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System of System Failures

Edited by Takafumi Nakamura

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Contributors

Liumila Muravieva, Steven Voldman, Martin Hromada, David Rehak, Jozef Zurek, Ryszard Kaleta, Datu Buyung Agusdinata, Takafumi Nakamura

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Meet the editor

Takafumi Nakamura has over 30 years of experience as an ICT infrastructure architect in the Japanese market and 5 years of experience in the Australian market. He is a principal IT architect at Fujitsu. His research interests include system management, software development, technical support for ICT systems, strategic maintenance planning, development of support technologies, and risk management. He holds a leadership role as an ICT architect, system analyst, and system thinker. He is currently working for the Fujitsu Fsas Inc. He is a member of the board and the president in System Support Promotion Unit.

Contents

Preface

The purpose of this book is to foster discussion on the current applications in the field of engineering safety by learning from previous system failures. This book contains various application examples to promote a holistic view to manage and therefore mitigate system failures. The predominant worldview in the current engineering arena is that system failures can be prevented at the design phase. This worldview is obvious if we examine the mainstream, current methodologies for managing the system failures. These methodologies use a reductionist approach. And it is often pointed out that most of such methodologies have difficulty coping with emergent properties in a proactive manner and preventing the introduction of various side effects from quick (i.e., temporary) fixes, which lead to repeating failures of similar type. This book intends to provide managers with a comprehensive overview of the current state-of-the-art praxises in the field of engineering safety by holistically examining the system failures to prevent further occurrence. Also, it provides managers with a bird's-eye view learning from various approaches through utilizing system of system methodologies (SOSMs). The brief introduction and core concept of SOSMs are provided in the introductory chapter. On the basis of SOSM framework, various approaches are developed for risk management and engineering system failure arena, that is, system of system failures (SOSFs). And SOSFs provide managers with a practical reflection to be able to bring to bear, on the complex, diverse, and rapidly changing problem situations they confront, holistic approaches based on the variety of possible perspectives.

The chapters address the most recent developments in the theoretical and practical aspects of these important fields, which, due to their special nature, bring together in a systematic way, many disciplines of engineering, from the traditional to the most technologically advanced. The authors of these chapters are various practitioners and theory developers involved in using the system thinking and system engineering approaches at the scale of increased complexity and advanced computational solutions to such systems. The chapters cover the areas such as failure assessment in aeronautical engineering, seismic resistance of offshore pipeline engineering, electrical engineering, critical infrastructure failure, and system of system theory.

The editor is grateful to all the authors and publishing process manager for their enthusiastic contributions.

Dr. Takafumi Nakamura
Fujitsu Fsas Inc., Japan

Section 1

Introduction

Chapter 1

Introductory Chapter: System of System Failures

Takafumi Nakamura

Additional information is available at the end of the chapter

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1. Introduction

Managers are expected to cope with ever-changing complexity and diversity. They are asked to tackle a much greater diversity of problems learning from previous failures. This book provides managers with a bird's eye view learning from various approaches through utilizing system of system methodologies (SOSM). In order to promote holistic view and promote creativity, Jackson [1, 2] introduced SOSM. SOSM classifies the world of objects into two dimensions: systems and participants. The system dimension has two domains: simple and complex. The participant dimension has three domains: unitary, plural, and coercive. On this basis, holistic approaches can be classified into four types (**Figure 1**):

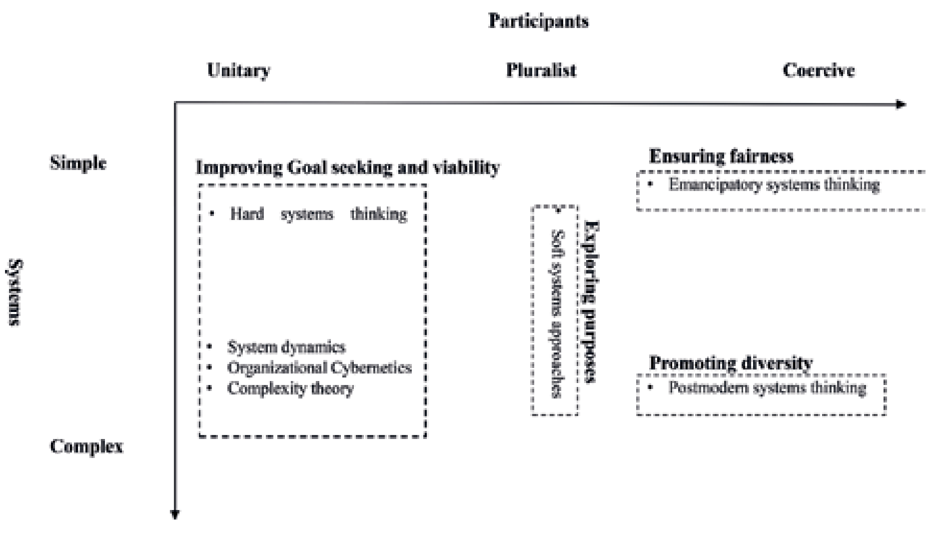

Figure 1. Systems approaches related to problem context in the system of system methodologies (SOSM).

