders to focus their attention only on the effects of the alternatives when they judged the weights of the criteria. Eventually, the benefit-cost ratio was used to obtain a measure of resource spending efficiency: the alternatives could then be ranked, from best to worst, in decreasing order of the ratio.

4.2.7. The evaluation activity

The evaluation activity was based on two methodologies:

- face-to-face interview with the representatives of the key stakeholders to assess the weights of the clusters and criteria;
- group discussion within the experts of the project team to evaluate the performances of the alternatives against the criteria.

The first consisted of the following stages:

- preparation of the interview;
- first-pass interview;
- consistency check and second-pass interview (if needed);
- input data to the model.

Two members of the project team, one of whom assumed the role of facilitator, conducted the interviews. As a first step, the main contents and objectives of NAPA project were recalled and the goals of the evaluation process were remarked. Secondly, the procedure of multi-criteria evaluation was presented, and the categories of objectives and the criteria were introduced and illustrated. Before the assessment exercise, its main steps were introduced with the help of the propositions reported below:

> *"In order to obtain the overall evaluation of each alternative, it is necessary to establish the level of importance ("weight") of each criterion in regard to the main goal: the higher the weight of a criterion, the higher will be that criterion's contribution to the overall performance of an alternative."*
>
> *"The levels of importance are derived from pairwise comparison of the criteria. For each pair of criteria (C1 and C2), you will be asked two questions:*

> *Considering criteria C1 and C2, which is more important with respect to the main goal (or are they equally important)?*
>
> *How much more important is that criterion?"*

The second judgment was based on the verbal scale proposed by Saaty that was briefly introduced to the respondents. Each stakeholder's evaluations were recorded in two different tables (see **Tables 1–6**): one for the pairwise comparisons of clusters and one for pairwise comparisons of criteria within a cluster. The results were then input to the software SuperDecisions for the consistency check.

The assessment of the alternatives' priorities against the criteria was the product of group discussions that involved the technical experts of the project team. Their contribution to the decision process assured a good level of technical soundness to the evaluation and the inclusion of the viewpoints of the port users and the promoters of the solutions.

5. Results and discussion

The results of the evaluation activity are reported in **Tables 1–16** starting with the data collected from the face-to-face interviews (**Tables 1–6**). Each of the three interviews with the key stakeholders' representatives produced two tables: the first shows the results of pairwise comparisons (in terms of importance) between clusters (or "categories of objectives"); and the second shows those between criteria of a cluster. The notation "A 5> B" means that the element A is five times more important ("moderately more important") than B, while the notation "A <5 B" means that the element B is five times more important than A, and "A = B" means that A and B are equally important. The tables show the measure of inconsistency produces by the software for the pairwise comparisons between three or more elements; Saaty remarks that inconsistency can be acceptable if it is not >10%.

Cluster i		Cluster j
Cohesion	<6	**Efficiency**
Cohesion	<3	**Sustainability**
Cohesion	4>	**Users' benefits**
Efficiency	4>	**Sustainability**
Efficiency	8>	**Users' benefits**
Sustainability	6>	**Users' benefits**
Inconsistency		0.08062

Table 1. Pairwise comparisons of clusters by FVG.

Only for stakeholder FVG, a second pass interview was necessary, due to the high inconsistency obtained after the first pass. Arguably, this situation can be attributed to the more limited knowledge of the NAPA project and its relation with TEN-T policy that the FVG's representative had with respect to the other two interviewees. Indeed, while APT and RFI had been involved in the NAPA project at an early stage, FVG was consulted only after the complete definition of the four alternatives. A second possible reason can be the fact that the consultation with FVG was the first of the three, and therefore, the two interviewers could improve their command over the interview flow in the second and third sessions.

The results of the pairwise comparisons of the alternatives against the criteria are reported in **Tables 7–16**. A total of 60 comparisons were made by the experts of the project team, which were based on the alternatives' features and expected performances in regard to the criteria. The grounds of the experts' judgments are briefly reported in the following paragraphs.

Cohesion			**Efficiency**			**Sustainability**		
IC	5>	**SQ**	**CB**	<3	**IM**	**RE**	=	**RX**
IC	<3	**IR**	**CB**	<7	**EE**		**Users' benefits**	
SQ	<7	**IR**	**IM**	<5	**EE**	**CG**	3>	**SS**
Inconsistency (cohesion)						0.06237		
Inconsistency (efficiency)						0.06239		

Table 2. Pairwise comparisons between the criteria of a cluster (FVG).

Cluster i		**Cluster j**
Cohesion	3>	**Efficiency**
Cohesion	5>	**Sustainability**
Cohesion	7>	**Users' benefits**
Efficiency	3>	**Sustainability**
Efficiency	5>	**Users' benefits**
Sustainability	3>	**Users' benefits**
Inconsistency		0.04381

Table 3. Pairwise comparisons of clusters by APT.

Interconnection (IC—**Table 7**). The candidate solutions do not have any significant effects in terms of the improvement of the interconnection between long-haul and short-haul sections of the Adriatic-Baltic and Mediterranean corridors.

Standard and quality of the infrastructures (SQ—**Table 8**). Both solutions "750 m A" and "750 m B" comply with the European standard, because they allow the 750 m-long train operations without disruptions, while "650 m" and "Do minimum" alternatives do not. In fact, "650 m" could deal with long trains but with an important increase in track occupancy and conflicts in the port.

Cohesion			Efficiency				Sustainability		
IC	<7	SQ	CB	<3		IM	RE	3>	RX
IC	<4	IR	CB	<7	EE		**Users' benefits**		
SQ	4>	IR	IM	<6		EE	CG	7>	SS
Inconsistency (cohesion)							0.07348		
Inconsistency (efficiency)							0.09609		

Table 4. Pairwise comparisons between the criteria of a cluster (APT).

Cluster i		Cluster j
Cohesion	<3	**Efficiency**
Cohesion	=	**Sustainability**
Cohesion	5>	**Users' benefits**
Efficiency	3>	**Sustainability**
Efficiency	5>	**Users' benefits**
Sustainability	3>	**Users' benefits**
Inconsistency		0.04324

Table 5. Pairwise comparisons of clusters by RFI.

Cohesion			Efficiency			Sustainability		
IC	<5	SQ	CB	7>	IM	RE	=	RX
IC	3>	IR	CB	5>	EE		**Users' benefits**	
SQ	7>	IR	IM	<3	EE	CG	<3	SS
Inconsistency (cohesion)						0.06239		
Inconsistency (efficiency)						0.06239		

Table 6. Pairwise comparisons between the criteria of a cluster (RFI).

Regional integration (IR—**Table 9**). "Do minimum" keeps the present configuration of the port railway infrastructure essentially unchanged, and some local studies have observed that it presents some weak points that affect the accessibility to other European regions (e.g., Central and Northern Europe). The other three solutions certainly improve the situation and "750 m B" should have a slightly better performance because it allows a direct connection (without decomposition) between the Port and the main network for long trains.

Removal of rail and road bottlenecks (CB—**Table 10**). The present infrastructure presents several bottlenecks (e.g., the limitation in the number of trains that can be dispatched to the network) that can be reduced by the new projects. However, the alternative "750 m B" is more effective than "650 m" and "750 m A" with this respect, because it may allow a higher number of long trains thus reducing the number of trains given the demand flows.

Interconnection		
650 m	=	750 m A
650 m	=	750 m B
650 m	=	Do minimum
750 m A	=	750 m B
750 m A	=	Do minimum
750 m B	=	Do minimum
Inconsistency		0.00

Table 7. Comparisons between the alternatives (IC).

Standard and quality of the infrastructures		
650 m	<5	750 m A
650 m	<5	750 m B
650 m	3>	Do minimum
750 m A	=	750 m B
750 m A	7>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.02752

Table 8. Comparisons between the alternatives (SQ).

Regional integration		
650 m	=	750 m A
650 m	<3	750 m B
650 m	5>	Do minimum
750 m A	<3	750 m B
750 m A	5>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.02752

Table 9. Comparisons between the alternatives (IR).

Removal of rail and road bottlenecks		
650 m	3>	750 m A
650 m	<3	750 m B
650 m	5>	Do minimum
750 m A	<5	750 m B
750 m A	3>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.04381

Table 10. Comparisons between the alternatives (CB).

Intermodality		
650 m	<7	750 m A
650 m	<9	750 m B
650 m	<5	Do minimum
750 m A	<3	750 m B
750 m A	4>	Do minimum
750 m B	6>	Do minimum
Inconsistency		0.08974

Table 11. Comparisons between the alternatives (IM).

Economic efficiency		
650 m	<7	750 m A
650 m	<9	750 m B
650 m	=	Do minimum
750 m A	<3	750 m B
750 m A	7>	Do minimum
750 m B	9>	Do minimum
Inconsistency		0.03410

Table 12. Comparisons between the alternatives (EE).

Intermodality (IM—**Table 11**). The infrastructure layout introduced by the alternative "650 m" may pose several problems to land-sea intermodal transport because the new terminal is quite far from the sea; therefore, the internal road traffic would increase causing potential congestion within the port road network. In this regard, the layout of "Do minimum" is better than that of "650 m"; nonetheless, "750 m A" and "750 m B" increase the capacity of the railway infrastructure and improve the current layout. “750 m B” is better than “750 m A” as it gives the opportunity to manage without disruptions trains 650 m-long too.

Economic efficiency (EE—**Table 12**). The alternatives “750 m A” and “750 m B” can make the port more attractive to freight forwarders that need to send their goods to Central and Northern Europe, because of the train capacity increase, their compatibility with European standards and the reduction of unproductive times (due to operational disturbances, for instance). “750 m B” is more flexible than “750 m A” as it allows to operate 650 m-long trains too without disruptions.

Reduction of emissions (RE—**Table 13**) and reduction of externalities (RX—**Table 14**). The performances of each alternative with respect to the two criteria are similar, even if the first one is mainly related to the infrastructure's operation and the second one to its layout and land use. The “Do minimum’ alternative is the worst against both criteria, and the “750 m B” is the best because it can assure a larger modal shift from road to railway than “750 m A” and “650 m.” These last two are similar with respect to RE, while the layout of “750 m A” is slightly more beneficial than that of “650 m” as far as external costs of transport are concerned.

Reduction of emissions		
650 m	=	750 m A
650 m	<3	750 m B
650 m	5>	Do minimum
750 m A	<3	750 m B
750 m A	5>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.02752

Table 13. Comparisons between the alternatives (RE).

Reduction of externalities		
650 m	<3	750 m A
650 m	<5	750 m B
650 m	3>	Do minimum
750 m A	<3	750 m B
750 m A	5>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.04381

Table 14. Comparisons between the alternatives (RX).

Congestion (CG—**Table 15**). The alternative "750 m B" can produce the most valuable results in terms of reduction of congestion in the port and in the surrounding area as it can significantly increase modal shift from road to railway transport. A similar effect is expected from "750 m A," though to a less extent. "650 m" introduces some additional movements of the trains within the terminal that imply just a slight improvement of train circulation with respect to "Do minimum," which is the worst.

Safety and security (SS—**Table 16**). The modal shift that is expected from alternatives "750 m A" and '750 m B' will provide benefits in terms of safety and security of freight and, because of the reduction in the number of trucks on the network, passengers. "650 m" has a slightly lower performance than the aforementioned two, but it is surely better than the current situation.

Congestion		
650 m	<5	750 m A
650 m	<7	750 m B
650 m	3>	Do minimum
750 m A	<3	750 m B
750 m A	7>	Do minimum
750 m B	9>	Do minimum
Inconsistency		0.06164

Table 15. Comparisons between the alternatives (CG).

Safety and security		
650 m	<3	750 m A
650 m	<3	750 m B
650 m	5>	Do minimum
750 m A	=	750 m B
750 m A	7>	Do minimum
750 m B	7>	Do minimum
Inconsistency		0.02752

Table 16. Comparisons between the alternatives (SS).

Table 17 (second column) displays the overall priorities of the alternatives that were obtained from the execution of the model. The alternative "Do minimum" is the worst of the four: in fact, congestion and bottlenecks are just the most evident problems that the current infrastructure causes and that triggered the project. In addition, the present configuration of the railway infrastructure of the port would not allow its inclusion in the TEN-T system. This same consequence would follow if the alternative “650 m” were implemented, as it does not comply with the European TEN-T's standards. Further, the layout and track circuits of this solution would increase the congestion in the port terminal. Conversely, the two alternatives “750 m” assure seamless integration of the port in the Baltic-Adriatic and Mediterranean corridors, the removal of the current bottlenecks and higher economic efficiency. Still, the solution “750 m B” is more flexible than “750 m A” because it enables to operate trains 650 m- and 750 m-long without increasing the occupancy of tracks or delaying train dispatching.

In order to evaluate the sensitivity of the alternatives’ priorities to changes in the stakeholders’ weights with respect to the overall goal, some different combinations of weights were tested. The interval of variation was set between 0.2 and 0.6, as these were reputed the minimum and maximum relative levels of importance of the key stakeholders that could be acceptable in the context of the decision. Even if there were some changes in the values of priorities, the overall ranking proved to be stable.

As a final step, the estimated capital costs of the alternatives were taken into consideration (**Table 17**, third column). The benefit-cost ratio, namely the ratio between an alternative's overall priority and the normalized capital cost, was used as an indicator of efficiency. **Table 17** (fifth column) shows the results: the alternative “750 m B” keeps the first position, while “Do minimum” gains two positions. In fact, this second alternative has a cost that is eight times lower than the capital cost of “750 m B,” but B's expense is repaid by its high level of overall benefits. The value of the ratio is low for “650 m,” and this seems to suggest that it should not be taken into consideration in the future stages of the project.

At the conclusion of the evaluation, the results were illustrated and discussed with the decision-makers, who approved the proposal of further investigating and refining the technical contents of solution “750 m B,” in order to seize opportunities for funding it.

Alternatives	Overall priority	Estimated investment cost (M€)	Normalized cost	B/C ratio
Do minimum	0.064	6.5	0.046	1.38
650 m	0.136	38.5	0.275	0.49
750 m A	0.276	45.0	0.321	0.86
750 m B	0.524	50.0	0.357	1.47

Table 17. Overall results.

6. Practice implications and lessons learned

The analysts who support the decision process usually face several practical problems concerning the development of the model and the interactions with the actors involved in the process. In the specific case, the activity was limited to the evaluation stage, which is part of a larger decision process; nonetheless, there were some issues related to the presence of several stakeholders and the need to translate the solutions’ specific technical features into the criteria, which represent properties that are more general but are strictly connected with the key objectives.

The key stakeholders had different roles (see Section 3), were involved in the project at different stages, and their representatives had different levels of expertise and knowledge of the problem. Such situation is not infrequent in strategic transport decisions and should be carefully managed. The opportunity to have an open and informative discussion with the stakeholders, and the quality of the information obtained can be delicate aspects. The case study confirms that it is necessary not only to identify the key stakeholders but also to individuate their representatives and involve them at an early stage of the evaluation process. However, the authors of this study observed that there is a relation between the interest and role of the stakeholder in the process (in particular, if a stakeholder is the promoter of one or more solutions) and the quality of the information retrieved from their representatives.

The interview of the actors is a key activity in multi-actor evaluation and should be carefully planned and, possibly, tailored to the respondent role (expert, policy maker etc.). In the specific, a structured interview was arranged only for the key stakeholders, while the experts were consulted in the context of group discussions within the project team. On the one hand, the interview allowed the respondents to focus their attention on the topics and their actual contribution to the evaluation; on the other, they did not always feel at ease with making comparisons between pre-determined criteria and asked for examples that could better describe their practical meaning. Not surprisingly, the representatives of the stakeholders involved in the NAPA project had less problems in the assessment.

The last observation is also valid for the experts of the project team. Still, some methodological issues were highlighted. Firstly, even if the separation between stakeholders' weighting of criteria and experts' judgment of the alternatives' performance was considered in line with the "political" and technical contents of the evaluation, an open discussion involving both figures could have been effective in exchanging viewpoints and circulating information. Secondly, the need to subsume many technical features of the solutions under broad criteria was considered arguable. In some cases, the association of the characteristics (such as track configuration, capacity, transit times, etc.) with a specific criterion was not immediate; further, this approach seemed to negatively affect the transparency of the evaluation. The opportunity that AHP offers for using both pairwise comparisons and direct measures could have been seized, and it could have satisfied some experts who stress the difference between "objective" and "subjective" measures of performance. However, this would have implied an additional effort to select the measures of performance that were meaningful for a criterion and non-redundant; in addition, the development stage of the project could not assure that the needed data were available. On these grounds, it was decided to employ the original methodological solution, based on pairwise comparisons. The last issue that was raised by the experts concerned the possible interdependencies among several factors (criteria or features), which were not considered in the AHP model. It was acknowledged that the model was a simplified representation of the problem: other methods that can deal with interdependencies, such as the analytic network process [36], should be used if a more refined evaluation was needed at the cost of a greater intellectual effort and a broader participation of experts and stakeholders.

7. Conclusion

The evaluation process satisfied the participants to the NAPA project concerning the development of the Port of Trieste: the objective of the evaluation was achieved, and the result was useful for the next stages of the project. The AHP allowed the implementation of a multi-criteria model in which the most important elements of the evaluation (key stakeholders and criteria aligned with EU's TEN-T policy) are plainly represented. This made the model transparent and easily understandable by the participants. An early involvement of the key stakeholders, who provide information that is essential to the assessment, can surely improve the quality of the evaluation, which depends on the knowledge of the problem and, perhaps less importantly, on the level of expertise in the technical field. The AHP may offer a representation of the decision problem that is too simplified in some cases; in particular, when interdependencies between elements of the problem cannot be overlooked. However, it is essential to consider if the improvement in the accuracy of the model is worth the increase in model complexity and in the amount (and quality) of the information that is required to produce reliable results.

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Author details

Cristian Giacomini, Giovanni Longo, Alice Lunardi and Elio Padoano*

*Address all correspondence to: padoano@units.it

Department of Engineering and Architecture, University of Trieste, Trieste, Italy

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Prioritizing Human Factors in Emergency Conditions Using AHP Model and FMEA

Fabio De Felice, Antonella Petrillo and
Domenico Falcone

Additional information is available at the end of the chapter

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Abstract

One of the most critical issues related to safety in industrial plant is to manage accidents that occur in industries. In general, the causes of accidents are twofold: the presence of dangerous equipment and human errors. The aim of this study is to propose a novel approach to ensure safety in emergency conditions in industrial plant considering both of these factors. The proposed idea aims to integrate the human reliability analysis (HRA) and the failure modes and effects analysis (FMEA). The human errors and failure modes are categorized using a multicriteria approach based on analytic hierarchy process (AHP). The final aim is to present a novel methodological approach based on AHP to prioritize actions to carry out in emergency conditions taking into account both qualitative and quantitative factors. A real case study is analyzed. The analysis allowed to identify possible failure modes connected with human error process.

Keywords: AHP, HRA, FMEA, emergency, human errors

1. Introduction

In recent years, various emergency events have caused loss of lives. The potential for major industrial accidents required a clearly and systematic approach to control the human errors and failure modes to ensure a proper approach in emergency conditions. One of the most important significant sources useful to monitor the emergency events is the database EM-DAT (http://www.emdat.be/). The database is a potential tool to investigate industrial accidents and disaster events worldwide. For instance, **Figure 1** shows the total number of industrial accidents, in Europe, between 1900 and 2015. As it is possible to note, during the period 1990–2008, there has

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been a growth in the number of accidents. This result is not a surprise as a consequence of growth on industrial processes and technology.

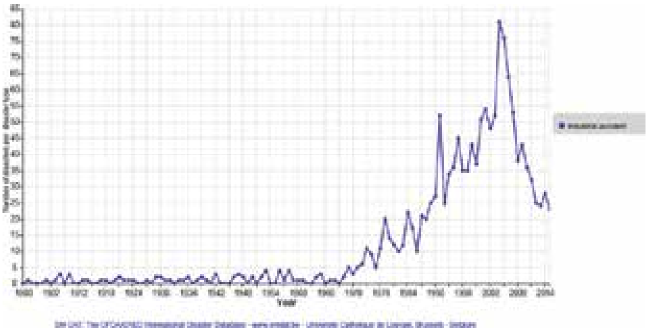


Figure 1. The total number of industrial accidents between 1900 and 2015 (source "http://www.emdat.be/").

Of course, the growth of industrial accidents, highlighted above, behave in accordance with an increase of the total number of economic damage as it is shown in **Figure 2**.

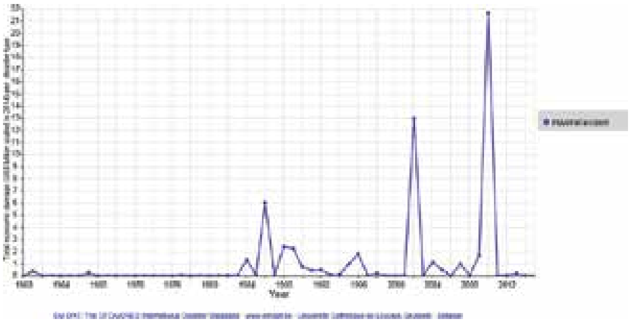


Figure 2. The total economic damage between 1900 and 2015 (source http://www.emdat.be/).

Among the major disasters that occur worldwide are the *Seveso disaster in Italy* (July 1976), caused by the release of dioxins into the atmosphere; the *Chernobyl disaster* in Ukraine (April 1986) happened after a test on a reactor; the *Shell Oil refinery* explosion in the USA (May 1988), caused by hydrocarbon gas leak; and the *Fukushima I* nuclear accidents in Japan (March 2011).

These undesirable events increased the importance of risk assessment and a good operational planning decisions [1, 2]. In this context, the critical elements to take into account are human factors and failure modes to design a systematic approach to improve the role of human element in a system performance. Thus, *what is the point?* In our opinion, it is necessary to provide a structured framework to prioritize risks taking into account the failure mode and the human errors.

For this reason in the present research, an integrated approach is proposed. In particular, the approach is based on three fundamental aspects that, in our opinion, help to analyze the problem globally: the *human reliability analysis* (*HRA*), the *failure modes and effects analysis* (*FMEA*), and the multicriteria approach using *analytic hierarchy process* (*AHP*). Here below, a brief overview of the above approaches is provided.

The HRA is a critical issue because the human errors involve the use of qualitative and quantitative aspects [3]. In literature, a great number of tools are proposed for human reliability analysis [4]. The limit of the HRA techniques is related to the uncertainty to consider organizational factors and errors of commission. One of the most important issues related to human errors is the performance shaping factors (PSFs). PSFs allow to assess all the environmental and behavioral factors that influence the decision and actions of man. In particular, the use of PSFs allows to simulate different scenarios. HRA tools include failure modes and effects analysis (FMEA), developed in the late 1950s. FMEA is one of the most popular methods used to perform the risk assessment [5]. The traditional FMEA approach has been extensively criticized due to the limitations in calculating the risk priority number (RPN) [6, 7].

Several methods have been suggested to improve the traditional HRA and FMEA. Among these methods, the multicriteria methods such as analytic hierarchy process (AHP) are very promising. AHP, developed by Saaty [8], is a useful approach to manage the complexity of decision problems. AHP technique is very suitable to determine the weights for each risk factor. With AHP, it is possible to evaluate the ambiguity of human perception and to transform it into a mathematical formula.

In this paper, the AHP technique is proposed to weigh and to prioritize failure modes and human factors that characterize actions in emergency conditions. AHP is used to assess the relative importance among human factors and failure modes. As a result, a new methodological approach to calculate the risk priority number using weighting method integrating with human factors is presented. To validate the application of the model and to examine its effectiveness, the proposed methodology is used for analyzing an emergency scenario in a petrochemical plant.

The rest of the paper is organized as follows. The literature review on emergency management is presented briefly in Section 2. The methods are introduced in Section 3. Section 4 is about the proposed evaluation methodology. Furthermore, a numerical example is presented. Conclusions are analyzed in Section 5.

2. Literature review on emergency management and human errors

In emergency management, it is necessary to collect many and different types of information to deal with emergency tasks in different phases and to deal with emergency situation such as stress, lack of time, and adequate training [9].

A systematic literature review was carried out to search if a similar study has already been published in the literature. We looked for studies in the *emergency management* area in Scopus database (www.scopus.elsevier.com). In particular, we investigated the “engineering field,” in which 8,445 documents came out during the period of 1925–2016. **Figure 3** shows the number of documents by year. Results point out that there is a growing interest on emergency management issue.

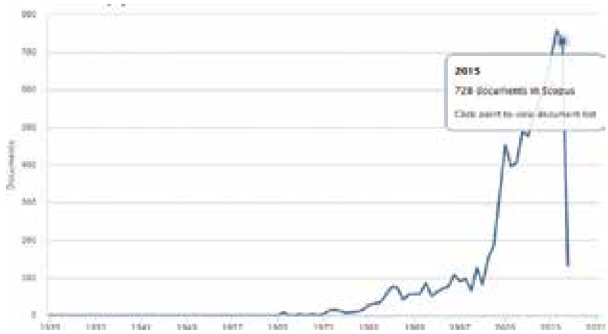


Figure 3. Documents by year.

A depth analysis shows that the majority of the researches are developed in the USA (**Figure 4**).

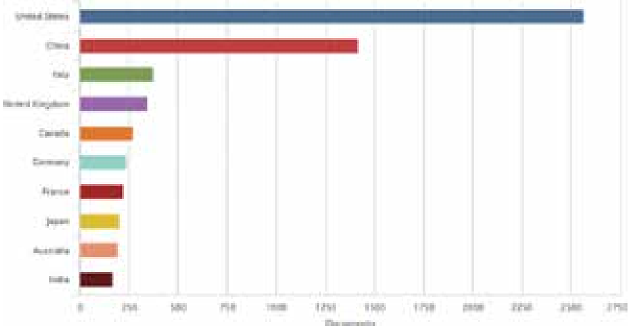


Figure 4. Documents by country/territory.

In recent literature, several approaches and models have been proposed to manage emergency conditions. For instance, Pérez et al. [10] in their study proposed a fleet assignment model for the Santiago Fire Department to maximize the number of incidents successfully attended. Omidvari et al. [11] developed a model based on analytical hierarchy process and failure modes and effects analysis logic to determine the factors influencing the fire risk of an education center. Bariha et al. [12] proposed the analysis of hazards associated with accidental release of high pressure from gas-pipeline transportation system. A probabilistic risk assessment from potential exposures to the public applied for innovative nuclear installations has been analyzed by Dvorzhak et al. [13]. While Shi et al. [14] used a technique plan repository and evaluation system based on AHP group decision-making for emergency treatment and disposal in chemical pollution accidents, Ergu et al. [15] applied the analytic network process, a generalization of the AHP, in risk assessment a decision analysis. Liu et al. [16] present a novel approach for FMEA based on AHP and fuzzy VIKOR method.

The above works relate to emergency management in the sense that they analyze multiple approaches to manage emergency conditions. However, no specific systematic approach is presented to take into account both qualitative and quantitative factors in the emergency management. Our work focuses in understanding the failure modes and human errors in emergency conditions, following a strict and standardized protocol to identify and to prioritize risks.

3. Methods

To design the model, a novel approach including HRA, FMEA, and AHP is defined. In this section, a short description of these methods is given.

3.1. The failure modes and effects analysis (FMEA): the traditional approach

According to the American Society for Quality [17], FMEA is a procedure that is performed after a failure modes and effects analysis to classify each potential failure effect according to its severity and probability of occurrence. Traditional FMEA method is based on risk priority number (RPN) for analyzing the risk associated with potential problems. RPN is calculated by multiplying the scores of severity (S), occurrence (O), and detection (D). In details:

- Occurrence (O) represents the probability that a particular cause for the occurrence of a failure mode occurs (1–10). The range of occurrence scale is from score 1 (failure is unlikely) to score 10 (failure is very high and inevitable).
- Severity (S) represents the severity of the effect on the final process outcome resulting from the failure mode if it is not detected or corrected. The severity scale is from score 1 (none effect) to score 10 (hazardous without warning).
- Lack of detectability (D) represents the probability that the failure will not be detected. The detectability scale is from score 1 (detection almost certain) to score 10 (absolute uncertainty).

Generally, it will give more importance to the failure modes with higher RPNs. The RPN method has been criticized due to its limitations, among which are:

- The relative weights of risk factors are not taken into account.
- S, O, and D indexes have the same relevance.
- Different sets of O, S, and D scores produce the same value of RPN.
- They are ordinal type of scale (not cardinal). Thus, no arithmetic operation among them is permitted.

To avoid some of the drawbacks mentioned above, some different approaches have been proposed in literature. For instance, Narayanagounder and Gurusami [18] used analysis of variance (ANOVA) to prioritize failure modes or using additional characteristic indexes to define the order to analyze (from a design point of view) the failure mode. However, this proposal are very complex, and it is not simple to apply it in industrial context. For this reason, our study aims to propose a simple application using AHP technique according to human reliability analysis that is explained in the next sections.

3.2. The human reliability analysis (HRA)

The development of human reliability methods occurred over time in three stages [19]: (1) the first stage (1970–1990), known as the *first human reliability method generation*; (2) the second phase (1990–2005), known as *the second human reliability method generation*; and (3) finally, the *third generation*, started in 2005 and still in progress [20, 21].

Among the several approaches that have been proposed and developed for error classification, we remember the Systematic Human Error Reduction and Prediction Approach (*SHERPA*) [22], the Cognitive Reliability Error Analysis Method (*CREAM*) [23], the Human Error Identification in Systems Tool (*HEIST*) and Human Error Assessment and Reduction Technique (*HEART*) [24], and the Human Factors Analysis and Classification System (*HFACS*) [25], among others.

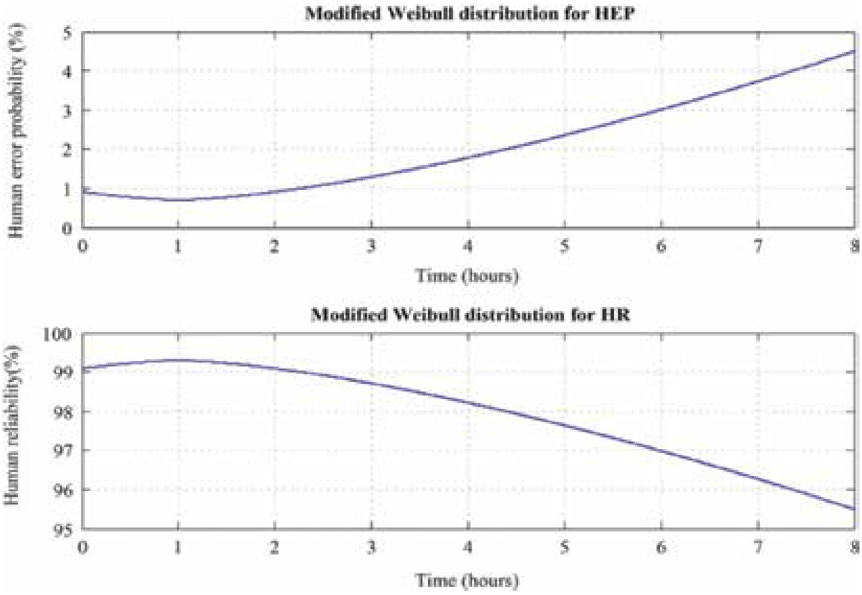


Figure 5. The Weibull function.

The common basis for all techniques is the assessment of the human error probability (HEP) representing the index of human error and its variation according to PSFs. The analysis of human error starts with a definition of HEP. Obviously, the probability of error is a growing function of the time. The HEP value can be calculated as:

$$\boldsymbol{HEP}_{nom} = 1 - \boldsymbol{e}^{-\alpha t^{\beta}} \tag{1}$$

The above formula can be changed in relation to the working hours. Since the operator's reliability is highest in the first hour of work and descending gradually, it gets closer to the eighth hour, and the unreliability decreases with the time (**Figure 5**).

$$\begin{cases} \boldsymbol{HEP}_{nom}\left(\boldsymbol{t}\right) = 1 - k * \boldsymbol{e}^{-\alpha(1-t)^{\beta}} \ \forall t \in \left[0;1\right] \\ \boldsymbol{HEP}_{nom}\left(\boldsymbol{t}\right) = 1 - k * \boldsymbol{e}^{-\alpha(t-1)^{\beta}} \ \forall t \in \left[1;\infty\right] \end{cases} \tag{2}$$

where α is the scale parameter and β is the shape parameter. The β parameter is defined as 1.5 by the scientific literature of the HEART method.

The α parameter is calculated by the following formula:

$$\alpha = \frac{-\ln\left[\frac{k\left(t=8\right)}{k\left(t=1\right)}\right]}{(t-1)^{\beta}} \tag{3}$$

Using (Eq. 2), it is possible to define the trend of reliability associated to specific generic task or human errors, as it is shown in **Table 1**.

#	Human errors/generic task	Limitations of unreliability for operation (%)	k (t = 1)	k (t = 8)
1	Total unfamiliar	0.35–0.97	0.65	0.03
2	Shift or restore system to a new or original state	0.14–0.42	0.86	0.58
3	Complex task	0.12–0.28	0.88	0.72
4	Fairly simple task	0.06–0.13	0.94	0.87
5	Routine highly practiced	0.007–0.045	0.993	0.955
6	Restore or shift a system to original or new state	0.008–0.007	0.992	0.993
7	Completely familiar	0.00008–0.009	0.99992	0.991
8	Respond correctly	0.00000–0.0009	1	0.9991

Table 1. Human errors scale.

One of the most important aspects is the study of factor interactions that increase the probability of error and interdependencies of performance shaping factors (PSFs). Specifically, the context in which humans make errors is analyzed. The PSFs allow the inclusion, in the model, of all the environmental and behavioral factors that influence the decision and actions of man [26]. In particular, the use of PSFs allows to simulate different scenarios. Analytically, the PSFs are modifying the value of the error probability because they introduce external factors that strain and distract the decision maker [27]. The PSF and their values are obtained from the literature, as is shown in **Table 2**. The PSFs considered are (1) *available time, (2) stress/stressor, (3) complexity, (4) experience and training, (5) procedures, (6) ergonomics, (7) fitness for duty, and (8) work processes.*

# PSFs	Levels	Values
1 Available time	Inadequate time	1
	Time available = time required adequate time	10
	Nominal time	1
	Time available > 5 time required (extra time)	0.1
	Time available > 50 time required	0.01
2 Stress	Extreme	5
	High	2
	Nominal	1
3 Complexity	Highly complex	5
	Moderately complex	2
	Nominal	1
4 Experience/training	Low	3
	Nominal	1
	High	0.5
5 Procedures	Not available	50
	Incomplete	20
	Available, but poor	5
	Nominal	1
6 Ergonomics	Missing	50
	Poor	10
	Nominal	1
	good	0.5
7 Fitness for duty	Unfit	1
	Degraded fitness	5
	Nominal	1
8 Work processes	Nominal	1
	Good	0.5

Table 2. PSFs scale.

It is important to note that four main sources of deficiencies can be identified in current HRA methods:

- No empirical data for model development and validation
- Lack of inclusion of human cognition
- Large variability in implementation
- Heavy reliance on expert judgment in selecting PSFs and the use of these PSFs to obtain the HEP in human reliability analysis

The limitations characterizing the FMEA and HRA methods are the motivation under our study and provide the reason to integrate them with AHP technique.

3.3. The analytic hierarchy process (AHP)

AHP uses mathematical objectives to process the inescapable, subjective, and personal preferences of an individual or a group making a decision [28]. In the AHP process, firstly, the hierarchy is defined. Secondly, judgments on pairs of elements with respect to a controlling element are expressed to derive ratio scales that are then synthesized throughout the structure used to select the best alternative [29]. The modeling process can be divided into different phases; to provide a better understanding of the main phases, they are described as follows:

1. *Pairwise comparison and relative weight estimation.* Pairwise comparisons of the elements in each level are conducted with respect to their relative importance toward their control criteria. Saaty suggested a scale of 1–9 when comparing two components. For example, a score of 9 represents an extreme importance over another element, while a score of 8 represents an intermediate importance between "very strong importance" and "extreme importance" over another element. The pairwise comparisons can be represented in the form of a matrix. Score 1 represents equal importance of two components, and score 9 represents extreme importance of the component i over the component j.

2. *Priority vector.* After all pairwise comparisons are completed, the priority weight vector (w) is obtained.

3. *Consistency index estimation.* The consistency index (CI) of the derived weights could then be calculated by $CI = (\lambda_{max} - n)/n - 1.$, where λ_{max} is the largest eigenvalue of the judgment matrix A and n is the rank of the matrix. In general, if CI is less than 0.10, the satisfaction of the judgments may be derived.

4. Research framework: Human reliability model based on AHP

In this section, a human reliability model is proposed to analyze the human reliability in emergency conditions, based on failure modes and effects analysis. Here, below is a brief description of the phases and steps characterizing the model.

4.1. The rationale

As reported in the previous sections, a quantitative method was developed to prioritize failure modes and human errors using AHP technique. The logic model is depicted in **Figure 6**. Each model phase is discussed in brief, as follows:

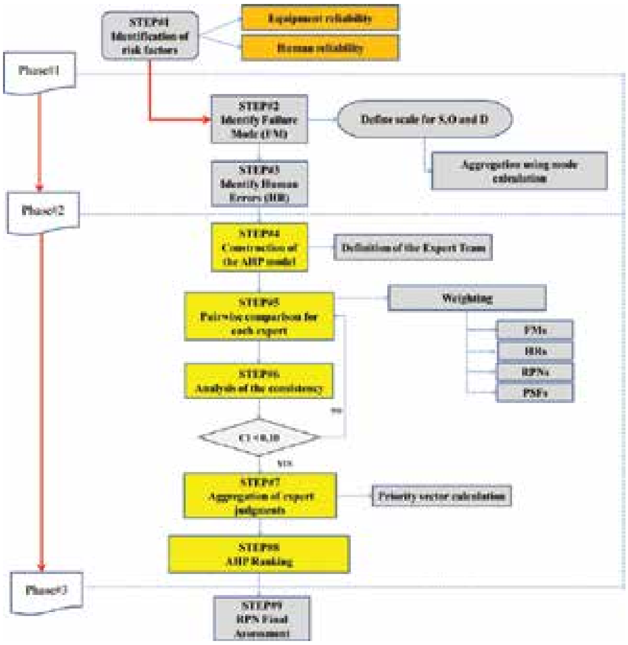


Figure 6. Methodological approach.

Phase #1: Preliminary analysis. The aim of the first phase was to identify scenario under study defining failure modes and human errors characterizing the accident. This phase represents the most critical phase because an incorrect assessment could determine the inappropriateness of the overall model. Three main steps were identified, as follows:

- Step #1: Identify of risk factors
- Step #2: Identify failure modes (FMs)
- Step #3: Identify human errors (HRs)

Phase #2: Multicriteria analysis. One of the crucial elements in measuring the effectiveness of a decision model is to obtain consistent results according to common standards. Thus, the aim of the second phase was to define the AHP model according to prioritize failure modes (FMs) and human errors (HRs), when there is a disagreement in ranking scale for severity, occurrence, detection, human errors, and PSFs. The final purpose of this phase was to define the final score for each criteria and subcriteria according to the AHP model and according to the expert team.

Four main steps were identified, as follows:

- Step #4: Construction of the AHP model
- Step #5: Pairwise comparison for each expert
- Step #6: Analysis of the consistency
- Step #7: Aggregation of expert judgments
- Step #8: Ranking

Phase #3: Synthesis. The aim of the last phase was to define the final assessment for RPN according to the expert team. One step was identified to carry out the phase, as follows:

- Step #9: Final assessment

4.2. Case study: the model validation

To demonstrate the proposed approach, a real-world application is employed in this section. The example is related to an emergency shutdown valve (ESDV) in a petrochemical plant. Of course, reliability is crucial to safety (**Figure 7**). An emergency shutdown valve is an actuated valve designed to stop the flow of a hazardous fluid upon the detection of a dangerous condition, protecting people, equipment, or the environment.

Figure 7. Example of emergency shutdown valve.

4.2.1. Phase #1: preliminary analysis

According to Step #1, the identification of risk factors were carried out. In detail, an expert team, composed by five engineers, was selected to develop the model.

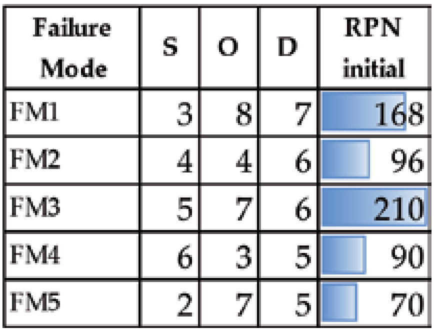
According to Step #2, the main failure modes characterizing the malfunction of an ESDV were identified: valve open (FM1), partially open (FM2), closed (FM3), partially closed (FM4), and wobble (FM5). The main failure causes were identified in broken and corrosion.

Scales for S, O, and D were defined by each expert, as is shown in **Table 3**.

Failure mode	S	O	D	RPN
Expert#1				
FM1	2	4	7	56
FM2	3	5	6	90
FM3	2	6	4	48
FM4	4	7	5	140
FM5	4	7	2	56
Expert#2				
FM1	3	5	7	105
FM2	2	4	8	64
FM3	3	7	6	126
FM4	6	3	8	144
FM5	7	7	1	49
Expert#3				
FM1	1	8	3	24
FM2	4	4	6	96
FM3	5	8	7	280
FM4	3	3	5	45
FM5	2	4	5	40
Expert#4				
FM1	3	8	7	168
FM2	4	2	6	48
FM3	5	7	6	210
FM4	6	3	5	90
FM5	2	4	5	40
Expert#5				
FM1	3	8	7	168
FM2	1	4	4	16
FM3	5	4	6	120
FM4	6	4	2	48
FM5	2	4	5	40

Table 3. Failure mode – for each experts.

The aggregation of values expressed by each experts was made *computing the mode* or in other words identifying the value that appeared most often in the set of data. For instance, if we consider the set data for FM1 related to the severity scale, the most frequent value or the mode value is 3. The final set of data used is shown in **Table 4**.



Failure Mode	S	O	D	RPN initial
FM1	3	8	7	168
FM2	4	4	6	96
FM3	5	7	6	210
FM4	6	3	5	90
FM5	2	7	5	70

Table 4. Calculation of the mode values for the five experts

Frequently, human errors are overlooked. Because the FMEA examines individual faults of system elements taken singly, the combined effects of coexisting failures are not considered. Thus, according to Step #3, the human errors (HR) were identified by the expert team. For the scenario under study, three HRs and three PSFs were selected, as is shown in **Tables 5** and **6**.

#ID	Human errors/generic task	Limitations of unreliability for operation (%)	k (t = 1)	k (t = 8)
2HR1	Shift or restore system to a new or original state	0.14–0.42	0.86	0.58
5HR2	Routine highly practiced	0.007–0.045	0.993	0.955
7HR3	Completely familiar	0.00008–0.009	0.99992	0.991

Table 5. Human errors selection.

# ID	PSFs	Levels	Values
1 PSF1	Available time	Inadequate time	1
		Time available = time required adequate time	10
		Nominal time	1
		Time available > 5 time required (extra time)	0.1
		Time available > 50 time required	0.01
2 PSF2	Stress	Extreme	5
		High	2
		Nominal	1
3 PSF3	Complexity	Highly complex	5
		Moderately complex	2
		Nominal	1

Table 6. PSFs scale.

Scales for PSFs were defined by each expert. In **Table 7**, a synthesis is shown.

Human error	PS1	PS2	PS3
HR1	10	1	1
HR2	1	5	1
HR3	5	1	2

Table 7. PSF scale—experts—synthesis.

4.2.2. Phase #2: AHP model

According to Step #4, the AHP model was built to determine the criteria and subcriteria weights. The model consists of eight criteria and six subcriteria. In **Figure 8**, the AHP model is shown.

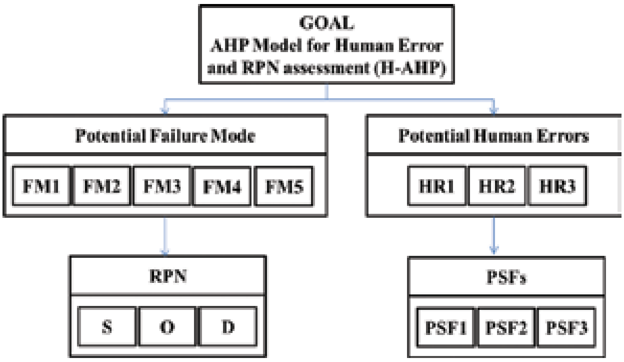


Figure 8. R-AHP model.

	FM1	FM2	FM3	FM4	FM5	Weight
FM1	1	5	5	6	6	0.547
FM2	1/5	1	3	4	4	0.215
FM3	1/5	1/3	1	3	3	0.121
FM4	1/6	1/4	1/3	1	2	0.065
FM5	1/6	1/4	1/3	1/2	1	0.050

Consistency: 0.078 < 0.10.

Table 8. Example of pairwise comparison for potential failure modes criteria.

In this phase, according to Step #5, pairwise comparison matrices were filled out by the expert team to define the weights of criteria and subcriteria. It is worth noting that the same importance was attributed to the main criteria or 50 % potential failure mode and 50 % potential human errors. **Tables 8** and **9** show two examples of pairwise comparison. For each pairwise comparison, according to Step #6, consistency analysis was carried out.

	HR1	HR2	HR3	Weight
HR1	1	1/3	1/3	0.139
HR2	3	1	1/2	0.332
HR3	3	2	1	0.527

Consistency: 0.051 < 0.10.