1. Systems approaches for improving goal seeking and viability.
2. Systems approaches for exploring purposes.
3. Systems approaches for ensuring purposes.
4. Systems approaches for promoting diversity.

2. System of system failures (SOSF)

Based upon the SOSM framework, various approaches are developed for risk management and engineering system failure arena, that is, system of system failures (SOSF) [3–5].

In the Preface, the editor noted that this book intends to provide the reader with a comprehensive overview of the current state-of-the-art in engineering safety by holistically examining system failures for the purpose of preventing further occurrence of system failures. This provides managers a practical reflection to be able to bring to bear, on the complex, diverse and rapidly changing problem situations they confront, holistic approaches based on the variety of possible perspectives.

3. The structure of the book

A short conclusion closes the argument. In this introductory chapter, the editor sought to make clear the structure of the book and the logic underlying that structure. The book structure is summarized by SOSM in **Table 1**.

Introductory chapter		
Improving goal seeking and viability	Chapter 2	System and Component Failure From Electrical Overstress and Electrostatic Discharge
	Chapter 3	Vibration Strength of Pipelines
	Chapter 4	Probabilistic Methods of Failure Assessment in Aeronautical Engineering Exploring purposes
Exploring purposes	Chapter 5	Failures in a Critical Infrastructure System
	Chapter 6	Dealing with Uncertainties in A System-of-Systems: Assessing the Robustness of Energy Infrastructure Investments

Table 1. Structure of the book.

Author details

Takafumi Nakamura

Address all correspondence to: tk_moek@nifty.com

Fujitsu Fsas Inc., Tokyo, Japan

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Section 2

Improving Goal Seeking and Viability

Chapter 2

System and Component Failure from Electrical Overstress and Electrostatic Discharge

Steven H. Voldman

Additional information is available at the end of the chapter

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Abstract

Electrical overstress (EOS) and electrostatic discharge (ESD) have been an issue in devices, circuit and systems for electronics for many decades, as early as the 1970s, and continued to be an issue to today. In this chapter, the issue of EOS and ESD will be discussed. The sources of both EOS and ESD failure history will be discussed. EOS and ESD physical models, failure mechanisms, testing methods and solutions will be shown. The chapter will close with discussion on how to provide both EOS and ESD robust devices, circuits, and systems, design practices, and procedures, as well as EOS and ESD factory control programs. EOS sources also occur from design characteristics of devices, circuits, and systems.

Keywords: electrical overstress, electrostatic discharge, latchup, system failure, component failure

1. Introduction

Electrostatic discharge (ESD) and Electrical overstress (EOS) have been an issue with the coming of the electrical age, when electricity and electrical product were first introduced into the mainstream of society [1–5]. With the scaling of semiconductor components, electrostatic discharge (ESD) has been a growing issue [2]. With the introduction of electrical power systems, the telephone, and electronics, inventions such as circuit breakers, and fuses became the first type of electrical overstress protection concepts to avoid over-load of electronic systems [1, 16–25]. Electrostatic discharge (ESD) and electrical overstress (EOS) will be discussed in the following sections.

In electronic design, a plethora of electrical events can occur. **Figure 1** illustrates the type of topics including ESD, EOS, latchup as well as electromagnetic interference (EMI), and electromagnetic compatibility (EMC).

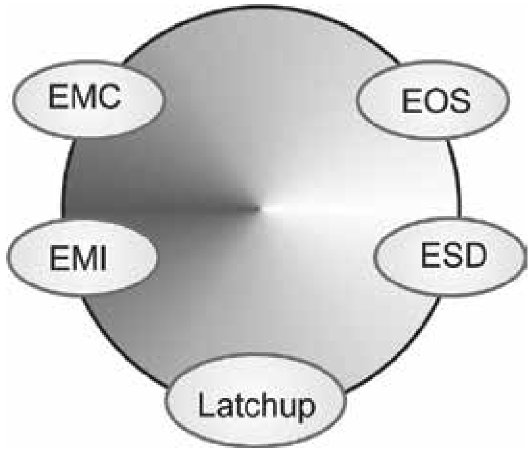

Figure 1. ESD, EOS, Latchup, EMI and EMC.

2. Electrostatic discharge (ESD)

Electrostatic discharge (ESD) is a common form of component level failure from manufacturing, shipping, and handling. Today, the ESD models and performed for qualification and shipping of semiconductor components are as follows [4]:

- Human Body Model (HBM).
- Charged Device Model (CDM).

Additional models that are still performed, but not used for qualification of components include [4]:

- Machine Model (MM).
- Transmission Line Pulse (TLP).
- Very-Fast Transmission Line Pulse (VF-TLP).
- Latchup.
- Transient Latchup.

2.1. Human body model (HBM)

ESD pulse models have been established to quantify the interaction of semiconductor chips and human beings. An important model is the human body model (HBM). Today, HBM is the most widely established standard for the reliability and quality in the semiconductor industry [2–4, 6]. The HBM test is integrated into the qualification and release process of the quality and reliability teams for components in corporations, and foundries [6].