Table 9. Example of pairwise comparison for potential error criteria.

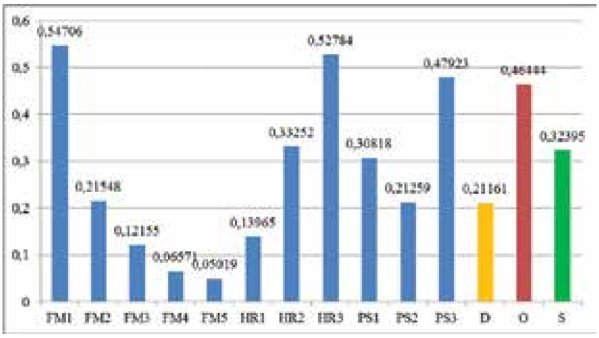


Figure 9. Final weights.

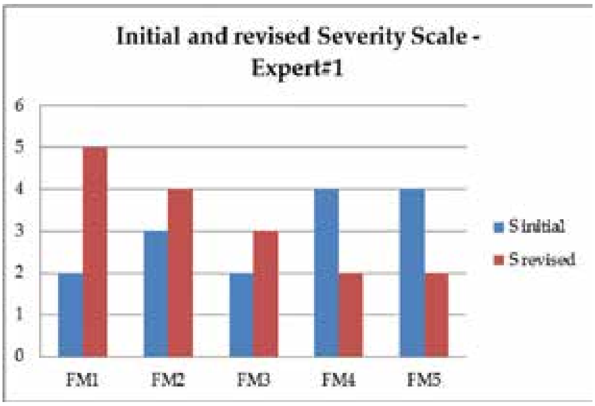


Figure 10. Example of initial and revised severity scale for Expert #1.

The determination of relative weights in AHP model is based on the pairwise comparison conducted with respect to their relative importance toward their control criterion. In detail, evaluation expressed in **Tables 4–7** was used. Furthermore, Saaty's semantic scale was used for the comparison.

Failure mode	S	O	D	RPN revised
Expert #1				
FM1	5	7	3	105
FM2	4	5	4	80
FM3	3	5	4	60
FM4	2	5	4	40
FM5	2	5	2	20
Expert #2				
FM1	4	5	7	140
FM2	3	6	5	90
FM3	3	6	5	90
FM4	6	3	4	72
FM5	6	7	1	42
Expert #3				
FM1	5	8	3	120
FM2	5	5	4	100
FM3	5	5	4	100
FM4	4	4	3	48
FM5	4	4	3	48
Expert #4				
5	8	3	120	5
4	5	4	80	4
5	7	2	70	5
4	3	2	24	4
2	4	4	32	2
Expert #5				
3	8	5	120	3
5	5	4	100	5
5	4	5	100	5
5	5	2	50	5
2	4	4	32	2

Table 10. Revised failure mode—for each expert.

Furthermore, according to Step #7, the *geometric mean* was used to synthesize the set of judgments given by the expert team.

According to Step #8, the ranking was obtained. The aim of the present step was to define the final score for each criteria and subcriteria according to the AHP model and according to the expert team. One step was identified to carry out the phase, as follows. The scores of these each weighted criteria and subcriteria are shown in **Figure 9**.

Results pointed out that, according to expert judgments, the occurrence is the most important parameter with a score of 46.4 % than the other (severity with a score of 32.4 % and detectability with a score of 21.2 %). Furthermore, the most critical failure mode is FM1 with a score of 54.7 %, the most critical human error is HR3 with a score 52.7 %, and the most important performance shape factor is PS3 with a score of 47.9 %.

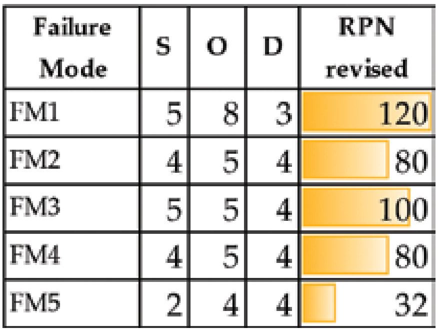
4.2.3. Phase #3: a new approach for prioritizing human errors and failure modes

Phase #3 is a crucial phase in the proposed methodological approach. In fact, it is important to note that, for instance, for Expert #1, FM1 and FM 5 had the same RPN (56) with different ranking values for occurrence, severity, and detection. For determining the most significant failure mode H-RPN, the weights defined through AHP model were used, as is shown in **Table 9**.

In detail, according to the final weights obtained with AHP, each expert expressed a reassessment judgments for S, O, and D scales. **Figure 10** shows an example of revised severity scale for Expert #1.

In a similar way, revised scales for occurrence and detectability were obtained by each expert, as shown in **Table 10**.

The aggregation of values expressed by each expert was made computing the mode, as shown in **Table 11**.



Failure Mode	S	O	D	RPN revised
FM1	5	8	3	120
FM2	4	5	4	80
FM3	5	5	4	100
FM4	4	5	4	80
FM5	2	4	4	32

Table 11. Revised calculation of the mode values of five experts.

Table 12 shows an example of new RPN.

	Severity	Occurrence	Detection	New RPN
Initial	3	8	7	168
Revised	5	8	3	120
Multicriteria RPN = % reduction in RPN = (RPN initial—RPN revised)/RPN initial				29 %

Table 12. Example of calculation of RPN.

Figure 11 shows a comparison between initial and revised RPNs, highlighting the *RPN reduction* for each FM. It is significant to point out that in general **Figure 11** shows, for the specific case study, a reduction of the RPN because usually the expert team have overestimated one parameter. But an *increase of RPN* could happen also.

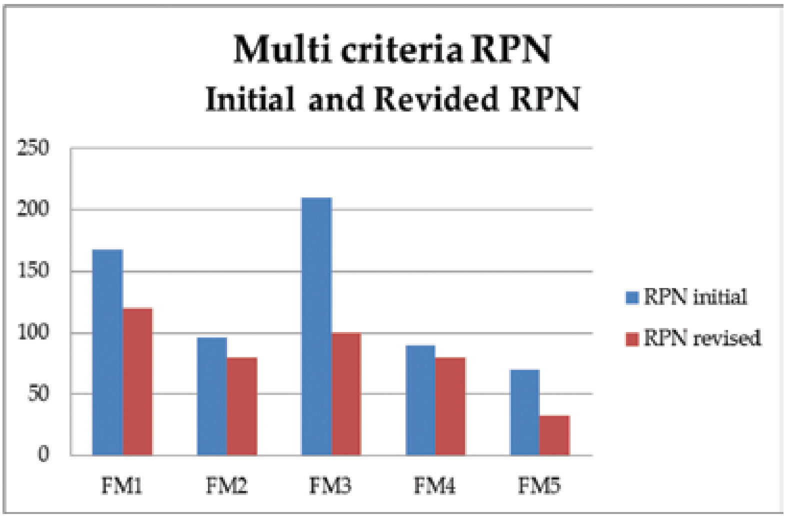


Figure 11. Comparison between initial and revised RPN.

Of course, in our opinion, the above assessment allows to evaluate the RPN more precisely and objectively with respect to the traditional approach.

5. Conclusion

This paper proposes a novel approach to prioritize failure modes taking into account human errors. The final aim was to improve the evaluation of risk priority number integrating human errors in the calculation. The goal was achieved through a multicriteria model, based on AHP. The method allowed us to weigh the failure modes integrating with human errors and to prioritize failure modes. The model can be applied when there is a disagreement in ranking scale for severity, occurrence, and detection. The novelty of the method is because there is no evidence in literature of this kind of approach using AHP. In our opinion, the proposed method ensures several benefits, as detailed follows: (1) it is a generic method that can be applied in several industrial processes; (2) it can be used to identify human errors that can become single points of failure; and (3) it can be used to define potential human errors that are the most critical by revealing the severity and probability of occurrence. Future research will investigate a great number of failure modes and human errors. Furthermore, several scenarios will be taken into account to compare results.

Author details

Fabio De Felice[1], Antonella Petrillo[2*] and Domenico Falcone[3]

*Address all correspondence to: antonella.petrillo@uniparthenope.it

1 University of Cassino and Southern Lazio, Cassino (FR), Italy

2 University of Napoli "Parthenope", Centro Direzionale, Napoli (NA), Italy

3 University of Cassino and Southern Lazio, Cassino (FR), Italy

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Chapter 8

Disaster Risk Assessment Developing a Perceived Comprehensive Disaster Risk Index: The Cases of Three Chilean Cities

Carmen Paz Castro, Juan Pablo Sarmiento and
Claudio Garuti

Additional information is available at the end of the chapter

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Abstract

A significant increase in the impacts caused by extreme events, of both natural and anthropogenic origin, has been observed in recent decades at a global scale. Chile is no exception to this dynamic. Hazards of various origins and their interactions with socioeconomic, urban, and demographic changes, combined with governance issues have led to a significant risk increase. An accurate assessment of this risk is a significantly complex problem and a holistic approach is required. To address this issue, a multi-criteria decision model has been designed, using the analytic hierarchy process (AHP), which includes qualitative and quantitative variables. The model can be adapted to different contexts, generating a comparable metrics (commensurable) for different cities. The three cities analyzed in this study (Iquique, Puerto Montt, and Puerto Varas) show different levels of risks as a result of a synergic and dynamic combination of factors related not only with natural and physical conditions but also particularly with the variables related to social vulnerability and resilience capacity.

Keywords: Disaster Risk Assessment, Comprehensive Disaster Risk Index, AHP, Commensurability, Risk Perception

1. Introduction

In Chile, the study of risks generates special interest as it is one of the countries with the highest seismic activity around the world. Furthermore, it is exposed to hydro-meteorological hazards, volcanic activity, and tsunamis, among others. Recently, the interest for research on risk

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assessment and improvement in managing risk has increased notably after the impacts produced by the February 27, 2010 earthquake followed by tsunami. The disaster which affected great parts of the national territory revealed not only the high exposure of the country to the hazard but also the high vulnerability in its various dimensions. The complexity and relevance of the theme deserve special attention to better understand the factors involved in the risk equation and the ability to face future events in better conditions.

More than a decade ago, Lavell (2003) said that disaster corresponds to the materialization of the pre-existing risks in a society, which involve multiple dimensions. Risks should be identified and evaluated urgently in order to take action, going beyond structural measures aimed at reducing the hazard, addressing aspects related to the reduction of vulnerability and exposure of the population and their assets (Siddayao et al., 2014).

In this sense, new determinants that explain the risk conditions in Chile have been mainly associated with changes in the development model of economic globalization followed in recent decades which have brought immense territorial changes. More recently, the climate change scenario, considered an amplifier of extreme events risk, has generated a need for new mitigation and adaptation strategies geared toward an increase in the resilience of the population living in specific territories.

In this context, the research questions that have been raised in this study relate to the issues described by Wilches Chaux (1993) about how risks arise, grow, and accumulate in a particular context. Later, a comprehensive multi-sectoral approach was introduced to improve disaster planning and build more resilient communities (Folke et al., 2002; Walker et al., 2002 in Henly-Shepard et al., 2015:110). Our research emphasizes the need to examine the interactions of the natural and anthropogenic phenomena which constitute the risk in a study area, and the analysis of the dynamics and trends in the construction of risk.

Our study methods are based on the analysis of data from previous research of the authors, the characteristics of the natural physical system in which the community is located, the perspective of evaluation processes that can become threatening, and the population vulnerability and resilience. Risk assessment, the main objective of this research, was based on the analysis of the three variables: hazard (H), vulnerability, and exposure (E). It was performed by applying multi-models and using the analytic hierarchy process (AHP) method (Saaty, 1980). The results allowed the definition of risk areas hierarchy in the three cities considered: Iquique, Puerto Varas, and Puerto Montt. The outcomes of this study will allow, at a later stage, the proposal of areas for protection and occupancy restriction in the territory.

2. Conceptual framework

Progress on the knowledge about social disaster risk construction has positioned the analysis and assessment of the social dimensions as key processes for understanding the underlying risk factors in a territory. These dimensions account for the heterogeneity of a territory expressed in local peculiarities, social perceptions of risk, conditions of vulnerability, and resilience capabilities of the population. A better understanding of the risk drivers requires the identification of social-ecological feedbacks. This is a very challenging issue because of disconnects between social actions and system feedbacks. Feedback mechanisms can be masked through economic distortions, and they may also be deferred in time and space (Berkes et al., 2006; Adger et al., 2009).

The risk is understood as the possibility of suffering losses due to the impact of adverse events such as earthquakes, tsunamis, landslides, and floods. It is related to both the likelihood that an event of specific characteristics occurs and its potential to cause damage which is associated with social and individual considerations as perception (Yamin et al., 2013).

The study of disaster risks has evolved significantly in recent years, having to adapt to new factors and processes that condition them such as the permanent increase in the population's vulnerability, especially in urban areas. As indicated by Kabisch et al., (2011), the risk is increased by factors such as new demographic trends and regional economic developments, which implies the need to study various territorial realities to define underlying causes of general and particular risks, seeking for a comprehensive understanding of the problem.

Earlier methodologies focused on the detection and mapping of natural hazard areas, and on handling emergencies, topics that continue to be relevant and in which significant progress has been made by the various disciplines involved. In this regard, Martinez (2009) notes that natural phenomena (of geological, geo-morphological, and hydro-climatic origin) represent complex subsystems, and become hazards in the presence of humans. The interactions between hazards and populations are under constant change, generating indeterminable possibilities that are manifested in determined levels of risk.

Currently, the need to incorporate the analysis of social vulnerability and exposure in risk assessment is also recognized, advancing a preventive approach that considers the different dimensions of this problem. This is consistent with Olcina's (2008) view that the risk analysis method has evolved from the detailed study of the natural hazard to the vulnerability assessment that those hazards imply and society's response capacity toward the effects of the phenomena of extraordinary range. Gellert (2012) highlights the role of social sciences that has helped address the problem in a more systemic and holistic manner, where a potentially dangerous natural phenomenon can become a hazard in the presence of vulnerable human groups. Actually, vulnerability is understood as a condition, encompassing characteristics of exposure, susceptibility, and coping capacity, shaped by dynamic historical processes, political economy, and power relations, rather than as a direct outcome of a perturbation or stress (Blaikie et al., 1994; Eakin and Luers, 2006 in Miller et al., 2010).

This factor is directly associated with the conditions of social, economic, and environmental fragility (Cardona, 2001), and with the development conditions (Cuny, 1983). These conditions are also defined as prevalent or inherent vulnerability, that is, the conditions under which a society is found when facing an extreme event, and on them depend in an important manner, the level of impact and their differential expression in a territory (Castro-Correa, 2014). According to Cutter et al., (2008), the potential risk is attenuated or increased by a geographic filter (site characteristics), as well as the social network that faces the event. This social network could have community experience in previous events, which can be seen as its capacity to respond, cope, recover, and adapt to adverse events, abilities which are, at the same time, influenced by economic, demographic, and housing characteristics.

Chardon (2002) describes three main problems referring to the risk in Latin American cities. The first relates to the difficulty of avoiding natural hazards (e.g., the case of earthquakes). Then, there is the scope and expansion mode of the urban phenomenon that normally increases risk and, lastly, the absence of the control of the urbanization process (e.g., land use, zoning, and building regulations).

However, individuals and social groups present vulnerabilities and capacities that increase or decrease resilience. The vulnerability includes the susceptibility of people and their livelihoods to suffer harm when facing a hazard, while resilience refers to the capacity of the same subjects to absorb changes and return to their original state (Mayunga, 2007), their ability to anticipate changes, and learn from the experience (Dovers & Handmer, 1992; Folke, 2006; Matyas & Pelling, 2012).

Recent discussions on the relationship between vulnerability and resilience have concluded that these concepts can no longer be analyzed in opposite ways; their analysis must strengthen areas of convergence and synergy between the two, depending on the complexity constituted by the study of socio-territorial systems (Miller et al., 2010). Resilience is not the opposite of vulnerability; the concepts are functionally interrelated. While vulnerability measures the susceptibility of a family group or community to a disturbance, resilience explores the abilities of families and communities to resist and recover from an impact. At the same time, both concepts have attributes that simultaneously manifest and affect the territory (Paton, 2000; Manyena, 2006).

The assessment of risk factors associated with a disaster allows us to identify interventions to improve territorial planning and contribute to increased security and welfare (Wachinger, G and Renn, O, 2010).

2.1. Assessing complex problems: features and advances in multi-criteria modeling methods

According to Yamin et al., (2013), risk assessment should include surveillance and monitoring of hazardous phenomena, along with studies of maps and models of hazard and exposure, to assess the vulnerability of the exposed components. The authors suggest that the difficulties to find adequate risk measurement models in objective terms has serious consequences, as it limits the decision-making process from the perspective of physical planning and the reduction and transfer of risk.

The incorporation of social values in risk assessment requires methods to measure the differences among entities such as money, environmental quality, health, and happiness. There is a broad agreement on the relevance of social aspects in the construction of risk; however, it is at the level of measurement where the challenge remains, because it is difficult to assess the various dimensions of vulnerability and its multi-faceted and dynamic nature (Birkmann and Fernando, 2008). However, the widespread incorporation and use of social scales and theory of measurement has not been incorporated. To address this problem, Professor Thomas L.

Saaty, Ph.D. in mathematics from Yale University, created a mathematical model called AHP in the late 1970s, an effective way to define measures for such elements and use them in the decision-making processes.

The AHP allows identification of the best alternative according to the needs and resources allocated. It acts as a scientific tool to address issues that are difficult to quantify, but nevertheless require a unit of measurement. AHP allows working with several scenarios at the same time with the ability to prioritize economic, environmental, cultural, and political goals. Moreover, it can be used with simultaneous participation of different groups with several objectives, criteria, and alternatives. Its use helps the working group to reach consensus between the interests of different stakeholders or power groups (Saaty & Peniwati, 2008).

The above ideas have been gradually validating themselves (Whitaker, 2007) and incorporating other application areas including the location of power facilities (Marinoni & Hoppe, 2006), planning of investment portfolios (Vaidya & Kumar, 2006), research technologies under uncertainty, territorial planning (Garuti & Castro, 2011; FAO, 1993), assessment of ***smart cities*** (Lombardi, 2012), local development strategies (Silva, 2003), land use and zoning (Siddayao et al. 2014), diagnostic assistance (Maruthur et al, 2014.), shiftwork prioritization (Garuti & Sandoval, 2006), measurements in weighted environments (Garuti, 2012), and decision-making in complex scenarios (Garuti & Escudey, 2005), among others.

The AHP methodology fits well to address problems where the variables involved are of different nature (economic, political, social, cultural, or environmental) and generally difficult to measure. The AHP methodology corresponds to a metric where there is none, or if there is, is not representative or shared unanimously by the decision makers. In fact, this methodology, is with the highest application in the world, has witnessed the fastest growth among the known multi-criteria methodologies (Wallenius et al., 2008).

The theoretical underpinnings of AHP are: (1) the theory of measurement, (2) the graph theory, (3) the sum of Cesaro, (4) the Perron-Frobenius theorem, (5) the theory of disturbances and equilibrium states. AHP also originates from psychological elements and is of biological character: (6) the processes of stimulus-response, and (7) the human capacity for interpretation and transmission of this information on the intensity and amount of electrical discharges of neurons.

The first five points are associated with the theory required to build a model of dominance intensity measurement, also known as ***order topology***, where processes of type are to be determined. For example, if AdB (A dominates B), CdB, and CdA, what is the preference relation between them? Here, it is worth recalling the Arrow's Impossibility Theorem, which says: "In an arrangement of dominances as the one indicated there can be no possibility of complete order."[1] However, it has been demonstrated that this proposition is incomplete (Saaty, 2001); (Saaty, 2006); (Saaty & Peniwati, 2008); (Garuti, 2012), as it supposed—as implicit hypothesis—that such dominances not be taken as cardinal values. That is to say, it is not

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[1] Complete order, refers to respecting the five natural properties of ordering set by Arrow).

possible to construct dominance cardinal intensities among the elements, which corresponds to an incorrect hypothesis, including the social aggregation of preferences.

The pursuit of these dominance intensities is associated with the first five points described. From this theoretical basis comes one of the most remarkable results of this method, and that corresponds to identify the vector itself as a reciprocal positive matrix (vector representing the final equilibrium state of a non-consistent or disturbed preference matrix), directly related to the intensities of preference or dominance. This allows associating a cardinal preferences vector to the preferences or dominance judgments initially issued by all decision makers present. On the other hand, the last two points (6 and 7) mentioned above are related to the law of stimuli perception, discovered by the psychologists Weber and Fechner in the nineteenth century. The basic principle of cognitive psychology, which explains stimuli perception, states: "If a stimulus grows in geometric progression, the perception will evolve in arithmetic progression." The principle delivers results in reason or ratio between stimuli as the basis of a fundamental scale (a logarithmic progression).

Thus, these two points (6 and 7) correspond to the construction of a fundamental scale (absolute ratio scale), representing the capabilities and limitations of human beings, and at the same time, respecting the Weber-Fechner law as a proportional cardinal type, that is, it allows the four arithmetic operations within it. All these scale properties are within Saaty's fundamental scale which ranges from 1 to 9, where the value 1 represents the comparison of two equally important elements (A = B), also called neutral value. The value 9 represents the state when one element is extremely important in comparison with the other (A = 9B). More details about this topic can be found in Saaty's book "Decision Making for Leaders".

The AHP theory and its metrics are very useful for complex problems such as risk assessment, where both quantitative and qualitative diverse variables interact synergistically, that must be synthesized to obtain, as in this case, a certain level of risk. These models also allow the analysis of sensitivity of results that can simulate future scenarios and the trends of risk and its components to evaluate decision alternatives.

In this sense, the **objective** of this paper is to conduct a risk assessment of three Chilean cities that have experienced strong growth in recent decades and which present different economic bases and geographical locations. This approach allows identification of the underlying risk factors that illustrate the process of disaster risk construction in intermediate Chilean cities.

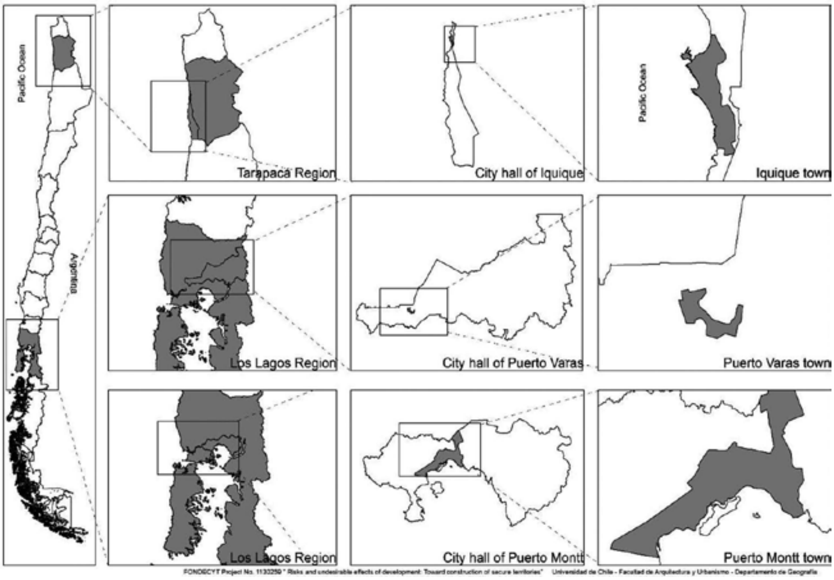
2.2. Working hypothesis

The hypothesis guiding this research emphasizes the importance of the social dimension in shaping risk. Risk increase is mainly related to urban sprawl and the significant weakness in land use planning, which have resulted in an increase in population exposure to natural hazards. At the same time, some risks can be accentuated by the manifestation of climate change and climate variability.

2.3. Study area

The three cities selected as study areas (**Figure 1**) have experienced significant spatial change and relevant urban modifications, processes which are explained by the development of their production bases: (1) Iquique (20°13.00′S–70°10′00′W), capital of the Tarapacá Region, free trade city port zone, with great expansion of tourism in the coastal zone, vulnerable to earthquake and tsunami hazards; (2) Puerto Montt (41°28′00′S–72°56′00′W), capital of Los Lagos Region, port and fishing city; and (3) Puerto Varas (41°19′00″–72°50′00′W) of great tourist expansion and satellite town of Puerto Montt. Both Puerto Montt and Puerto Varas are subject to seismic and volcanic hazards.

The three cities selected are prone to hazards of low frequency but high magnitude, in addition to meteorological hazards characterized by high frequency and low magnitude, especially in the south.



FONDECYT Project No. 1130259 " Risks and undesirable effects of development: Toward construction of secure territories" Universidad de Chile - Facultad de Arquitectura y Urbanismo - Departamento de Geografía

Figure 1. Area of study: Location of Iquique, Puerto Montt, and Puerto Varas cities.

3. Methodology

The methodology for this study is a multi-model approach with four models, each one based in the AHP (Saaty, 1980, 1996), with the goal of assessing disaster risk in a holistic view. This method uses hard data and expert opinion, and provides its own evaluations (based on their knowledge and experience) to obtain the relative weights of the criteria. Through a mathematical process known as hierarchy superposition, the model obtains the value for each alternative using a rating scale (absolute measurement (AM)). The alternatives correspond to the city blocks,[2] and the values correspond to the level of hazard, exposure, and vulnerability.

The process described above allowed us to build a comprehensive index for disaster risk (Disaster Risk Index (DRI)) at block level with four different AHP models (hazards, exposure, prevailing social vulnerability (PSV), and subjective resilience (SR)).

The four models were applied to the three Chilean cities: Iquique (located in the north of Chile), Puerto Montt, and Puerto Varas (both located in the South of Chile). The analysis of the cities was performed at block level, ranking them according to the level of risk, considering the hazards (hazards and exposure), and the social dimension (vulnerability and resilience). This method allowed the study of the functional interactions between the disaster risk components (hazard and social dimension) and its overall impact on the system. The recurring spatial patterns of risk in the study area were evaluated through this multi-model scheme in order to determine the factors that explain the increase of fragility.

The assessment based on the DRI is the result of four evaluation models, namely:

H: Hazard (in negative terms)

E: Exposure (in negative terms)

PSV: Prevailing social vulnerability (in negative terms)

SR: Subjective resilience (in positive terms and acting as a general modulator as an indicator of resilience).

When these four elements are present in a specific order of magnitude, we face a possible disaster.

The outcomes of the four models are synthesized into one to reveal the final value of disaster risk. The values obtained from the four models (which belong to absolute ratio scale) are combined in a way that is mathematically correct. Accordingly, the values of each model have to be commensurate with the values of each of the other models considered.

To accomplish that, the system is divided into two parts or associated functions intrinsically related: H (for hazard) and E (for exposure) on the one hand, and PSV (for PSV) on the other. First, we need to commensurate H with E, by weighting the importance of H and E with the parameters of weight "h" and"e", using "hH+eE". Then, weighted sum of both parts (hazard and exposure from one side with vulnerability from the other) is calculated as: α_1 (hH + eE + HE) + α_2 (PSV). With: α_1: the importance of hazard and exposure, and α_2: the importance of the PSV. Of course, h + e = 1.0 and $\alpha_1 + \alpha_2 = 1.0$. Then, a modulation by (1-SR) over the result of both parts is performed.

It is important to note that SR operates in positive terms, it signifies a value for "capacity of self-protection" or "existing resilience" in the population considered in the study.

Thus, the final expression for DRI is presented as:

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[2] A block is an urban space built or intended for building, bounded by streets on all sides.

$$DRI = \left\{ \alpha_1 \left(hH + eE + H * E \right) + \alpha_2 \left(PSV \right) \right\} * \left\{ 1 - SR \right\} \tag{1}$$

It should be noted that the values of the weights: h, e, α_1, α_2 depend on each situation (of the case study).

The weights (h, e) and (α_1, α_2) were obtained using expert opinion, comparing first the importance of H with E, then the importance of pair (H, E) with PSV. This comparison has to be performed for each location. Also, h, e, α_1, and α_2 represent the values that allow us to add the different absolute scales of measurement involved in EQ1 (hazard and exposure represented by H and E, and social vulnerability represented by PSV).

> *Note: The theoretical case of "SR" = 1 (100% capacity for self-protection or resilience), then DRI = 0, (no risk of disaster), irrespective of the values of hazard or exposure.*

In parallel, theoretical thresholds were calculated for each model and then combined using EQ1, giving an evaluative threshold for a general qualification. The levels to compare the different output values obtained for DRI are: high risk of disaster, medium-high risk, medium-low risk, and low risk of disaster. Each level with a threshold number is built from the local scales of measurement of each model (H, E, PSV, SR) and synthesized using EQ1.

The weighting values of H and E (pair-comparing hazard with exposure) is: h= e= 0.5. This means that hazard and exposure are equally important in the three cities or cases of study.

The weighting values of hazard and exposure with respect to PSV for the three cities are:

City of Iquique: The weighting value for hazard and exposure is 67% and PSV is 33%. This implies that one unit of H and E is twice more important than one unit of PSV.

City of Puerto Montt and city of Puerto Varas: The weighting value for hazard and exposure is 58% and PSV is 42%. This implies that one unit of H and E is 1.38 times more important than one unit of PSV.

A complete explanation of these values (the weights of the models for each city) is given later in "Degree of consistency of decision-makers in comparisons."

3.1. Model criteria

To build the comprehensive DRI, there was a need for adjustments to address the specificities of the hazards present in each city. These adjustments were made in the hazard model, as Iquique (city in the north of Chile) faces substantially different hazards from those found in the cities of Puerto Montt and Puerto Varas (cities located in the south of Chile), as will be explained later in this chapter.

3.2. Criteria and subcriteria weights

To determine the weights of each variable used, an expert enquiry was made with specialists in the area (listed below). This was performed through a pair-comparison matrix taking its principal eigenvector as the representative of their priorities (which correspond to their metric of preferences), accompanied with the consistency index of their comparisons (which correspond to the consistency of that metric).

The four models obtained represent the consensus of these opinions, which were statistically acceptable with a high level of consistency for the four constructed models (exposure, hazard, prevalent social vulnerability, and SR). The consistency, according to this method, indicates that it is a possible measure to be used numerically and its compliance can work numerically with these figures (this rule constitutes a stable measure). The index measures the degree of coherence among the answers of each actor and experts involved in the pair-comparison process.

3.3. Degree of consistency of decision makers' comparisons

Once sorted and entered, the answers in the different models, the level of consistency of answers was checked, grouped by pair-wise comparison matrix, using the formula by Saaty (1980) for consistency:

$$\begin{aligned} CI &= \left[\left(\lambda_{max} - n\right) / \left(n - 1\right)\right] \\ RC &= CI / RI < 0.1\left(10\%\right) \end{aligned} \tag{2}$$

Where:

CI = consistency index

$\lambda_{\max}$ = highest eigenvalue in comparison matrix (associated with the principal eigenvector)

n = dimension of the comparison matrix

RI = random index of consistency (Saaty, 1980)

RC = ratio of consistency

In cases where the consistency ratio exceeds numeral 0.1 (10%), the response is discarded.

Note: In general, 10% is the value corresponding to the threshold of acceptability of inconsistency. But, if the pair-comparison matrix is a 3 × 3 matrix, the numeral should not exceed 5%.

Overall results for consistency:

Hazard model (H): 0% = 100% consistency

Exposure model (E): 2% = 98% consistency

Subjective resilience model (SR): 3% = 97% consistency

Non-subjective prevalent vulnerability model (PSV): 3% = 97% consistency

Expert judgments provide a high level of confidence to the construction of models and their interpretation (completeness and accuracy in assessing the importance(s)). Using the judgments, arranged in pair-wise comparison matrix for each level of the hierarchy, and the mathematical operator eigenvector, the AHP methodology delivery priorities are outlined in the four models: SR, prevalent social vulnerability, hazard, and exposure.

The variable for SR was obtained through surveys on social perception of a representative sample of the resident population in each of the cities. However, as the surveys do not allow generalization of the results to the entire block, they cannot be represented spatially as the other variables of vulnerability. Thus, our study does not produce SR mapping. The value of SR in our study represents the city as a whole.[3]

SR is of great importance for the development of prevention plans that promote the strengthening of a self-care culture and social participation in risk management in the community, where citizens feel responsible for reducing susceptibility conditions and taking action together with the responsible institutions.

The National Risk Reduction Platform created in Chile by the National Emergency Office of the Ministry of Inner Affairs in May 2013 also targets this objective, recognizing the role of the population in disaster risk management. The Platform is aware that the downward trend observed in the loss of human life in recent extreme events experienced in Chile is mainly due to people's actions that have incorporated the experience of past generations for their protection.

SR measured through perception is a continually changing variable, influenced by factors such as age, knowledge, experience, gender, education level, and cultural factors.

For this reason, SR has been incorporated into the model as a modulator element of the existing level of risk. The values for hazard, exposure and PSV have been weighted by the value calculated for SR.

The H and E modules are considered the most important dimensions in the shaping of the overall risk indicator. In the case of Iquique, 67% of relevance is assigned for H and E due to the geographical location of the city in an area subject to particularly dangerous phenomena such as earthquakes and tsunamis. However, the scale or measurement model of the PSV was assigned 33% importance. This result could be explained by the fact that most of the vulnerable populations are mainly located outside the area of higher risk.

In the case of Puerto Montt and Puerto Varas, even though H and E continue to be the most relevant dimensions, the weighting assigned to them is lower (58%) as tsunami is not a significant hazard in this geographical zone. Vulnerability is assigned 42% weight, an important problem in the cities with many socially fragile zones, usually associated with old informal settlements consolidated within urban areas.

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[3] The subjective resilience that measures the social risk perception is a dynamic condition which depends upon many factors. For this reason, and due to the fact that in this case it is a result of a survey applied to a percentage of the population, it was measured through an index that represents the city's population generalized perception in a specific determined time, and which allows to establish relationships based upon the other criteria considered to assess risk. Thus, a sensibility analysis has been generated to assess the prevalence of this dimension over the final result of the DRI.

The exposure variable (E) is weighted by the hazard, as it does not exist if there is no population or its belongings exposed. Thus, its magnitude depends on the relevance of the phenomena as well as the possible social impact it may have, two components of risk that are closely related.

3.4. Specialists consulted

The specialists consulted for the evaluation were:

- Laura Acquaviva, architect, specialist in disaster recovery processes, PNUD consultancy.
- Fabiola Barrenechea, geographer, Risk Management Department, National Emergency. Office (ONEMI).
- Miguel Contreras, specialist in social geography, Assistant Professor of the Geography Department of Universidad de Chile.
- Consuelo Cornejo, psychologist, Civil Protection Office Head of the National Emergency Office (ONEMI).
- Edilia Jaque, specialist in disasters risk reduction issues, Deputy Dean of the Faculty of Architecture, Urbanism and Geography at the Universidad de Concepción.
- Jorge Ortiz Véliz, Associate Professor for the Geography Department at Universidad de Chile, specialist in urban geography.
- Silvia Quiroga, geographer, consultant in risk management issues at OFDA/USAID, professor at Universidad Nacional de Cuyo.
- Jessica Romero, geographer, evacuation programs area, National Emergency Office (ONEMI).

The four models were adapted from the Castro-Correa doctoral study (2014).

4. Risk models

4.1. Risk modeling of natural hazards in the cities of Iquique, Puerto Montt, and Puerto Varas

To comply with the stated objective, four assessment models were run to deliver a synthetic index (DRI) of disaster risk level of each single city block under study.

4.2. Construction of thresholds

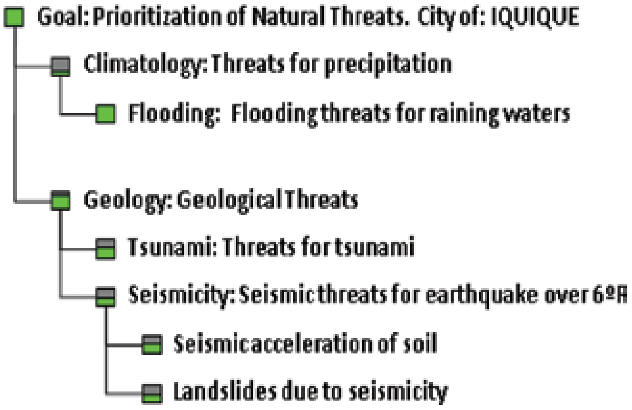
With the configuration of a proportional metric with AM, it was feasible to mathematically construct theoretical thresholds representing the measurement scales of each model. The thresholds were built using the scales of the terminal criteria as information basis, also known as transformation functions, and their corresponding weights. It should be clarified that the assigning of weights to the strategic criteria, as well as to the measurement scales, reflect the national and local realities regarding this subject.

The thresholds help to establish points of reference or classification of each model according to their level of vulnerability to natural hazards. Thus, it can be seen that they do not correspond to ranges of uniform size; on the contrary, they are measures that seek to represent reality in the best possible way.

Next, the four multi-criteria models on the AHP platform (Hazard, Exposure, Social Vulnerability and SR), all in AM mode are presented below. The weighting of the criteria of each model can be seen in brackets to the right of each criterion.

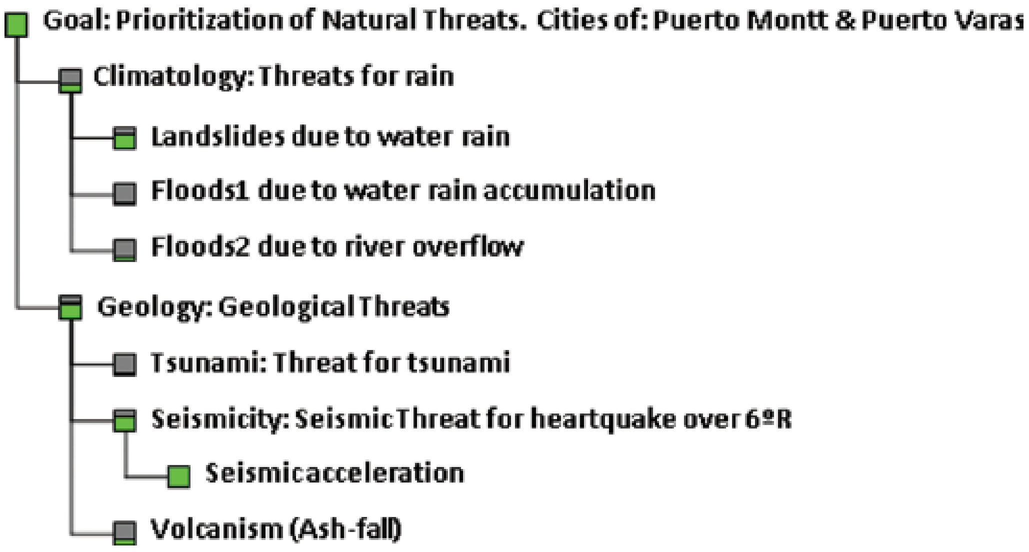
4.3. Hazard models (H)

Two different models were run for the cities located in different geographical locations, as geological positions and morpho-climates influence the existence of certain types of hazards. A model of hazards for Iquique (HI), a city located at a zone corresponding to a coastal desert area, and one for Puerto Montt and Puerto Varas (HP), cities located in the southern rainy and cold region, were defined. Next, the adjustments carried out in each (HI) and (HP) are explained (**Table 1** and **Table 2**).



Climatology	Hazards due to precipitation
Flooding	Flooding hazards due to raining waters
Geology	Geological hazards
Tsunami	Hazards due to tsunami
Seismicity	Sesimic hazards due to earthquakes over six in Richter scale
Seismic acceleration	Soil acceleration
Landslides	Landslides hazards due to seismicity

Table 1. Criteria definition table for the model of hazards in the city of Iquique (HI).



Climatology	Hazards due to precipitation
Floods1	Flooding hazards due to raining waters
Floods2	Flooding hazards due to river overflow
Geology	Geological hazards
Tsunami	Hazards due to Tsunami
Seismicity	Sesimic hazards due to earthquakes over six in magnitude scale
Seismic acceleration	Acceleration of soil
Volcanism	Volcanism hazards due to ash fall

Table 2. Criteria definition table for the model of hazards in the cities of Puerto Montt and Puerto Varas (HP).

4.4. Hazard model for the city of Iquique (HI)

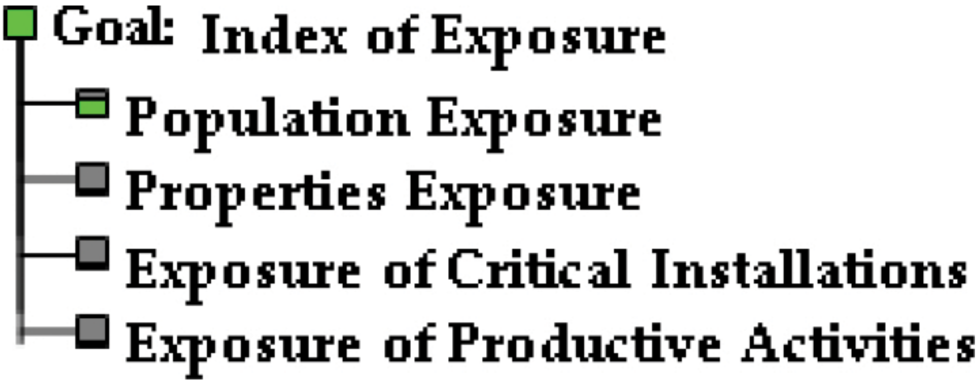
In the model Hazards Iquique (HI), the geological hazards with a weight of 77.8% outweigh the weather hazards (22%) due to the low rainfall experienced in the city. The seriousness of the geological hazards, earthquakes and tsunamis, is the reason for their importance (46.7%) in comparison to all other hazards considered for the city. The model rates the importance of geological hazards at 46.7% in comparison with other hazards, mainly because of the seriousness of earthquakes and tsunamis in Iquique.

4.5. Hazard model for the cities of Puerto Montt and Puerto Varas (HP)

In this case of HP, the geological hazards (67.1%) exceeded the climatic ones (32.9%), but the difference between the two is not as great as in the case of Iquique. The city of Puerto Varas is not located in the coastal zone and Puerto Montt is protected from large tsunamis, so the main geological hazard is the seismic one (44.2%). Another hazard of geological origin, volcanoes, is weighted low (17.6%), as it is only present in the form of ash fall and not lava or lahars (**Table 2**).

4.6. Exposure model for the three cities (E)

The model for E is a fairly simple one and consists of four criteria or variables that allow measuring exposure of people and their livelihoods to the hazards defined in the previous model. The criteria are: Population, Housing, Critical Facilities, and Productive Activities (**Table 3**).

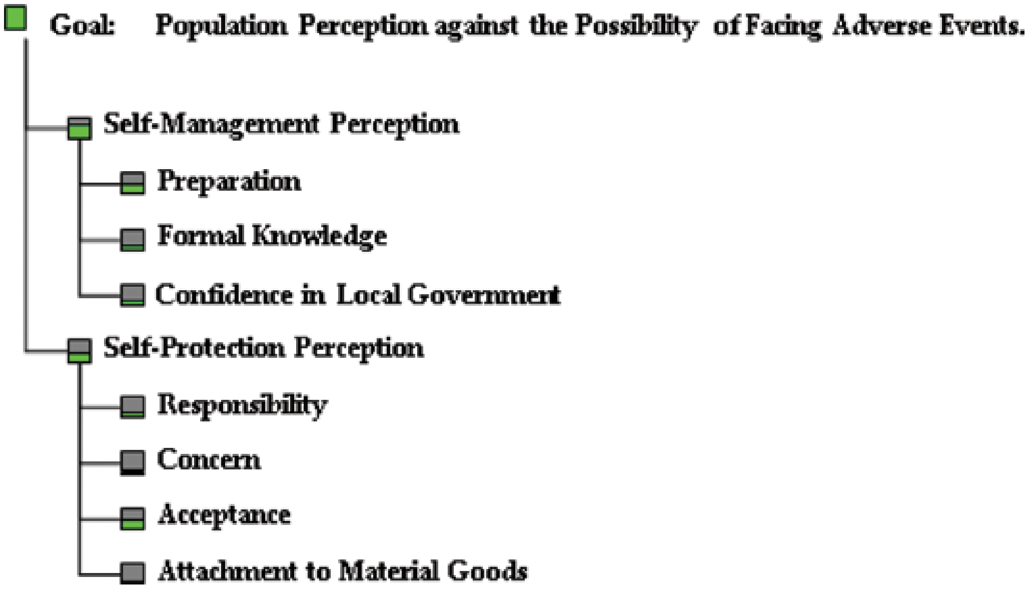


Population exposure	Degree of exposure of people to the natural hazards (the most important exposure)
Properties exposure	Degree of exposure of properties to the natural hazards
Exposure of critical installations	Degree of exposure of electricity, telephone lines, water pipes, and waste waters installations
Exposure of productive activities	Degree of exposure of the most important productive activities in the city

Table 3. Criteria definition table for the model of exposure (E).

4.7. SR model for the three cities (SR)

The next model measures the population's SR. This corresponds to measuring the perception of the population's possibility of facing adverse events, specifically to evaluate their resilience capabilities. As resilience mitigates risk, the model operates in the opposite direction of risk, which explains the use of SR as (1-SR), a risk modulator, in Eq. (1) (**Table 4**).



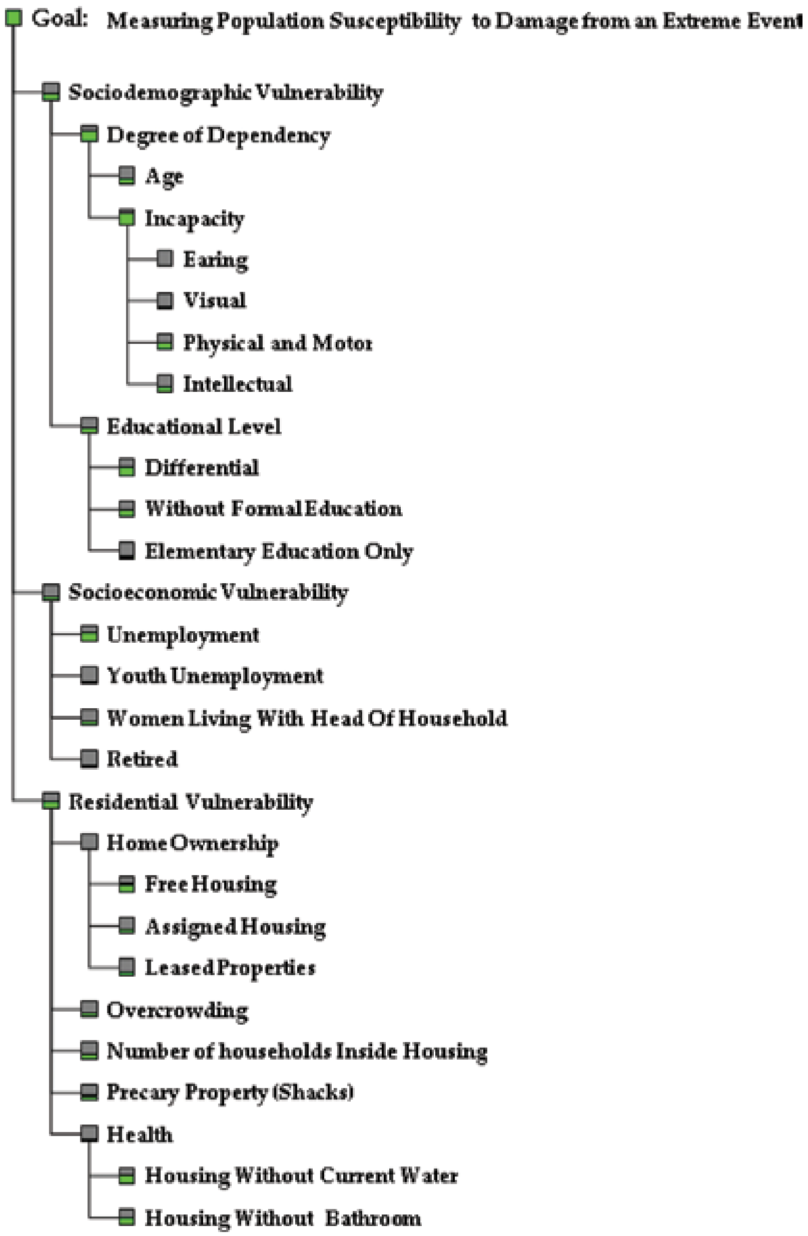
Self-management perception	People's perception about their own preparation, formal knowledge, and confidence in local government to face adverse events
Preparation	Level of preparation of people to face adverse events (perception)
Formal knowledge	Formal knowledge about how to face adverse events
Confidence in local government	Degree of confidence of people in the local authorities
Self-protection perception	People's perception about their own responsibility, concerns, acceptance, and attachment to material goods to face adverse events
Responsibility	Level of responsibility (perception) to face adverse events
Acceptance	Level of acceptance (perception) to face adverse events
Attachment to material goods	Level of attachment to material goods (perception) when facing adverse events

Table 4. Criteria definition table for the model of subjective resilience (SR).

When reviewing the model, it is possible to verify that the two variables or criteria most important to measure the subjective perception of the population are: the level of preparation of the population to face these events (30.2%) and the level of acceptance of the situation (18.1%). Slightly less importance was given to the level of formal knowledge (formal education) (15.1%), which was valued equivalent to the level of confidence that exists for local institutions (15.1%) to face extreme situations.

4.8. Prevalent social vulnerability model for the three cities (PSV)

The model of PSV is the most complex one and is linked to the non-subjective prevailing vulnerability, that is, the vulnerability of the population before the occurrence of an extreme event that responds to the factors identified in the model (**Table 5**).



Socio-demographic vulnerability	Degree of vulnerability due to socio-demographic characteristic of people in the block
Degree of dependency	Measures the degree of dependency in the block
Age	Age of people in the block
Disability	Different types of disability reported: hearing, and visual impairments, physical and intellectual disability
Educational level	Level of formal education (differential, without formal education or elementary only)
Socioeconomic vulnerability	Degree of vulnerability due to socioeconomic characteristics of people in the block, it depends on number of: unemployed people, unemployed youth women acting as head of household, and retired (jubilee) people.
Residential vulnerability	Degree of vulnerability due to the residential precariousness
Home ownership	Vulnerability due to type of ownership: free housing, assigned housing, or leased
Overcrowding	Vulnerability due to overcrowded house
Number of families inside a dwelling	Vulnerability due to more than one family present inside one dwelling
Precarious property	Vulnerability due to precarious level of property (shacks)
Health	Vulnerability due to level of health inside the residence, produced primarily by two issues: housing without current water and housing without bathroom.

Table 5. Criteria definition table for the model of social vulnerability.

The two most important criteria are residential vulnerability (42.3%) and socio-demographic vulnerability (35.9%). On the other hand, the most relevant criteria or measuring indicators within socioeconomic vulnerability is unemployment (12.4%). Within residential vulnerability, it is the substandard housing (12%), the number of families per dwelling (10.3%), and overcrowding (8.2%), whereas in socio-demographic vulnerability, the most relevant criteria include physical-motor disability (9.5%) and intellectual disability (6.2%). These six indicators account for almost 60% of the total weight of the 20 indicators that make this model, demonstrating its importance as factors that explain the PSV.

5. Application of the risk models to the cities of Iquique, Puerto Varas, and Puerto Montt

To apply the metrics of each model on the three cities analyzed, the information of all the criteria or variables considered for each cell[4] or block of the city was analyzed. 1500 cells for

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[4] A cell is the territorial unit selected in the study where the four models are applied and for which DRI is calculated.

the city of Puerto Montt, and 3000 cells for all three cities were assessed. Each cell was assessed in absolute measurement at each terminal criterion or model indicator, using a specific cardinal scale (natural) to the terminal criterion or measurement model indicator. This was done systematically for each cell of each model.

Finally, the four models (H, E, PSV, and SR) were integrated using EQ1 and as a result, we obtained the comprehensive DRI of each cell.

It is important to remember that:

- The sum of the different models (each containing different metrics) is possible because the integration formula considers the weighting values: **h**, **e**, $\boldsymbol{\alpha}_1$ $\boldsymbol{\alpha}_2$ The weighting values "h" and "e" make the measurement units of hazard and exposure comparable. The weighting values $\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$ make the common measurement unit (H-E) commensurable with unit of measurement of PSV. The final outcome is weighted by (1-SR), which is the complement value of SR. Since SR is a positive element in the disaster risk equation (EQ1), it works as a modulator or "shock absorber" of the overall risk in each cell of the city.
- The level or scale of analysis achieved is feasible because the required information is at the block/cell level, which allows a very detailed disaster risk analysis for each city.

5.1. DRI, city of Iquique

The modeling considered the different variables or risk factors for the city of Iquique and applied the DRI index to the block level. The result of this graphical process (**Figure 2**) shows that medium-low risk conditions is dominant in the city, while low-risk areas, mostly near the civic center, are scarce. These results are consistent with the reality of a city that is, like many Chilean cities, exposed to different hazards like earthquakes, tsunamis, and landslides. Moreover, a distinct level of social vulnerability expressed through factors such as the precariousness in housing, overcrowding, poor education, disability, and unemployment, among others, increases the susceptibility to suffering damages and difficulties in recovering from a disaster event.

The Iquique waterfront shows a medium-high level of risk, mainly due to the significant and growing population exposure to tsunamis in this area. Although a medium-high level implies greater danger, the risk becomes somewhat lower when integrated with the hazard modeling and exposure to the PSV. This is justified because the Iquique waterfront is characterized by low PSV, as it is generally inhabited by people of medium-high and high socioeconomic strata. Their economic capabilities allow them to prepare for emergencies and quickly recover post disasters events as seen after the earthquake in 2014. In addition, this population, with a strong support network, demonstrates independence in decision-making, showing management capacity, and resilience which modulates or dampens the hazard and exposure present in the cells of this zone. These results indicate that the process of integration of the four models is not only interesting but also necessary for proper assessment and later qualification of the degree of disaster risk in a specific area.

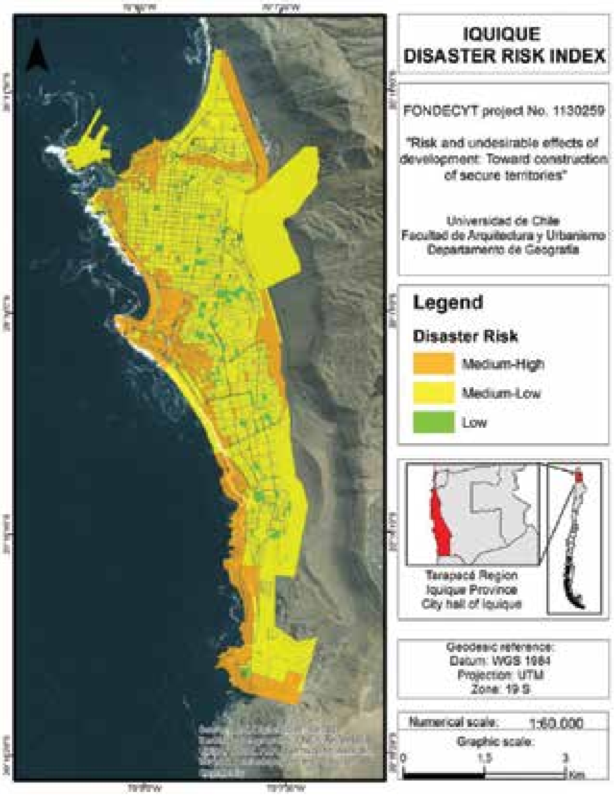

Figure 2. Disaster Risk Index, Iquique City.

The northern coastal area, an industrial region, with a high probability of a tsunami, shows a low-medium risk as it has virtually no residents (E = 0) and thus does not present values of social vulnerability (PSV = 0). However, this result could be questioned as a sizeable number of people work in this area during the day. The model, in the first instance, does not consider this floating working population due to lack of information about them. This could be remedied by performing a sensitivity analysis by incorporating this population and its characteristics, building a scenario where DRI values display the day index situation in the zone's cell.

There are zones with a medium-high risk immediately south of the industrial area with values in the upper limit, that is, a slight deterioration in their condition can move the zones to the category of high or unacceptable risk. This area brings together several negative conditions that maximize each other: the exposure of large populations and critical facilities (health care) to tsunamis, along with vulnerable populations such as a large number of dependent people, people with cognitive disabilities, people with low education level, unemployed people, and a significant number of female as heads of households. This outcome is reflected in the comprehensive risk index at the cell level (as shown in the value of the integrated DRI index).

The classification of cells by risk levels helps the prioritization of risk interventions and resources allocation.

The application of the EQ1 for Iquique is given in **Table 6**.

Alternative	α_1	Hazard (H) (a = 0.5)	Exposure (E) (e = 0.5)	α_2	PSV	SR	DRI(37)
Block 37 (Medium-high)	2/3	0.5243	0.8650	1/3	0.4209	0.2676	**0.6636**
		Medium-High	*High*		*Medium-High*	*Medium-Low*	*Medium-High to High*

Table 6. Applying EQ1 equation to calculate[21] the DRI in block[22] 37 Iquique city.

DRI(37) = [2/3*(0.5*0.5243 + 0.5*0.8650 + 0.5243*0.8650) + 1/3*(.4209)] * [1 - 0.2676] = 0.6636 (Risk medium – high to high).

Notice: Block 37 has a DRI = 0.6636 ≈ 0.6832, is only 2.9% below the limit considered unacceptable (0.6832). Also, the exposure value for this block (0.8650) is far over the specific threshold for exposure (0.6003), this is about 44.1% over the upper limit.

The upper limit (threshold) of DRI calculated for Iquique is 0.6832. Anything above should be considered unacceptable level of risk disaster.

This analysis methodology (working with cardinal numbers) also allows analysis of an average cell or average block, for the city of Iquique. The average cell is representative of the average behavior of the city, as if this were all included in a single cell.

Below is a table with the behavior of the average cell in each model and its final value calculated using Eq. (1) (**Table 7**).

	α1	**Hazard**	**Exposure**	**α2**	**PSV**	**SR**	**DRI**	**Qualification**
Average Cell	2/3	0.1946	0.4563	1/3	0.2299	0.2676	**0.2585**	Medium-low

Table 7. Average block behavior Iquique.

Note: It is important to remember that the values obtained for Iquique DRI have a different rule of measurement than the cities of Puerto Montt and Puerto Varas, (since it has a different Hazard model). Therefore, they are not comparable values. This "non-comparability" also applies for the outcome of the average cell.

5.2. DRI, city of Puerto Varas

The most populated area of Puerto Varas generally presents a low average risk; however, its expansion areas, such as the northwest area of the city, have a (medium-high) risk. The lower-risk area is located in the city center, away from flood or landslide prone areas, and only presents the same risk level as the rest of the city for the hazards of volcanic ash fall and earthquakes. In contrast, some areas near the waterfront in the southern part of the city have very high exposure levels to landslides. The population here, with no formal or only basic education, is highly dependent because of the significant presence of seniors and to a lesser extent, people with hearing impairment.

These factors explain the level of risk in this zone which could be mitigated by infrastructure and territorial planning.

The south of Puerto Varas (an area furthest from the lake at a higher elevation) is associated with high overall risk mainly because of higher social vulnerability along with the high impact, low frequency hazards such as earthquakes and ash fall. The frequently recurring hazards like floods and landslides do not pose significant impacts.

5.3. DRI, Puerto Montt City

The city of Puerto Montt presents a medium-high risk level virtually in its entire urban area (**Figure 4**). Overall, the risk in the city is associated with the escarpments of marine terraces and presence of areas prone to landslides. The landslides have led to the loss of homes, and a high risk for families who inhabit those neighborhoods and have already experienced damage

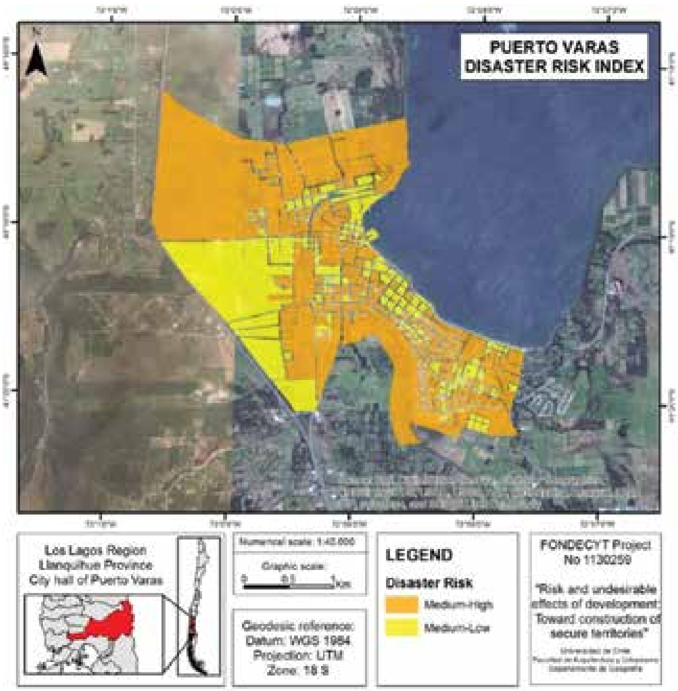

Figure 3. Disaster Risk Index (DRI), Puerto Varas.

and losses in dwellings and livelihoods. The local government is working on regulations to limit the use of areas at risk for residential purposes, and to relocate the existing population, designating this land as environmental protection zones. Another significant hazard is linked to the stream banks that cross through the city and cause flooding during heavy rainfall episodes. These areas are usually occupied by informal settlements characterized by precarious homes and utilities, resulting in medium-high risk levels, very close to unacceptable risks.

The areas of future expansion present a medium-low level of risk, as despite the low exposure of population and infrastructure, these are landslide prone and recurrent floodplain areas which require important investments in mitigation works to assure a sustainable future.

The recent expansion areas situated westward, toward the airport, exhibit the same precarious features mentioned above, and have been urbanized with densely populated plots and very few green areas, normally associated with populations with a high level of social vulnerability. However, there is a potential for risk reduction through improved infrastructure.

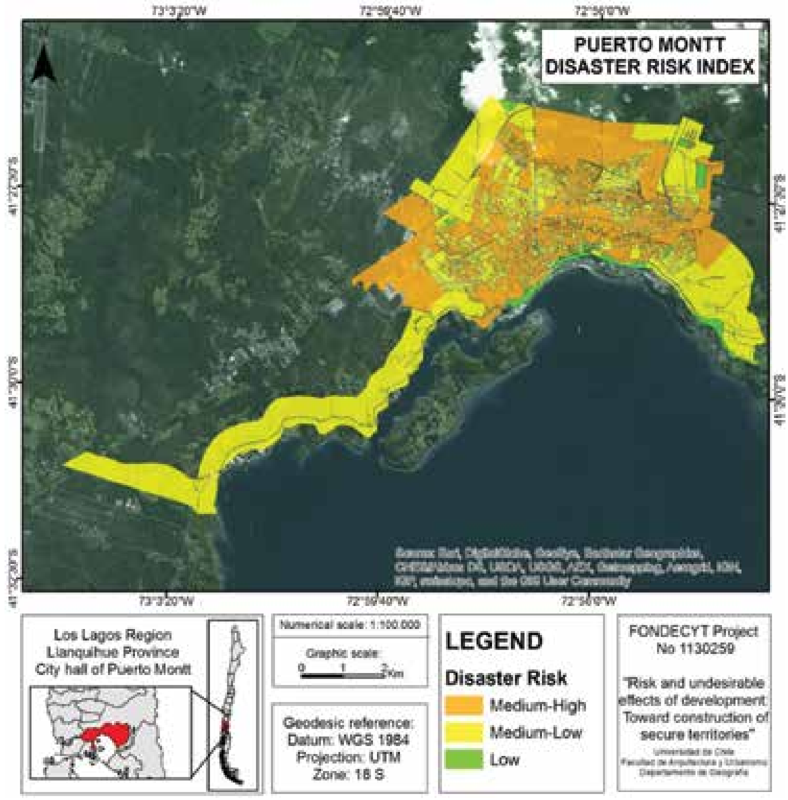

Figure 4. Disaster Risk Index (DRI), Puerto Montt City.

The city in general is exposed to seismic and volcanic hazards (volcanic ashes) and a low risk of tsunami. However, other recurring hazards of hydro-meteorological type affect the inhabitants throughout the year, causing small but cumulative impact resulting in deterioration of their health and quality of life.

5.4. Comparative analysis of the two cities: Puerto Varas and Puerto Montt

It is at the local level that risk is built and consequences of adverse events experienced. Hence our analysis recognizes the significance of conducting risk assessment at the local level, taking into account its main components (hazard, vulnerability, and exposure), to generate a significant differentiation between and within cities.

The assessment at the block level helps to improve decision-making regarding resource allocation for disaster risk reduction, as it identifies the most critical blocks for prioritization of intervention. At the same time, it is also possible to work on prospective risk management, addressing and seeking to avoid the construction of new or increased disaster risks, and defining the best options for the city expansion.

Table 8 shows a comparative analysis between the two cities evaluated with the same model (Puerto Varas and Puerto Montt). An "average" block or representative of each model H, E, PSV, and SR was selected as the arithmetic average of the values of the cells of each city to calculate the representative DRI.

Comparative analysis Of The Average Behavior Puerto Montt V/S Puerto Varas

	$\alpha 1$	Hazards	Exposure	$\alpha 2$	PSV	SR	DRI	Qualification
PuertoVaras	0.580	0.2820	0.4440	0.420	0.2570	0.3230	**0.2648**	Medium-low
Puerto Montt	0.580	0.4362	0.4857	0.420	0.2566	0.5120	**0.2430**	Medium-low
		54.6%	9.5%		0.2%	58.7%	**9.0%**	Differences (%)

Table 8. Comparative analysis of the average behavior: Puerto Montt v/s Puerto Varas.

In analyzing the above table, it can be seen that the perceived DRI Puerto Varas is 9.0% higher than that of Puerto Montt. Even though it seems counterintuitive at first (it is the general perception that Puerto Varas has a lower risk than Puerto Montt), the result is considered reasonable. The hazard in Puerto Montt (0.4362) is rated 55% higher than in Puerto Varas (0.282) but at the same time, the SR in Puerto Montt (0.5120), 59% higher than Puerto Varas (0.3230), compensates for the hazard.

Note that both E as well as PSV are almost the same in both cities (9.5% and 0.2% difference), making the overall difference indecisive.

In an analysis by rating of cell, it can be said that there is only 9% difference in the overall perceived disaster risk between the two cities. Puerto Montt has more cells qualified in medium-high risk than in Puerto Varas, but this is offset by the fact that Puerto Montt has several cells qualified as low risk cells, while Puerto Varas has none.

The perception that Puerto Varas' hazards have less potential impact compared with Puerto Montt holds true. However, a comprehensive risk assessment considering all the variables reveals that the level of overall risk of Puerto Varas is higher, mainly due to social and subjective factors.

6. Conclusions

The result of each model as well as the perceived comprehensive DRI was represented cartographically (**Figures 2–4**), finding spatial patterns in the disaster risk level of the city and its explanatory variables (risk drivers). The DRI showed a clear spatial pattern in the cities—three zones of different risk levels are seen, predominantly medium-high level, in most of the consolidated urban area.

The result is the combination of the four models (hazards, exposure, PSV and SR) that were used for the evaluation of risk at the city block level, according to the weights set, representing the current or actual perceived risk of the cities. This complete model can also be used to build future disaster risk scenarios, using the possible values of the four models as parameters to analyze potential interventions and their ability to reduce risks.

The sensitivity analysis shows a high susceptibility of SR, demonstrating the need to focus efforts on improving the capabilities of self-protection and self-management of the population. Any change in these capabilities is first reflected in the population's perception, and then immediately in the overall disaster risk of the city.

The three cities analyzed have different levels of risk associated with their geographical location and hazards determined by the geological and morpho-climatic context. The risk also responds to social fragility situations such as poverty, lack of education, precarious housing, among others, as well as to the population's lack of capacity for self-development and self-management. These variables, aggravated by exposure of the population and their livelihoods to socio-natural hazards, result in a significant heterogeneity in disaster risk levels among and within the three cities analyzed.

The block-level modeling allows us to acquire detailed information about the factors that contribute to building disaster risk within the cities, informing the decision making process geared to reduce it. The variables considered are dynamic, vary in time and space, and most of them can be mitigated. The modeling of natural hazards can be generalized to different settlements with similar geographic conditions. The social vulnerability and SR variables must be locally analyzed as they present great variations that resulting in distinct disaster risk levels. The relevance of social risk construction and its future trends is acknowledged.

This comprehensive analysis allowed us to objectively measure the comprehensive DRI level of each city. When metrics allowed, we compared the results for the studied cities (Iquique, Puerto Montt and Perto Varas) using four individual models (H, E, PSV, and SR) as well as the comprehensive DRI average. This *holistic* assessment approach can be transferred to other cities, countries, and regions, allowing generic and standardized processes, while respecting unique local features.

Author details

Carmen Paz Castro[1], Juan Pablo Sarmiento[2] and Claudio Garuti[3*]

*Address all correspondence to: claudiogaruti@fulcrum.cl

1 Department of Geography, University of Chile, Santiago, Chile

2 Extreme Events Institute, Florida International University (FIU), Miami, USA

3 Fulcrum Engineering Ltd. (Decision making engineering), Santiago, Chile

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Framework for Optimal Selection Using Meta-Heuristic Approach and AHP Algorithm

Ramo Šendelj and Ivana Ognjanović

Additional information is available at the end of the chapter

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Abstract

Many real-life decisions are focused on selecting the most preferable combination of available options, by satisfying different kinds of preferences and internal or external constraints and requirements. Focusing on the well-known analytical hierarchical process (AHP) method and its extension CS-AHP for capturing different kinds of preferences over two-layered structure (including conditionally defined preferences and preferences about dominant importance), we propose a two-layered framework for identifying stakeholders' decision criteria requirements and employ meta-heuristic algorithms (i.e., genetic algorithms) to optimally make a selection over available options. The proposed formal two-layered framework, called *OptSelectionAHP*, provides the means for optimal selection based on specified different kinds of preferences. The framework has simultaneously proven optimality applied in software engineering domain, for optimal configuration of business process families where stakeholders' preferences are defined over quality characteristics of available services (i.e., QoS attributes). Furthermore, this domain of application is characterized with uncertainty and variability in selection space, which is proven and does not significantly violate the optimality of the proposed framework.

Keywords: AHP, CS-AHP, genetic algorithms, optimal selection, two-layered criteria structure, user preferences

1. Introduction

Many real-life decisions are made by considering and analyzing different kinds of preferences with different impacts on final selection of option among available, with more often optimization problems defined in terms of both hard and soft constraints. The modeling of user

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preferences is a great challenge, as it is difficult to express human opinion in a way that can be easily processed by computers [1]. Researchers in many different fields (such as, economics, risk management, decision theory, social choice theory, operational research, intelligent systems, databases, etc.) studied the representation of preferences, its processing and practical use [2].

Additionally, there is one more demand on allowing automated support for selection of the most preferable combination of available options, with respect to specified preferences and constraints if exist. In order to develop a framework for both, representing and reasoning about different kinds of requirements, the following two issues should be carefully analyzed: (i) comprehensive model for presentation of different kinds of preferences, on which bases develop (ii) the approach for automated selection by optimizing the fitting degree of satisfying specified preferences.

Traditional elicitation methods are typically developed based on pair-wise comparisons, priority groups, networks for decision-making and cumulative ratings [3, 4]. They usually collect independent preferences, under the mutual preference independence (MPI) hypothesis [5], which means that a user's preference for an option is independent of the other options [1]. However, the MPI hypothesis is not always true in practice [6] since people often express conditional preferences as to be more natural to the human way of thinking [1]. This is why well-accepted and widely used analytical hierarchical process (AHP) algorithm proposed by Saaty [7] has been recently extended in order to handle conditionally defined preferences over two-layered hierarchical structure, namely CS-AHP [2].

On the other hand, there is a wide range of different optimization and search techniques that have been used for solving the optimization problems [8]. Classical techniques [such as linear programming (LP)] are often distinguished as straightforward deterministic algorithms which are distinct from meta-heuristic search, such as, hill climbing [9], simulated annealing [10] and genetic algorithms (GAs) [11]. However, these deterministic optimization algorithms are often inapplicable in many real-world problems, because the problems have objectives that cannot be characterized by a set of linear equations [12].

In this chapter, we demonstrate how the selection processes can be automated in a more scalable manner by using AHP (and its extension for handling conditionally defined preferences, CS-AHP) and Genetic Algorithms (GA) for presentation and analyses of different kinds of preferences and solving the problem of the optimal selection over the set of available options. Our framework, called *OptSelectionAHP*, provides the following major benefits to the process of prioritization, decision making and optimal selection:

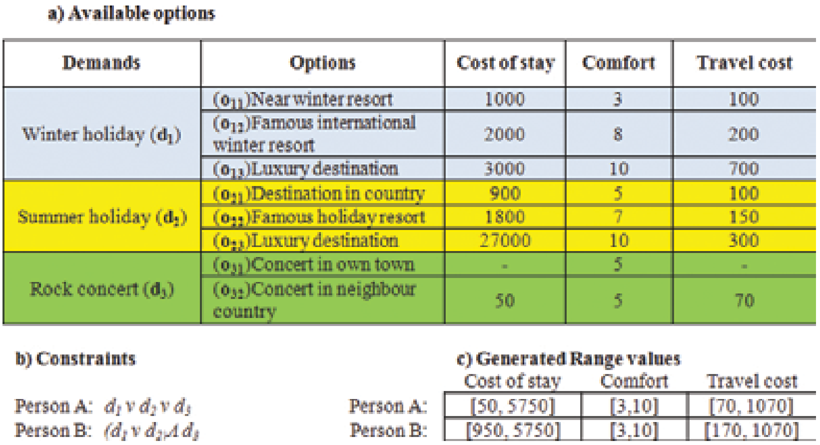
1. It proposes an adoption of CS-AHP method that enables its use for both, capturing and handling different kinds of preferences, as well as definition of optimal selection goals over two-layered selection criteria structure;
2. It proposes the use of genetic algorithms adapted to quality measurements defined on the bases of CS-AHP outputs over created two-layered selection criteria structure;
3. It is able to effectively solve optimal selection problems and its optimality is not affected by the presence of uncertainty and variability in the selection space.

In the rest of the chapter, we first introduce an illustrative example about real-life decision-making scenarios that will be employed throughout the chapter (Section 2). In Section 3, we introduce the whole approach and formalize selection of problem over available options and different kinds of preferences defined over two-layered decision criteria structure (as defined by CS-AHP algorithm). Section 4 formalizes quality measurements induced by CS-AHP outputs, on which bases optimal selection goals are formalized and genetic algorithms adopted for their solving. Finally, Section 5 presents simulation analyses in the area of business process families for the problem of optimal service configuration, but it is clear that our proposed work in this chapter is general enough to be applied to any optimal selection processes and domains. The critical review of methods and frameworks from related work is presented in Section 6 before the chapter is concluded.

2. Running example

In order to exemplify the whole approach, we analyze simplified example of persons planning how to spend annual budget for vacations and other expenditures that are not ordinarily calculated (e.g., concerts of famous rock groups, theaters, sport events, etc.).

Person A is aware of total budget expenditure which cannot be exceeded (e.g., 7000) and interested for at least one of three demands (summer/winter holidays and rock concert). Several options are available for each demand, such as summer holidays can be spent in own country, or in the famous holiday resorts, or at a luxury destination. On the other side, three different options are also available for winter holidays: near winter resort, famous international winter resort and luxury destination. He/She is interested to attend two different concerts: one in own city, and another in the neighbor country (which requires additional traveling costs).



a) Available options

Demands	Options	Cost of stay	Comfort	Travel cost
Winter holiday (d_1)	(o_{11})Near winter resort	1000	3	100
	(o_{12})Famous international winter resort	2000	8	200
	(o_{13})Luxury destination	3000	10	700
Summer holiday (d_2)	(o_{21})Destination in country	900	5	100
	(o_{22})Famous holiday resort	1800	7	150
	(o_{23})Luxury destination	27000	10	300
Rock concert (d_3)	(o_{31})Concert in own town	-	5	-
	(o_{32})Concert in neighbour country	50	5	70

b) Constraints

Person A: $d_1 \vee d_2 \vee d_3$
Person B: $(d_1 \vee d_2) \wedge d_3$

c) Generated Range values

	Cost of stay	Comfort	Travel cost
Person A:	[50, 5750]	[3,10]	[70, 1070]
Person B:	[950, 5750]	[3,10]	[170, 1070]

Figure 1. Illustrative example: (a) available options characterized in accordance with selection criteria, (b) defined constraints and (c) aggregated range values for selection criteria.

Even that money is a key limitation factor, person A would like to be satisfied with fulfillment of other personal attitudes and preferences, such as high comfort, low traveling costs, but in the case of medium comfort, he/she accepts to spend money on higher travel costs.

On the other side, person B could spend between 3000 and 4000 for the same demands (summer and winter holidays and rock concerts), and he/she is not highly interested for comfort, and he/she would like to see as many famous destinations as possible. Also, person B is interested to both have at least one holiday and attend the concert. Available options and values of key decision criteria are illustrated in **Figure 1**.

3. Overview of the approach

In this section, we give an overview of the proposed work, called *OptSelectionAHP*. First, we present selection problem we are analyzing. Then, we describe different types of preferences captured by our approach and how they are modeled and ranked. Later, we introduce the optimal selection problem and define some optimization issues.

3.1. Selection-making criteria and available options

Real-life scenarios often impose availability of different options with different characteristics, while our requirements can be dependent on other internal or external factors. Let us consider general case when the set of decisions about n demands should be made to achieve an objective, while ith (i=1,..,n) decision should be made among m_i alternative solutions (i.e., options). The reality usually imposes different interconnections and dependencies between our demands [e.g., person A is interested at least at one event (summer/winter holidays or concert), etc.], making decision process more complex and sophisticated. With no losing generality, let us assume that uncertainties, interconnections and dependencies among demands can be formalized with q logical statements (in accordance with reference [13]) (see **Figure 1b**).

Stakeholders usually have different selection criteria, e.g., costs of stay, comfort, travel costs, etc., and define own preferences over k criteria. Consistent with the contemporary research on decision-making modeling, we impose that (i) the sets of available options are defined for each decision that should be made and (ii) each available option is annotated in accordance with defined selection criteria (see **Figure 1a**).

Formally, the selection criteria values of available options for demand d is denoted with a vector $Q_d = q_1(d),\ q_2(d),\ \ldots,\ q_k(d)$, where the function $q_i(d)$ determines the values of the ith selection criteria. On the basis of selection criteria values of available options and existing uncertainties, interconnections and dependencies among demands formalized with q logical statements, lower and upper values of each selection criteria can be calculated for the whole model by propagating the values of available options (as formalized in [13]). In our illustrative example, range value for price is [70, 5750] (see **Figure 1c**).

In our approach, the ranges of selection criteria for the whole model $\left(Q_{agg}^{LB}, Q_{agg}^{UB}\right)=\left(Q_1^{LB}, \ldots, Q_k^{LB}, Q_1^{UB}, \ldots, Q_k^{UB}\right)\in R^k x R^k$, will be used for defining stakeholders' preferences as described in the following section. Also, by following the same approach (as in [13]) for each combination of options, aggregated values per each selection criteria can be calculated (i.e., by use of elementary functions: min, max, sum, average, etc., depending on the nature of selection criteria [13]). In case of our running example, selection criteria "costs of stay" and "travel costs" should be aggregated by summing values, while aggregation of selection criterion "comfort" will be performed by calculating average value.

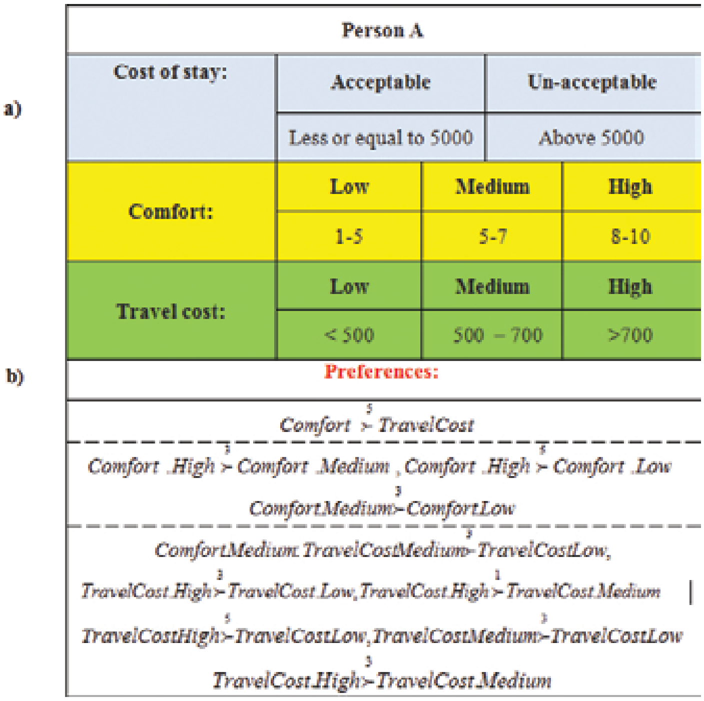
3.2. Different kinds of users' preferences

Presentation of selection-making criteria that will be used throughout this chapter is focused on *hierarchical structure of concerns and qualifier tags* [14]. Even the structure is two-layered with simple practical use, it mostly corresponds to preferences in human thinking, since experimental results in reference [15] showed that it is possible to infer all ratings from a few rules if a user is given the freedom in defining the structure, thus lessening users' workload.

The set of concerns $C=\{C_1, \ldots, C_k\}$, adopted from the Preview framework [16], is considered to be any set of selection criteria that is of interest to the user, such as costs of stay, comfort, travel costs. The set of qualifier tags (i.e., set of possible values of the concern) $QT_i=\left\{qt_1^i, \ldots, qt_{|QT_i|}^i\right\}$ is considered to be a collection consisting of the values of each of the selection-making criteria (e.g., the qualifier tags for price could be cheap, expensive and reasonable). Usually, instances are assigned with lexical meanings or marks; for example, the quality criterion may indicate that the high, medium or low level, while the price for traveling costs that instances of "low cost", may indicate the interval [10, 100], represented by local currency, in which the meaning low price applies.

Defined two-layer structure in addition to presenting the value and/or possible instances of selection-making criteria allows the definition of preferences and attitudes over possible values of given criteria. In this way, if the available options are annotated in relation to developed structure, those options having more preferable value of selection-making criteria can be considered as more appropriate to define preferences and requirements. As the set of qualifier tags consisting of disjunctive elements, each option o is characterized with the most one qualifier tag of each of the concerns, i.e., each option is characterized with k-tuple $\left(qt_1^{i_1}, \ldots, qt_k^{i_k}\right)$, where $i_j\in\{1, \ldots, |QT_j|\}$. In case that a value of some concern is not known or for some reason cannot be estimated, the options are not characterized by any qualifier tag of the concern and in this case, $qt_j^{i_j}=\varnothing$.

Let us consider our illustrative example where the total cost of stay for person A is associated with range of [70, 5750]. Stakeholder A could also define that based on his own financial options, values above 5000 are not acceptable (even the total budget is limited to 7000), thus defining two qualifier tags (as shown in **Figure 2a**). On the other side, person B could define three qualifier tags for the same criterion "cost of stay": low (for values less than 3000), medium (for values between 3000 and 4000) and high (for values above 4000).



a)

Person A			
Cost of stay:	Acceptable	Un-acceptable	
	Less or equal to 5000	Above 5000	
Comfort:	Low	Medium	High
	1-5	5-7	8-10
Travel cost:	Low	Medium	High
	< 500	500 – 700	>700

b)

Preferences:

$\mathit{Comfort} \overset{5}{\succ} \mathit{TravelCost}$

$\mathit{Comfort.High} \overset{3}{\succ} \mathit{Comfort.Medium}, \mathit{Comfort.High} \overset{5}{\succ} \mathit{Comfort.Low}$

$\mathit{Comfort.Medium} \overset{3}{\succ} \mathit{Comfort.Low}$

$\mathit{Comfort.Medium}: \mathit{TravelCost.Medium} \overset{3}{\succ} \mathit{TravelCost.Low},$

$\mathit{TravelCost.High} \overset{3}{\succ} \mathit{TravelCost.Low}, \mathit{TravelCost.High} \overset{1}{\succ} \mathit{TravelCost.Medium}$ |

$\mathit{TravelCost.High} \overset{5}{\succ} \mathit{TravelCost.Low}, \mathit{TravelCost.Medium} \overset{3}{\succ} \mathit{TravelCost.Low}$

$\mathit{TravelCost.High} \overset{3}{\succ} \mathit{TravelCost.Medium}$

Figure 2. Illustrative example—Person A's: (a) structure of concerns and qualifier tags over selection criteria and (b) preferences over created structure.

Following the well-known Analytical Hierarchy Process (AHP) framework for expressing and ranking user preferences [7], stakeholders can use *OptSelectionAHP* to define their preferences in the form of relative importance [typically defined with odd numbers ranging from 1 (equal importance) to 9 (extreme importance)] between concerns and between qualifier tags of each concern. The set of options $\{o_1, \ldots, o_m\}$ available to the stakeholders is also associated with qualifier tags, $o_j = qt^1_{j_1}, \ldots, qt^k_{j_k}$, $1 \le j \le k$. Then, AHP performs a tuned pair-wise comparison of the options. The outcome of the procedure are ranks $\{r_1, \ldots, r_m\}$, which provide values from the [0,1] interval over the set of available options by performing two main steps: (i) the set of concerns and their qualifier tags are locally ranked, let annotate with $\{r_{c_1}, \ldots, r_{c_m}\}$ obtained ranks of concerns from the set C and $\{r^1_{qt_1}, \ldots, r^1_{qt_{|QT_1|}}\}, \ldots, \{r^k_{qt_1}, \ldots, r^k_{qt_{|QT_k|}}\}$ obtained ranks of the set of qualifier tags of the *1st,…, kth* concern, respectively; (ii) rank of each available option (combination of one tag per concern) is calculated on the basis of the ranks of the qualifier tags that are associated with that option, i.e., $r\left(qt^1_{j_1}, \ldots, qt^k_{j_k}\right) = f\left(r_{c_1} \bullet r^1_{qt_{j_1}}, \ldots, r_{c_k} \bullet r^k_{qt_{j_k}}\right)$, $1 \le j \le m$, where f is a predefined function (i.e., minimum, maximum, or mean). Furthermore, *OptConfBPMF* uses the extended AHP framework (CS-AHP) [2], which allows use of conditional preferences and preferences about dominant relative importance. For example, stakeholders are often aware of making compromise regarding their requirement of low price: they are interested to pay a higher price only for higher quality of product/service; otherwise, they will accept only a low price.

Let us assume that person A defined his preferences over the obtained range values as presented in **Figure 2b**. Since he/she is highly interested in higher comfort; i.e., higher values are more important than medium values, medium values are more important than low values, and high values are extremely more important than low values; the CS-AHP algorithm gives us the following ranks:

$$r\left(Comfort.High\right)=0,67;r\left(Comfort.Medium\right)=0,23;r\left(Comfort.Low\right)=0,10$$

Stakeholder A also defined his conditional preferences over traveling costs, and ranks are calculated accordingly: in case of medium comfort, the ranks are:

$$r\left(TravelCost.Low\right)=0,14;r\left(TravelCost.Medium\right)=0,43;r\left(TravelCost.High\right)=0,43$$

otherwise

$$r\left(TravelCost.Low\right)=0,67;r\left(TravelCost.Medium\right)=0,23;r\left(TravelCost.High\right)=0,10.$$

Since person A defined the upper bound for costs of stay as limiting factor (total costs of stay must not increase 5000), we will calculate ranks for two other criteria since person A is highly interested for comfort (compared to travel costs): $r(Comfort) = 0.83$, $r(TravelCost) = 0.17$. Finally, if we consider two combinations of options: $o_{13,}$ o_{22} and o_{12}, o_{21}, 0_{31} that give the summarized values of (4800, 8.5, 850) and (2900, 6, 300) for costs of stay, comfort and travel costs, respectively, we can see that both combinations fulfill the limitation in both, total costs (less than 7000) and acceptable costs of stay (less than 5000), and their final ranks in regard with other two criteria are calculated as: $(0.83 \times 0.67 + 0.17 \times 0.10)/2 = 0.29$ and $(0.83 \times 0.23 + 0.17 \times 0.14)/2 = 0.11$. Thus, combination of services $o_{13,}$ o_{22} is more preferable combination of options for stakeholder A, compared to the option o_{12}, o_{21}, o_{31}.

By considering the calculated ranks, it can also be concluded that high comfort and low travel costs is the most preferable combination of those selection criteria, i.e., any value belonging to intervals [8, 10] x (-, 500) fits best to stakeholders' preferences.

On the other hand, it can be seen that a rank value of 0.43 is assigned to the whole interval of high travel costs (in case of medium comfort) representing the level of satisfaction of the preference defined by stakeholder A. It means that there is no difference between combinations of options with aggregated different values from the whole interval [e.g., travel costs of 500 and 700 (in local currency)], which, obviously, does not correspond to realistic scenarios.

Thus, once the preferences are defined, the results of CS-AHP algorithm should be used as the main instrument for measuring the level of satisfaction of user preferences with a particular combination of options. The formal foundations of measurements are presented later in Section 4.

Additionally, as usual for the optimal selection tasks, *hard* constraints might be defined for special demands for limiting the corresponding selection-making criteria. That is, those preferences are not only defined as appropriate relative importance in the selection criteria model. For example, person A defined that total costs of stay should not be over 5000. It means that any combination of options which has the best characteristics with respect to the stakeholders' other preferences and which violates this specified value of price should be eliminated and should not be evaluated any further.

Formally, ***hard constraints*** can be defined as a set of constraints: cl_i ($o_1, \dots , o_n, \leq u_i, i \in \{1, .. ,l\}$, is a constant limitation value. In our illustrative example, both total budget limitations (defined by person A) should be considered as hard constraints.

3.3. Problem of optimal selection

The ***optimal selection problem*** can be defined as a problem of unique options derivation, such that stakeholders' preferences are satisfied. In our approach, once the preferences are obtained, genetic algorithm (GA) is used for the selection of the most desirable demands and the relevant options that collectively maximize the stakeholders' satisfaction. Furthermore, constraints defined in GA will guarantee that every combination of options will be valid with respect to the interdependencies and other relations between demands, as proved in reference [17].

4. CS-AHP model for optimal selection problem

In this section, we formally construct the quality model under the presence of variability and uncertainty among demands in decision-making process. The CS-AHP algorithm is adopted for specification of stakeholders' preferences and for further measurements during the optimal selection. Furthermore, we analyze different kinds of preferences and define final configuration goals induced by the constructed quality model.

4.1. The two-layered selection criteria structure

In a given model, let each demand will be available with a finite set of options characterized with respect to selection criteria. Having in mind that stakeholder defines his/her own preferences about overall values (i.e., person A specified overall budget and expectations regarding the level of personal satisfaction and conformity), we will create the structure of concerns and qualifier tags with respect to aggregated values of each selection-making criterion:

Step 1. Generate *lower and upper bound values of each selection criteria dimension* $\left(Q_{agg}^{LB}, Q_{agg}^{UB}\right)=(Q_1^{LB}, ..., Q_k^{LB}, Q_1^{UB}, \dots, Q_k^{UB}) \in R^k x R^k$

Step 2. Stakeholders should define own preferences about aggregated values presenting own attitudes and personal fillings about each selection criteria dimension, in the form of covering subintervals $QT = QT_1^1, .., QT_{k_1}^1, \ldots, QT_1^k, .., QT_{k_n}^k$. *Each subinterval* QT_i^j *is open, semi-open or close interval* $(a_i^j, b_i^j), (a_i^j, b_i^j], [a_i^j, b_i^j), [a_i^j, b_i^j]$ *which satisfies the conditions* $\bigcup_{i=1}^{k_j} QT_i^j = [Q_j^{LB}, Q_j^{UB}]$: *and* $QT_i^j \cap QT_l^j = \emptyset, 1 \le i < l \le k_j$, *for each fixed* $j \in \{1, \ldots, n\}$.

Furthermore, each combination of options $o_1, .., o_n$ is characterized by aggregated values of selection-making criteria, $Q_{agg} = q_1^{agg}, \ldots, q_k^{agg} \in R^k$ [18], which belongs to exactly one combination of covering subintervals $QT_{i_1}^1 x \ldots x QT_{i_k}^k$.

Accordingly, aforementioned combination of options in our running example, o_{13} and o_{22} (with total comfort of 10 and travel costs of 850) belongs to combination of covering subintervals [8, 10] x (700, -) defined by stakeholder A. Since stakeholder A mostly prefers values from combination of subintervals [8, 10] x (-, 500) (see Section 3.2), other combinations of available options should be analyzed in order to check if any belongs to the most preferable combination of subintervals. Furthermore, combination of options belonging to the most reachable combination of subintervals should be considered as the most appropriate combination of options. Finally, if we have several combinations of options belonging to the same combinations of covering subintervals, the difference of their selection criteria values should be quantitatively measured and compared.

Thus, based on the output ranks of the CS-AHP method, we define measures of selection-making criteria fitting degrees, as follows:

Definition 1 (CS-AHP selection making degree measurements). *For a given model (C,* $Q_{agg}^{LB}, Q_{agg}^{UB}$*, QT, P), where C is a set of concerns, QT is a set of qualifier tags over aggregated intervals* $[Q_{agg}^{LB}, Q_{agg}^{UB}]$ *for k selection-making criteria, and P represents the set of specified preferences, the standard CS-AHP algorithm defines the measurements obtained on the bases of output ranks over the set of selection-making criteria (written as* $r_1^C, \ldots, r_k^C$*) and a collection of covering subintervals (written as* $r_1^1, \ldots, r_{i_1}^1, .., r_1^k, \ldots, r_{i_k}^k$*), as follows:*

(1′) 1-dimension selection criteria fitting degree of covering interval QT_j^i: $r^{QT}(QT_{ij}^i) = r_i^C \bullet r_j^i$

(1) Selection criteria fitting degree of combination of covering subintervals $QT_{i_1}^1 x \ldots x QT_{i_k}^k$:

$$r^{QT}\left(QT_{i_1}^1 x \ldots x QT_{i_k}^k\right) = \frac{1}{k}\sum_{j=1}^{k} r^{QT}\left(QT_{i_j}^j\right), i_j \in \{1,\ldots,k_l\}, l \in \{1,..,k\}$$

(2′) Fitting degree of combination of options for the ith selection criteria dimension:

$$\boldsymbol{r}_i^S\left(o_1,\ldots,o_n\right)=\begin{cases}\boldsymbol{r}_i^C\cdot\left[\boldsymbol{r}_j^i+\dfrac{\boldsymbol{m}_i^j-\boldsymbol{q}_i^{agg}}{\boldsymbol{m}_i^j-\boldsymbol{m}_i^{j-1}}\left(\boldsymbol{r}_j^i-\boldsymbol{r}_{j-1}^i\right)\right], & \boldsymbol{q}_i^{agg}\leq\boldsymbol{m}_i^j\\ \boldsymbol{r}_i^C\cdot\left[\boldsymbol{r}_j^i+\dfrac{\boldsymbol{q}_i^{agg}-\boldsymbol{m}_i^j}{\boldsymbol{m}_i^{j+1}-\boldsymbol{m}_i^j}\left(\boldsymbol{r}_{j+1}^i-\boldsymbol{r}_j^i\right)\right], & \boldsymbol{q}_i^{agg}\geq\boldsymbol{m}_i^j\end{cases}$$

where$q_i^{agg}\in QT_j^i$*is the aggregated value of the ith selection criteria dimension,*$m_i^j=\frac{a_i^j}{2}+\frac{b_i^j}{2}$*-middle of the jth covering subinterval*QT_j^i, $r_0^i=r_1^i+\frac{r_2^i-r_1^i}{m_2^i-m_1^i}\left(a_1^i-m_1^i\right)$*and* $r_{k_i+1}^i=r_k^i+\frac{r_{k-1}^i-r_l^i}{m_{k-1}^i-m_k^i}\left(b_k^i-m_k^i\right)$.

(2) Fitting degree of combination of options: if the overall selection criteria values $Q_{agg}=q_1^{agg},\ \ldots,\ q_k^{agg}\in R^k$*of the combination of options*$o_1,\ \ldots,\ o_n$*belongs to the combination of covering subintervals*$QT_{i_1}^1x\ldots xQT_{i_k}^k$*, then its selection criteria fitting degree is measured by:*

$$r^S\left(o_1,\ \ldots,\ o_n\right)=\frac{1}{k}\sum_{i=1}^{k}r_i^S\left(o_1,\ \ldots,\ o_n\right).$$

For better clarity, measurements are at first defined for one selection criteria dimension (*1′* and *2′*), and then generalized for *k* selection criteria dimensions (*1* and *2*). It is succeeded by considering all interested selection criteria dimensions in the weighted sum in the functions $r^{QT}()$ and $r^S()$ under the hypothesis that the aggregated values for quality dimensions can be evaluated as the average of the corresponding quality dimensions of component options [18, 19].

The main aim of these two measurements are to (i) measure **stakeholders' interests over selection criteria** (as quantified with measure r^{QT} measure), and (ii) measure **how the selected combination of options fulfill defined preferences** (as quantified with measure r^S measure).

4.2. Characteristics of the two-layered model for selection-making criteria

Created two-layered structure with both measurements represents an integral **selection-making model,** with the following characteristics induced by the basic characteristics of its integrated components:

i. Fitting degree measurements $r^{QT}()$ and $r^S()$ are unit measurements, i.e., $0\leq r^{QT}(),\ r^S()\leq 1$, according to the basic characteristics of the CS-AHP algorithm [2];

ii. The ranks obtained by CS-AHP algorithm are at first assigned to the covering subintervals for creation of selection criteria fitting degree measurement $r^{QT}()$, and thus its higher values correspond to the **more preferable combination of covering subintervals according to stakeholders' preferences**;

iii. Quality measure $r^{QT}()$, in general case, does not correspond to monotonic tendency of selection criteria dimensions (i.e., increasing and decreasing) introduced in reference [18]. The CS-AHP framework takes as input the set of stakeholders' preferences about the relative importance between covering subintervals which are not required to be monotonically increasing or decreasing, and, thus, observed ranks do not correspond to any monotonic function;

iv. The ranks obtained by CS-AHP algorithm are also assigned the middle values of covering subintervals with uniform distributions to ranks of the first neighbors. Thus, higher values of selection criteria fitting degree measurement for combination of options $r^{S}()$ correspond to the **combination of options that are better suited for the stakeholders' preferences with respect to selection criteria** [20];

v. The computation of $r^{QT}()$ and $r^{S}()$ measures takes polynomial time complexity to the size of the set of available options [2], while the queries about the most preferable combination of covering subintervals and the best-suited combination of options are in the worst-case non-deterministic polynomial-time hard (NP-hard) [18];

vi. Both measurements in the selection criteria model give quantification of stakeholders' preferences over a two-layered structure, according to contained sufficient expressiveness and interpretation of preferences [1]. For simplicity, the schematic representation of the defined measures and their interrelation for one selection criteria dimension is given in **Figure 3**. Even in the simplest one-dimensional case, there is no clear interrelation between defined measures in the selection criteria model (see QT_2^k and $QT_{i_k}^k$ where inequality $r_2^k > r_{i_k}^k$ holds for quality measures of covering subintervals, while there is no unique relation between corresponding selection criteria measures of combination of options).

The characteristics of introduced measurements reflect uncertainty and conditionality in user preferences (which, to the best of our knowledge, mostly correspond to realistic scenarios [2]), and thus the *OptSelectionAHP* approach is developed in a manner which uses identified characteristics for faster convergence in the heuristic approach for optimal selection problem.

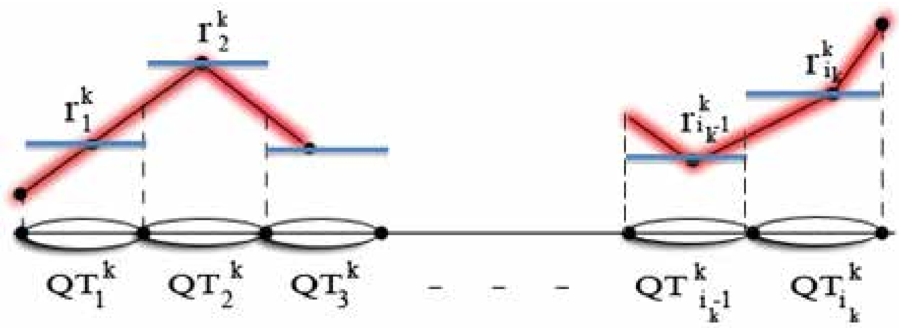


Figure 3. Schematic representation of r^{QT} and r^{s} measures for one selection criteria dimension.

4.3. Optimal selection goals

Finally, in the proposed selection criteria model, the final optimal selection goal is defined as the determination of the most preferable combination of available options based on both measurements representing stakeholders' requirements and preferences. Thus:

Definition 2 (**optimal selection goal**). *Given a set of user demands* $\{d_i\}_{i=1,\ldots,n}$ *with interdependencies defined with q logical statements, and associated with available set of options* $\{o_{ij}\}_{i=1\ldots n,\, j=1\ldots m_i}$*, where* m_i *is the number of available options for ith demand, and CS-AHP selection criteria model (C,* Q_{agg}^{LB}*,* Q_{agg}^{UB}*, QT, P), where C is a set of concerns, QT is a set of qualifier tags over aggregated intervals* $\left[Q_{agg}^{LB}, Q_{agg}^{UB}\right]$ *for k selection-making criteria, and P represents the set of specified preferences; the* **optimal selection goal** *is to find a valid combination of options which maximizes the overall selection criteria fitting degree* $r^S(o_1, \ldots, o_n)$*, subject to its affiliation to the most preferable combination of selection criteria and the hard constraints satisfaction.*

It is necessary to notice that in comparison to standard optimization goals widely used in the literature [21–23], defined as *maximization of the overall aggregated values*, definition 2 additionally requires affiliation to the most preferable combination of selection criteria.

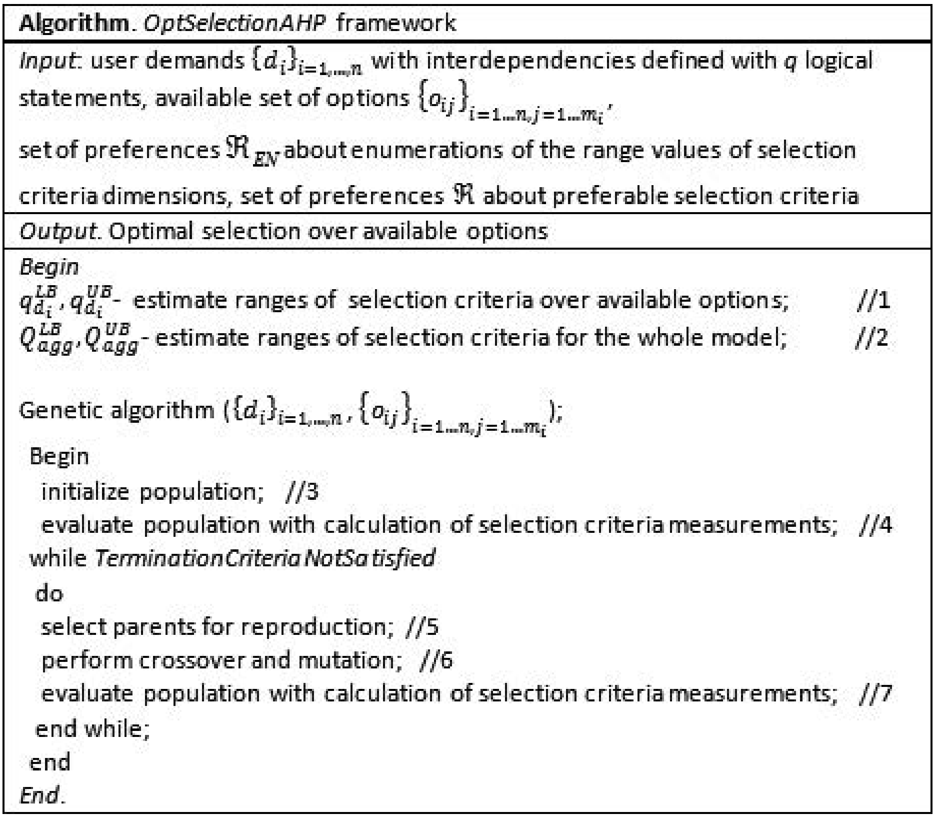
In the following, we propose a meta-heuristic search approach that overcomes the aforementioned complexities.

5. Optimal selection framework (*OptSelectionAHP*)

In this section we present our approach, called *OptSelectionAHP*, for optimal selection problems by use of GAs adapted to proposed selection criteria model. GAs are adaptive heuristic search algorithms which simulate processes of natural selection, natural evolution and genetics, in full accordance with Charles Darwin principles of "survival of the fittest" [11]. GAs start with a set of solutions (represented by "chromosomes") called "population". The relative success of each individual on the problem is considered its "fitness", and used to selectively reproduce the fittest individuals to produce similar but not identical offspring for the next generation. In that sense, crossover (that combines bits of two individuals to produce one or more individuals) or mutation operators (that makes random modifications on individual genomes) are applied. By iterating this process, the population efficiently samples the space of potential individuals and eventually converges into the fittest one.

5.1. GA adoption with optimization steps

In our approach, we use GAs for evaluation of different combinations of options in order to optimize stakeholders' preferences with satisfaction of the constraints defined among certain demands. Since the proposed two-layered decision criteria model lacks optimality in execution, we propose a parallelized implementation based on GAs. The quality measurements are dynamically calculated as each valid configuration is created (//4 and //7 in the algorithm), which imposed dynamism (i.e., adaptivity) of some other parts of the GA, in accordance with well-accepted and widely recommended approaches in optimization techniques [11, 24, 25]. The complexity benefits are estimated and discussed later in Section 5.2, while the adoption of all GA elements is presented in **Figure 4**.



```
Algorithm. OptSelectionAHP framework
Input: user demands $\{d_i\}_{i=1,\dots,n}$ with interdependencies defined with $q$ logical
statements, available set of options $\{o_{ij}\}_{i=1\dots n, j=1\dots m_i}$,
set of preferences $\Re_{EN}$ about enumerations of the range values of selection
criteria dimensions, set of preferences $\Re$ about preferable selection criteria
Output. Optimal selection over available options
Begin
$q_{d_i}^{LB}, q_{d_i}^{UB}$ - estimate ranges of selection criteria over available options;   //1
$Q_{agg}^{LB}, Q_{agg}^{UB}$ - estimate ranges of selection criteria for the whole model;   //2

Genetic algorithm ($\{d_i\}_{i=1,\dots,n}$, $\{o_{ij}\}_{i=1\dots n, j=1\dots m_i}$);
 Begin
  initialize population;  //3
  evaluate population with calculation of selection criteria measurements;  //4
 while TerminationCriteria NotSatisfied
  do
   select parents for reproduction;  //5
   perform crossover and mutation;  //6
   evaluate population with calculation of selection criteria measurements;  //7
  end while;
 end
End.
```

Figure 4. *OptSelectionAHP* framework.

Service chromosome encoding. An array encoding $e_1, \dots, e_n$ is used to represent a potential solution (i.e., one combination of available options) as a chromosome. The set of possible values for *i*th element in the array *ei* is the set of available options of demand d_i. Additionally, if the *i*th demand is optional, the set of possible values for the *i*th element in the array additionally includes 0 (representing that demand which is not fulfilled).

Initial population. In order to start with GA search process, initial population should be created. It is generated randomly, representing random combinations of options, and hence, may not be valid with respect to *q* logical statements which defined interconnections between demands. In order to solve the problem of generating invalid elements in the population, we use a simple *optionsTransform* algorithm as introduced in reference [20].

Fitness evaluation. The fitness function quantifies the performance of an individual solution. There are a variety of studies regarding the definition of appropriate fitness functions [24, 26] and the major recommendation is to use fitness functions that penalize individuals that do not meet the problem constraints, which will eventually drive the evolution towards constraint satisfaction [27]. The main advantage of this approach is that we can incorporate any constraint into the fitness function, along with an appropriate penalty measure for it, and we can expect the GA to take this constraint into account during optimization. Relative penalty values may be chosen to reflect intuitive judgments of the relative importance for satisfying different kinds of constraints [22]. Our fitness function takes two types of information into account, namely, the structural constraints, and the stakeholders' preferences as follows.

Structural constraints might be defined for special demands for limiting the corresponding selection criteria properties and its violation should directly eliminate the corresponding combination of options. The penalty factor is defined as the weighted distance from constraint satisfaction which is measured as: $D(e_1, \ldots, e_n)=\sum_{i=1}^{l} cl_i(e_1, \ldots, e_n)\cdot y_i$, where

$$y_i=\begin{cases}0, & cl_i(e_1, \ldots, e_n)\leq u_i\\ 1, & cl_i(e_1, \ldots, e_n)>u_i\end{cases}.$$

In the literature [25], the penalty weight in a fitness function is dynamically increased with the number of generations and with higher value of the weight than the requirements. If the weight for the penalty factor is low, there is the risk that individuals will not be discarded although they violate the constraints [27].

However, the optimal selection goal is to find the combination of options which maximizes both kinds of stakeholders' preferences about selection criteria, as follows:

2(a) In order to ensure falling into the most preferable combination of covering subintervals, we use a dynamic penalty factor defined as the ratio of the absolute distance between the decision criteria fitting degree $r^{QT}\left(QT_{i_1}^{1}x \ldots xQT_{i_n}^{n}\right)$ of combination of covering subintervals reached by the running configuration of services, and the most preferable combination of covering subintervals reached by current population, annotated with $r_{MAX-gen}^{QT}()$. The penalty is updated for every generation according to the information gathered from the population, and in the literature known as *adaptive penalty* [17]. Time complexity needed for the calculation of this penalty factor is small since it includes only comparison of the decision criteria fitting degrees of new elements in the population with the previous most preferable combination of covering subintervals.

2(b) The overall quality of the combination of options is measured by decision criteria fitting degree $r^{S}()$, but in order to provide positive values of fitness function [11], we decided to use its reciprocal value where higher values correspond to less preferable combinations of options. Thus, the optimal selection process is driven by finding the minimal value of fitness function defined as:

$$Fitness\left(e_1,..,e_n\right)=\frac{1}{r^S\left(\left\langle e_1,..,e_n\right\rangle\right)}+w\left(gen\right)D\left(\left\langle e_1,..,e_n\right\rangle\right)+\frac{\left|r^{QT}_{MAX-gen}\left(\ \right)-r^{QT}\left(QT^1_{i_1}x\ldots xQT^1_{i_k}\right)\right|}{r^{QT}_{MAX-gen}()}$$

Proposed modification in the penalty factors makes changes in the defined stopping criterion: once all hard constraints are met [i.e., $D(g)=0$], then the process is continued for a fixed number of iterations in order to reach lower values of fitness function. Alternatively, iterate until the best fitness individual remains unchanged for a given number of iterations.

Crossover and mutation. Traditional schemes utilize two operators which combine one or more chromosomes to produce a new chromosome: mutation and crossover [11]. The *k*-point crossover operator is used as common for non-binary genomes, which splits the genome along randomly selected *k* crossover points, pasting parts which alternate among parental genomes. After performing the crossover operator, random point mutation operator will be applied by selecting random position in the genome and putting randomly generated values. As a result of both operators, invalid chromosomes might be generated and we will employ the *optionsTransform* algorithm as a repair method that restores feasibility in the chromosome.

5.2. Complexity analysis

The algorithm complexity of the *OptSelectionAHP* can be decomposed as follows. First, let us use the following notations: *k* is the number of selection criteria, *n* the number of demands in selection process, *m* the maximal number of available options per each demand, *s* the maximal number of covering subintervals per each selection criteria and *r* is the number of preferences over two-layered selection criteria model.

Step //1 in the algorithm requires O(*knm*) time to estimate ranges of each selection criteria dimension for each demand in selection process. The propagation of selection criteria ranges (step //2) costs *0 (k*logn)*, as explained in reference [13]. So, the two-layered selection criteria structure creation has polynomial time complexity.

The complexity of the adopted GA can be decomposed as follows.

Step //3 requires $O(P * n * T(optionsTransform))$, where *T(optionsTransform)* is time needed for the *optionsTransform* algorithm. In reference [27], it is estimated as $O\left(cnk * log^2 k\right)$, where *c* is the maximum number of constraints. The calculation of selection criteria measurements for population (step //4) takes $O\left(P\left(r+\frac{k^2}{2}+n\bullet\frac{s^2}{2}\right)\right)$ operations [2].

The following steps are repeated *G* times:

(step //5) The parents selection operation costs 0(1)

(step //6) The crossover operation costs *0*(*n*) and mutation operator costs 0(1) (step //7) Replace operator costs $O(P)$; the validity of each element of the population is checked with the *optionsTransform* algorithm, which takes *T(optionsTransform)*. Over each element of population, the selection criteria measurement is calculated, which takes $O\left(r + \frac{k^2}{2} + n \bullet \frac{s^2}{2}\right)$ operations as given earlier.

Thus, the iteration steps of the GAs take $O_{GA} = O\left(G\left(r + \frac{k^2}{2} + n \bullet \frac{s^2}{2} + n + P + cnk \bullet log^2 k\right)\right)$. This is significantly reduced complexity compared to our previous work [20] where the complexity was exponential to the size of selection criteria model.

6. Simulation analyses

The *OptSelectionAHP* provides meta-heuristic approach for optimal selection problem, whose effectiveness and efficiency should be analyzed and evaluated. We have chosen the closeness to an optimal solution as the criterion which is used to estimate the efficiency of the approach.

Furthermore, the *OptSelectionAHP* approach provides an optimization of the approach from our previous work [20], which has been shown to be efficient with almost 90% of optimality applied in software engineering environment for the problem of optimal configuration of business process families. The optimization proposed with *OptSelectionAHP* approach is made in accordance with characteristics of introduced selection criteria structure (as described in Section 4). This is the reason why we decided to make simulation comparison of *OptSelectionAHP* approach with meta-heuristic approach previously developed in reference [20].

Furthermore, domain of business process families is characterized with optimality and uncertainty in configuration process, as well with sets of integrity constraints, thus allowing to analyze how variability in selection space influence on optimality of proposed approach.

With this in mind, we defined the following hypothesis that we tested in our experiments.

H1. There is no significant difference between the distances to the optimal solution, compared to un-optimized meta-heuristic approach.

H2. In case of different distributions of optional elements, there is no significant difference between the distances to the optimal solution.

For testing the hypotheses and making an estimation of the average distance to an optimal solution, we performed several experiments which are explained in the next section.

6.1. Experimental setup

In order to perform the analyses, we separately performed two different experiments, described later in this section. Each experiment includes generation of business process families with parametrically changeable values of descriptive parameters [i.e., number of activities and their interconnections, available services, quality of services (as criteria for making configurations) and set of preferences]. In that sense, two generators are used similarly as in previous experiments [20]. Also, we use the brute-force algorithm and previous GA adoption in order to obtain the optimal solution and solution with un-optimized approach and compare them with the solution of *OptSelectionAHP*.

In our previous work [28], we suggested the number of seven qualifier tags in the two-layered structure, as optimal number manageable by humans. We also set 100 options as maximum number of available options. All values are generated randomly. The four groups of selection criteria are considered (in domain of business processes configuration that are Quality of Services (QoS) attributes [29] with random number of characteristics to each group [22, 30].

No systematic parameter optimization process has so far been attempted, but we use the following parameters in our experiments: population size $P = 1$, maximum generation $G = 200$, crossover probability = 1 (always applied), mutation rate = 0.1, dynamic penalty factor, $w(gen) = C \bullet gen$, C = 0.5 [31].

6.1.1. Experiment 1: Comparison of optimal and heuristic algorithms

Our main goal in this experiment is to estimate differences between qualities of solutions as a measure of how close our proposed algorithm is to an optimal solution. Also, we analyze whether optimization issues significantly influence the optimality of the approach (defined as H1).

The approximation ratio (heuristic utility vs. the optimal value) is used as an appropriate metric of closeness to the optimal solution. Random generations of business process families and appropriate selection criteria models (QoS attributes) are performed 1000 times; the optimization goals are solved simultaneously with both heuristic approaches while a brute-force algorithm is used for obtaining the optimal solution.

Given the type of the collected data in the simulations, we analyzed them with standard descriptive statistics including mean (M) and standard deviation (SD) values. The hypothesis is tested by ANOVA for comparing means for multiple independent populations to see if a significant difference exists in the distances to the optimal solution in cases of using optimized approach compared to previous un-optimized approach (H1).

Experimental results. Calculated mean value of relative distance between configurations obtained by *OptSelectionAHP* and optimal configurations is equal to 10.41% (SD = 0.964%). Thus, the optimality of our approach is around 89.5%.

Furthermore, the mean value of the results obtained by un-optimized approach for optimal configuration, the same collection of business process families is equal to 10.20% (SD = 0.928%). Even if the mean values of both approaches are close, graphical representation (shown in **Figure 5**) shows incoherence between optimality of two approaches. Only in 23.00% (line 2), both approaches have the same precision, while in 13.4% (line 1) and 17.2% (line 3), the solutions of both approaches are optimal.

Figure 5. Scatter diagram of relations between distances to optimal solution of meta-heuristic approaches.

As the collected data were not normally distributed, a one way ANOVA test was used over the log-transformed data to compare the means of obtained relative distances to the optimal solution. The results show a non-significant difference between approaches F(1,782) = 11.814, $p = 0.229$. Thus, hypothesis H1 is accepted and we can conclude that the optimization issues do not have a significant impact on the optimality of the approach. This finding is important, since the complexity of the whole approach is reduced to polynomial without loss of accuracy.

6.1.2. Experiment 2: Analyses of the performance characteristics in the cases of different characteristics of input parameters

For testing the hypothesis H2, we performed several simulations with different distributions of optional elements in the business process families. Distributions of optional elements are determined with the percentage ratio and we considered the following values: 25%, 50%, 75% and 100% (these are referred to as groups 1–4, respectively). Each simulation is performed 1000 times and the collected data are used for testing the hypotheses with ANOVA for comparing means for multiple independent populations to see if a significant difference exists in the distances to the optimal solution.

Experimental results. The results show a non-significant difference between approaches related to different distributions of optional elements in business process families: F(3,584) = 28.489, $p = 0.171$; mean values for each group are presented in **Table 1**.

Percentage ratio of optional elements in business process model	Relative distance compared to optimal solution	Percentage ratio of optional elements in business process model	Relative distance compared to optimal solution
	Mean, SD		Mean, SD
25%	9.98%, 0.548	75%	10.34%, 0.736
50%	10.21%, 0.294	100%	10.52%, 0.341

Table 1. Mean values of relative distance between solutions of *OptSelectionAHP* compared to optimal solution for different distributions of optimal elements in business process model.

Experiment conclusion. The observed results show that variability elements do not represent a source of statistical impact on optimality of obtained results. Hence, hypothesis H2 is accepted. In *OptSelectionAHP* approach, dynamic penalties in the fitness function are defined on the basis of qualitative measurements and identified characteristics of different kinds of preferences, therefore proving the importance of dynamic penalties for convergence of the whole approach.

6.1.3. Discussion

Experimental results show that proposed *OptSelectionAHP* approach has proven optimality for optimal selection goals. Furthermore, its convergence guided by dynamic penalties has shown good characteristic even in cases of different distributions of optional elements in the experiment.

7. Related work

Having in mind that our work in *OptSelectionAHP* is general enough to be applied in different domains, with performed evaluation analyses in domain of business process families, this section compares our work with work on (i) methods for representation and ranking of different kinds of requirements; and (ii) approaches for service and business process configuration, including exact and heuristic techniques.

7.1. Different kinds of requirements and prioritization algorithms

Different researchers have been interested in developing tools and techniques for eliciting, formalizing and interpreting stakeholders' priorities over the existing options such as the pairwise comparison method, priority groups, networks for decision-making and cumulative ratings [3]. The selection of appropriate prioritization technique directly depends on its characteristics as well as the domain of application [32]: it is practical and universal to use qualitative concept to describe users' preference while the quantitative values corresponding to the qualitative concepts are not straightforward [33].

In our previous work [2], we gave the comprehensive review on methods for representation and prioritization of qualitative and quantitative preferences from different fields of research and standards. There, it is shown that one of the best-known frameworks for addressing conditional preferences introduced by CP-nets and TCP-nets [3, 34] is not completely quantified yet [35] and some other improvements need to be done in order to be used for effective ordering of decision outcomes.

On the other hand, there is a variety of methods based on quantitative measurements with supporting of only unconditional requirements, such as the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method [36], Simple Additive Weighting (SAW) [37], Linear Programming Techniques for Multidimensional Analysis of Preference (LINMAP) [38], Complex Proportional Assessment (CORPAS) [39], etc.

7.3. Configuration of business processes and service selection approaches

Many researchers have been studying the problems of business process configuration and service selection by using GA-based solutions with different characteristics and elements.

The genetic approach for service selection and composition, proposed by Canfora et al. [22], uses one-dimensional chromosomes and utilizes fitness function with penalty factor to select genomes and lead the convergence process to optimal solution. Similarly, GA-based approach is proposed by Gao et al. [40], by using tree-coded algorithm for service selection and composition.

Furthermore, different studies and experiments are developed aimed on making comparisons of GA-based solutions with other approaches widely used for solving optimal problems. Jaeger and Mühl [41] showed that GA-based approach has better performance compared to Hill-Climbing (HC) approaches measured with both, reached overall quality and the closeness to the optimal solutions. Canfora et al. [22] conducted empirical research showing that GA-based solutions are more scalable than Integer Linear Programming (ILP) solutions. Furthermore, they showed slower performance of GA-based solutions which is significantly increased with larger number of available options.

However, the use of well-known heuristic techniques for many NP-hard problems (including ILP) have proven limitations [27] to be applied for the problem of service selection optimization, since various structural and semantic constraints cannot be handled straightforward. Additionally, the problem of business process families' configuration is more complex due to simultaneous selection of activities for which desired services should also be selected.

The application of genetic algorithms imposes additional concerns regarding specification of stakeholders' preferences regarding selection criteria aspects [22, 40]. Commonly used approach consider simple weighting schema (e.g., Simple Additive Weighting (SAW) [42]) for defining coefficients in the fitness function, which does not respect real-world scenarios and the needs for complex weighting mechanism for the ranking and prioritizing stakeholders' requirements.

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8. Conclusions

In this chapter, we proposed a novel framework which takes into account various requirements and preferences of users to produce a final optimal selection over available options. The framework is evaluated in domain of business process models configurations and obtained relative distance to optimal solution is 10.41%. The *OptSelectionAHP* approach combines novel selection criteria model for representing different kinds of preferences and overall selection criteria measurements, with dynamic penalty factors for both structural constraints and the stakeholders' preferences, to obtain fast convergence of genetic algorithms. The definition of domain-dependent quality characteristics [29] with presented optimized search process, enable the scalability of our solution up to potential use in different domains and scenarios.

Proposed framework have potentials to be used in different domains, ranging from software engineering and problems of optimal services selection, to learning environments [43] and problem of optimal learning paths creation [44].

In our future work, we will investigate how to develop user friendly application implementing developed *OptSelectionAHP* framework, thus enabling practical use in different domains for resolving problems of optimal selections over available options. Also, our empirical work will be aimed on analyzing sensitivity of GA operators (e.g., different repair operators [45] etc.) and comparison with other approaches as alternative to meta-heuristic approach (e.g., integer linear programming [46], etc.).

Author details

Ramo Šendelj and Ivana Ognjanović*

*Address all correspondence to: ivana.ognjanovic.edu@gmail.com

University Donja Gorica, Montenegro

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Chapter 10

Evaluation of Growth Simulators for Forest Management in Terms of Functionality and Software Structure Using AHP

Clemens Blattert, Renato Lemm, and Oliver Thees

Additional information is available at the end of the chapter

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Abstract

A range of computer models exist for simulating forest growth, with different model functions, spatial resolutions and regional calibration specifications. Choosing a suitable simulator is difficult due to its abundance and complexity. The aim of the project is to evaluate a simulator that could be adapted to conditions in Switzerland and used to support decision-making processes in both forest enterprises and scientific contexts. Fourteen potentially suitable forest growth simulators were identified through a literature review, which was then narrowed down to four: BWINPro, SILVA, MOSES and PrognAus. In the second phase, these were systematically evaluated in terms of functionality and software structure using AHP, in order to identify a suitable simulator. The AHP evaluation entailed: (1) determining the decision criteria and hierarchy, (2) performing pairwise comparisons and calculating the utility values and (3) conducting a sensitivity analysis. AHP was found to provide a transparent, verifiable evaluation process for simulator selection. This enabled a critical argumentation and assessment of the simulators. In the third phase, not covered by this article, the selected simulator will be parametrised for Swiss conditions and incorporated into an overarching decision-support system for forest planning and management.

Keywords: AHP, decision support, forest management, forest growth simulator, evaluation

1. Introduction

With rising demand for timber and the ecological and social services provided by forests, as well as sustainability requirements, there is an increasing need for reliable forecasts concerning the likely impacts of alternative silvicultural treatment strategies on forest growth [1].

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To produce such long-term forecasts at forest enterprise level, a computer simulation model for forest growth is essential. In this context, a growth simulator means a computer program used to predict and simulate silvicultural scenarios, consisting of one or more growth models that biometrically and mathematically reproduce the biological growth process [2].

Simulators increasingly play a key role in decision support for forest management, particularly in the context of climate change and the associated adaptation strategies. They provide information on the likely outcomes of different forest-management strategies, allowing users to select the most suitable strategy for achieving their management goals [3].

To meet the broad range of demands associated with forest management, simulators ideally need to be able to support both economic and ecological decisions by simulating management strategies and disturbances and their ecological and economic impacts on different tree species and stand types at different sites. No such 'comprehensive' simulator is currently available in Switzerland.

Figure 1 shows the basic elements of forest growth modelling. A tree's increment depends on its initial state, site factors and stand structure. The stand structure has a crucial impact on competition for water, nutrients and light. It is shaped by anthropogenic interventions, natural mortality processes and tree growth. The increment of an individual tree is described by diameter and height growth functions, which depend on competition, site factors and the tree's initial dimensions.

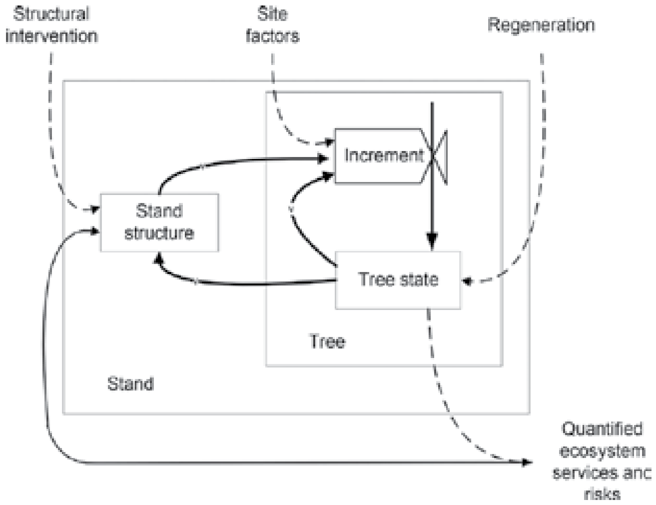

Figure 1. Modelling forest stand dynamics [4].

Stand structure is influenced by anthropogenic thinning and final harvest as well as natural mortality processes. These are modelled by appropriate algorithms. Ingrowth or regeneration models are also required to generate new trees in the system. If one also wishes to produce reliable forecasts of tree-volume (stemwood) and financial-yield development, accurate stem-form and assortment models are essential, as well as specific models for calculating timber-harvesting expenses. The respective state variables of trees can be used to derive other secondary variables such as the biomass of branches, bark, needles and leaves as well as their nutrient content, in order to estimate the nutrient removal that would result from whole tree harvesting. Other types of ecosystem services such as carbon sequestration, biodiversity and the windthrow risk of trees can also be modelled from the tree state variables.

There exists a whole series of simulators with different model functions, spatial resolutions and regional calibration specifications, developed for a wide variety of applications. This makes it difficult to evaluate and select a suitable simulator for one's own purposes.

Different methods exist, which can support the evaluation of software packages. One of the most widely used methods is the analytic hierarchy process (AHP) (e.g. [5–8]). Until now AHP was used only once in forestry for the evaluation of an IT system [9]. Thereby, an IT system which supports the business processes in forest enterprises was evaluated. AHP was not used so far for the assessment and selection of a growth simulator for forest management.

The goal of the project presented here is to evaluate a forest growth simulator that could be adapted to conditions in Switzerland. The simulator needs to not only support stand-level decision processes within a forest enterprise but also be suitable for use in scientific contexts. It should be able to map climate changes or allow climate sensitivity to be integrated at a later stage [10].

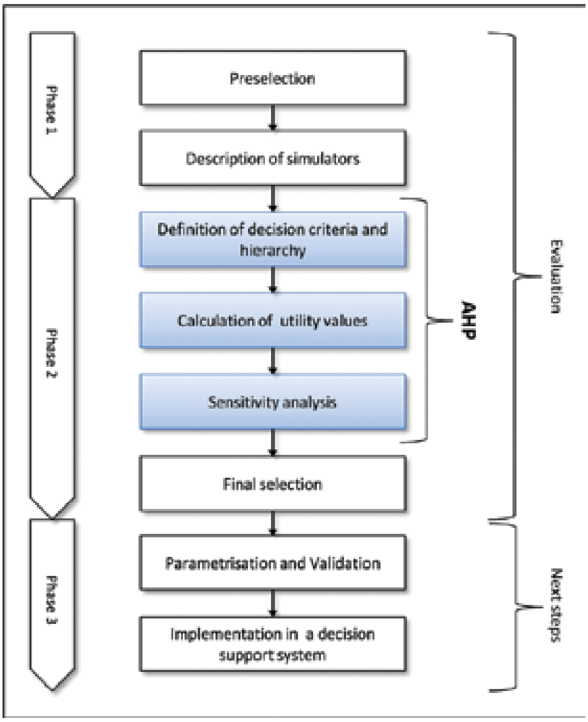

Figure 2. Procedural method of the project (phase 3 is not described by this article).

The process for the evaluation of a suitable growth simulator is divided into three phases (**Figure 2**). The first phase involves a literature review in which 14 potentially suitable simulators are identified. In a preselection phase, the 14 forest growth simulators are narrowed down to a few. In the second phase, an AHP model is created for the systematic comparison and assessment of the remaining simulators [11, 12]. Using AHP, the four simulators are evaluated in greater depth in terms of their functionality and software structure. Based on the AHP results, a suitable forest growth simulator is selected. In the third phase, the chosen simulator is reparametrised using real data from Switzerland and the simulation results are checked for validity. The simulator is also intended to be incorporated into a decision support system (DSS), used to assist forest planning and management processes. However, phase three is not described in this article.

2. Preselection of simulators

In an initial literature review, 14 forest growth simulators were identified and their main characteristics were recorded (**Table 1**). The simulators were selected based on the following key requirements:

- Suitability for forest management: Can it simulate treatment strategies?
- Availability/quality of descriptions: Is there written documentation on the simulator and does it explain its structure and functionality?
- Area of application: Where was the simulator developed (country/region) and could it be adapted to Switzerland?

		FBSM	SiWaWa	MASSIMO	ForClim	SILVA	PrognAus	MOSES	BWINPro	PICUS	STAND	MOTTI	FVS	FORECAST	TASS
Support for forest decision processes		+	+	-	-	+	+	+	+	-	+	+	+	-	+
Treatment and thinning methods		-	-	-	+	+	+	+	+	+	-	-	+	-	+
Ecosystem services	Economic	+				+	+	+	+		+	+		-	+
	Ecological			-	+	+			+	+	+	+	+	+	-
Main tree species found in Switzerland		+	-	+	+	+	+	+	+	+	-	-	?	?	
Forest types	Mixed stands			+	+	+	+	+	+	+	?	+	+	+	
	Uneven-aged stands			+	+	+	+	+	+	+			+	+	
Spatial resolution at individual tree level		+		+	+	+	+	+	+		?	+	+		+
Parametrisation using inventory and experimental -plot data		+	+		+	+	+	+		?	+	+	+	+	

Note: + = represented in the simulator, - = moderately represented, no sign = not represented, ? = no information available.

Table 1. Validation of the simulators during the preselection.

A geographical filter was applied to the selection process. All major simulators developed in Switzerland were considered, provided that they met the key requirements, while from neighbouring countries, Scandinavia and the English-speaking world only the best known and well-documented simulators were examined. The following simulators were included:

- *Switzerland:* FBSM [13, 14], SiWaWa [15], MASSIMO [16, 17], ForClim [18]
- *Austria, Germany:* SILVA [4, 19], PrognAus [20], MOSES [21, 22], BWINPro [23–25], PICUS [26, 27]
- *Scandinavia and English-speaking countries:* STAND [28], MOTTI [29], FVS [30, 31], FORECAST [1, 32], TASS [33, 34]

Based on this review, four simulators were chosen for the AHP evaluation, namely BWINPro, SILVA, MOSES and PrognAus. The preselection was based on positive performance in the following areas (**Table 1**):

- Suitability for supporting forest decision processes
- Simulation of common treatment and thinning methods
- Output of economic and ecological indicators
- Representation of the main tree species found in Switzerland
- Simulation of uneven aged and mixed stands
- Spatial resolution at individual tree level
- Scope for parametrisation using Swiss inventory and experimental-plot data

3. Description of simulators

A uniform and comprehensive description of BWINPro, SILVA, MOSES and PrognAus is a key prerequisite for performing an evaluation. These descriptions provide a basis for decision-making in the pairwise comparison. **Tables 4–7** in the appendix describe the sub-models and functionalities for each of the four simulators.

4. AHP analysis

The AHP analysis was the central component of the final selection and involved comparing the selected simulators—BWINPro, MOSES, SILVA and PrognAus—with each other and evaluating them. The AHP analysis comprised the following steps:

- Defining the decision criteria and hierarchy based on a detailed set of requirements (4.1)
- Calculating the utility values by means of pairwise comparisons (4.2) and

- Performing a sensitivity analysis (4.3).

4.1. Decision criteria and hierarchy

Based on the widely accepted recommendations concerning the uniform and standardised description of forest growth simulators [35], decision criteria were defined and structured hierarchically using a decision tree (**Figure 3**). On the one hand, the recommendations enable the requirements for the chosen simulator to be defined. On the other hand, they provide a framework for the decisions based on which of the individual simulators can be thoroughly scrutinised, particularly in terms of their model and software structure and functionalities.

The decision tree comprises eight main criteria (model approach, range of application, calibration specification, input, sub-models for growth, output, environmental influence and

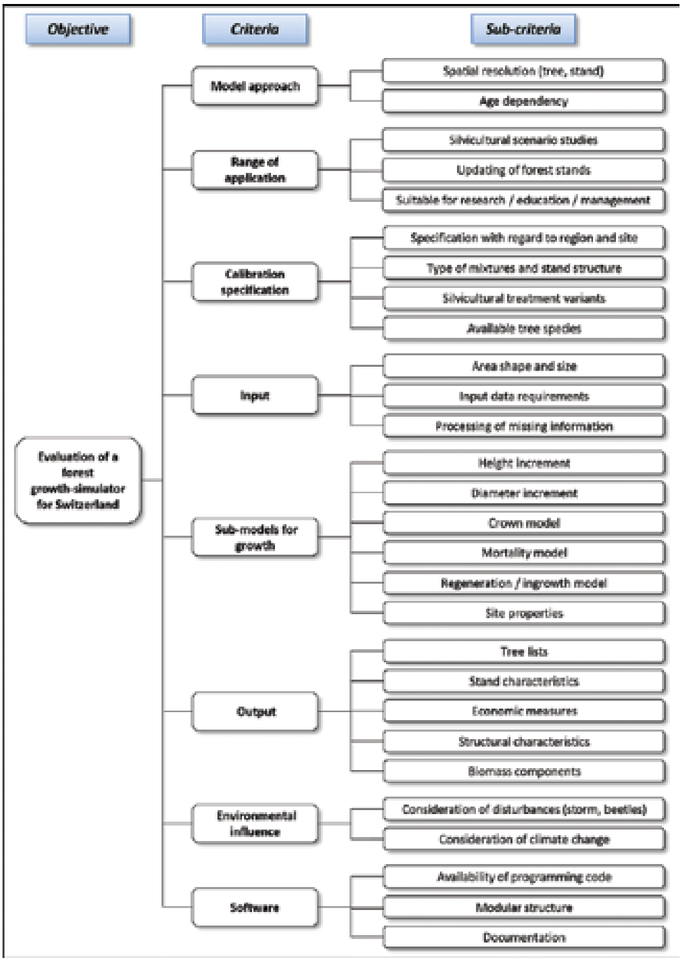

Figure 3. Decision-making hierarchy.

software), which in turn are divided into 28 sub-criteria. The decision criteria supplement the basic requirements presented in **Table 1**. The simulator that best fulfils all the criteria represents the ideal simulator for the purposes of the evaluation. The main criteria are explained below.

4.1.1. Model approach

- **Spatial resolution:** The simulator should apply an individual-tree approach to stand description, either considering the tree position using coordinates (distance dependent) or without individual-tree coordinates (distance independent). This enables the simulation of individual tree-oriented harvesting strategies, which are especially important in continuous cover forestry. In addition, more detailed conclusions can be drawn concerning the structural development of stands; these are mainly relevant for ecological assessments.
- **Age dependency:** The site index (based on top height) at a particular age is often used to assess the quality of the site (at the age of 50 or 100 years). It must, therefore, be possible to determine the age of the stand. This is not a problem with even-aged single-layer stands. However, in the case of uneven-aged and mixed stands, estimating the age is difficult, if not impossible. A model approach that does not depend on age is therefore an advantage.

4.1.2. Range of application

- **Silvicultural scenario studies:** Simulating silvicultural scenario studies serves to determine the quantitative, financial and structural effects of different treatment strategies on thinnings and surviving growing stock. Based on the results, the silvicultural scenario best suited to meet the specified goal can be identified.
- **Updating of forest stands:** It should be possible to simulate individual stands over a period of 40–50 years in management cycles of 5–10 years.
- **Suitable for research/education/management:** Initially, the simulator will be used primarily for research purposes. However, it should also be suitable for use in forest management and education in the future.

4.1.3. Calibration specification

- **Specification with regard to region and site:** It must be possible to transfer the simulator to Switzerland and use it for the different regions and sites within Switzerland. The model can also be optimally adapted to Switzerland by parametrising it using data from long-term experimental plots and the National Forest Inventory (NFI).
- **Type of mixtures and stand structure:** In addition to modelling even-aged high forest systems, the simulator must also be able to model mixed and uneven-aged stands.
- **Silvicultural treatment variants:** The simulator must be able to model the main treatment variants such as final crop tree thinning, target diameter harvesting, thinning from the top and thinning from below, and planting.

- **Available tree species:** The simulator must be able to represent the main tree species in Switzerland, including spruce, fir, pine and larch as well as beech, maple, ash and oak.

4.1.4. Input

- **Area shape and size:** It should be able to generate user-defined polygonal areas as well as present stands as a standardised square area.
- **Input data requirements:** It should be possible to initialise simulation runs using input data that is easy to collect in forestry practice (random sampling unit, inventory).
- **Processing of missing information:** There should be a routine for adding missing input data (e.g. tree positions, tree heights, dbh distributions), so that a simulation can be performed even with incomplete information.

4.1.5. Sub-models for growth

The following sub-models are summarised in this section:

- **Height increment**
- **Diameter increment**
- **Crown model**
- **Mortality model**
- **Regeneration/ingrowth model**
- **Site properties**

The simulator should include these algorithms so that it can model stand growth in its structural development. The individual growth algorithms can be implemented using a variety of approaches. It is also necessary to record site properties so that different local growing conditions can be taken into account. Aside from the widely used site index (based on top height), there are also approaches that describe the site effects on tree growth with respect to soil properties as well as prevailing temperatures and precipitations. These are often not age dependent and therefore offer a clear advantage over the site index in the case of uneven-aged stands. The corresponding database, equations and parameters for the individual algorithms must be accessible.

4.1.6. Output

In addition to analysing different treatment strategies purely from a forest management perspective, the simulator should also enable an assessment of ecological and social aspects. This requires not only common forestry parameters such as individual-tree data, stand characteristics and economic measures but also outputs relating to stand structure and biomass components.

The simulator should generate results for the following criteria:

- **Tree lists/individual-tree data:** Tree species, age, height, diameter at breast height (dbh), increment, volume, slenderness (ratio of tree height and dbh), crown base, crown width, crown percent and coordinates (tree position)
- **Stand characteristics per hectare:** Mean basal area tree, height of mean basal area tree, top height of the stand (H100; H50), number of trees, basal area, volume, number of trees in thinnings, basal area of thinnings, volume of thinnings as well as stocking degree and tree species composition
- **Economic measures per hectare:** Volume of timber harvested (in cubic metres without bark), assortments, timber harvesting revenues and timber-harvesting expenses
- **Structural characteristics at stand and enterprise level:** Described by various structures and species indices
- **Biomass components per hectare:** Biomass of stemwood, branches, bark, needles, leaves and roots

4.1.7. Environmental influence

Forest ecosystems are open systems, in other words, they are dependent on and can be influenced by external factors. A forest growth simulator should be able to take account of the effect of such factors on tree and stand growth.

- **Consideration of disturbances:** For example, windthrow/wind breakage, snow breakage or beetles
- **Climate change:** It is very important to be able to simulate the effect of a temperature rise on growth as well as the impact of changes in precipitation (drought). The simulator should ideally already include such a feature or at least have scope to incorporate it.

4.1.8. Software

- **Availability of programming code:** The programming code must be freely available so that the simulator can be used for the required research purposes. This means that the processes inside the simulator are clearly understandable and the derivation of the results can be traced. It must also be possible to alter the simulator or remove sub-models from it.
- **Modular structure:** A modular structure has the advantage that when changes need to be made, it is not necessary to overhaul the entire simulator but only the module concerned, as the individual components interact with one another via precisely defined interfaces. It also means that individual modules can easily be replaced or supplemented by models developed in-house.
- **Documentation:** Comprehensive documentation on the simulator, explaining the underlying functionalities, model equations and parameters, and a user guide are important to provide a detailed insight into the simulator. This is the key to understanding how it works.

4.2. Results of the pairwise comparisons

Once the criteria and hierarchy have been established, the individual criteria are compared pairwise with each other. This pairwise comparison method allows the decision maker to extract a highly accurate evaluation from the numerous competing criteria.

The pairwise comparisons were supported by the software 'CelsiEval', which also calculated the normalised weights for the respective criteria. In this case, the criterion software receives the highest weighting (0.306) in relation to the overarching goal of the evaluation. The second-level criteria are model approach, range of application, calibration specification, growth and environmental influence (0.121), with the input and output criteria (0.046) coming last (**Table 2**).

Criteria (normalised weights)		**Sub-criteria (normalised weights)**		**(Relative priorities)**			
				BWINPro	**SILVA**	**MOSES**	**PrognAus**
C1 Model approach	0.121	Spatial resolution	0.800	0.125	0.375	0.375	0.125
		Age dependency	0.200	0.125	0.125	0.125	0.625
C2 Range of application	0.121	Silvicultural scenario studies	0.429	0.250	0.250	0.250	0.250
		Updating of forest stands	0.429	0.250	0.250	0.250	0.250
		Suitable for research/education /management	0.143	0.250	0.250	0.250	0.250
C3 Calibration specification	0.121	Specification with regard to region and site	0.068	0.068	0.390	0.390	0.152
		Type of mixtures and stand structure	0.152	0.250	0.250	0.250	0.250
		Silvicultural treatment variants	0.390	0.500	0.167	0.167	0.167
		Available tree species	0.390	0.375	0.125	0.125	0.375
C4 Input data	0.046	Area shape and size	0.143	0.250	0.250	0.250	0.250
		Input data requirements	0.429	0.250	0.250	0.250	0.250
		Processing of missing information	0.429	0.313	0.313	0.313	0.063
C5 Sub-models for growth	0.121	Height increment	0.143	0.167	0.167	0.167	0.500
		Diameter increment	0.143	0.375	0.125	0.125	0.375
		Crown model	0.143	0.250	0.250	0.250	0.250
		Mortality model	0.143	0.400	0.200	0.200	0.200
		Regeneration/ingrowth model	0.143	0.300	0.100	0.300	0.300
		Site properties	0.286	0.083	0.417	0.083	0.417
C6 Output	0.046	Tree lists	0.344	0.250	0.250	0.250	0.250
		Stand characteristics	0.344	0.250	0.250	0.250	0.250

Criteria (normalised weights)		**Sub-criteria (normalised weights)**		**(Relative priorities)**			
				BWINPro	**SILVA**	**MOSES**	**PrognAus**
		Economic measures	0.129	0.152	0.390	0.390	0.068
		Structural characteristics	0.129	0.375	0.375	0.125	0.125
		Biomass components	0.055	0.313	0.313	0.313	0.063
C7 Environmental Influence	0.121	Consideration of disturbances	0.125	0.100	0.100	0.400	0.400
		Consideration of climate change	0.875	0.083	0.417	0.083	0.417
C8 Software	0.306	Availability of programming code	0.400	0.625	0.125	0.125	0.125
		Modular structure	0.400	0.523	0.200	0.200	0.078
		Documentation	0.200	0.390	0.152	0.390	0.068
		Utility value of the alternatives		**0.319**	**0.240**	**0.214**	**0.227**

Note: The utility values of the alternatives are shown at the end of the table.

Table 2. AHP-calculated normalised weights for the criteria and sub-criteria as well as the relative priorities of the different alternatives in respect to the sub-criteria.

The next step was to compare the model alternatives with each other in pairs. Therefore, the information in the appendix (**Tables 4–7**) was used as a basis for the decision-making process. The pairwise comparisons were performed in group discussions by three scientists from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), who have a sound knowledge of forestry science and management.

Afterwards, the relative priorities of the model alternatives in relation to the sub-criteria and the utility value for the different alternatives were calculated (**Table 2**). In the AHP analysis performed here, BWINPro achieves the highest utility value of 0.319. In other words, it is likely

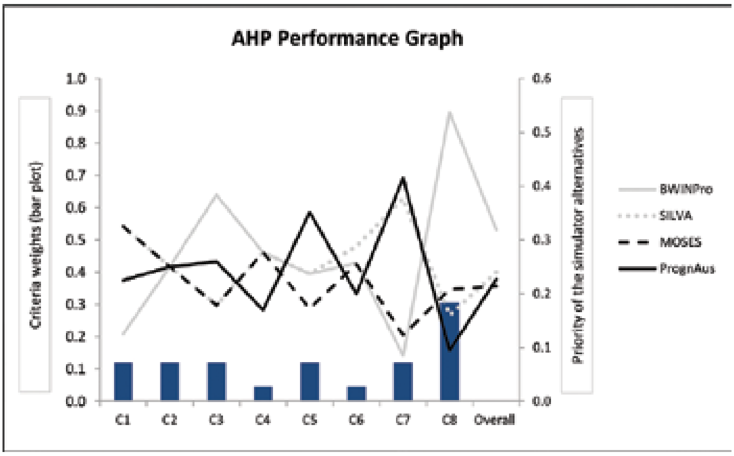

Figure 4. AHP performance graph.

to be the most suitable simulator for the goals specified in the AHP. The AHP performance graph shows how the individual simulators perform in relation to the main criteria (**Figure 4**). It can be seen that BWINPro is not the best-performing simulator in all criteria. The contents of the performance graph are explained in the following sections.

Model approach: SILVA and MOSES use a distance-dependent approach based on individual-tree coordinates, which the decision makers consider important for the simulation of a continuous cover forestry system. They, therefore, receive the highest priority on the first criterion. PrognAus is rated higher than BWINPro because its approach is not age dependent. However, because the 'age-dependency' criterion has a lower weighting than 'spatial resolution', this rating has less of an impact on the ranking (**Table 2**).

Range of application: The simulators scored equally in the three sub-criteria 'silvicultural scenario studies', 'updating of forest stands' and 'suitable for research/education/management'.

Calibration specification: Although MOSES and SILVA (site performance model) have been partially parametrised with Swiss data from long-term forest experimental plots, BWINPro receives a higher priority than the other models on this criterion. This is partly attributable to the 'silvicultural treatment variants' criterion: BWINPro offers treatment concepts geared towards nature conservation and promoting biodiversity, such as protecting trees with a dbh above a certain value or the possibility of selecting habitat trees. In addition, the model has been parametrised for a whole range of tree species. Only the PrognAus model offers a similarly extensive selection of tree species.

Input: The four simulators scored equally on the 'area shape and size' and 'input data requirements' sub-criteria. However, PrognAus receives a lower priority than the other simulators due to its lack of a structure/stand generator.

Sub-models for growth: PrognAus receives the highest priority in this criterion, mainly owing to its potential-independent approach for describing height and diameter increment. The decision makers rated this higher than a potential-dependent approach. Furthermore, PrognAus describes the site potential in terms of multiple site factors. On the 'crown model' sub-criterion, the four simulators were ranked equally as no direct conclusion can be made without comparing model results with real data. The decision makers feel that this aspect is not so important in the context of the AHP comparison because the selected simulator is to be adapted to Swiss conditions in phase 3. In the 'mortality' sub-criterion, BWINPro receives a higher priority than the other simulators as it considers age-related as well as simply density-related mortality. In the 'regeneration/ingrowth' criterion, SILVA was rated lower due to its lack of a corresponding sub-model (cf. [10]).

Output: SILVA receives the highest priority in this area as it provides a variety of economic and ecological indicators needed for the planning and management of forest stands. BWINPro and MOSES receive the second-highest priority. In BWINPro's case, this is due to its inability to calculate timber-harvesting expenses, while for MOSES the lower ranking is owing to its limited output on stand structure. PrognAus receives the lowest priority of all the simulators as it delivers limited output on economic indicators and stand structure and none at all on biomass.

Environmental influence: PrognAus features a calamity model to simulate random harvesting as a result of windthrow/wind breakage, snow breakage and beetle infestation. The height and basal area increment model has also been expanded to include climatic variables. As a result, this simulator receives the highest priority, followed by SILVA in second place. SILVA does not consider disturbances but is able to simulate climatic influences, which are covered by the empirical database. MOSES comes third. It is not climate sensitive, but does enable an estimate of windthrow and snow breakage based on slenderness. BWINPro receives the lowest priority as it cannot currently simulate either disturbances or climatic influence.

Software: In the 'software' criterion, which has the heaviest weighting of all the main criteria, BWINPro receives the highest priority by some distance. This simulator has the advantage of being freely available online. It was programmed in the Java programming language as part of the TreeGrOSS (Tree Growth Open Source Software) project, using open-source software packages. The advantage of this is that the software is free of charge, the program code is clearly identifiable and users can easily adapt the program to their specific needs. Another advantage of BWINPro is its object-oriented software structure consisting of multiple Java packages. SILVA and MOSES also feature sub-modules and components, but because less information was available about these, they were both rated below BWINPro. SILVA receives a slightly lower priority than MOSES because it did not have a user manual, although in other respects this simulator is well documented. PrognAus receives the lowest priority as it performed badly in all three sub-criteria, although the main reason was its patchy documentation.

4.3. Sensitivity analysis

The utility values of the simulator alternatives are heavily dependent on the normalised weights of the main criteria. Consequently, small changes in the weights could alter the ranking of the alternatives. Because the weightings are based on subjective decisions, the stability of the alternative ranking must be verified using different normalised weights. A sensitivity analysis was therefore conducted to determine how stable the utility values would remain if the criteria weightings were to be subsequently changed. Should the change in weightings cause a variation in the utility value ranking, a review/revision would be needed. To this end, nine additional scenarios were simulated with different normalised weights for the main criteria:

- Same weighting of each criteria (0.125)
- Different weighting, with one criterion in each case being considered as very important (0.500) and the rest as equally 'unimportant' (0.071) (e.g. C1 = 0.5 and C2–C8 = 0.071).

The results are presented in **Table 3**. By comparing the total number of position points it can be seen that BWINPro, SILVA and PrognAus come very close together in the various sensitivity scenarios. However, BWINPro is still the best simulator in five of the nine scenarios, slightly outperforming SILVA in terms of the total number of position points.

Criteria weights			Utility value and Simulator position							
			BWINPro		SILVA		MOSES		PrognAus	
i)	C1–C8	=0.125	0.269	1	0.262	2	0.224	4	0.246	3
ii)	C1 Model approach	=0.5	0.207	4	0.289	1	0.267	2	0.237	3
	C2 Range of application	=0.5	0.261	1	0.257	2	0.235	4	0.248	3
	C3 Calibration specification	=0.5	0.318	1	0.226	3	0.204	4	0.252	2
	C4 Simulator input	=0.5	0.272	1	0.268	2	0.246	3	0.213	4
	C5 Sub-models for growth	=0.5	0.255	2	0.252	3	0.202	4	0.291	1
	C6 Simulator output	=0.5	0.264	2	0.273	1	0.237	3	0.226	4
	C7 Environmental influence	=0.5	0.190	3	0.311	2	0.181	4	0.318	1
	C8 Software	=0.5	0.384	1	0.218	2	0.217	3	0.181	4
Sum of position points (lowest = best)				16		18		31		25

Note: Calculated utility values if the normalised criteria weights are changed, (i) same weighting of each criteria (0.125), (ii) with one criterion in each case being considered as very important (0.500) and the rest as equally 'unimportant' (0.071). The last row contains the sum of the position points.

Table 3. Results of the sensitivity analysis.

5. Future steps

The next phase involves parametrising the chosen simulator using data from Switzerland and then checking its validity, that is, how accurately it reflects reality [36]. During the parametrisation process, the simulator's key sub-models, such as diameter and height increment, mortality and ingrowth, will be described climate-sensitively and optimally adapted to the available data using appropriate functions. Consequently, it only makes sense to validate the simulator results once the reparametrisation has taken place. Furthermore, the individual-tree simulators in question consist of multiple sub-models. Pre-validating the sub-models would be highly resource intensive and not justified for the purposes at hand.

At a later stage, the chosen simulator will be integrated into an overarching DSS covering forest planning and management processes.

DSSs are crucial because the management of a forest is a challenging task as all the major ecosystem services, such as timber production, recreation, biodiversity conservation and carbon storage, occur side by side on a small scale and are highly demanded by society. Wrong management decisions can have huge consequences, ranging from a loss of ecological and social values up to a loss of economic income. This situation underlines the urgent need for appropriate concepts and tools for decision support that consider all ecosystemservices and can help forest managers to find an optimal management strategy to fulfil the diverse societal and political demanded services [3]. Climate change additionally exacerbates the problems [37].

For decision support systems, it is vital that the forest growth simulator links and interacts with multi-criteria decision analysis (MCDA) [3, 38, 39]. Only the combined use of simulators and MCDA will cover all the phases involved in the forest-planning process. This includes recognising a decision-making problem, developing management alternatives and, ultimately, selecting an alternative and authorisation to implement it [39].

6. Conclusion

AHP analysis provides a structured evaluation process to support simulator comparison. Using the pairwise comparison matrix, AHP-enabled quantitative ratios were obtained based on the individual qualitative assessments. This made comparison of the simulators much easier by providing a transparent and traceable basis for:

1. the process of selecting comparison criteria
2. the pairwise comparisons of criteria and
3. the pairwise evaluations of the alternatives with respect to each criterion [9].

The comparison criteria were established based on the recommendations concerning the uniform and standardised description of forest growth simulators [35]. On the one hand, these enabled the requirements for the chosen simulator to be defined. On the other hand, they provided a framework for the decisions based on which the individual simulators could be thoroughly scrutinised, particularly in terms of their model and software structure and functionalities and which enabled a critical argumentation and assessment. Particularly when comparing such complex instruments, AHP provides a sound basis for ensuring that all key factors are taken simultaneously into account in the decision. Thanks to quantitative representations, the results are rendered transparent and comparable and ‘gut decisions’ are significantly reduced.

The main weakness of the AHP method is that it becomes very complicated when a large number of criteria are involved. In such cases, evaluation of all the pairwise comparisons is much more time consuming than when the number of pairwise comparisons is kept to a strict minimum. Furthermore, a comprehensive assessment often results in ‘unnecessary evaluations’ and this overdetermination can lead to inconsistencies [9].

In general, AHP has proved well suited in evaluating a forest growth simulator. However, it should be noted that AHP itself only provides a subjective basis for decision-making, although the margin of subjectivity can be controlled by means of a sensitivity analysis. This shows whether the result would be significantly different if the criteria weightings were slightly changed. In this case, the ranking of the alternatives proved relatively robust, even with the sensitivity analysis. However, the sensitivity analysis also revealed that, with different criteria weights, SILVA and PrognAus receive higher utility values than BWINPro in some cases. In addition to the sensitivity analysis, therefore, several different decision makers could potentially be involved in performing the AHP analysis. This could generate alternative results, enabling a ‘final’ end comparison.

The AHP model presented here found BWINPro to be a suitable simulator for the defined objectives. The main reasons for this choice were BWINPro's free availability as open-source software and its modular structure in the Java programming language. On the one hand, this enables the parametrisation of sub-models for Swiss conditions or the replacement of individual components with components developed in-house. In addition, the transparent model structure provides the basis for further development into a climate-sensitive version. The model also offers a broad range of treatment variants commonly found in forestry practice, including those aimed at nature conservation and promoting biodiversity.

Using AHP, a simulator was evaluated which will go on to be parametrised for Swiss conditions with data from long-term forest experimental plots and the National Forest Inventory. Furthermore, the detailed analysis of the different functionalities of the four simulators found that the simulator in question lends itself particularly well to implementation in a DSS. This DSS could support forest planning and management processes in the future.

Acknowledgements

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Nomenclatures

Assortment: The breakdown of a stand of timber/trees into different products.

Basal area: The total area of the stem cross-sections of all living trees.

Biomass: All organic matter in an ecosystem. It includes both living and dead material.

Continuous cover forestry: Continuous cover is defined as the use of silvicultural systems whereby the forest canopy is maintained at one or more levels without clear felling.

Crown: Branches and upper part of the stem of tree. Tree crown can be measured by crown base (stem height where the branches begin), crown height (from crown base to the top of the tree) and crown per cent (ratio of crown length and tree height).

Diameter at breast height (dbh): Diameter of a tree stem 1.3 m above ground (convention on standardised measurement of stem thickness).

Ecosystem Service: Function of an ecosystem that contributes to human well-being, for example, timber production or carbon storage.

Final Harvest: Harvest (clearance) of a forest stand that has reached the planned harvesting age.

Forest enterprise: Organisational unit, which, as a public or private legal entity or natural person, manages forests strategically and operatively.

Crop tree (Future tree): Trees which will be selected in an early stage of stand development and which are expected to become a component of a future commercial harvest. Through periodical thinnings competing trees are removed.

Growing stock: This is the volume of stem wood with bark of all living trees and shrubs in a stand of area. The growing stock is usually given in cubic metres of wood per hectare forest.

High forest: A high forest is a type of forest originated from seed or from planted seedlings. It usually consists of large, tall mature trees with a closed canopy.

Ingrowth: The volume, basal area or number of those trees in a stand that were smaller than a prescribed minimum diameter or height limit at the beginning of any growth-determining period and, during that period, attained the prescribed size.

Increment: Increase in diameter, height, circumference, basal area, volume or value of a stand or individual tree within a defined time interval.

NFI: Sampling inventory for a whole country. It periodically records the condition of the forests and any changes that have taken place. On the basis of these data, statistically reliable conclusions can be drawn for a whole country. The primary source of data are aerial images, data collected in forests and surveys of the forest service.

Planting: Planting of young trees in a forest to regenerate it.

Regeneration: Establishment and growth of young trees. Regeneration that takes place without human involvement is called natural regeneration (opposite planting)

Silviculture: Silviculture is the practice of controlling the establishment, growth, composition, health and quality of forests to meet diverse needs and values.

Site: Entirety of all the environmental factors that affect plant communities.

Site factors: Environmental factors influencing plants, either > biotic (e.g. vegetation competition and harmful organisms) or abiotic (e.g. geology and weathering).

Site index (based on top height): A species-specific measure of actual or potential forest productivity (site quality), expressed in terms of the average height of trees included in a specified stand component at a specified base age.

Stand: Tree collective with homogeneous structure and tree species composition. It represents the smallest spatial unit for silvicultural activities.

Stocking: Collective of trees or shrubs in a forest.

Target diameter: Diameter at breast height at which trees will be harvested.

Thinning: A silvicultural treatment made to reduce stand density of trees primarily to improve growth, enhance forest health, or recover potential mortality.

Timber-harvesting expenses: Cost and effort involved in preparing the wood (timber harvest)

Timber-harvesting revenues: Through the sale of wood earned money.

Top height: The average height of the 100 trees/ha of the largest diameter.

Tree volume (or stemwood): Aboveground wood of the tree stem (without branches, but with bark), unit of measure is solid cubic meter standing wood.

Appendix

Tables 4–7 describe the sub-models and functionalities for each of the four simulators.

1.1	Spatial resolution	Semi-distance-dependent individual-tree model
1.2	Age dependency	Age dependent
2.1	Silvicultural scenario studies	*ForestSimulator:* simulation and analysis of individual stands; *WaldPlaner:* simulation, analysis and optimisation of multiple stands in a forest enterprise
2.2	Updating of forest stands	In 5-year steps, a simulation of more than 30–40 years is not recommended
2.3	Suitable for research/education/ management	Yes
3.1	Specification with regard to region and site	Parametrised for northwest Germany, southern Germany [40, 41], Saxony [42]
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Final crop tree selection (interactive and automatic), protection of trees above a specified dbh (for nature conservation), protection of minority species (biodiversity), selection of habitat trees, target diameter harvesting, shelterwood cutting, clear cutting, thinning from below, planting
3.4	Available tree species	A total of 19 tree species; the following are fully parametrised: oak, beech, spruce, Douglas fir, pine
4.1	Area shape and size	Model stands based on a square or circular sample plot
4.2	Input data requirements	Sample plots from forest inventory can be analysed
4.3	Processing of missing information	Data addition routine for diameter distributions, missing height values, estimated age, crown bases, crown widths, tree positions
5.1	Height increment	Potential-dependent estimate using yield tables, distance-independent; model and coefficients: [25]
5.2	Diameter increment	Potential-independent, distance-independent; model and coefficients: [25]
5.3	Crown model	Crown base, crown width; model and coefficients: [25]
5.4	Mortality model	*Density-related mortality:* model and coefficients: [25]; *Age-related mortality:* activated above a specified maximum age
5.5	Regeneration/ingrowth model	Ingrowth is regulated via regeneration layers (manually or automatically); automatic routine: sub-model determines whether and how much of which species is set as regeneration and how much is attributed to ingrowth (dbh > 7 cm)

5.6	Site properties	Regional site index, site index (based on top height) at age 100
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment, calculation of timber-harvesting revenues
6.4	Structural characteristics	Number of species, Shannon index, species profile index, percentage of height mixing, percentage of diameter mixing, percentage of species mixing, quantity of deadwood
6.5	Biomass components	Done as part of the assortment + key nutrients per assortment
7.1	Consideration of disturbances	No
7.2	Consideration of climate change	In progress
8.1	Availability of programming code	BWINPro is available online as TreeGrOSS (Tree Growth Open Source Software).
8.2	Modular structure	Yes
8.3	Documentation	Good to very good

Table 4. Characteristics of BWINPro.

1.1	Spatial resolution	Distance-dependent individual-tree model
1.2	Age dependency	Not age dependent
2.1	Silvicultural scenario studies	Enables the development and optimisation of silvicultural treatment strategies
2.2	Updating of forest stands	Possible, interactive and in batch operation, in 5-year steps
2.3	Suitable for research/education/management	Yes
3.1	Specification with regard to region and site	*Site performance model:* parametrised with data from long-term experimental plots in Bavaria, Lower Saxony and Switzerland; *Increment, crown development, mortality:* parametrised with data from long-term experimental plots at TU München
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Thinning from below, thinning from top, selective thinning, final crop tree technique, target diameter harvesting, combination of individual techniques in relation to strength and intervention time
3.4	Available tree species	Spruce, fir, pine, beech and oak
4.1	Area shape and size	Stand is simulated as a rectangular area, the size depends on the stand density and the number of trees
4.2	Input data requirements	Interface for processing inventory data

4.3	Processing of missing information	Spatial stand structure is added via SILVA-STRUGEN structure generator [43], missing tree and stand indicators via tariff and model functions
5.1	Height increment	Chapman-Richards function, potential derived from site factors, distance dependent; model: [4], coefficients: [19]
5.2	Diameter increment	Potential dependent, distance dependent; model: [4], coefficients: [19]
5.3	Crown model	crown base, crown width; model: [4], coefficients: [19]
5.4	Mortality model	LOGIT function, mortality is determined by a random number (if Pm > random number --> mortality); model: [44], coefficients: [19]
5.5	Regeneration/ingrowth model	Not available
5.6	Site properties	Species-specific unimodal dose-response functions: aggregate nine site factors which describe the effect of the site on the potential height increment [45]
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment [46], timber-harvesting expenses, timber-harvesting revenues
6.4	Structural characteristics	Characteristic values of stand structure, stand stability and diversity (Clark–Evans index, Pielou index, species profile index, species mixing and diameter differentiation)
6.5	Biomass components	Derived by estimators from tree dimensions
7.1	Consideration of disturbances	No
7.2	Consideration of climate change	Simulation of reactions to changed environmental conditions is possible within the scope specified by the empirical database (see site model)
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	Structured into various sub-modules
8.3	Documentation	Good

Table 5. Characteristics of SILVA.

1.1	Spatial resolution	Distance-dependent individual-tree model
1.2	Age dependency	Age dependent
2.1	Silvicultural scenario studies	Possible
2.2	Updating of forest stands	In 5-year steps, the maximum simulation length is 40 growth periods
2.3	Suitable for research/education/ management	Yes
3.1	Specification with regard to region and site	Parametrised with data from long-term experimental plots in Austria and Switzerland

3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Clear cutting, thinning from top, thinning from below, random thinning, target diameter harvesting, planting
3.4	Available tree species	beech, oak, other hardwood, spruce, pine, fir, Swiss stone pine, larch, other softwood
4.1	Area shape and size	Stand is simulated as a rectangular area, size can be freely selected
4.2	Input data requirements	Stands can be generated based on a survey or angle count sampling
4.3	Processing of missing information	STANDGEN: stand generation program, from even-aged monospecific (monoculture in even-aged forest) to uneven-aged mixed (selection forest)
5.1	Height increment	Potential dependent, determined by top height curves from different yield tables, distance dependent; model: [21, 47], coefficients: [48], MOSES 3.0
5.2	Diameter increment	Potential dependent, based on dbh/height ratio, distance dependent; model: [21, 47], coefficients: [48], MOSES 3.0
5.3	Crown model	Periodic adjustment of crown base; model: [47], coefficients: [48], MOSES 3.0
5.4	Mortality model	LOGIT function, mortality is determined by a random number (if P < random number --> mortality); model: [21], coefficients: MOSES 3.0
5.5	Regeneration/ingrowth model	Regeneration sub-model: the algorithm predicts the probability, species composition and density of regeneration. From a height of 1.4 m, trees are simulated using the standard growth functions
5.6	Site properties	Regional site index, site index (based on top height) at age 100
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment, timber-harvesting expenses
6.4	Structural characteristics	Aggregation index, mixing index
6.5	Biomass components	Biomass of wood over 7 cm in dbh, biomass from the bark, branches and needles and total biomass
7.1	Consideration of disturbances	Estimate of windthrow and snow breakage based on h/d ratio
7.2	Consideration of climate change	No
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	Consists of multiple components: MOSES 3.0 (C++), MOSESbatch (Perl), STANDGEN (Delphi), MOSESFramework (C#), Graphical User Interface (C#)
8.3	Documentation	Good to very good

Table 6. Characteristics of MOSES.

1.1	Spatial resolution	Distance-independent individual-tree model
1.2	Age dependency	Not age dependent
2.1	Silvicultural scenario studies	Possible to a limited degree (see 3.3)
2.2	Updating of forest stands	In 5-year steps
2.3	Suitable for research/education/ management	Primarily for research and education
3.1	Specification with regard to region and site	Parametrised with data from the Austrian forest inventory
3.2	Type of mixtures and stand structure	Even-aged as well as uneven-aged and mixed stands
3.3	Silvicultural treatment variants	Percentage removal from defined dbh classes, target diameter harvesting, removal along an equilibrium curve, LOGIT model for tree removal, defined number of trees; harvesting interventions can be performed interactively or automated [49]
3.4	Available tree species	All common Austrian species
4.1	Area shape and size	Possible to define area size
4.2	Input data requirements	Processing of routine inventory data
4.3	Processing of missing information	No
5.1	Height increment	Potential independent, according to the Evolon model type; model and coefficients: [50]
5.2	Diameter increment	Potential independent, distance independent; model: [51], coefficients: [48]
5.3	Crown model	Crown ratio (CR); model: [52], coefficients: [48]
5.4	Mortality model	LOGIT function; model: [53], coefficients: [48]
5.5	Regeneration/ingrowth model	Ingrowth determination involves five sub-models: (i) calculation of ingrowth probability, (ii) probability of species occurrence, (iii) its number, (iv) diameter and v) height of the trees [54]
5.6	Site properties	Description based on the following factors: elevation, slope, exposure, relief, soil depth, humus thickness, soil type, soil moisture content, vegetation type and growing space
6.1	Tree lists	Yes
6.2	Stand characteristics	Yes
6.3	Economic measures	Assortment including ABC classification [55]
6.4	Structural characteristics	Dbh distribution, species distribution and various individual-tree attributes
6.5	Biomass components	No
7.1	Consideration of disturbances	Calamity model for windthrow/wind breakage, snow breakage and beetle infestation [56]

7.2	Consideration of climate change	Height increment model [57] and basal area increment model [58] have been expanded to include climatic variables (total precipitation and temperature per year and growing period, average totals for a 30-year period).
8.1	Availability of programming code	Not freely available, not open source
8.2	Modular structure	?
8.3	Documentation	Satisfactory

Table 7. Characteristics of PrognAus.

Author details

Clemens Blattert*, Renato Lemm, and Oliver Thees

*Address all correspondence to: Clemens.blattert@wsl.ch

Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

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Chapter 11

Measuring in Weighted Environments: Moving from Metric to Order Topology (Knowing When Close Really Means Close)

Claudio Garuti

Additional information is available at the end of the chapter

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Abstract

This chapter addresses the problem of measuring closeness in weighted environments (decision-making environments). This chapter show the importance of having a trustworthy cardinal measure of proximity in weighted environments. A weighted environment is a nonisotropic structure where different directions (axes) may have different importance (weight), thus there exist privilege directions. In this kind of structure, it would be very important to have a cardinal reliable index that can say the closeness or compatibility of a set of measures of one individual with respect to the group or to anyone other. Common examples of this structure are the interaction between factors in a decision-making process (system-values interaction), matching profiles, pattern recognition, and any situation where a process of measurement with qualitative variables is involved.

Keywords: weighted environments, measurement, compatibility, compatibility index G, order topology

1. Introduction

This chapter addresses the problem of measuring closeness in weighted environments (decision-making environments), using the concept of compatibility of priority vectors and value systems.

When using the concept of closeness, it comes in mind immediately what means to be close (when close really means close). Thus, when measuring closeness or proximity, we should add

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a point of comparison (a threshold) that makes possible to compare or decide if our positions, system values, or priorities are really close.

For our purposes, compatibility is defined as the proximity or closeness between vectors within a weighted space [1].

We show a proposition for a compatibility index that can measure closeness in a weighted environment, thus can assess pattern recognition; medical diagnosis support measuring the degree of closeness between disease-diagnosis profiles, buyer-seller matching profiles; measuring the degree of closeness between house buyer and seller projects, or employment degree of matching; measuring the degree of closeness between a person's profile with the desired position profile; in curricula network design, conflict resolution; measuring closeness of two different value systems (the ways of thinking) by identifying and measuring the discrepancies, and in general measuring the degree of compatibility between any priority vectors in cardinal measure bases (order topology) [1, 2].

The chapter first presents some theory behind distance (measurement) and closeness concepts in different cases as well as a nice statistical view of distance. Then, it presents the concepts of scales, compatibility, compatibility index G, and some analogies among G and distance concept. Next, it shows a comparison with another compatibility indices present in the literature, reflecting the advantages of G in front of the others (especially within weighted environments). Then, it presents a necessary threshold, which allows establishing "when close really means close" in weighted environments.

Finally, three relatively simple examples are developed, each one presenting a different application for the compatibility index G. One for questioning if the order of choice should be a must to say if two rankings are compatible or not, one for quality testing (testing the Saaty's consistency index through compatibility index G), and one for measuring comparability between two different rules of measurement (two different points of view).

2. Literature review

In metric topology [2], the particular function of distance $D(a,b)$ is used to assess the closeness of two points a, b as a real positive function that keeps three basic properties:

1. $D(a,b) > 0$ and $D(a,b) = 0$ iff $a = b$ (definition of zero distance)
2. $D(a,b) = D(b,a)$ (symmetry)
3. $D(a,b) + D(b,c) \geq D(a,c)$ (triangular inequality)

The general function of distance used to calculate the separation between two points is given as follows:

$$D(a,b) \ = \ \lim(\Sigma_i (a_i - b_i)^n)^{1/n} (i = 1,\ldots,n; n = \text{ dimension of the space}).$$

$$n \to k$$

When applying different values of k, different norms of distance appear:

> For $k = 1$, $D(a,b) = \Sigma_i \text{abs}(a_i - b_i)$. Norm1, absolute norm, or path norm: this norm measures the distance from a to b within a 1D line, "walking" over the path, in one-line dimension.
>
> For $k = 2$, $D(a,b) = [(\Sigma_i(\text{a}_\text{i} - \text{b}_\text{i})^2)]^{1/2}$. Norm2 or Euclidean norm: this norm measures the distance from a to b, within a 2D plane ($X-$ plane) getting the shortest path (the straight line).
>
> For $k = +\infty$, $D(a,b) = \text{Max}_i(\text{abs}(a_i - b_i))$. Norm ∞ or Norm Max: this norm measures the distance from a to b within a ∞D hyperplane, getting the shortest path (the maximum coordinate) from all the possible paths.

In the field of statistics, we may note an interesting (and beautiful) case of distance calculation, which is known as distance of Mahalanobis [3], which meets the metric properties shown before. This distance takes into consideration parameters of statistics such as deviation and covariance (which can be assimilated to concepts of weight and dependence in the Analytic Hierarchy process/Analytic Network Process (AHP/ANP) world). Its formal presentation is:

$$d_m(x,y) = \sqrt{(X-Y)\Sigma^{-1}(X-Y)} \text{ with } \Sigma^{-1} \text{ the matrix of covariance betweem } X, Y.$$

But, for a more simple case (without dependence), this formula can be written as:

$$d_2\left(x_1, x_2\right) = \sqrt{(\frac{(x11 - x12)}{\sigma 1})^2 + (\frac{(x21 - x22)}{\sigma 2})^2} \text{or } d_e(X_1, X_2) = \sqrt{\left(X_1 - X_2\right)^{\mathrm{T}} S^{-1}(X_1 - X_2)},$$

with S^{-1} the diagonal matrix with the standard deviation of variables X, Y.

It is interesting to see that the importance of the variable (to calculate distance) depends on the deviation value (bigger the deviation smaller the importance), that is, the importance of the variable does not depend on the variable itself, but just on the level of certainty on the variable (is this statement always true?).

We consider this approach into discussion, since factors such as weight and dependence are in the bases of AHP and ANP structures [4, 5]; but instead to understand and deal with probabilities and statistics (which by the way are not easy to build and later interpret), the idea here is to apply the natural way of thinking of human being which is based more on priorities than on probabilities. Indeed, we can manage the same information in a more comprehensive, complete, and easy to explain form by combining AHP/ANP with compatibility index G, and working with priorities, avoiding the needs of collecting big databases or understanding and interpreting complex statistic functions.

Thereby, the Multicriteria Decision Making (MCDM) approach through AHP/ANP method gives a very nice tool for our investigation and treatment of the knowledge and experience that experts possess in different fields, and at the same time staying within the decision-making domain (order topology domain), avoiding building huge, and costly databases where the knowledge about the individual behavior is lost.

3. Hypotheses/objectives

In order topology measurement deals with dominance between preferences (intensity of preference), for instance $D(a,b) = 3$ means that dominance or intensity of preference of "*a*" over "*b*" is equal to 3, or that, *a* is three times more preferred than *b*. When talking about preferences, a *relative absolute ratio* scale is applied. *Relative*: because priority is a number created as a proportion of a total (percent or relative to the total) and has no need for an origin or predefined zero in the scale. *Absolute*: because it has no dimension since it is a relationship between two numbers of the same scale leaving the final number with no unit. *Ratio*: because it is built in a proportional type of scale (6 kg/3 kg = 2) [2].

So, making a general analogy between the two topologies, one might say that *"Metric Topology is to Distance as Order Topology is to Intensity"* [2, 6].

An equivalent concept of distance is presented to make a parallel between the three properties of distance of metric topology [1, 2].

This is applied in the order topology domain, considering a compatibility function (Eq. (1)) similar to distance function, but over vectors instead of real numbers.

Consideration: *A*, *B*, and *C* are priority vectors of positive coordinates and $\Sigma iai = \Sigma ibi = \Sigma ici = 1$.

$G(A,B)$ is the compatibility function expressed as:

$$G(A,B) = \tfrac{1}{2}\sum\left(\left(ai + bi\right)\frac{\mathrm{Min}(ai,bi)}{\mathrm{Max}(ai,bi)}\right) \tag{1}$$

This function presents [1, 2, 5, 6]:

1. $0 \le G(A,B) \le 1$ (*nonnegative real number*)

   The compatibility function, *G*, returns a nonnegative real number that lays in the 0–1 range. With $G(A,B) = 0$, if *A* and *B* are perpendicular vectors ($A \perp B$), and represent the definition of total incompatibility between priority vectors *A* and *B* ($A \circ B = 0$).

   Also, $G(A,B) = 1$, if *A* and *B* are parallel vectors ($A = B$ for normalized vectors), and represent the definition of total compatibility between priority vectors *A* and *B* ($A \circ B = 1$).

2. $G(A,B) = G(B,A)$ *(symmetry)*

Symmetry condition: the compatibility measured from *A* to *B* is equal to the compatibility measured from *B* to *A*.

Easy to proof, just interchanging *A* for *B* and *B* for *A* in the compatibility function *G*.

3. $G(A,B) + G(B,C) \geq G(A,C)$ (*triangular inequality*)
4. If *ACB* and *BCC* ⇔ *ACC* (*nontransitivity of compatibility*): if *A* is compatible with *B*, and *B* is compatible with *C*, does not imply that *A* is necessarily compatible with *C*.

For property 3, it is easy to prove that if *A*, *B*, and C are compatible priority vectors (i.e., $0.9 \leq G_i \leq 1.0$ for *A*, *B*, and *C*), then property 3 is always satisfied. But, this property is also satisfied for the more relaxed (and interesting) condition where only two of the three vectors are compatible. For instance, if *A* is compatible with *B* ($G(A,B) \geq 0.9$) and *A* is compatible with *C* ($G(A,C) \geq 0.9$), or some other combination of *A*, *B*, and *C*, then condition 3 is also satisfied. This more relaxed condition allows compatible and noncompatible vectors to be combined while property 3 is still satisfied.

This situation can be geometrically viewed in the next figure.

Figure 1 shows the compatibility neighborhood for *A*, in relation to *B* and *C*, with its minimum compatibility value of 0.9 represented by the radius of the circle (in the center, the compatibility reaches its maximum value of 1.0). Thus, $G(A,B) = G(A,C) = 0.9$ represents the minimum compatibility point, or the maximum distance for positions *B* and *C* to still be compatible with position *A*. Of course, $G(B,C) < 0.9$ that represents a noncompatible position for points *B* and *C*.

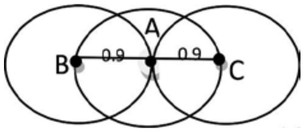


Figure 1. Maximum circle of compatibility for position A, related to B and C [2].

Notice that property 3, $G(A,B) + G(B,C) \geq G(A,C)$ is still valid, indeed any combination that one can be made will keep the inequality satisfied since if *C* gets closer to *A* (increasing the right side of the equation), then *G*(*B*,*C*) will also grow. The extreme case when *C* is over *A* ($G(A,C) = 1.0$), then $G(B,A) + G(B,C) = 0.9 + 0.9 = 1.8 > 1.0$ keeping the inequality satisfied [2].

We may also define incompatibility function as the arithmetic complement of the compatibility:

Incompatibility = 1 – Compatibility.

Thus, incompatibility is equivalent to 1 – *G*. *By the way, the incompatibility concept is more close to the idea of distance, since the greater the distance the greater the incompatibility* [1, 2, 5, 6].

Two simple examples of this parallel between *D*(*x*,*y*) and *G*(*X*,*Y*) are given. But first, to make *D* and *G* functions comparable, absolute distance *D* must be transformed into relative terms as a percentage value since the priority vectors are normalized vectors for the *G* function. Thus, the maximum possible value for D^1 (Norm1) is 2 and for D^2 (Norm2) is $\sqrt{2}$, while performing the ratios with respect to the maximum possible value and obtaining D in relative terms as percentage of the maximum value.

For the first example, two different and very different vectors A and B with coordinate: {0.3, 0.7} with {0.7, 0.3} and {0.1, 0.9} with {0.9, 0.1} are considered.

Considering also incompatibility = 1 – Compatibility or 1 – $G(A,B)$. Then:

> Compatibility between A and B is shown by $G(A,B)$ (*real positive value laying in 0–1 range*).

Incompatibility between A and B is shown by 1 – $G(A,B)$ (*real positive value laying in 0–1 range*).

Table 1 shows the results of applying D^1, D^2, and (1 – G) functions.

A*, *B **Coordinates**	**$D^1(a.b)$ Distance *A–B* in Norm1 (normalized)**	**$D^2(a,b)$ Distance *A–B* in Norm2 (normalized)**	**Incompatibility = 1 – G(*A*,*B*)**
$A = \{0.3, 0.7\}$ $B = \{0.7, 0.3\}$	0.8/2 = 0.4 (40%)	$0.4\sqrt{2}/\sqrt{2}$ = 40%	1 – (0.3/0.7) = 57%
$A = \{0.1, 0.9\}$ $B = \{0.9, 0.1\}$	1.6/2 = 0.8 (80%)	$0.8\sqrt{2}/\sqrt{2}$ = 80%	1 – (0.1/0.9) = 89%

D^1= Sum (Abs(differences)/2) D^2= Sqroot(Sum(Square(differences))2)

Table 1. Evaluating distance and incompatibility for nonsimilar set of coordinates.

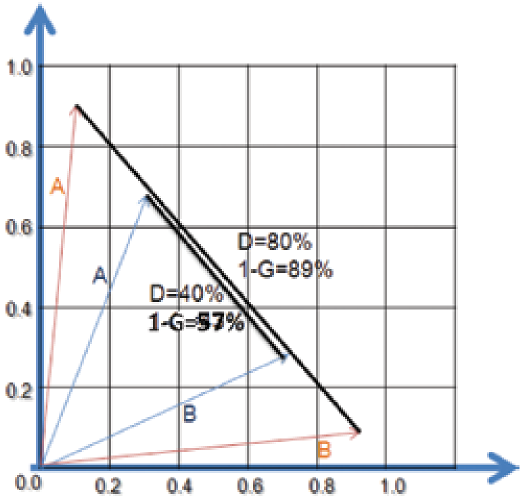


Figure 2. Two examples for distance and compatibility functions for far and very far A and B.

Figure 2 shows in 2D Cartesian axes how far (incompatible) is *A* from *B* in both cases. Notice that for the case represented in brown (for *D* = 80% and *G* = 89%), vectors *A* and *B* are (geometrically) almost in a perpendicular position (*A* relative to *B*) [2].

$$1 - G = 57\%$$

Next, using the same procedure, we compare for similar and very similar *A* and *B* vectors with coordinates: {0.3, 0.7} compared with {0.4, 0.6} and {0.10, 0.90} compared with {0.11, 0.89}.

Table 2 shows the results of applying D^1, D^2, and 1 – *G* (incompatibility = 1 – compatibility).

***A*, *B* Coordinates**	**D^1(%)**	**D^2(%)**	**Incompatibility = 1 – *G*(%)**
A = {0.30, 0.70} *B* = {0.40, 0.60}	0.2/2 = 0.1 (10%)	$0.1\sqrt{2}/\sqrt{2} = 10\%$	1 – 0.820 = 18%
A = {0.10, 0.90} *B* = {0.11, 0.89}	0.02/2 = 0.01 (1%)	$0.01\sqrt{2}/\sqrt{2} = 1\%$	1 - 0.981 = 1.9%

Table 2. Calculating distance and incompatibility for similar set of coordinates.

The trend of the results for *D* and G functions is the same in both cases, when increasing the distance or making vectors more perpendicular and when decreasing the distance or making the vectors more parallel. This is an interesting parallel to these concepts and their trends, considering that different concepts (distance and incompatibility in different ratio scales) are being used [2].

4. Research design/methodology

One way to calculate compatibility in a general form is by using the inner or scalar vector product, defined as $A \circ B = |A||B|\cos\alpha$. This expression of dot product is preferable to the Cartesian version, since it highlights the relevance of the projection concept represented by $\cos\alpha$ and also because when working with normalized vectors the expression $A \circ B$ becomes equal to $\cos\alpha$, which shows that the projection part of the dot product is the most relevant part.

4.1. Definitions and conditions [2]

Assuming:

A. Two normalized vectors are closer (compatible), when the angle (α) formed by both vectors on the hyperplane is about 0° or $\cos\alpha$ is near to 1. From a geometric point of view, they will be represented by parallel or nearly parallel vectors. In this case, they will be defined as compatible vectors.

B. Two normalized vectors are not closer (not compatible) when the angle (α) formed by both vectors on the hyperplane is near 90° or cos α is near to 0. From a geometric point of view, they will be represented by perpendicular or nearly perpendicular vectors. In this case, they will be defined as noncompatible vectors.

Figure 3 [1, 2] shows the geometric interpretation of vector compatibility. Therefore, there is an operative way to measure compatibility in terms of vector projection. This interpretation of dot product will be very useful for the purposes of finding a compatibility measurement of two priority vectors in the domain of order topology.

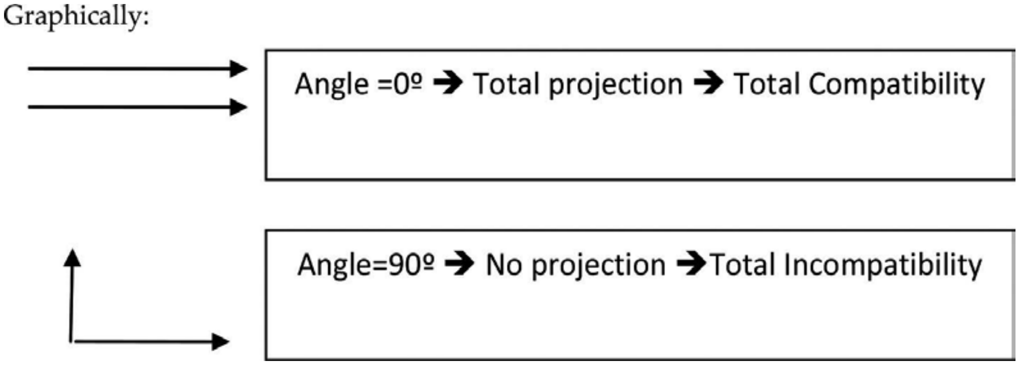


Figure 3. Geometric interpretation of vector compatibility in terms of its projection.

Since the space is weighted (we are working in weighted environment), it is also necessary to weight each projection (each cos α_i) and to take into account the changes of the angle and the weight coordinate by coordinate (coordinate "i" may have a different projection and weight than coordinate "$i + 1$"). Thus, the final formula to assess a general compatibility index of two consistent or near consistent vectors A and B from point to point throughout the both profiles is [1, 2, 5–7]:

$$G(A,B) = ½\sum\left(\left(ai+bi\right)\frac{\mathrm{Min}(ai,bi)}{\mathrm{Max}(ai,bi)}\right)$$

$$\text{With}: \quad \Sigma a_i = \Sigma b_i = 1$$

$$G\left(A,B\right) = \text{general compatibility index of DM1 with respect of DM2.}$$

This can be shown graphically in **Figure 4** [1, 2].

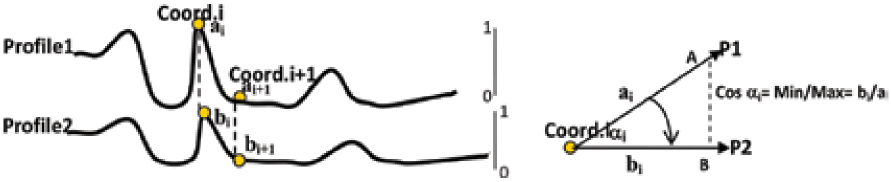


Figure 4. Representation of the cosine projection changing point to point in terms of the profiles.

The *G* function is a transformation function that takes positive real numbers from the range [0, 1], coming from normalized vectors *A* and *B* and returns a positive real number on the same range:

$$a_i, b_i X[0,\ 1] \rightarrow G(A,B) \rightarrow R^+ X[0,\ 1]$$

This transformation has two particularly good properties [2]:

1. It is bounded in 0–1 (presenting no singularity or divergence).
2. The outcome is very easily interpreted as a percentage of compatibility, representing the 0 = 0%, or total incompatibility and 1 = 100%, or total compatibility.

It is also possible to define a threshold for compatibility index at 0.90[1,2]. Thus, when two vectors have an index of compatibility equal or greater than 90%, they should be considered compatible vectors.

Since, incompatibility = 1 – compatibility, then the threshold for tolerable incompatibility is 10%. (This threshold is equivalent with the consistency index in AHP that tolerates a maximum of 10% of inconsistency in the pair comparison matrix.)

Next, a simple application example for 2D vectors *A* and *B* is presented.

The first case is for equal vectors *A* = *B*.

A = {0.5; 0.5}; *B* = {0.5; 0.5}, then:

$$G(A,B) = ½((0.5 + 0.5)(1/1) + (0.5 + 0.5)(1/1)) = 1.$$

Being 100% compatible or 1–1 = 0% incompatible, this result is expected because *A* and *B* are the same vectors.

The second case is for two very different vectors.

A= {0.10; 0.90}; *B* = {0.90; 0.10}, then:

$$\text{Min}\{a1;b1\} = \text{Min}\{0.1;\ 0.9\} = 0.1;\ \text{Max}\{a1;b1\} = \text{Max}\{0.1;\ 0.9\} = 0.9, \text{ and } (\text{Min}/\text{Max})_1 = 0.111.$$

The same for coordinate 2:

$(\mathrm{Min/Max})_2 = 0.111$, and $G(A,B) = ½((0.1 + 0.9)0.111 + (0.9 + 0.1)0.111) = 0.111$ (11.1% of compatibility or 88.9% $\gg$ 10% of incompatibility). This is also an expected outcome since geometrically they are almost perpendicular vectors (vector A has almost no projection over B).

5. Comparing G with other compatibility indices in the literature

It should be noted that when using other compatibility index formulae, for instance, the classic dot product and dividing the result by "n" (*"n" is* the vector dimension), this operation is like taking the average instead of weighting to evaluate the incompatibility, the result of this operation applied on the last example of vectors A and B is: $(0.1/0.9 + 0.9/0.1)/2 = 4.55$ (or 355% of incompatibility or deviation from n) [1, 2, 6, 7].

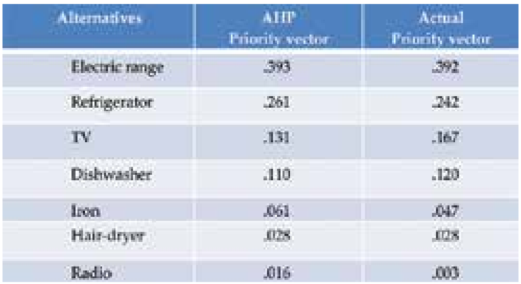
Doing the same in a matrix environment, that is forming the Hadamard product [4, 5] and dividing by n^2 instead of "n" (again taking double average instead of weighting) to assess the deviation, the result is $83.012/2^2 = 20.75$ ($20.75 - 1 = 19.75$ or 1975% of incompatibility or deviation from n^2, presenting both situations a singularity problem (not bounded function). So, they do not seem to be adequate compatibility indices.

Another formula to evaluate incompatibility is the David Hilbert's formula [8, 9], whose expression is $\log(\mathrm{Max}_i(a/b)/\mathrm{Min}_i(a/b))$.

When applying this expression, the formula returns the value of 1.908 (191% of incompatibility). Thus, it also presents a singularity problem (results above the 100% value tough to be interpreted).

Note: *In this research, it was not included compatibility indices based on ordinal scale, because the ordinal scale is not able to respond adequately to the more rich and complex concept of proximity (distance). In fact, the order topology shows clearly that is the intensity (not the ranking), what really matter to establish proximity between vectors.*

A simple example is shown in **Figure 5** [10].



Alternatives	AHP Priority vector	Actual Priority vector
Electric range	.393	.392
Refrigerator	.261	.242
TV	.131	.167
Dishwasher	.110	.120
Iron	.061	.047
Hair-dryer	.028	.028
Radio	.016	.003

Figure 5. Example of relative electric consumption of household appliances.

5.1. Comparing performance of G with other compatibility indices

Suppose the next situation, having an AHP and actual priority vectors for the relative electric consumption of household appliances.

The AHP priority vector is the priority vector that is obtained from the 7 × 7 pair comparison matrix of the alternatives, and actual priority vector is using the direct relation between the consumption of each alternative related to the total.

We have:

S	= 1.455 (= 46% > 10%	➔ incompatible)	(Saaty's index)
H	= 0.832 (= 83% > 10%	➔ incompatible)	(Hilbert's index)
IVP	= 1.630 (= 63% > 10%	➔ incompatible)	(inner vector product)
G	= 0.920 (= 92% > 90%	➔ compatible)	(G index)

So, AHP and actual vectors are noncompatible under S, H, or IVP indices, yet, compatible under G index. However, AHP and actual values are compatible vectors indeed (as expected), and G is the only index that captures correctly this condition of closeness between vectors [1, 2, 5, 6].

The first three formulae present a divergence process (singularities). As vector A deviates from vector B (being more and more incompatible), they become closer to perpendicular vectors.

The G function becomes the only formula capable of correctly assessing the compatibility without falling in a singularity (*divergence*), or remaining immobilized, as a standard distance calculation does when the absolute difference between the coordinates is kept constant. In fact, a complete study[1] of the behavior of different compatibility indices is presented in **Table 4**[2] [2, 6, 7].

The study was made initially for a 2D space (vectors of two coordinates), since the idea was to perform a sensitive analysis and observe the patterns of behavior of different compatibility indices in two special situations:

A. Parallel trend situation: when two vectors are near each other or close enough to be considered parallel vectors.

B. Perpendicular trend situation: when two vectors are separate or far enough to be considered perpendicular vectors.

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[1] Claudio Garuti, "When close really means close?" Paper of Compatibility. Presented in the ISAHP9 Symposium and Proceeding. Viña del Mar-Chile, 2007.

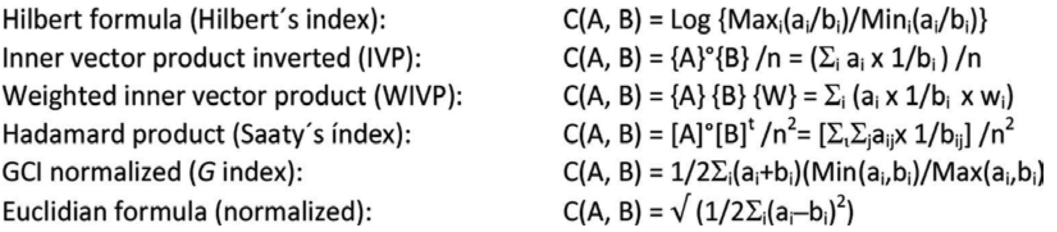
[2] The different compatibility indexes analyzed were taken from the literature and from linear algebra definitions.

On medicine	Measuring the degree of matching (proximity) between patient and disease diagnose profiles
On buyers-seller profiles	Measuring the degree of matching between house buyers and sales project
On group decision making (conflict resolution)	Measuring how close are two (or more) different value systems (where they differ and for how much)
On quality tests	Measuring what MCDM decision method can builds a better metric
On agricultural production and supplier selection	Measuring the proximity between the cultivate plants against a healthy plant (based on its micro & macro nutrients) and selecting the best nutrient seller
On shift-work prioritization	Measuring how close are the different views among the different stakeholders (workers view, company view, community view)
On company social responsibility (CSR)	Measuring how close are the different views among the different stakeholders (economic, environmental and social view)

Notice: all the examples mentioned above are coming from real cases of application.

Table 4. Possible field of applications for index *G*.

Figure 6 summarizes the compatibility indices that exist, adding the option of Euclidian norm (the classic distance calculation based on Norm2), normalized by its maximum possible value of to present the results in a percentage format.



Hilbert formula (Hilbert´s index): $C(A, B) = Log \{Max_i(a_i/b_i)/Min_i(a_i/b_i)\}$

Inner vector product inverted (IVP): $C(A, B) = \{A\}^{\circ}\{B\} /n = (\Sigma_i a_i \times 1/b_i) /n$

Weighted inner vector product (WIVP): $C(A, B) = \{A\} \{B\} \{W\} = \Sigma_i (a_i \times 1/b_i \times w_i)$

Hadamard product (Saaty´s índex): $C(A, B) = [A]^{\circ}[B]^t /n^2 = [\Sigma_i\Sigma_j a_{ij} \times 1/b_{ij}] /n^2$

GCI normalized (*G* index): $C(A, B) = 1/2\Sigma_i(a_i+b_i)(Min(a_i,b_i)/Max(a_i,b_i)$

Euclidian formula (normalized): $C(A, B) = \sqrt{(1/2\Sigma_i(a_i-b_i)^2)}$

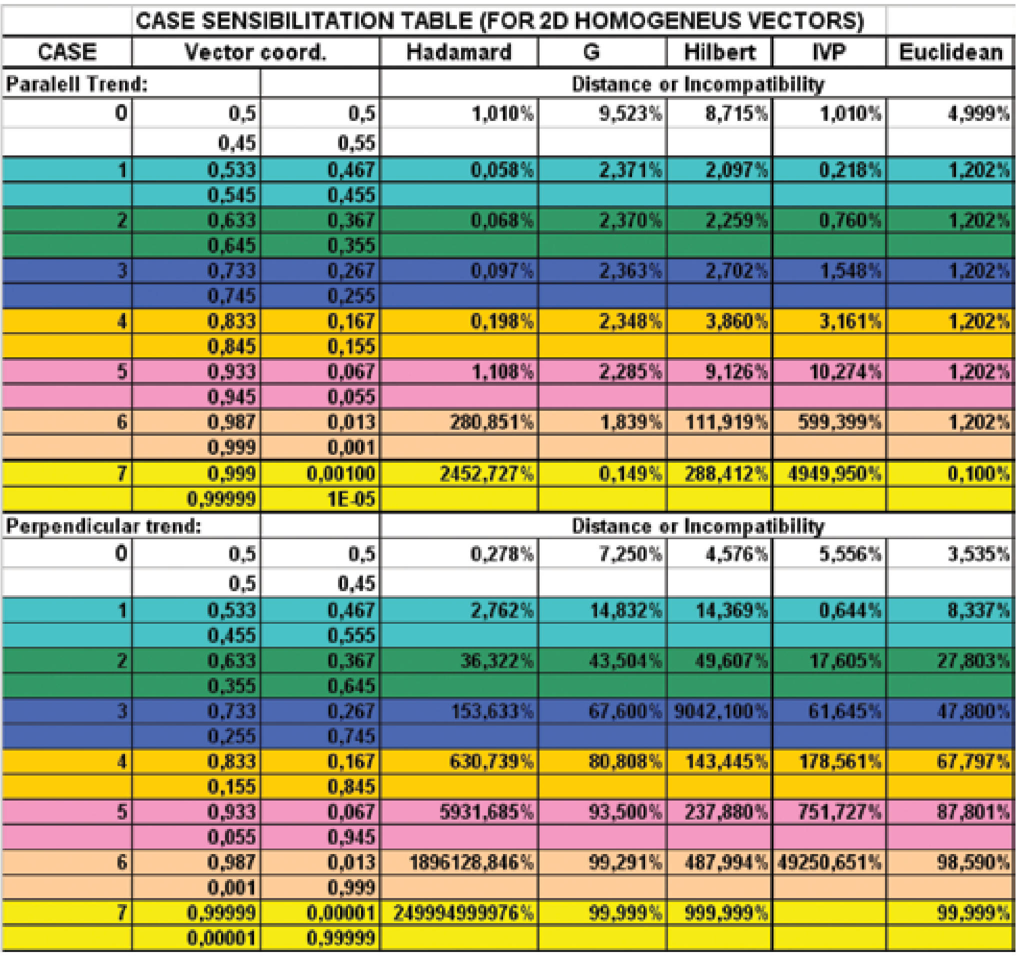
Figure 6. Definition of different formulas for compatibility assessment.

Six formulae in a 2D vector for seven cases for two different trends (parallel trend and perpendicular trend) were tested. The results are shown in **Figure 7**.

6. Generating a threshold for compatibility index *G*

To answer the initial question (*when close really means close*), first it is necessary to have a reliable index of compatibility. However, that is not sufficient; it is also necessary a second condition: a limit or threshold for the index.

For useful purpose, it is necessary to have a limiting lower value (minimum threshold) to indicate when two priority vectors are compatible or close to be compatible, in order to define precisely when close really means close.



	CASE SENSIBILITATION TABLE (FOR 2D HOMOGENEUS VECTORS)						
CASE	Vector coord.		Hadamard	G	Hilbert	IVP	Euclidean
Paralell Trend:			Distance or Incompatibility				
0	0,5	0,5	1,010%	9,523%	8,715%	1,010%	4,999%
	0,45	0,55					
1	0,533	0,467	0,058%	2,371%	2,097%	0,218%	1,202%
	0,545	0,455					
2	0,633	0,367	0,068%	2,370%	2,259%	0,760%	1,202%
	0,645	0,355					
3	0,733	0,267	0,097%	2,363%	2,702%	1,548%	1,202%
	0,745	0,255					
4	0,833	0,167	0,198%	2,348%	3,860%	3,161%	1,202%
	0,845	0,155					
5	0,933	0,067	1,108%	2,285%	9,126%	10,274%	1,202%
	0,945	0,055					
6	0,987	0,013	280,851%	1,839%	111,919%	599,399%	1,202%
	0,999	0,001					
7	0,999	0,00100	2452,727%	0,149%	288,412%	4949,950%	0,100%
	0,99999	1E-05					
Perpendicular trend:			Distance or Incompatibility				
0	0,5	0,5	0,278%	7,250%	4,576%	5,556%	3,535%
	0,5	0,45					
1	0,533	0,467	2,762%	14,832%	14,369%	0,644%	8,337%
	0,455	0,555					
2	0,633	0,367	36,322%	43,504%	49,607%	17,605%	27,803%
	0,355	0,645					
3	0,733	0,267	153,633%	67,600%	9042,100%	61,645%	47,800%
	0,255	0,745					
4	0,833	0,167	630,739%	80,808%	143,445%	178,561%	67,797%
	0,155	0,845					
5	0,933	0,067	5931,685%	93,500%	237,880%	751,727%	87,801%
	0,055	0,945					
6	0,987	0,013	1896128,846%	99,291%	487,994%	49250,651%	98,590%
	0,001	0,999					
7	0,99999	0,00001	249994999976%	99,999%	999,999%		99,999%
	0,00001	0,99999					

Figure 7. Sensitive analysis for different compatibility indices.

We have four different ways to define a minimum threshold for compatibility [2]:

(1) Considering that compatibility is ranged between 0 and 100% ($0 < \cos \alpha < 1$) being 100% the case of total compatibility (represented by parallel vectors), it is reasonable to define a value of 10% of tolerance (1/10th of 100%) as a maximum threshold of incompatibility to consider two vectors as compatible vectors (which means a minimum of 90% of compatibility to consider two vectors compatible), this explanation is based on the idea of one order of magnitude for an admissible perturbation for measurement. This lower bound is also based on the accepted 10% used in AHP for the consistency index. In the comparison matrix of AHP, the 10% limit of tolerate inconsistency comes from the ratio of consistency (CR) obtained from consistency index compared to a random index (CR = CI/RI), that in general has to be less equal 10% (except for the 3 × 3 and 4 × 4 matrix cases). This is telling that as far as CI is from the RI (random index response) as better is CR. It is interesting to recall that CR is built as a comparison from the statistical analysis of RI (this idea will be reviewed in the last case analysis).

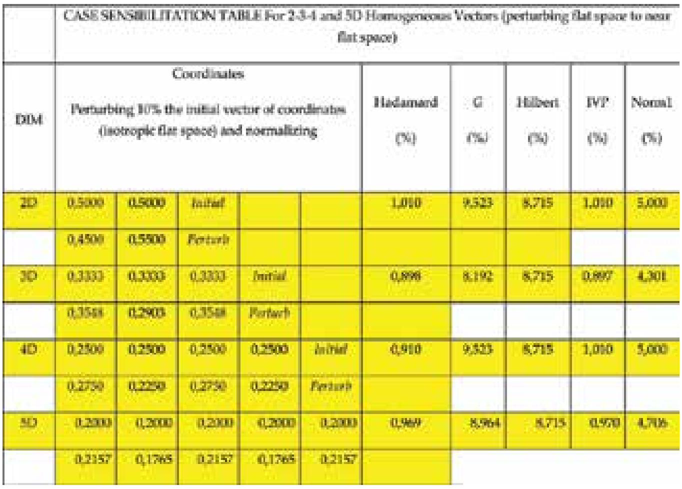
(2) The compatibility index is related to a topologic analysis since compatibility is related to measuring closeness in weighted environments (weighted spaces). **Figure 8** presents a sequence of two, three, four, and five dimensional vectors, the first or initial vector is obtained as an isotropic flat space situation, that is, with equal values ($1/n$) in each coordinate (no privileged direction in the space); the second one is a vector obtained perturbing (adding or subtracting) 10% on each coordinate, creating "small crisps" or little privileged directions, then the incompatibility index is calculated with the five different formulas (the reason to use all formulae is because we are working on a near flat space [no singularities], where every formula works relatively well).

When looking the outputs for incompatibilities, it is possible to observe a good response for everyone (equal or less than 10%), with G and Norm1 ca. 10% and 5% as upper bound in every case.

(3) In **Figure 9**, a simple test was run over an Excel spreadsheet, using the common area example of AHP, where the result (the importance of the area of the figures) can be calculated precisely with the typical geometric formulas and then normalizing its values to obtain the exact priorities as a function of the size of their areas. Doing this way, it is possible to have a reference point of the element values (the right coordinates for the actual area vector).

The next step is perturbing the actual area values by ± 10% producing a new vector of areas, finally over these two vectors (actual and perturbed) is applied the G function to measure their compatibility obtaining a value for compatibility index of 91.92% (or 8.08% of incompatibility). This result is very close to the standard error deviation calculated as Σabs(perturbated − actual)/actual = 10%, this shows that 90% might represent a good threshold, considering that the difference between both outputs is related to the significant fact that this numbers are not just numbers but weights.

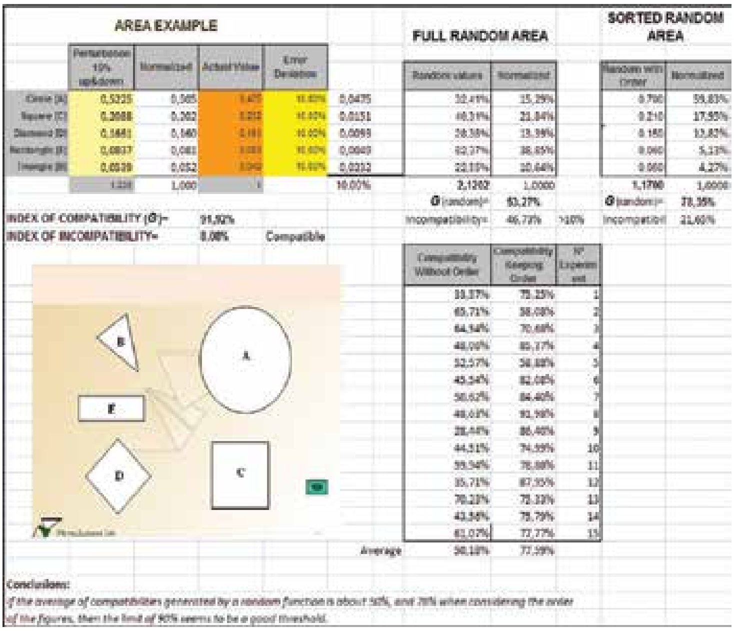
(4) The last way to analyze the correctness of 90% for threshold was carried out, it consists in working with a random function and filling the area vector with random values and calculating G for every case. The goal is to generate an average G for the case of full random values for the areas ("*full random*" means without any previous order among the areas, like figure A is clearly bigger than figure B, and so on), and again producing random values but this time keeping the correct order among the figures (imitating the behavior of a rational DM), and once again generating an average G for this case, then both results are compared against actual values.



	CASE SENSIBILITATION TABLE For 2-3-4 and 5D Homogeneous Vectors (perturbing flat space to near flat space)									
DIM	Coordinates Perturbing 10% the initial vector of coordinates (isotropic flat space) and normalizing					Hadamard (%)	G (%)	Hilbert (%)	IVP (%)	Normal (%)
2D	0,5000	0,5000	*Initial*			1,010	9,523	8,715	1,010	5,000
	0,4500	0,5500	*Perturb*							
3D	0,3333	0,3333	0,3333	*Initial*		0,898	8,192	8,715	0,897	4,301
	0,3548	0,2903	0,3548	*Perturb*						
4D	0,2500	0,2500	0,2500	0,2500	*Initial*	0,910	9,523	8,715	1,010	5,000
	0,2750	0,2250	0,2750	0,2250	*Perturb*					
5D	0,2000	0,2000	0,2000	0,2000	0,2000	0,969	8,964	8,715	0,970	4,706
	0,2157	0,1765	0,2157	0,1765	0,2157					

Figure 8. Defining a possible threshold of 10% for *G* function.

The average *G* for 15 experiments in the first case (keeping no order) was around 50% of compatibility and 78% for the second case (keeping the order among the five figures), both results show that limit of 90% might be a good threshold, in the first case the ratio between threshold and the full random *G* is almost twice bigger 1.8 (0.90 over 0.50), keeping the 0.90 compatibility threshold far from random responses.



AREA EXAMPLE

	Perturbation 10% up&down	Normalized	Actual Value	Error Deviation	
Circle (A)	0,5325	0,565	[illegible]	10,00%	0,0475
Square (C)	0,2088	0,262	[illegible]	10,00%	0,0151
Diamond (D)	0,1681	0,140	[illegible]	10,00%	0,0093
Rectangle (E)	0,0837	0,081	[illegible]	10,00%	0,0049
Triangle (B)	0,0539	0,052	[illegible]	10,00%	0,0232
	1,110	1,000	1		10,00%

INDEX OF COMPATIBILITY (Ḡ)= 91,92%
INDEX OF INCOMPATIBILITY= 8,08% Compatible

FULL RANDOM AREA

Random values	Normalized
32,41%	15,29%
46,31%	21,84%
28,38%	13,39%
82,37%	38,85%
22,15%	10,64%
2,1202	1,0000

Ḡ (random)= 53,27%
Incompatibility= 46,73% >10%

SORTED RANDOM AREA

Random with Order	Normalized
0,700	59,83%
0,210	17,95%
0,160	13,68%
0,060	5,13%
0,050	4,27%
1,1700	1,0000

Ḡ (random)= 78,35%
Incompatibil 21,65%

	Compatibility Without Order	Compatibility Keeping Order	N° Experiment
	33,37%	75,25%	1
	65,71%	58,08%	2
	64,54%	70,68%	3
	48,08%	85,17%	4
	52,57%	58,88%	5
	45,34%	82,08%	6
	58,62%	84,40%	7
	48,63%	91,98%	8
	28,44%	86,40%	9
	44,51%	74,59%	10
	59,54%	78,88%	11
	35,71%	87,35%	12
	70,23%	73,33%	13
	43,54%	75,79%	14
	61,07%	77,77%	15
Average	50,18%	77,59%	

Conclusions:
If the average of compatibilities generated by a random function is about 50%, and 78% when considering the order of the figures, then the limit of 90% seems to be a good threshold.

Figure 9. Possible threshold of 10% for *G* function.

In the second case (threshold over sorted figures), the ratio is much more closer (as expected to be), with a value of 1.16 (0.90 over 0.78), saying that order may help to improve compatibility but is not enough, it needs to consider the weights (not just the preference but the intensity of the preference) which is related to the values of the elements that belong to the vector, as well as the angles of both vectors point to point (geometrically viewed as profiles).

Of course, this test should be carried out for a large number of experiments to have a more reliable response. A second test conducted for 225 experiments (15 people making 15 experiments each) has shown more or less the same initial results for average *G* value in both cases with and without orders (± 0.78 and ± 0.50).

Next, **Table 3** provides the meaning of ranges of compatibility in terms of index *G* and its description.

Degree cof compatibility	**Compatibility value range c(G%)**	**Description**
Very high	≥90%	Very high compatibility Compatibility at cardinal level of measurement (totally compatible)
High	85–89.9	High compatibility (almost totally compatible)
Moderate	75–84.9	Moderate compatibility (compatibility at ordinal level)
Low	65–74.9	Low level of compatibility
Very low	55.1–64.9	Very low compatibility (almost incompatible)
Null (random)	≤55%	Random compatibility (totally incompatible)

Table 3. Ranges of compatibilities and its meaning.

Finally, another interesting way to illustrate the 90% as a good threshold for compatibility is the pattern recognition issue. Compatibility is the way to measure if a set of data (vector of priorities or profile of behavior) correspond to a recognized pattern or not. For instance, in the medical pattern recognition application, the diagnose profile (the pattern) is built with the intensity values of sign and symptoms that correctly describe the disease and then is compared with the sign and symptoms gathered from the patient, when these two profiles were about 90% or more of matching, then the physician was confident to say that the patient has the disease.

When the matching between those profiles were 85–90%, the physicians in general agreed with the diagnoses offered by the software, but when the *G* values was below 85% (between 79–84%), then the doctor sometime found trouble to recognize if the new sign and symptoms (the new patient's profile) was corresponding or not to the disease initially presented (nonconclusive information). Finally, when the matching value (the *G* index) was below 75%, the physician was not able anymore to clearly recognize in the patient's profile the disease initially offered.

Notice: the new profiles were built artificially, changing some values of sign and symptoms in an imaginary patient profile, in order to achieve matching values of 90%, 85%, 80%, and so on, the intention was to evaluate when an experimented doctor change his perception (mostly based on his pattern recognition ability).

Thus, two vectors may be considered compatible (similar or matching patterns) when *G* is greater or equal 90% with great certainty or confidence. Also, values between 85% and 90% in general have a good chance to be correct (to have a good level of certainty or approximation).

7. Three simple applications of compatibility index *G*

7.1. Is the order of choice a must?

We use to say that under the same decision problem, two compatible persons should make similar decisions. But, what do we mean when we say: "two compatible people should make similar decisions" [6, 7].

It means that they should make the same choice?

Take a look to the following case:

Two candidates: A and B for an election.

Three people, P1: choose candidate A, P2 and P3: choose candidate B.

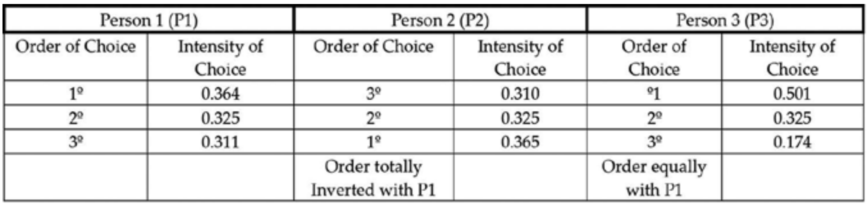
P1 and P2 are moderate people, thus their intensity of preference for the candidates are for person 1: 55–45, for candidate A, and person 2: 45–55 for candidate B.

On the other hand, P3 is an extreme person, thus his intensity of preference is 5–95 for candidate B.

Is really P3 more compatible with P2 than P1 just because P3 makes the same choice of P2? (both have the same order of choice voting by candidate B). It seems that the order of choice is not the complete or final answer.

On the other hand, we know that in order topology, metric of decision means intensity of choice (dominance of A over B). So, compatibility is not related only to the simple order of choice, but also something more complex, more systemic, which is related with the intensity of choice.

Let us see the next numerical example (**Figure 10**).



Person 1 (P1)		Person 2 (P2)		Person 3 (P3)	
Order of Choice	Intensity of Choice	Order of Choice	Intensity of Choice	Order of Choice	Intensity of Choice
1º	0.364	3º	0.310	º1	0.501
2º	0.325	2º	0.325	2º	0.325
3º	0.311	1º	0.365	3º	0.174
		Order totally Inverted with P1		Order equally with P1	

Figure 10. Comparing intensities and order of choices of three people.

Suppose three people are having equal and different order of choices and its related priority vectors.

As we can see from **Figure 10**, the order of P1 is the same than the order of P3 and inverse of P2.

Order(P1) = Order(P3) ≠ Order(P2) (inverse order actually)

Considering just the above information, may we say that P1–P3 is closer than P1–P2?

Making the numbers (calculating G, for both combination P1–P3 and P1–P2), we found:

G(P1;P2) = 0.9 (≥90%), which implies that P1 and P2 have compatible choices (very high compatibility).

G(P1;P3)= 0.77 (<90%), which implies that P1 and P2 have noncompatible choices (moderate to low).

This is a very interesting result, considering that P2 have a totally inverted order of choice compared with P1. Yet, they are compatible people.

On the other side, P1 and P3, which have the same order of choices, are not compatible people.

Hence, it is very important to be able to measure the degree of compatibility (alignment) in a reliable way.

Note: in Alice in wonderland of Charles Lutwidge Dodgson (Lewis Carroll) is a phrase saying: “I tell you, sometimes 1-2-3 might look more like 3-2-1 than 1-2-3” [6, 7].

7.2. Mixing consistency and compatibility indices in a metric quality test drive

A different and interesting application of *G* is possible when it is used to check the quality of a metric.

When it is possible to compare a metric obtained with some method with the expected or actual metric, then the compatibility index *G* represents a great tool to test and verify the quality of the created metric.

Suppose (for instance), we want to measure the quality of the following simple example.

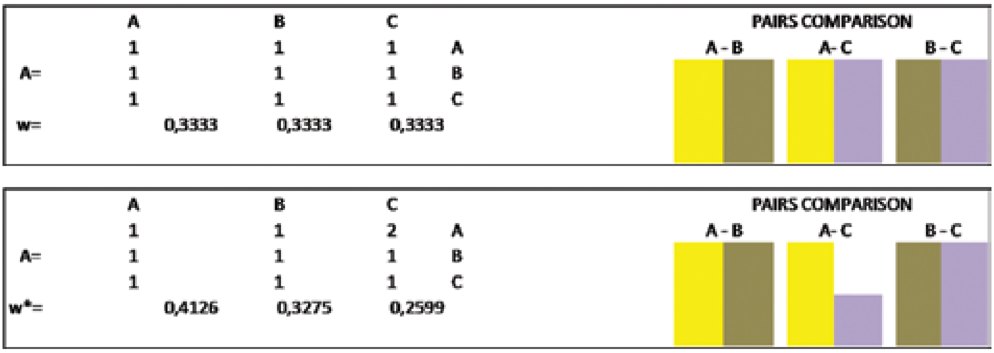
7.2.1. The problem (the criticism)

Setting an hypothetic problem (a criticism made by some critic person) about the quality of the consistency index in pair comparison matrices (Saaty's index) [4, 5].

The hypothetical critic says: the index of consistency (Saaty's index) is wrong, since it lest pass through values (comparisons) that are not acceptable by common sense.

Suppose, three equal bars of same length like the ones in **Figure 11**.

Figure 11. Bar comparisons.



	A	B	C	
	1	1	1	A
A=	1	1	1	B
	1	1	1	C
w=	0,3333	0,3333	0,3333	

	A	B	C	
	1	1	2	A
A=	1	1	1	B
	1	1	1	C
w*=	0,4126	0,3275	0,2599	

Figure 12. Possible application of index *G*. (a) Bar comparisons. (b) Bar comparisons.

Of course, the correct matrix comparison for this situation is the following (consistent) comparison matrix:

The obvious (correct) priority vector "*w*" is: 1/3, 1/3, 1/3, with 100% of consistency (CR = 0).

Suppose now that (due to some visualization mistake), the new appreciation about the bars is:

The new (perturbed) priority vector w^* is 0.4126, 0.3275, 0.2599, with CR = 0.05 (95% of consistency), which according to the theory is the maximum acceptable CR for a 3 × 3 comparison matrix.

The critic claims that the *A*–*C* bars comparison has a 100% of difference (100% of error), which is not an acceptable/tolerable error (easy to see even at naked eye).

Also, the global error in the priority vectors is 15.85%, calculated with the common formula: $e = \text{abs}(u - v)/v$, for each coordinate and then take the average of the coordinates.

But, Saaty's consistency index says that (CR = 95%), which is tolerable for a 3 × 3 comparison matrix. Hence, the critic claims that Saaty's consistency index is wrong.

7.2.2. The response

The already described problem has at least two big misunderstanding issues:

First:

- The CR (the Saaty's index of consistency) comes from the eigenvalue-eigenvector problem, so it is a systemic approach (does not care in a particular comparison) [4, 5].

Second:

- The possible error should be measured by its final result (the resulting metric), not in the prior or middle steps.

7.2.3. The explanation

The first misunderstanding is explained by itself.

For the second one, before any calculation, we need to understand what kind of numbers are we dealing with (in what environment we are working), because it is not the same to be close to a big priority than to a small one. This is a weighted environment and the measure of the closeness (proximity) has to consider this situation.

We must work in the order topology domain to correctly measure the proximity (closeness) on this environment. To do this correctly, two aspects of the information must to be considered: the intensity (the weight or priority) and the degree of deviation between the priority vectors (the projection between the vectors). The index that takes good care of these two factors simultaneously is the compatibility index *G*.

Summarizing, the vectors of correct and perturbed metric are:

Correct metric (priority vector):	0.3333	0.3333	0.3333
Perturbed or approximated metric (priority vector):	0.4126	0.3275	0.2599

The basic question here is how close is the approximated metric to the correct metric?

Evaluating *G*(correct – perturbed), the *G* value obtained is 85.72%, which in numerical terms represents almost compatible metrics (high compatibility).

As explained at the end of point 5, *G* = 90% is a threshold to consider two priority vectors as compatible vectors. Also, *G* = 85% is an acceptable lower limit value (high compatibility).

Hence, the two metrics are relatively close (close enough considering that they are not physical measures).

Of course, better consistency can be achieved.

The question is do we really obtain a better result when being totally consistent?

And the answer is: probably no. Because, in real problems we never have the "real" answer (the true metric to contrast). Experience shows that pursuing consistent metrics per se may provide less sustained results.

For instance, in the presented problem one could answer that $A - B = 2$, $A - C = 2$, and $B - C = 1$, and he/she would be totally consistent, but consistently wrong.

By the way, the new priority vector would be $w^{**} = (0.5, 0.25, 0.25)$, with CR = 0 (totally consistent), and $G = 71.5\%$, which means incompatible vectors (low compatibility). Thus, a totally consistent metric is incompatible with the correct result.

So, at the end it is better to be approximately correct than consistently wrong.

(The consistency index is just a thermometer not a goal).

Note 1: CR == 0.05 is the maximum acceptable value for inconsistency thus, I cannot go further with the bar comparison number (that means I cannot put a 3 instead of 2 in the cell (1, 3)).

Note 2: If metric B is compatible with metric A, then it is possible to use metric B as a good approximation of A. This is a useful property when metric A is not available (the most of the times we do not know the correct/exact metric).

Note 3: The same exercise was performed from 4 × 4 to 9 × 9 matrices that is, putting a value (n – 1) in the cell-position: (1, n), (n = matrix dimension), obtaining similar results (some times even better).

7.3. Using compatibility index *G* to measure the comparability (closeness) of two different metrics

When you have two rules of measurement in the same structure of decision *(two different system values),* how to combine and or compare the outcome of both?

First option:	Try to reach a verbal consensus *(the verbal or psychological option)*
Second:	Using the geometric mean *(the numerical or statistical option)*

Third: Measuring the compatibility *(the topological or closeness option)*

The first two options are long known and described in the literature [1, 2, 4, 5]. The third one is based on the compatibility principle and presents the following five advantages [6]:

1. Find out if the output of one rule is comparable with the other (compatible rules).
2. Find out the closeness between the two rules (how much comparable they are?).
3. Find out the criteria responsible for the possible gap (where to act in the most efficient way?).
4. Find out the closeness between the initial personal rule with the final group rule. Assessing: *G*(P1,GM).

5. Use the numerical option (geometric mean) when and where it is necessary (modifying values in the places where is more necessary in terms of efficiency).

For a better explanation, we will use an example to illustrate in details the already exposed idea.

Suppose that we are in front the following problem, a mine company needs to change its shift-work system, from the actual 6 × 1 × 2 × 3 (from family of shifts of eight working hours), to the new (desired) shift-work system 4 × 4 (from family of shifts of 12 working hours).

6 × 1 × 2 × 3 means a shift of 6 days of work 1 day off, 6 days of work 2 out and 6 days of work 3 out, with 8 h per day, every week). After calculation, we have 144 of total working hours in 24 days of each working cycle.

4 × 4 means 4 days of work followed by 4 days off with 12 h per day every week). After calculation, we have again 144 of total working hours in 24 days of each working cycle.

Are those shifts equivalents? How to know what shift work is better? (or less risky, since any shift is bad by essence).

Even if the total labor hours is the same (in terms of quantity of working hours), the shift-works are not equivalent (in terms of quality of life and production), it depends on a bunch of interdependent variables (numbers of working hours per day, the entry time, the number of free days per year, the number of complete weekends per year, the number of nights per shift, the number of changes day/night/day per cycle, the number of sleeping hours, the opportunity of sleep, among many others), it depends also on how those variables are settled down and, of course, the weight (the importance that each variable has), which in time depends on what people you ask for (workers, managers, stakeholders, owners, family, or even the people that live surrounding the mine).

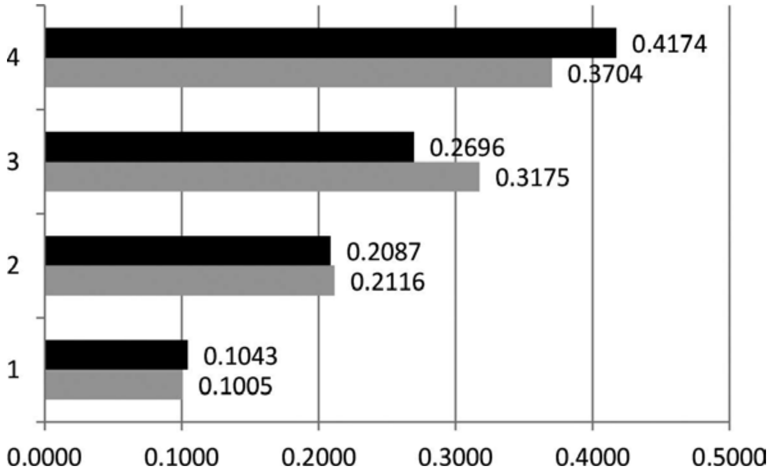


Figure 13. Comparing two rules of measurement.

Suppose now we have two evaluation scenarios:

First: The decision rule (DR) of measurement is built with the people that work in the 6 × 1 × 2 × 3 shift-work (weighting the variables involved in the rule of measurement of this shift), since they know better how it work their shift-work.

Second: The DR of measurement is built with the people that work in the 4 × 4 build weighting the variables involved in rule of measurement of this shift, since they know better their shift-work.

As the process concludes, we end with two different outputs: for the 6 × 1 × 2 × 3 shift (using the first rule of measurement), we have an impact index of 0.33 (33%), while for the second shift (with the second rule), we have an impact index of: 0.37 (37%). Of course, I cannot say that shift 6 × 1 × 2 × 3 is better than 4 × 4 just because it has a lower impact (0.33 < 0.37), since they were built with different rules of measurement.

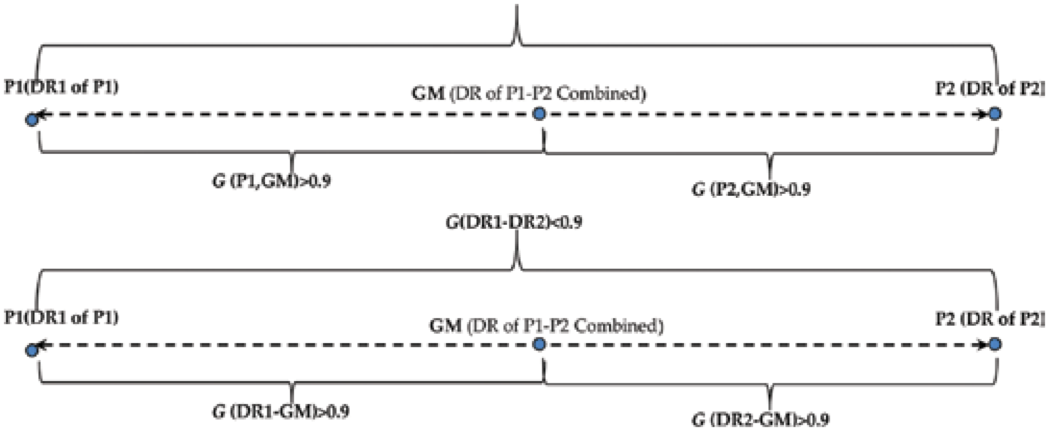
At the end, we have two DRs for the same problem; of course the question is not what rule is better, but how to make comparable both DRs.

One option could be to agree to use the same DR for both cases (the consensus, or verbal solution). But, this is not an option since the knowledge is located in different groups of people and is specific for each case; also they did not feel comfortable making this agreement.

Another option could be to take the geometric average (GM) of both rules and work with it as the final rule. Even if this could be a possibility, we really do not know what we are doing when combining or mixing both rules (as an analogy we cannot just combine one rule of measurement in meters with one rule in inches). We need to know first if both DRs are comparable.

Graphically:

The problem statement can be placed as "are these two set of decision criteria (profiles gray and black of **Figure 13**) comparable/compatible among them?



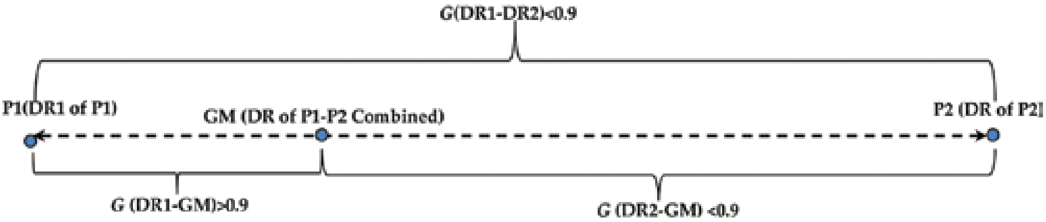


Figure 14. (a) Compatibility as a concept of distance. (b) Compatibility as a concept of distance. (c) Compatibility as a concept of distance.

Recall that they represent two different DRs. Rule one (the black bars) represents the rule of measurement for 6 × 1 × 2 × 3 shift-work and is formed by four criteria (extracted from the global rule). Rule two (in gray) represents the rule of measurement for 4 × 4 shift-work and is formed by the same four criteria, but with different intensities.

By the way, when saying comparable DR, it means compatible DR (equivalents of measure), that is we can measure the level of risk of the alternatives with any of the two rules described above.

To establish if both DR are equivalent, it is necessary to calculate *G* of both profiles:

$G(\text{Profile gray} - \text{Profile black}) = 0.91\ (91\%) \geq 90\%$, which means they are compatible (sometimes, we can take 85% as an acceptable limit point of compatibility, but no less).

Thus, we can use any of the two DRs to measure the effect of the changing shift-work. Moreover, we may use the geometric mean (GM) of both DRs as the final rule, but now knowing that we are combining rules that are compatible in fact, we are not mixing two far away points of view.

This is a relevant issue, which helps a lot when working with different groups of decision making.

But, how to make both DR comparable when they are not compatible? (or what rule to use to measure the alternatives?)

There are four different cases of compatibility for DR where "*G*" can be applied:

Case 1: Case 1 is the case already described where the DR of each group decision making is compatible.

In this case, it is possible to use any of the two rules or (still better) use the geometric mean of both DRs.

Graphically, it can be seen as:

Analytically: $G(\text{DR1,GM})$ and $G(\text{DR2,GM}) > G(\text{DR1,DR2}) > 0.90$ (GM rule is better than any of the other two).

When measuring the alternatives with this final DR, make the results to be comparable.

Case 2: The DRs of both persons (or groups) are not comparable (compatible) among them, but are compatible with the GM:

In this case, take GM of both rules then measure the compatibility of each DR with regard to the GM rule. If both initial DRs are compatible with the GM rule, then you may use the GM rule as the final rule.

Graphically:

Analytically: $G(\text{DR1},\text{GM})$ and $G(\text{DR2},\text{GM}) \geq 0.9 > G(\text{DR1},\text{DR2})$

When measuring the alternatives with this final DR, make the results to be comparable.

Case 3: The DRs of both persons are not compatible among them, but one is compatible with the GM.

In this case, look at the compatibility profile of GM with P2, G(GM;P2), for the position with the smallest number and proceed in the next sequence.

First, check if it is any "entry" error in the calculation process of P2 profile (some large inconsistency, or inverse entry in the comparison matrix).

Second, check if the comparisons in the matrix associated to that position is what P2 really meant to say.

Third, suggesting P2 to test acceptable numbers that produce a bigger *G*(getting closer to GM rule), until you can fall in Case 2.

Graphically:

Analytically: $G(\text{GM},\text{P1}) > 0.9 > G(\text{P1},\text{P2})$; $G(\text{GM},\text{P2}) > G(\text{P1},\text{P2}) < 0.9$

When measuring the alternatives with this final DR, make the results to be comparable.

There is a fourth case. The case where the initial DRs are not compatible among them and any of two DRs are also not compatible with GM rule. This is the toughest case, since P1 and P2 have very different points of view.

The suggestion for this case is as follows: Revise the structure of the model to find some lost criterion or border condition. The weights of the criteria have to be checked, and support information of P1 and P2 opinions revised.

If there are no changes with the initial position, you may (as last resource) apply (or impose) the GM as the final rule, but probably both people (or group) may feel not fully represented by that imposed DR.

8. Conclusions

There are two global conclusions on this study:

First, we need some kind of index for distance/alignment measurement in weighted environments (order topology domain), in order to mathematically define if two profiles (or behaviors) are really close.

This index (the compatibility index) makes possible:

- a matching analysis process
- analysis and test of quality of the results
- have one more tool for conflict resolution on group decision making to achieve a possible agreement considering that those profiles may represent system values
- a pattern recognition process (assessing how close is one pattern to another)
- making a better benchmarking
- membership analysis (closeness analysis to estimate if an element belong to one set of elements or another).

Second, this analysis shows that the only compatibility index that performs correctly for every case is the *G* index, keeping the outcome always in the 0–100% range (like Euclidean formula), and this is an important condition, since any value out of the 0–100% range would be difficult to interpret (and the beginning of a possible divergence).

It is also important to note the *G* and Euclidean outcomes in **Table 4** are close, but *G* is much more accurate or sensitive to changes, because *G* is not based on absolute differences (Δx_i) as distance does, but on relative absolute ratio scales. We have to remember that we are working on ratio scales (absolute ratio scale to be precise). In fact, the Euclidean distance calculation shows no differences in the distance of parallel trend from case 1 to 6 (see **Figure 8**), Euclidean-based index cannot detect the difference in the compatibility value among those cases because the absolute difference of the coordinates remains the same.

Therefore, with the Euclidian-based index one may reach the wrong conclusion that no difference exists for vector compatibility from cases 1 to 6 in the figure (the first case study is as incompatible as 2, 3, 4, 5, or 6), which is not an expected result. This unexpected behavior occurs because the Euclidean norm is based on differences, and also because it is not concerned about the weights of the coordinates and the projection between the priority vectors. It is important to remember that the numbers inside the priority vector represent preferences. Hence, in terms of proximity, it is better to be close to a big preference (big coordinate) than to the small one and this issue is better resolved in ratio scales.

Other tests made in greater spaces (3D to 10D) show the same trend. Even more, the bigger the space dimension the greater the likelihood of finding singularity points for the others formulae, in both trends parallel and perpendicular.

It is interesting to note that function *G* is not the simple dot product, since it depends on two different dimensional factors. On the one hand, it is the intensity of preference (related with the weight of the element), and on the other hand it is the angle of projection between the vectors (the profiles).

It means that G is a function of the intensity of preference (I) and the angle of projection (α between the priority vectors, that is $G=f(I,\alpha)$.

Clearly, the G function is not the simple dot product (as normally defined), but something more complex and rich of information.

It is also important to note that both data (intensity and angle) are normally implicit in the coordinates of the priority vectors and have to be correctly extracted; it depends also if the priorities are presented in relative measurement (RM) or absolute measurement (AM) format.

The possible applications of this index are huge and for different fields, as an example, for social and management sciences the possibilities are.

8.1. Concluding remarks

There are many different applications for index G, next a summary with all possibilities that G may have:

- **Compatibility of systems value:**

  G is an index able to be used in social and management sciences to measure compatibility of group decision-making (DMs) intra- and intergroups. The expression of G for this case is G(DM1 – DM2), which means level of compatibility (closeness) between DM1 and DM2. With DM1 and DM2, the decision's metric of each decision maker.

- **Compatibility for quality test:**

  G can help to assess the quality of a built decision metric. As presented in point 7.2, G may help to evaluate the quality of any new metric based in a ratio scale. The result is achieved comparing the new metric with some standard or with an already known result.

- **Profiles alignment**

  G can help to establish if two different profiles are aligned. In general, it is not an easy task to know if two complex profiles are aligned, especially when the profiles are complex with many variables, with different importance and different behavior on each one. This is the case when try to measure the degree of matching between a medical diagnose and a list of diseases, or the degree of matching between a sale project and its possible buyers and many other similar cases.

  Formula expression: G(Profile1 – Profile2) =

- **Compatibility for comparability**

  G can help to establish if two different measures are or not comparable, one relevant point when compare numbers from different outcomes is to know if those numbers are comparable or not. For instance, if I know that the impact of strategy A is 0.3 and the impact of strategy B is 0.6, I cannot say that strategy A impacts twice than strategy B, at least both strategies were measured with exactly the same rule. But, for many reasons, sometimes that is not possible. In that case I need to know if the rules of measurements are compatible among them. If so, it is possible to compare both numbers, else it is not possible.

- **Compatibility for sensitive analysis and threshold**

  G can help to establish the degree of membership or the trend for membership (tendency) of an alternative. The idea is equivalent to the classic sensitive analysis when making small changes in the variables. The change resulting in the *G* value (before and after the sensitive analysis) would show where the alternative is more likely to belong (trend of belonging).

Author details

Claudio Garuti

Address all correspondence to: claudiogaruti@fulcrum.cl

Fulcrum Ingenieria Ltda., Santiago, Chile

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Chapter 12

Combining AHP Method with BOCR Merits to Analyze the Outcomes of Business Electricity Sustainability

Rabah Medjoudj, Fairouz Iberraken and
Djamil Aissani

Additional information is available at the end of the chapter

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Abstract

Over the last three decades, many researchers and decision makers have investigated separately the issues of economic growth, profitability, and quality of life when thinking about business electricity sustainability. The correlations between these paradigms still remain at the stage of discussions, debates, and forecasts as a reaction to the occurred conflicts and disasters. There is a lack of real encryption that demonstrates their interactions. It is useful to materialize the expectations of stakeholders by mathematical modeling and providing answers to specific wants of each society according to its financial resources, its concrete societal objectives, especially to which kind of energy legacy it wants to contribute to future generations. It is imperative that experts assist decision makers, through transparent methods that seek consensus. To this end, the analytic hierarchy process (AHP) method was proposed as it has proven its efficiency in many areas of human activities. The outcomes were analyzed using this method, and the findings were compared and recommendations were made using other multi-criteria decision-making (MCDM) methods. As for energy sustainability, it is imperative to move toward renewable energy resources while trying to hold together the benefits, opportunities, costs, and risks (BOCR). We have retained that status quo is not sustainable.

Keywords: electricity sustainability, AHP, BOCR, renewable energy resources, cost-benefit analysis

1. Introduction

Sustainable development revolves around the legacy we bequeath to future generations, but it must meet the aspirations of the current generation. Can we build the future by ignor-

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ing the present? No. How about the electricity sustainability? The Electric Power Research Institute (EPRI) describes electricity as a solution, an essential foundation for a sustainable world. Modernization of the electric system will increase productivity, contribute to economic growth, and transition to cleaner technologies and environmental sustainability, and it can also increase the reliability and safety of food while reducing the risk of failure or dangerous electrical disturbances as stated by North American Electric Reliability Corporation [1] and Bauchot and Marcaux [2]. In this chapter, we have investigated the main indicators of electricity sustainability, the multi-criteria decision-making methods that allow highlighting decision makers' attitudes and customers' reactions, and finally the merits of some energy resources taking into account simultaneously profitability and quality of life. Nowadays, many companies face the option to expand their business and venture into new global market. For their long-run growth planning, they are required to consider sustainability as a performance index. Decision makers should combine several indicators such as economic, social, and environmental, which are the three main pillars of sustainability. Many opinions were raised on the importance of such an area. Based on the Brundtland report of the United Nations in 1987, some researchers consider equal importance for the three areas [3]. However, Doane and Mac Gillivray [4] have reported that most of the existing sustainability management tools and systems are mainly designed by environmentalists and social scientists. Some do refer to economic sustainability but are so sketchy that they would be inadequate for actually managing a real business. They have shown that maintaining high and stable levels of economic growth is one of the key objectives of sustainable development. Murphy [5] has stated that a relatively limited treatment has been afforded to the social pillar. The author showed the way to expand the parameters of the latter by connecting it empirically to the environmental imperatives. The tilting of the societies in the areas of new technologies and sustainable development is a matter of decision making, knowing that the tools are available with the duty of obtaining the desired results. Today, we should face the decision making on business electricity sustainability in a multi-criteria context, including various energy resources technologies with their positive and negative attributes. Over the past three decades, a considerable progress has been made in multi-criteria decision analysis (MCDA), and many examples of applications can be found in the literature in different areas, such as design and control of complex systems, energy management, environment protection, territory planning and development. To provide knowledge and to assist decision makers, several researchers in sustainability have suggested the use of multi-criteria decision-making methods (MCDM) [6–10]. A review of the literature on analytic hierarchy process (AHP) and BOCR combination has generated a great interest in such fields, and it will be generalized to both enterprise long growth and electricity sustainability. The rest of the chapter is organized as follows: The BOCR subnets development is discussed in Section 2. AHP development is provided in Section 3. It is followed by reviews of its combination with BOCR merits and a concept development in Section 4. Section 5 is devoted to the economic criteria and to cost-benefit analysis methods. The electricity sustainability development with an application to a case study is discussed in Section 6. Conclusion and future work are provided in Section 7.

2. BOCR sub-nets developments for business electricity sustainability

For an energy project leader in business electricity sustainability, we have performed about 40 parameters (with some repetitions), classified into 12 groups, and specific for both BOCR merits and sustainability's main pillars. These groups are as follows: positives, characteristics, factors, results (considered twice), choices, policies, financials, resources, constraints, outlays, and sensitivities. The project leader is also requested to conceal growth and profit seen as key measurements of success, with sustainability observed as an obvious key measurement of quality of life and being better. He is asked for prudent management of risks and opportunities, and for optimistic assessment of benefits and costs. In this way, many researchers have proposed various methods to evaluate environmental, economic, and technical benefits. The important one evolved is the cost-benefit analysis [11, 12]. The BOCR merits toward business electricity sustainability are shown in the flowchart of **Figure 1**. The latter outlines in detail the different interactions between the criteria, the expectations, and the scenarios linked to the nature of the used energy resource. The examination of the hierarchy shows an interesting link between internal and external stakeholders sub-criterion with the BOCR merits regarding the environment pillar of sustainability. When dealing with the benefits, it is a factor. It is a constraint for costs, a policy for opportunities, and sensitivity for risks. That is to say that for energy sustainability, the project holder should join with the partners, contrary to what is done actually, where the tendency is going with political decisions taken at the head of governments. The second lesson drawn comes from the growth and development, which appears as a benefit to get and an opportunity to use, and concerns both economic and environment pillars. The third point discussed concerns job creation and employment. They are highlighted by costs and opportunities for social aspects; they also remain as a former evaluation index of the governments' performance. Unfortunately, nowadays we can observe that statistics confirm a lack of creation due to the inertia in technological transfer regarding restructuration and decentralization on power systems. In their recent publications, many authors [11–16] have stated that for solving a problem by BOCR analysis, they consider both positive attributes (benefits and opportunities) and negative ones (costs and risks) to determine a preference of alternatives in relation to a specific goal. They have defined for costs the following constituents: the capital cost (investment), operation and maintenance cost, pretreatment cost, land use cost, and finally ecological damage cost.

Five formulas were suggested to calculate the overall priorities of the alternatives by synthesizing the priority (B_i, O_i, C_i, R_i) of each alternative under each merit with the corresponding priorities (b, o, c, r) such as

Multiplicative:

$$P_i = B_i.O_i / C_i.R_i \tag{1}$$

Additive:

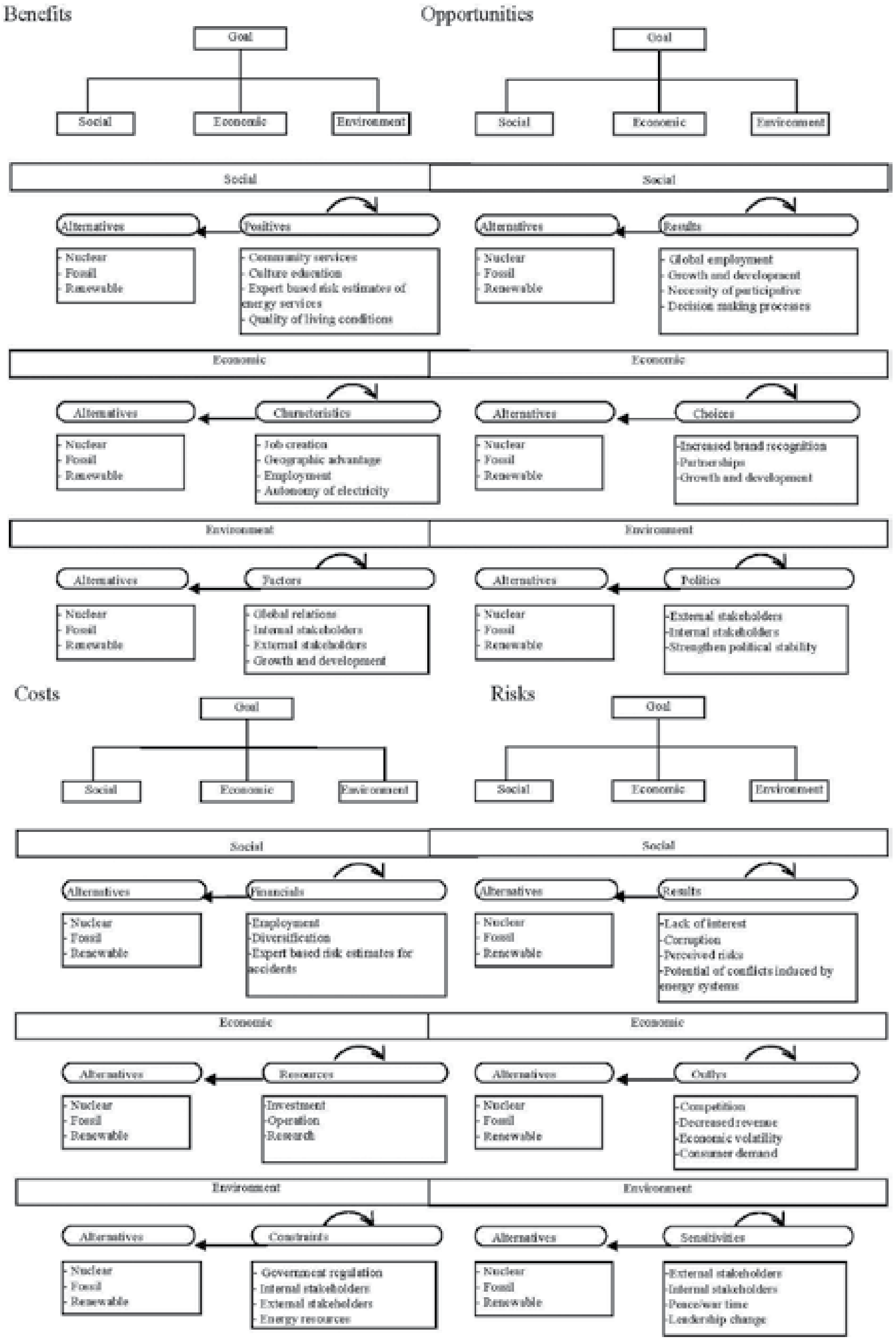

Figure 1. BOCR (benefits, opportunities, costs, and risks) networks of electricity sustainability.

$$P_i = bB_i + oO_i + c(1/C_i)_{Normalized} + r(1/R_i)_{Normalized} \tag{2}$$

Probabilistic additive:

$$P_i = bB_i + oO_i + c(1/C_i)_{Normalized} + r(1/R_i)_{Normalized} \tag{3}$$

Subtractive:

$$P_i = bB_i + oO_i - cC_i - rR_i \tag{4}$$

Multiplicative priority powers:

$$P_i = B_i^b . O_i^o . \left[(1/C_i)_{Normalized}\right]^c . \left[(1/R_i)_{Normalized}\right]^r \tag{5}$$

3. Analytic hierarchy process (AHP) development

The analytic hierarchy process (AHP) is a method of the first performance aggregation-based approaches, and it was introduced by Saaty with the aim of evaluating tangible and intangible criteria in relative terms using an absolute scale. A literature review of around 150 applications was performed, and it stated that AHP use is increasing in the developing countries and augurs well with the economic development of emerging countries [17]. In a recent research dealing with renewable energy reviews, it was stated that the AHP method is popular looking to its simplicity, flexibility, and intuitive appeal [6]. The AHP method is judged as a transparent process and an appropriate tool to avoid conflict of interest when acting in a monopoly business environment and in a regulated market. This is the case of several societies today, where a lot of questions around the energy issues are posed. The approach defined by Rafikul and Saaty [18] involves the identification of the goal, the development of potential scenarios that can meet the desired objective, and the identification of the criteria and sub-criteria that influence the decision, it is summarized as follows:

i. Having defined the objective of the decision to be reached and knowing a priori the basic scenarios and the criteria of each scenario, we model the problem as a hierarchy;

ii. Beyond making judgments and using pair-wise comparisons between elements of the hierarchy, we come to establish their priorities;

iii. After synthesizing the judgments to give a set of global priorities of the hierarchy, we verify their consistency and come to the final decision. Thanks to the sensitivity analysis, we can change a weight or delete a criterion if the consistency returns did not agree within the required tolerance.

Sensitivity measures are developed to determine the robustness of the consistency ratio and the principal right eigenvector to perturbation in the group judgments of the pair-wise comparison matrix, defined as A. The elements of this matrix are designated as a_{ij}, as a quantified judgment.

If A is a consistency matrix, the relations between weights W_i and judgments a_{ij} are simply given as $a_{ij} = \frac{W_j}{W_i}$ (for $i,j = 1,2,\ldots,n$). The largest eigenvalue $\lambda_{\max}$ is given as

$$\lambda_{\max} = \sum_{j=1}^{n} a_{ij} \times \frac{W_j}{W_i} \tag{6}$$

If A is a consistency matrix, the eigenvector X can be calculated as

$$(\mathrm{A} - \lambda_{\max}\mathrm{I})\mathrm{X} = 0 \tag{7}$$

The consistency index CI and the consistency ratio (CR) were proposed to verify the consistency of the comparison matrix. It is adopted that

$$C\mathrm{I} = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

$$CR = \frac{C\mathrm{I}}{CR\mathrm{I}} \tag{9}$$

where the values of CRI are varying with the consistency matrix size. In the AHP, the pair-wise comparisons in a judgment matrix are considered to be adequately consistent if the corresponding (CR) is less than 10%.

4. An overview on AHP-BOCR concept development

In a recent publication [13], authors have reviewed the MCDM methods of sustainability and have highlighted their great potential in the field of energy. AHP is the first popular method, and it was found that AHP and its associated family of methods account for 65% of the published papers. They have stated that to deal with the bipolarity of decision attributes more comprehensively, BOCR merits can be introduced into the AHP method to solve a problem. Saaty [19] asserts that the integration of BOCR into AHP allows for more comprehensive way to achieve meaningful preference scores, and it is well suited for the purpose of comparing and assessing energy technologies. It is also regarded as a suitable method to perform sustainability evaluation owing to its flexibility and the possibility of facilitating the dialog between stakeholders, analysts, and scientists [20]. Recent advances in the literature dealing with the combination of AHP with BOCR have treated the issues, such as AHP-BOCR for energy planning including strategic analysis of wind projects in China [21], electricity supply chain analysis and multi-criteria, multi-actors high-tech selection problem in Turkey [15, 22], analysis of hybrids in renewable power energy generation in China [23] and on the evaluation of sustainable energy based on the view of different stakeholders for North Korea [24]. Other works dealing with AHP-BOCR combination were investigated to help select the suitable wind firm project [21] and the optimal hydrogen production method [25]. AHP-BOCR models have found their applications in economics, industry, and manufacturing, such as evaluation model of buyer-supplier relationships in high-tech industry [26], evaluation of the optimal recycling strategy in upstream of solar energy industry [27], and revitalization strategies in historic transport [28].

The objective of the present investigation is to select the appropriate technology of energy production (from three types of energy sources such as fossil, nuclear and renewable technologies), depending on the scenarios reflecting the behavior of decision makers. BOCR merits are often considered as control criteria as shown in **Figure 2**. For benefits are selected four main sub-criteria such as profitability, power customer satisfaction, life quality, and reduction of vulnerability of energy dependences. The first two criteria can be satisfied simultaneously. The enterprise can enhance performances and realize profits while satisfying the customer wants in terms of quality of service, reliability, and a minimal cost of the kWh delivered [17]. As for life quality, some researchers have measured it using life quality index (LQI) defined as a marginal function [29]. However, the reduction of vulnerability of energy dependences is an issue that concerns economists, politics, and managers. The entities doing forecasts to leave nuclear plants and jump to clean energies in the horizon 2020 or 2025 should take into account the operation feasibility as a function of financial resources needed to uninstall nuclear power plants. This allows us to introduce the costs side, where the cost-benefit analysis method is suggested associated with the economic criteria in uncertain future. It is dependent on the attitudes of decision makers summarized in four scenarios, such as optimistic, pessimistic, prudent, and gambler. Opportunities are also gathered in four clusters such as global employment, growth and development, external and internal stakeholders, and Enhance political stability. They are largely explicated in **Figure 2**, and their impacts are visible in medium- and long-term periods planning. The fourth merit describes the risks such as economic volatility, consumer demand, government regulation, and potential of conflicts. Profitability can be modeled as the gain that the enterprise has to procure; this is why we have introduced in the goal the term business. For costs, two groups are defined: external and internal costs with many constituents, namely capital cost (investment), operation and maintenance cost, pretreatment cost, land use cost, and ecological damage cost. We can define for each alternative a total cost as the sum of those of the constituents. It is to say that usually the cost can be defined as a sum of two costs: fixed cost and variable cost. This question is largely defined in reference [17] as well as for the attitudes of decision makers.

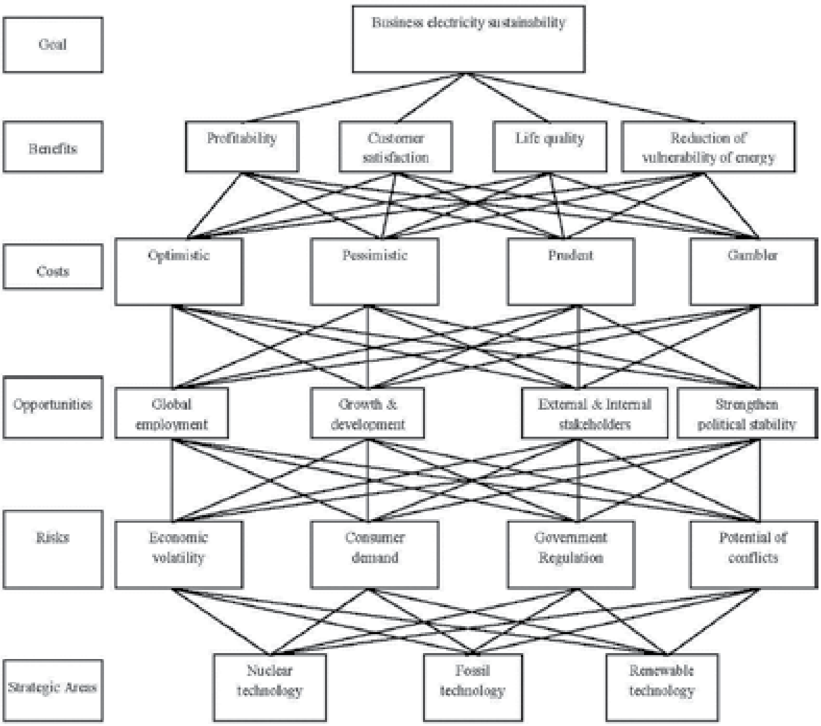

Figure 2. An explicit hierarchy to determination of business electricity sustainability.

5. Economic criteria and cost-benefit analysis

Research and development in the field of electrical energy is not oriented to the production part only, but it should be achieved through management of transmission and distribution networks. Due to the volatility of renewable resources, their integration poses major stability problems in overall networks. It is important to emphasize that technological advances have certain inertia and uncertainties in the outcome. Compared to these two characteristics, it is highly useful to introduce an adequate method of cost/benefit analysis and the decision applicability following economic criteria in uncertain future.

Cost-benefit analysis (CBA) incorporates many different aspects and interests of the involved parties in the decision of the investment strategy. In the traditional least cost planning method, the project with the lowest cost is selected. In that case, the overall cost involves operational, maintenance, and investment costs. However, this is only an economic criterion, and an energy production project might still not be able to provide satisfactory profit, as many parties are affected and during the project period the system configuration may change (e.g., increasing clean energy and decreasing fossil one, and vice versa). The proposed method will help select the project with a discounted benefit greater than its discounted cost, given as an indication of its profitability. It should be combined with the multi-criteria analysis described earlier to provide satisfactory information for a confident solution. We propose a CBA that considers environmental, economic, and social benefits. The expression of these benefits turns around the rest of the difference between the revenues and the total costs. For economic criteria inspired from the game theory, there are a number of criteria for the analysis of game matrix and decision choice [17, 30].

In the Bayes-Laplace criterion, a probability or a weight is associated with each scenario i. If the cost associated with scenario i for a strategy j is V_{ij} and the probability of each scenario is Q_j, then the selection is made as follows:

$$Z_{BL} = \min_i \sum_j Q_j V_{ij} \tag{10}$$

In this economic criterion, each scenario is taken into account, and its importance is reflected through its probability of occurrence. The advantage of this criterion is that it leads to a risky decision.

In Laplace's criterion, the occurrence probabilities of scenarios are unknown, and the events are assumed equality probable. Laplace's criterion is processed as an optimal solution, minimizing the mathematical expectation of costs; its formulation is as follows:

$$Z_L = \min_i \frac{1}{n} \sum_j V_{ij} \tag{11}$$

The mini-max decision rule is to seek decision makers' action, which minimize the maximum potential loss. A decision maker who uses the mini-max criterion acts extremely conservative. He seeks the actions that achieve the best outcome under the worst scenario. The optimal solution is given as follows:

$$Z_{mM} = \min_i \ \max_j \ V_{ij} \tag{12}$$

The maxi-min criterion, known as Wald one, describes a prudent attitude of a decision maker. Its objective involves the identification of a scenario leading to worse outcomes. A decision maker adopting this criterion tries to cover himself by providing the least bad possible result. This technique provides information that the evolution of the competition (scenarios) is detrimental to the company.

$$Z_{Mm} = \max_i \ \min_j \ V_{ij} \tag{13}$$

Adopting the Hurwitz criterion consists of the assessment for each strategy a weighted average of the worst and the best of its potential outcomes and choose the one for which the solution is the largest. According to this criterion, the solution is given as follows:

$$Z_H = \min_i \left[\alpha . \max_j (V_{ij}) + (1 - \alpha) . \min_j (V_{ij}) \right] \tag{14}$$

where $0 \le \alpha \prec 1$ is a parameter indicating planers' attitude toward risk. The value $\alpha = 1$ reduces Hurwitz' criterion to mini-max criterion as described above and corresponds to an extremely pessimistic decision maker. The value $\alpha = 0$ corresponds to an extreme optimism.

6. Electricity sustainability development

6.1. Criteria and indicators

This investigation was conducted to assist decision makers to understand the societal, economic, and environmental issues of the need for sustainable energy transition. The assumptions and models were summarized on the basis of existing data provided in the bibliographic references. They were submitted to experts to select those that meet the criteria of quality and relevance. The data used in this work are obtained from the statistical treatment and probabilistic modeling in the case where there are no archive data or a limited number available, with the help of expert judgments. Experts are energy service providers, politics oriented to research and development, specialists in the integration of renewable resources to networks, nuclear and nonrenewable energy scientists, researchers in risk analysis, and specialists in the management of energy-related conflicts. Each expert group dealing with the issue of sustainable development can provide a range of economic, environmental, and social indicators. As noticed in the literature, economic and environmental indicators seem to be obvious and common to the overall society, but it is not the case for social ones. Certainly, the sources of conflicts and accidents in the energy field are not frequent looking to electricity, but the impact of nuclear component highlights the main concerns. They reside in the utilities dysfunction causing blackouts due to their high capacities of production and risk of contamination in the case of accidents (random or premeditated (sabotage)). As for sustainable development, electricity sustainability (ES) is based on the three known pillars such as social aspects, economic and environment criteria, and indicators noted (*Ci*) and their associated subcriteria noted (*Cij*).

Environment (C1): Resources (C11; energy resources and mineral resources), Climate change (C12), Ecosystem damage (C13; impacts from normal operation and impacts from severe accidents), Waste (C14; chemical waste in underground depositories and radioactive waste in geological repositories).

- Economy (C2): impacts on customers (C21; price of electricity), impacts on the overall economy (C22; employment and autonomy of electricity generation), impacts on utility (C23; financial risks and plant operation characteristics).
- Social aspects (C3): The continuity of electricity supply (C31); stability of decisions centers (C32); the issue of energy systems and the stakeholders' contribution in decision making (C33); risks of accidents, perceived risks, and terrorist threat, the quality of living conditions (C34).

6.2 Case study application, simulation, and results

To the hierarchy given in **Figure 1**, were associated the criteria and their sub-criteria introduced in -Section 6.1 and using energy production resources as alternatives, we have determined a long-run growth of a company in the context of electricity sustainability.

To highlight the great interest of AHP application in sustainability, particularly in the field of energy, we have applied this process with the objective to compare the obtained results with those outlined by other MCDA methods summarized by Hirschberg [3], investigating the development of sustainability assessment at PSI. The different steps of AHP applications were followed, and the pair-wise comparison results between the indicators with respect to the goal are given in **Table 1**.

	Environment (C1)	Economy (C2)	Society (C3)	Priorities
Environment (C1)	1	1	1.1	0.343
Economy (C2)	1	1	1.1	0.343
Society (C3)	1/1.1	1/1.1	1	0.312
	$\lambda_{max} = 3.001$	CI=-0.0001	$CR = 0.00002$	

Table 1. Pair-wise comparison matrix of the criteria with respect to the goal.

It appears clearly that the criteria are equally prioritized and shown in **Figure 3(a)**. In **Figure 3(b)** are given the proportions (in %) of each sub-criterion against its main criterion (red color % represents the main criterion, black color % represents the sub-criterion against the main criterion, and blue color % represents the sub-criterion against the goal). Each value of a sub-criterion can be found using the following operation: (sub-criterion priority (in %) = the sub-criterion priority (in %) against the goal/the main criterion priority (in %) against the goal). In this case, the advantage of the AHP method is that it is possible to change weights to have an appropriate priority. However in the case of MCDA proposed in reference [3], the results are obtained from a survey work. The results in **Table 2** show the priorities of alternatives are based on all sub-criteria. The results have allowed us to do a synthesis in the case of equal priorities of main criteria, as given in **Table 3**. From decision makers' point of view, this consideration shows the prudent attitude. And the results show a high priority to renewable resources, followed by nuclear one, but the gap is not significant.

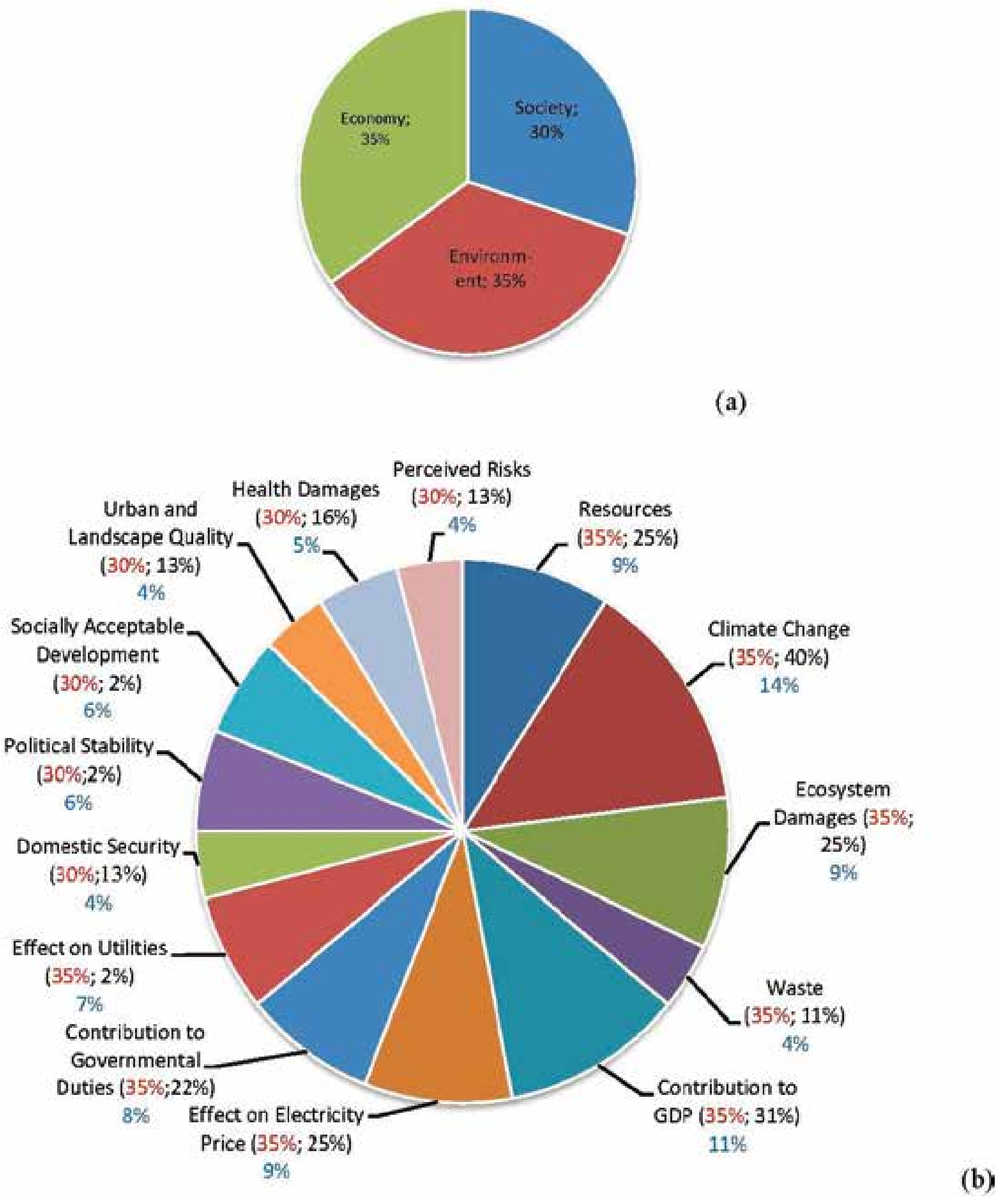

Figure 3. Syntheses of criteria and sub-criteria priorities (case of a prudent decision maker): Main criteria with relatively equal priorities (a) and sub-criteria weights (% in black) using AHP, to achieve the priorities (% in blue) compared to the goal (b).

C11	**A1**	**A2**	**A3**	**Priorities**	**C12**	**A1**	**A2**	**A3**	**Priorities**
A1	1	½	1/3	0.222	A1	1	3	1/3	0.249
A2	2	1	1/6	0.112	A2	1/3	1	1/6	0.097
A3	3	6	1	0.666	A3	3	6	1	0.654
	λ_{max} = 3.000	CI = 0.00002	CR = 0.00003			λ_{max} = 3.018	CI = 0.0009	CR = 0.0158	
C13	A1	A2	A3	Priorities	C14	A1	A2	A3	Priorities
A1	1	1/3	1/5	0.105	A1	1	½	1/4	0.135
A2	3	1	1/3	0.256	A2	2	1	1/3	0.235
A3	5	3	1	0.639	A3	4	3	1	0.630
	λ_{max} = 3.038	CI = 0.0193	CR = 0.0332			λ_{max} = 3.0536	CI = 0.0268	CR = 0.0462	
C21	A1	A2	A3	Priorities	C22	A1	A2	A3	Priorities
A1	1	3	5	0.637	A1	1	½	2	0.297
A2	1/3	1	3	0.258	A2	2	1	3	0.539
A3	1/5	1/3	1	0.104	A3	1/2	1/3	1	0.163
	λ_{max} = 3.0385	CI = 0.0193	CR = 0.0332			λ_{max} = 3.0092	CI = 0.0046	CR = 0.0079	
C23	A1	A2	A3	Priorities	C24	A1	A2	A3	Priorities
A1	1	2	3	0.527	A1	1	3	2	0.539
A2	1/2	1	3	0.332	A2	1/3	1	1/2	0.163
A3	1/3	1/3	1	0.139	A3	1/2	2	1	0.297
	λ_{max} = 3.0536	CI = 0.0268	CR = 0.0462			λ_{max} = 3.0092	CI = 0.0046	CR = 0.0079	
C31	A1	A2	A3	Priorities	C32	A1	A2	A3	Priorities
A1	1	2	5	0.581	A1	1	2	4	0.558
A2	1/2	1	3	0.309	A2	1/2	1	3	0.319
A3	1/5	1/3	1	0.109	A3	1/4	1/3	1	0.122
	λ_{max} = 3.0037	CI = 0.0018	CR = 0.0032			λ_{max} = 3.0183	CI = 0.0091	CR = 0.0158	
C33	A1	A2	A3	Priorities	C34	A1	A2	A3	Priorities
A1	1	1/2	3	0.332	A1	1	2	3	0.539
A2	2	1	3	0.527	A2	1/2	1	2	0.297
A3	1/3	1/3	1	0.139	A3	1/3	½	1	0.163
	λ_{max} = 3.0536	CI = 0.0268	CR = 0.0462			λ_{max} = 3.0092	CI = 0.0046	CR = 0.0079	
C35	A1	A2	A3	Priorities	C36	A1	A2	A3	Priorities
A1	1	2	1/4	0.218	A1	1	2	1/5	0.186
A2	1/2	1	1/3	0.151	A2	1/2	1	1/4	0.126
A3	4	3	1	0.630	A3	5	4	1	0.687
	λ_{max} = 3.1078	CI = 0.0539	CR = 0.0930			λ_{max} = 3.0940	CI = 0.0470	CR = 0.0810	

Table 2. Comparison matrices and local priorities.

	ENVIRONMENT (C1)				**ECONOMY (C2)**				**SOCIETY (C3)**						**Priorities**
Weights	**0.343**				**0.343**				**0.314**						
Sub-criteria	C11	C12	C13	C14	C21	C22	C23	C24	C31	C32	C33	C34	C35	C36	
Weights	0.254	0.346	0.242	0.157	0.321	0.252	0.226	0.200	0.139	0.207	0.205	0.149	0.153	0.145	
Nuclear resource	0.222	0.249	0.105	0.135	0.637	0.297	0.527	0.539	0.581	0.558	0.332	0.539	0.218	0.186	0.364
Fossil resource	0.112	0.097	0.256	0.235	0.258	0.539	0.332	0.163	0.309	0.319	0.527	0.297	0.151	0.126	0.266
Renewable resources	0.666	0.654	0.639	0.630	0.104	0.163	0.139	0.297	0.109	0.122	0.139	0.163	0.630	0.687	0.370

Table 3. Final results using synthesis (equal importance of main criteria).

In the case where the decision maker is optimistic toward environment effects, a high priority is given to the environmental aspects as highlighted in **Table 4** and confirmed in **Figure 4**; it shows that the renewable resources won the highest priority with an important gap compared to the other alternatives.

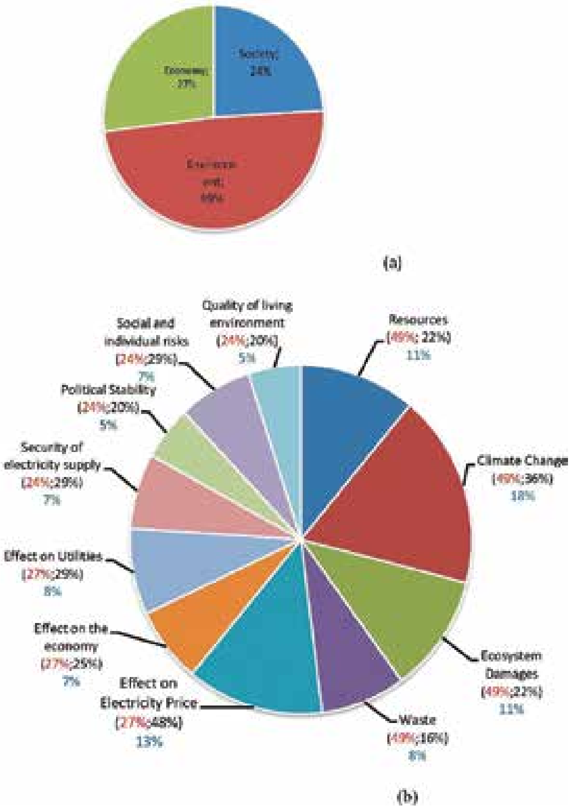

Figure 4. Syntheses of criteria and sub-criteria priorities (case of an optimistic decision maker toward environment): Main criteria with the main dominance of environment criterion (a) and sub-criteria weights (% in black) using AHP, to achieve the priorities (% in blue) compared to the goal (b).

Main criteria	**Environment (C1)**				**Economy (C2)**			**Society (C3)**				**Priorities**
Weights	**0.490**				**0.270**			**0.240**				
Sub-criteria	C11	C12	C13	C14	C21	C22	C23	C31	C32	C33	C34	
Weights	0.229	0.368	0.229	0.173	0.458	0.256	0.284	0.291	0.208	0.291	0.208	
Nuclear resource	0.222	0.249	0.105	0.644	0.297	0.547	0.539	0.218	0.558	0.218	0.333	0.283
Fossil resource	0.112	0.097	0.256	0.270	0.539	0.263	0.163	0.630	0.319	0.151	0.569	0.274
Renewable resources	0.666	0.654	0.639	0.085	0.163	0.189	0.297	0.151	0.122	0.630	0.097	0.443

Table 4. Final results using synthesis (with the dominance of environmental aspect).

Based on the investigation of Doane and Mac Gillivray [4], where they have stated that the economic criterion should be of high interest compared to the other criteria, we have considered that the decision maker is optimistic toward economy and relatively pessimistic toward social and environmental issues. The synthesis given in **Table 5** shows a high priority for nuclear resource with a nonsignificant gap compared to the other alternatives.

	Environment (C1)				**Economy (C2)**				**Society (C3)**						**priorities**
Weights	**0.270**				**0.490**				**0.240**						
Sub-criteria	C11	C12	C13	C14	C21	C22	C23	C24	C31	C32	C33	C34	C35	C36	
Weights	0.229	0.368	0.229	0.173	0.321	0.252	0.226	0.200	0.139	0.207	0.205	0.149	0.153	0.145	
Nuclear resource	0.222	0.249	0.105	0.644	0.637	0.297	0.527	0.539	0.581	0.558	0.332	0.539	0.218	0.186	0.395
Fossil resource	0.112	0.097	0.256	0.270	0.258	0.539	0.332	0.163	0.309	0.319	0.527	0.297	0.151	0.126	0.276
Renewable resources	0.666	0.654	0.639	0.085	0.104	0.163	0.139	0.297	0.109	0.122	0.139	0.163	0.630	0.687	0.329

Table 5. Final results using synthesis (with the dominance of economic aspects) with a completed number of sub-criteria.

Through this simulation, we retain the interest of the environmental aspect in sustainable development, and the development of renewable resources is imperative. From decision makers' point of view, the AHP method allowed us to simulate attitudes of managers without difficulty.

7. Conclusion and future work

Today, many countries set a policy goal commonly recognized in the long term, energy supply must be laid out more sustainably. The fossil energy source, which is still largely used to satisfy this demand, is the main cause of climate change. Energy demand cannot be satisfied with a sustainable and climate-friendly way that if energy supply and energy use are reworked in depth. Two lines of action are preferred: first, energy demand should be reduced substantially by its more efficient use and voluntary parsimony (sobriety); second, the energy supply in the future must be based on renewable energy sources. The investments required for this reorganization of the energy system are enormous, and it will change in depth the energy sector and consumption patterns. This requires political framework conditions granted internationally. Compared to this point, we have used in this work evaluating method of cost/ benefit analysis and introduced the economic criteria in uncertain future for the assessment of costs.In the coming decades, nuclear power stations of the majority of countries will reach the end of their life in terms of the installations security. Approximately half of the current electricity supply will no longer be available. Meanwhile, despite the efficiency improvements, demand continues to increase, with the use of new technologies requiring electricity, population growth, increased consumption possibilities, and substitution of fossil fuels in the areas of heating (heat pump) and mobility (electric vehicles).The accident at the Japanese nuclear plant in Fukushima in March 2011 has raised a new urgency to the question of how the majority of developed countries rely on ensured electricity supply. Nuclear technology has at least for now lost acceptance; availability to start the "energy revolution" seems to have increased. To meet this energy revolution, we must, however, make decisions under uncertainty. Always incur certain risks, and it is unclear how to react dynamic system made by humans and their environment. Decisions must be taken, so that the electricity supply remains assured on one hand, and can be adapted to the changed framework conditions on the other.It must also respond to economic issues: how the investments are made in a liberalized electricity market, in which the generation, transmission, and distribution are separated? How will be the future of the business of electricity supply companies? so they must be compatible with a decentralized production of renewable electricity, more efficient use of electricity by consumers, and maintenance.The supply of future electricity of any country depends largely on technical and economic developments. The preferences of individual electricity consumers and the behavior of electricity producers and network operators in terms of investments likewise play a central role. Finally, political and legal decisions also influence the future of electricity supply. These decisions concern the efficient use of electricity, renewable electricity, the problem of adjustment and storage, network expansion, and liberalization of the electricity market. The decisions of the months and years ahead will influence the supply of electricity for decades. The question therefore arises of the bases on which lay the next milestones. And it is in this context that the AHP-method-based consensus was introduced with the details of the opportunities, benefits, costs, and risks of all proposed alternatives. The AHP method combined with BOCR merits becomes popular, looking to its simplicity, flexibility, and intuitive appeal. It was demonstrated that this combination allows the project holder to think objectively and to consider simultaneously profitability, customer satisfaction, and life quality on one hand and have the certitude that status quo is not sustainable on the other. The future work consists of the issue of combining AHP-BOCR paradigm with new information and communication technologies to solve the problem of unpaid bills of diminished customers by transforming state's aids on energy prepaid cards using the advantages of smart energy counters from one hand and the management of high pick of energy demand by shedding load for customers' owners of emergency resources instead of ordinary customers, using current power lines (CPL) from the other hand.

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Author details

Rabah Medjoudj[1*], Fairouz Iberraken[1] and Djamil Aissani[2]

*Address all correspondence to: r.medjoudj66@gmail.com

1 Department of Electrical Engineering, University of Bejaia, Algeria

2 Department of Operation Research, LaMOS Research Unit, University of Bejaia, Algeria

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A Prototype AHP System for Contractor Selection Decision

Emmanuel O. Oyatoye and Adedotun A. Odulana

Additional information is available at the end of the chapter

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Abstract

Contractor selection process is generally believed to be marred with lots of bias in most developing nations, which sometimes leads to incompetent contractor being selected because it is based mainly on human experience and feelings. In particular, in a culturally biased country like Nigeria where most contractors' selection process is not based on performance but rather on whom you know, not paying attention to important factor/criteria but rather on selfish personal gains, which directly or indirectly affect the public in different forms could have some negative effects on projects. The failure of managers to be objective in decision-making in regard to contractor selection has great consequences for the government as well as corporate organizations in terms of cost incurred, delivery time, and impact on the general welfare of the people. Hence, there is a need for managers to be interested in the selection of contractors, suppliers of materials, equipment, and services as failure or inefficiency on the part of the contractor that could affect the well-being of the people negatively and damage the performance rating of the government. Developing an appropriate model to address the problem of poor contractor evaluation would, no doubt, be a great relief in the selection of contractors. This chapter presents a prototype system for contractor evaluation decision.

Keywords: prototype, AHP system, contractor, selection, evaluation, decision

1. Introduction

For many years, there has been a great concern on the number of abandoned projects by different tiers of government in several developing nations. This is because subjective judgments such as political patronage, selfish interest, friendship, and satisfying the interest of some highly placed people were often used when contracts are to be awarded. In cases where projects were

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even completed, the qualities of work done were found to be far below standard. These authors thus believe that the most prudent process of selecting the most qualified contractor for any government or organization project is through contractor prequalification based on some criteria, sub-criteria, and alternatives (choice of the most qualified contractor). Even when the right model for contractor selection is developed, most people find the implementation of such model on the computer difficult to get the desired results on the ratings of the criteria, sub-criteria, and alternatives.

This chapter addresses how an analytic hierarchy process (AHP) model developed for contractor selection can be implemented on the computer to get the right ratings using some existing computer software programs. Thus, the main objective of this chapter is to illustrate how an AHP model for contractor selection can be implemented on personal computer using existing software.

2. Literature review on contractor selection

The past literature reveals that there are three types of tender that are practiced in Europe [1], Malaysia, and Nigeria [2]. These are:

- Open tender: where all interested contractors submit tenders.
- Restricted/selected tender: where only invited or selected contractors are allowed to bid. Reference [3] reveals that most organizations in the UK and many other countries adopt this method.
- Negotiated tender: where client consults the chosen contractors and negotiates the terms of contract with them.

According to Ref. [4], the tendering process begins with the analysis to ensure that tender specification meets with end users' needs, followed by contractor selection which starts with tender invitation and ends with contract award and contract monitoring. In Nigeria, contractors are invited to submit tender submission through advertisement in major national publications [5]. Thereafter, contractors who have interest in bidding for the tender as per the conditions contained in the advert will purchase the tender documents and provide the information required as stated in the advert. The completed documents are then submitted to the tender board not later than the submission deadline stated in the advert. Information contained in the tender documents includes the instruction to bidders, the conditions under which contract will be awarded, and the necessary technical specifications of the contract. Contractors are also expected to submit the bill of quantities and list of forms that have been submitted. At the end of the closing date of the advert, all tenders are pulled together and opened. Tenders received are then assessed so as to decide on the most eligible contractor to be awarded the contract. Even with this well-laid-down procedure, contracts are often awarded to unqualified contractor.

According to Ref. [6], assessment is the most crucial stage in the tendering processes due to the fact that it contributes to the decision in choosing the most qualified contractor to be awarded the contract. However in all these processes, hardly is any decision support system (such as models) used in making a decision by most organization, that is, decision is often based on subjective comparisons.

3. Prototype development

In order to illustrate the implementation of a prototype system for contractor selection based on AHP methodology, a case study of the selection of a contractor for the infrastructure

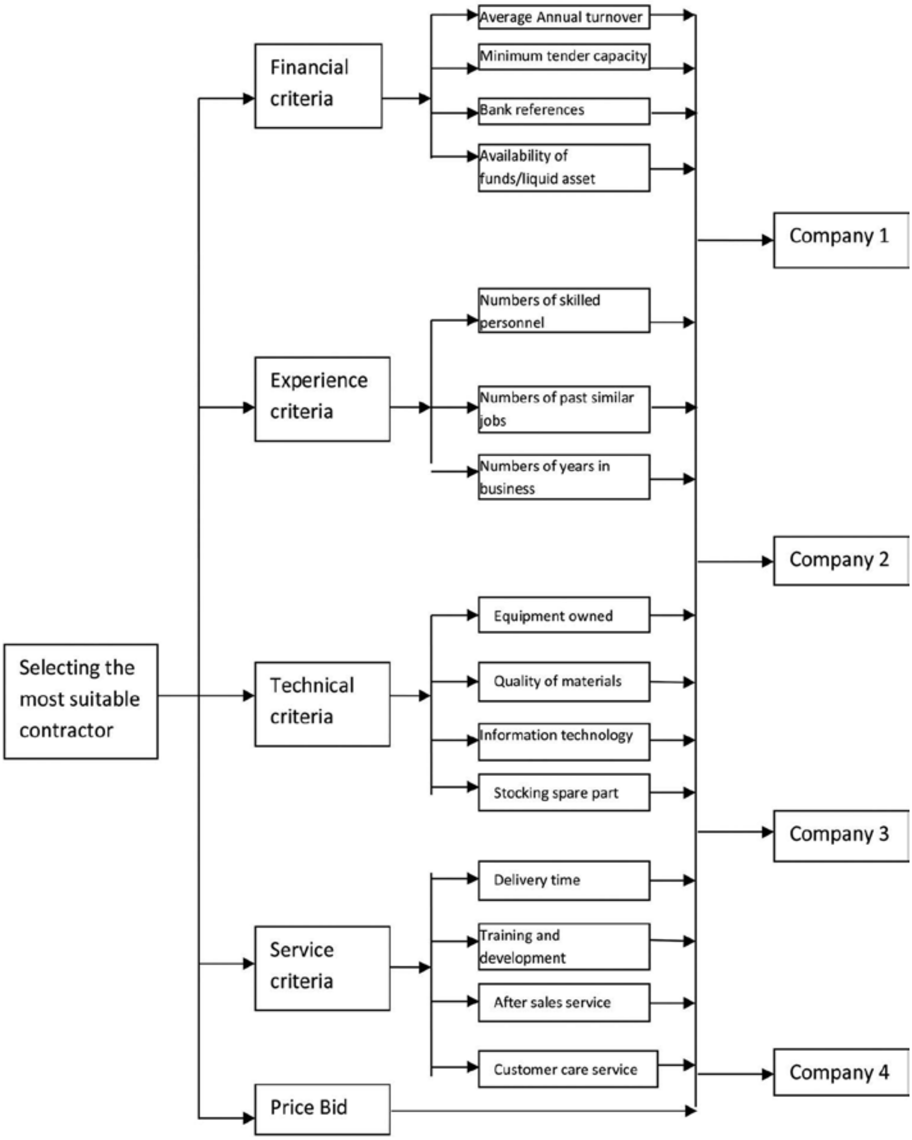


Figure 1. Hierarchical structure of the AHP model.

development of the National Centre for Technology Management (NACETEM), an agency of the Federal Ministry of Science and Technology in Nigeria, is used as illustration. NACETEM is an agency vested with the mandate of training and developing middle- to high-level manpower and conducting policy research in the areas of science, technology, and innovation management for all tiers of government and the private sector.

To select the most suitable contractor for the infrastructural development of the agency base on AHP methodology, information was gathered from all the departments in the organization on the selection process and later carefully analyzed so that standard criteria and sub-criteria could be established and later adjusted with respect to the general goal. Once the problem has been defined as selecting the best contractor, the process starts with the design of the prototype system, which includes designing the system architecture and identifying the implementation and operational framework. The knowledge acquired through the knowledge acquisition process is represented in the prototype in four main steps:

1. Developing the hierarchy as shown in **Figure 1**
2. Pairwise comparison of criteria and sub-criteria
3. Synthesis of the AHP model
4. Measuring inconsistency in decision-maker's judgments

Judgment of the results by the expert (i.e., tenders board) and evaluation of the prototype are carried out, whereby the effectiveness of the software and hardware is checked. If the results or findings from the evaluation require some improvement, the prototype is modified and redesigned as appropriate.

4. Evaluation of the prototype system

The aim of the evaluation is to determine the usability and functionality of the finished prototype. This would be achieved through interviews and questionnaire administered to the experts (tenders board).

5. Operation of the prototype system

The developed prototype system provides a decision support tool to decision-maker by aiding in the selection of the most qualified contractor to upgrade internet infrastructure. The system allows for input from users in the decision-making process. The prototype system:

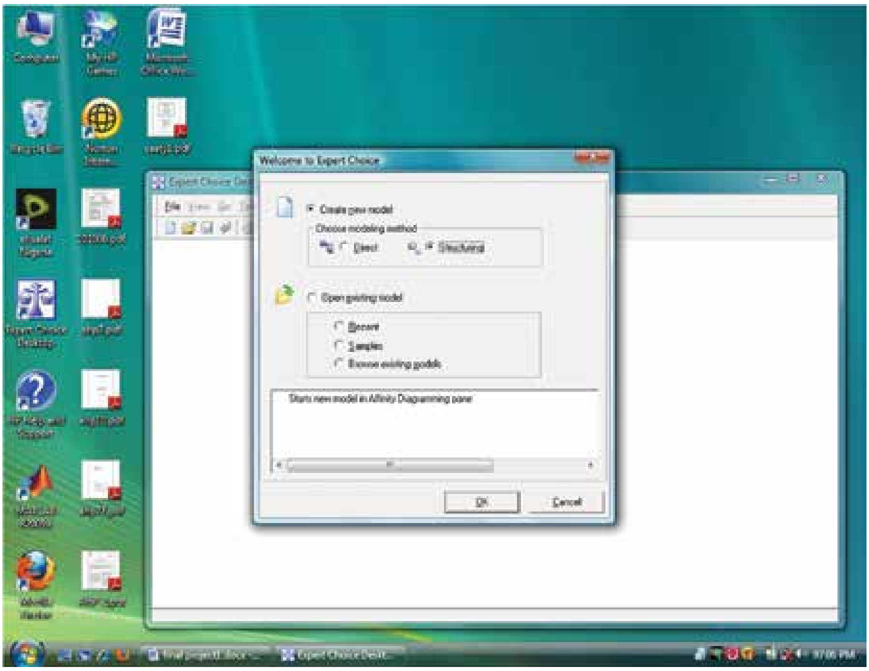
- provides a clear and structured framework of implementation of the decision-making process, which assists the user in the selection of the most qualified contractor to upgrade the internet infrastructure based on the criteria and sub-criteria included in the AHP model

- supports the decision-making process by providing simplified information on the selection process; and
- assists the decision-maker to take rational and justified decision through graphical reports and sensitivity analysis

Goal	Criteria	Sub-criteria	Alternatives
Level 0 (1 node)	Level 1 (5 nodes)	Level 2 (15 nodes)	Level 3 (4 nodes)

5.1. System requirement

The prototype system operates on personal computer running window XP or later version for smooth operation. However, it can still work with lower versions of window XP. It requires Expert Choice 11 which is the current version, Microsoft Office 2003 or later version (MS Word, MS Excel, MS Access, etc.) to be installed. It is also advisable to have relatively large memory and storage capacity (say, 1 G of RAM and 100 G of hard disk size).



Welcome to Expert Choice

● Create new model

Choose modeling method: ○ Direct ● Structural

○ Open existing model

○ Recent
○ Samples
○ Browse existing models

Starts new model in Affinity Diagramming pane

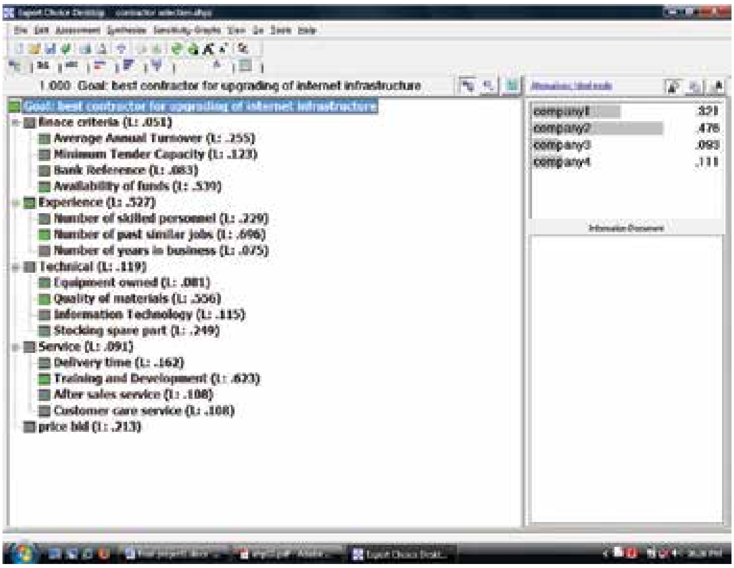
Figure 2. Expert Choice welcome window view panel that is divided into three major panes.

5.1.1. Starting the prototype system

The prototype system is stored as an Expert Choice file called "contractor selection.ahpz" and held in directory with specific name, e.g., "C:\users\Ola-dotun\document\contractor selection.ahpz."

To start the application, click on Start button on the desktop, then select All Programs, and click on Expert Choice or double-click on Expert Choice from the desktop to open the application (**Figure 2**); if one is designing a fresh model, then click on Create New Model, select Structuring, and click Ok. The application will display a dialog box where you can type the name of the model and save to Start Building a New Model.

1. *The Tree View pane*. The hierarchy displayed in this (contractor selection model) consists of five main criteria and fifteen sub-criteria with the goal being to select the best contractor for the upgrading of internet infrastructure (**Figure 3**).
2. *Alternative pane*. The list of alternative is displayed here. That is, the four companies that is being considered in handling the project.
3. *Information document pane*. This includes information on operating the system and links to other information document files, which may be of importance for easy understanding of the system.



1.000 Goal: best contractor for upgrading of internet infrastructure

- Goal: best contractor for upgrading of internet infrastructure
  - finace criteria (L: .051)
    - Average Annual Turnover (L: .255)
    - Minimum Tender Capacity (L: .123)
    - Bank Reference (L: .083)
    - Availability of funds (L: .539)
  - Experience (L: .527)
    - Number of skilled personnel (L: .229)
    - Number of past similar jobs (L: .696)
    - Number of years in business (L: .075)
  - Technical (L: .119)
    - Equipment owned (L: .081)
    - Quality of materials (L: .556)
    - Information Technology (L: .115)
    - Stocking spare part (L: .249)
  - Service (L: .091)
    - Delivery time (L: .162)
    - Training and Development (L: .623)
    - After sales service (L: .108)
    - Customer care service (L: .108)
  - price bid (L: .213)

company1	.321
company2	.476
company3	.093
company4	.111

Figure 3. Contractor selection system using Expert Choice.

5.1.2. Assigning judgment in pairwise comparison

One of the main strengths of AHP is the use of pairwise comparisons to derive accurate ratio scale priorities. The pairwise comparison process compares the relative importance, preference, or likelihood of two elements with respect to each other. A judgment is made as to which is more important and by how much. Judgment about the relative importance of criteria is made with respect to the parent node in the hierarchy (either the goal or a higher-level criterion). Judgments about the relative preference of alternatives are made with respect to each criterion. You can make judgments/pairwise comparisons starting with the goal and working down to the alternatives (top-down), or you can make judgments about the alternatives before making judgments about the objectives (bottom-up). The bottom-up approach is usually better because the insights you gain about the trade-offs among the alternatives will help in making judgments about the importance of the objectives [8]. Expert Choice provides judgment in three different forms, namely pairwise numerical comparison, pairwise verbal comparison, and pairwise graphical comparison (**Table 1**).

Subjective judgment of preference	Rating
If criterion (a) is extremely more preferred than criterion (b)	9
If criterion (a) is very strongly to extremely preferred than criterion (b)	8
If criterion (a) is very strongly preferred than criterion (b)	7
If criterion (a) is strongly to very strongly preferred than criterion (b)	6
If criterion (a) is strongly preferred than criterion (b)	5
If criterion (a) is moderately to strongly preferred than criterion (b)	4
If criterion (a) is moderately preferred than criterion (b)	3
If criterion (a) is equally to moderately preferred than criterion (b)	2
If criteria (a) and (b) are equally preferred	1

Source: Saaty [7].

Table 1. Rating of pairwise comparison of a pair of criteria and sub-criteria using AHP preference scale.

For instance, the user makes judgments about the preference of a contractor (company) with respect to the criterion, "average annual turnover." The steps to take include:

1. Click on the sub-criteria average annual turnover under the first set of criteria in the hierarchy "Finance."

2. From the Menu, select Assessment; then select Pairwise. You will be taken to the verbal comparison window (the default) (**Figure 4**). Since you are comparing the alternatives (companies) with respect to the objective, average annual turnover, the judgment type is "preference." **Figure 4** shows the judgments.

3. The judgment that best reflects the subjective feeling of the decision-maker base on the pairwise comparison is selected by dragging the verbal scale indicator up or down to the appropriate position. **Figure 4.** shows that company 2 is strongly more preferred to company 3 when the criterion of average annual turnover is considered. In the case where company 3 is more preferred to company 2, the indicator is dragged down toward company 3 and stationed at the appropriate level of preference.

The lower cell is called the active cell and contains the numerical (in black) representations by which the elements (i.e., companies) displayed along the rows are more preferred to those displayed along the columns in a matrix format, based on the comparison of average annual turnover criterion, while any judgment shown in red indicates that the column element is preferred to the row element.

4. The above process (step 3) is repeated until all the companies have been compared, by pairing them in twos, with respect to their average annual turnover.

Inconsistency: Possible errors and actual inconsistency in judgment are identified by the inconsistency measure shown in the bottom-left cell of the matrix. For the decision-maker's judgment to be reasonably consistent, the inconsistency ratio must be less than 0.1. The decision-maker should only change an inconsistent judgment if he truly feels that the initial comparison was in error.

5. Recording judgments and calculating priorities.

When all judgments have been made, one is prompted to record judgments and carry out necessary calculation. Select YES so as to return to the Model View.

The priorities of alternatives with respect to average annual turnover are automatically computed and displayed in the Pane of the Model View. **Figure 5** shows the priorities of the companies with respect to "average annual turnover."

In a situation where the resulting relative priorities do not reflect the decision-maker's feelings, the pairwise comparison process is repeated. These can be achieved either by using the verbal mode or by switching over to either the graphical mode or numerical mode. To obtain the right result, the user should click on the tab of one of the three pairwise comparison tabs. The user then selects the mode that he feels will make the most sense and later uses the selected mode to obtain the judgment for the current set of criteria (or sub-criteria) being compared.

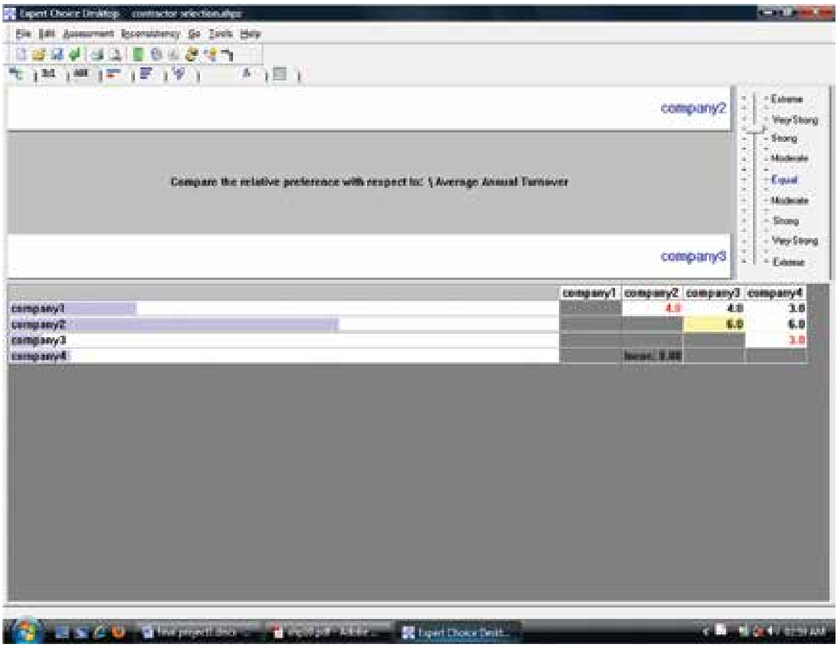
6. Processes 1–5 are repeated until all comparisons for sub-criteria (15 nodes) and criteria (5 nodes) have been made.

7. Assignment of judgment.

To assign judgment to the sub-criteria against criteria as well as to criteria against the goal, the user (decision-maker) must change the comparison type from "preference" to "importance."

To change the assessment type:

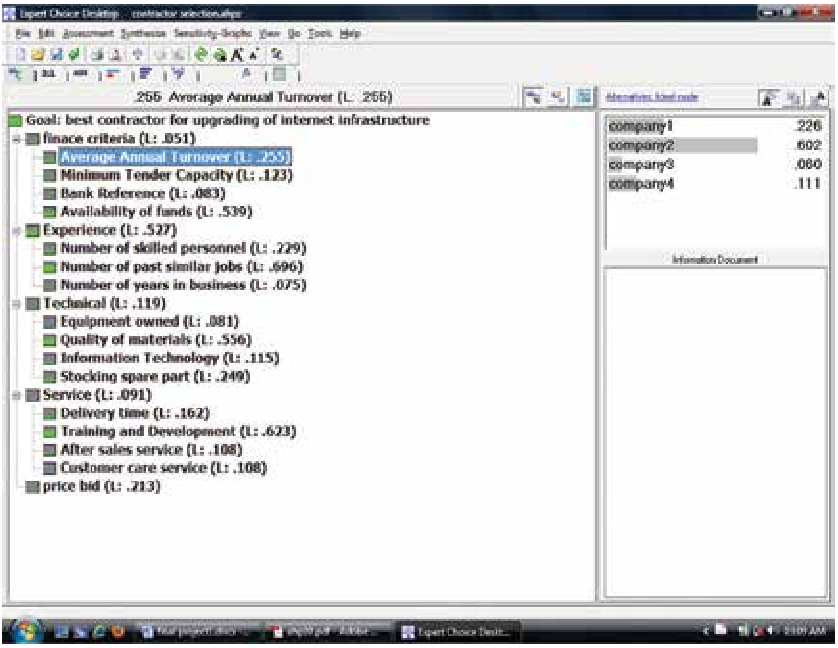
- Select assessment.
- Select type.
- Select importance.



Compare the relative preference with respect to: \ Average Annual Turnover

	company1	company2	company3	company4
company1		4.0	4.0	3.0
company2			6.0	6.0
company3				3.0
company4		Incon: 0.08		

Figure 4. The verbal comparison window.



.255 Average Annual Turnover (L: .255)

- Goal: best contractor for upgrading of internet infrastructure
  - finace criteria (L: .051)
    - Average Annual Turnover (L: .255)
    - Minimum Tender Capacity (L: .123)
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    - Information Technology (L: .115)
    - Stocking spare part (L: .249)
  - Service (L: .091)
    - Delivery time (L: .162)
    - Training and Development (L: .623)
    - After sales service (L: .108)
    - Customer care service (L: .108)
  - price bid (L: .213)

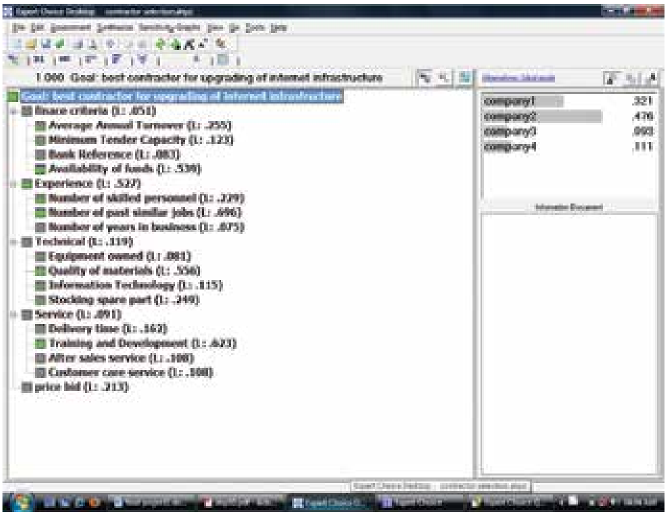
company1	.226
company2	.602
company3	.060
company4	.111

Figure 5. Derived priorities of the alternatives with respect to average annual turnover.

5.1.3. Synthesizing and measuring inconsistency

Tree View in both graphic and numerical form.

To examine the synthesis, select Synthesis, with respect to the goal to produce the display shown in **Figure 6**, while **Figure 7** shows the Synthesis window displaying the charts.



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  - After sales service (L: .108)
  - Customer care service (L: .108)
- price bid (L: .213)

company1	.321
company2	.476
company3	.093
company4	.111

Figure 6. Model View showing the synthesized results with respect to the goal.

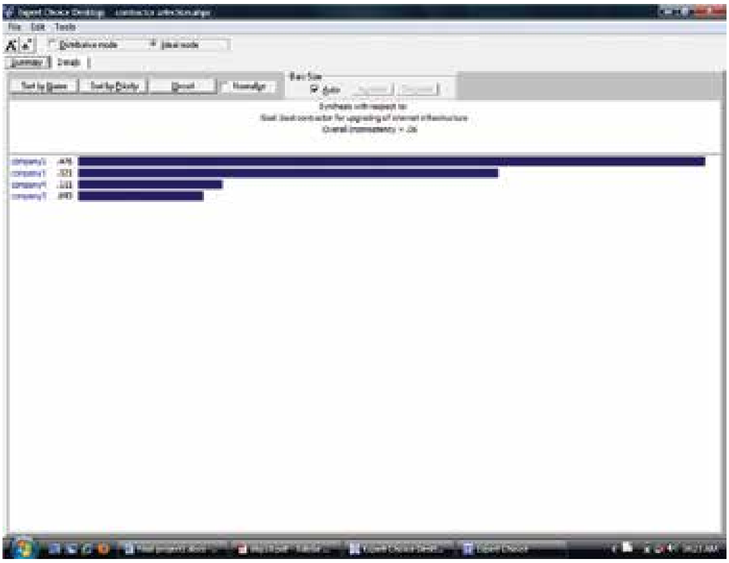

Figure 7. Synthesis window.

In Expert Choice, the "Distributive Mode" and "Ideal Mode" are two synthesis methods that can be used to derive the results. Distributive Synthesis is used when the users are interested in prioritizing alternatives from which they may pick more than one alternative, while the ideal Synthesis should be used when one is interested in only one alternative, and the remaining alternatives are no longer relevant. The difference in results obtained using the ideal or distributive synthesis modes is usually negligible and more of theoretical than practical interest.

5.1.4. Sensitivity analysis

Expert Choice provides tools for performing sensitivity analysis. Sensitivity analysis displays how the alternatives change priorities if there is a change in the importance of the criteria or sub-criteria graphically. Starting with the goal node, sensitivity analysis displays the sensitivity of the alternatives with respect to all the criteria below the goal. Since the AHP model in use as illustration has more than three levels, sensitivity analysis can also be performed from the nodes below the goal to show the sensitivity of the alternatives with respect to the criterion and sub-criterion [8]; and according to Ref. [9], when performing a sensitivity analysis, the user may change the priorities of the criteria and observe how the priorities of the alternatives would change.

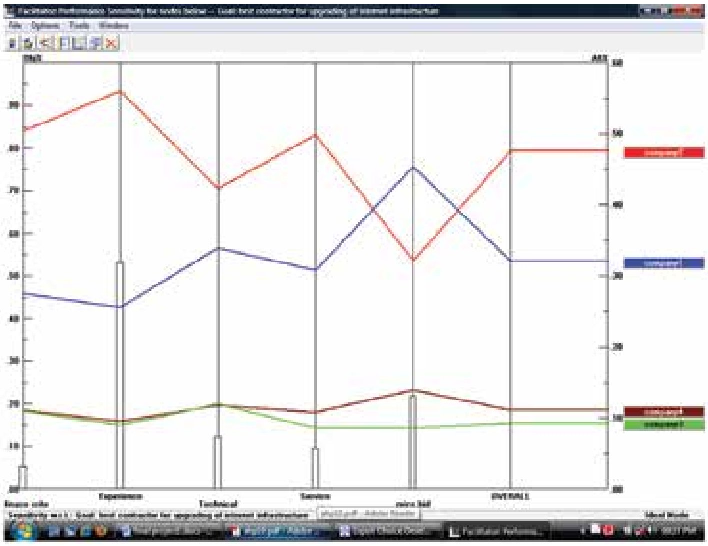

Figure 8. Graph of sensitivity analysis.

There are five types of sensitivity analysis that can be carried out in Expert Choice, namely, performance, dynamic, gradient, head-to-head, and two-dimensional plot. The first three are often used to perform the sensitivity analysis because you can dynamically vary them by dragging the objective bars.

To perform sensitivity analysis from Tree View, click on the goal or criteria or sub-criteria that you want to perform analysis on with respect to the alternatives, and select sensitivity graph, then click the type of sensitivity analysis you want to perform.

- Performance sensitivity: This analysis displays how the alternatives perform with respect to all criteria; that is, it shows how each alternative is prioritized relative to other alternatives when considering each criterion as well as the overall goal (**Figure 8**). By dragging each criterion bar up and down, we can temporarily alter the relationship between the alternatives and their criteria.
- Dynamic sensitivity: This is concerned with how the choice of priorities of the alternatives changes when the priority of one criterion is varied. Dynamic sensitivity analysis is used to dynamically change the priorities of the objectives to determine how the changes affect the priorities of the alternative choices. By dragging the priority bar of the objective on the left column of **Figure 9** toward the left or toward the right, the priorities of the alternatives also change along the right column. In a situation where the decision-maker feels that a criterion is of greater importance than originally indicated, the priority bar of the objective is dragged toward the right to increase the priority of the criterion; while if the criterion is of less importance than originally indicated, the decision-maker drags the priority bar of the objective toward the left to decrease the priority of the criterion so as to assess the impact on the alternatives (**Figure 9**).

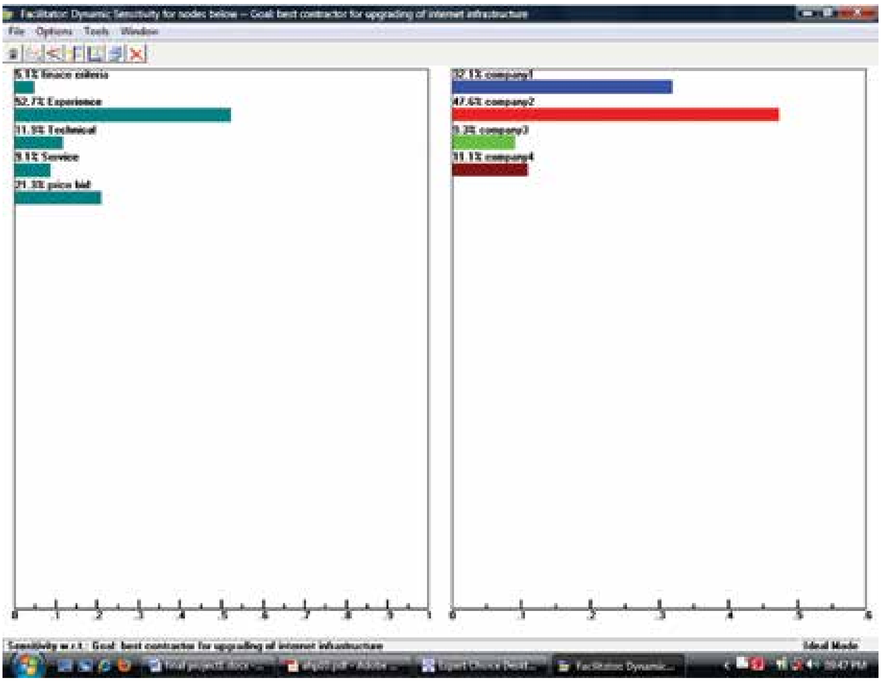

Figure 9. Graph of dynamic sensitivity analysis.

- Gradient sensitivity: This displays the composite priority of the alternatives with respect to the priority of a single criterion. **Figure 10** displays the priorities of the alternatives (contractors) with respect to a criterion, one at a time. The priority of the selected criterion is represented by the vertical solid line and be read where the line intersects the X-axis. However, the priorities of the alternatives are read along the Y-axis. In order to change the priority of the objective, the vertical solid bar is dragged toward either the left-hand side or right-hand side as one desires, and the new priority of the objective is displayed along the dotted bar.
- Head-to-head sensitivity: Displays how any of the two alternatives compare with respect to each criterion and the goal.
- Two-dimensional sensitivity: Displays how alternatives perform with respect to any of the two criteria.

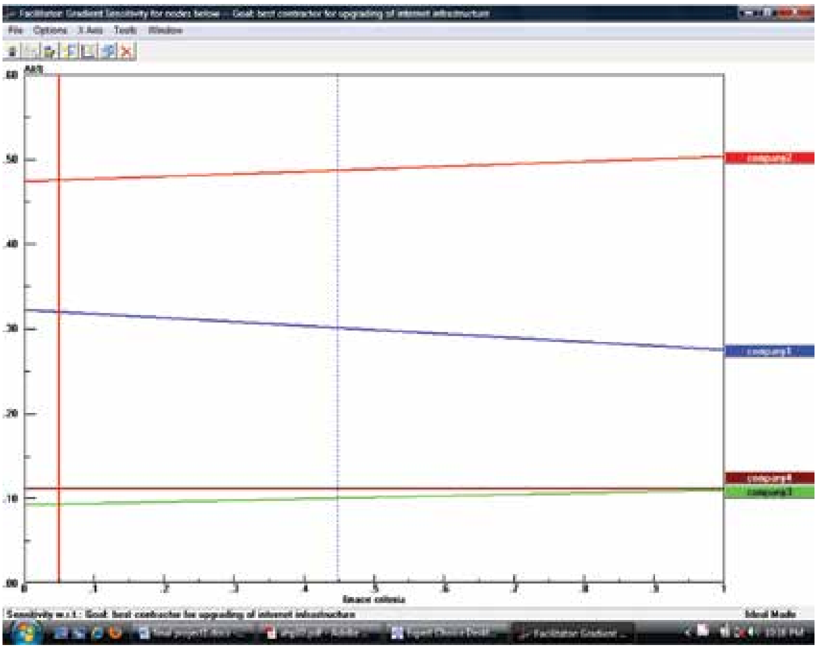

Figure 10. Graph of gradient sensitivity analysis.

6. Conclusion

This chapter simply demonstrates how an AHP model for contractor selection can be implemented on the computer to get the desired results. However, this does not foreclose the use of the procedure enumerated in the chapter for AHP model on other issues. Once the criteria, sub-criteria, and alternatives for any AHP model are clearly identified and stated, the step-by-step use in this chapter can be adopted to generate the needed result. It is believed that the procedure enumerated in the chapter will lessen the difficulty encountered by students and users of AHP models in getting results.

The managerial implication of the chapter lies in the fact that once the correct AHP is developed by them or a professional decision support system (DSS) expert based on internally and externally generated ideal information from experts saddled with the decision problem, implementation of the model to arrive at the right decision becomes easy.

Author details

Emmanuel O. Oyatoye* and Adedotun A. Odulana

*Address all correspondence to: eoyatoye@unilag.edu.ng

Department of Business Administration, University of Lagos, Akoka, Yaba, Lagos, Nigeria

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Thomas L. Saaty and Antonella Petrillo

The purpose of this book is to provide an introduction to the theory and applications in the field of decision making, especially focused on Analytic Hierarchy Process, a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Prof. Thomas L. Saaty in the 1970s and has been extensively studied and refined since then.

The idea of the book is to expand the reader's consciousness to deal with problems regarding the decision making. This book presents some application examples of Analytic Hierarchy. It contains original research and application chapters from different perspectives, and covers different areas such as supply chain, environmental engineering, safety, and social issues. This book is intended to be a useful resource for anyone who deals with decision making problems.

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