The human body model is regarded as an electrostatic discharge (ESD) event, not an electrical overstress (EOS) event [1–11]. HBM represents the interaction the electrical discharge from a human being and component. The model assumes that the human being is the initial condition.

The human body model (HBM) became of interest in early days in the mining industry in the 1950s. In the Bureau of Mines, investigation reports discussed the issue of electrostatic in the mining industry. A first publication was published by P.G. Guest, V.W. Sikora, and B.L. Lewis as the *Bureau of Mines, Report of Investigation 4833*, U.S. Department of Interior, January 1952 [7]. A second article of interest was published by D. Bulgin, referred as D. Bulgin. Static Electrofication. *British Journal of Applied Physics*, Supplemental 2, 1953 [8].

An early investigator of issues with the human body model standard was T. M. Madzy and L.A. Price II of IBM in 1979 discussed a test system titled "Module Electrostatic Discharge Simulator" [4]. In this article, it was discussed that the ESD simulator was used within IBM since 1974. In 1980, H. Calvin, H. Hyatt, H. Mellberg, and D. Pellinen proposed values for the resistance and capacitance for the human ESD event for the finger tip and field enhanced discharges in "Measurement of Fast Transients and Application to Human ESD," published in the 1980 Proceedings of the EOS/ESD Symposium [4, 10–11]. The proposed resistance for the finger tip was averaged 1920 Ω, and capacitance of 110 pF, whereas the field enhanced discharge was a resistance of 550 Ω, and 120 pF. In 1981, H. Hyatt, H. Calvin, and H. Mellberg investigated the human ESD event, published in the 1981 Proceedings of the EOS/ESD Symposium, titled "A closer look at the human ESD event" [4, 10–11].

HBM failure mechanisms are associated with permanent damage on the peripheral circuitry of a semiconductor chip [3]. Additionally, HBM failures can occur power rails and ESD power clamps between the power rails. HBM failures can occur in both passive and active semiconductor devices. The failure signature is typically isolated to a single device, or a few elements. ESD circuits are designed to be "tuned" to be responsive to specific pulse widths; this is an issue for EOS events since they are not "tuned" for EOS events. For example, the RC-triggered ESD power clamp is tuned to the HBM pulse, not EOS events.

HBM ESD failures are also distinct from EOS events [1, 4]. HBM events will not typically cause failures in the package, printed circuit board (PCB), or single component devices mounted on a printed circuit board.

Human body model (HBM) failures can occur in diode and MOSFET structures. Integrated circuit diode structures fail at the contact interface, silicon surface, or junction region. Human body model failure occurs in a metal oxide semiconductor field effect transistor (MOSFET) structure. Integrated circuit MOSFET structures failure occurs from MOSFET source-to-drain, or at the MOSFET gate. From HBM failures, typically, the failure is MOSFET source-to-drain failures [2, 3].

An example of an ESD protection network is known as a dual-diode network [3]. The dual-diode ESD network is a commonly used network for complimentary metal oxide semiconductor (CMOS) technology. A first p-n diode element is formed in an n-well region where the p-anode is the p-diffusion implant of the p-channel MOSFET device and the n-cathode is the n-well region connected to the power supply V_{DD}. This is sometimes referred to as the "up diode." A second p-n diode element is formed in an p-well or p-substrate region where the n-cathode is the n-diffusion implant of the n-channel MOSFET device, or the n+/n-well implant and the p-anode is the p-well region or p-substrate region connected to the power supply V_{SS}. This is sometimes referred to as the "down diode." This circuit provides a "forward bias" ESD protection solution for positive and negative ESD pulse events to the two power rails V_{DD} and V_{SS}. An advantage of the dual-diode ESD network is that it is easily to migrate from technology generation to technology generation. In shallow trench isolation (STI) technology, this structure is scalable. A second advantage is that it has a low turn-on voltage of 0.7 V. A third advantage is that it can be designed with low capacitance, making it suitable for CMOS, advanced CMOS, and RF technologies. A fourth advantage is that it does not contain MOSFET gate dielectric failure mechanisms.

An example of a signal pin ESD network consisting of a grounded gate n-channel MOSFET device [3]. The grounded gate NMOS (also referred to as GGNMOS) ESD network is a commonly used network for complimentary metal oxide semiconductor (CMOS) technology. Typically, it is a n-channel MOSFET whose MOSFET drain is connected to the signal pin, and whose MOSFET source and gate are connected to the ground power rail. This circuit remains "off" in normal operation. When the signal pin exceeds the MOSFET snapback voltage, this circuit discharges to the V_{SS} power rail. When the signal pin is below the ground potential, the MOSFET drain forward biases to the p-well or p-substrate region. An advantage of the GGNMOS ESD network is that it is a natural scalable solution. As the technology scales, the MOSFET snapback voltage reduces, leading to an earlier turn-on of the MOSFET.

2.2. Charged device model (CDM)

The charged device model is an electrostatic discharge (ESD) test method that is part of the qualification of semiconductor components [4]. The charged device model (CDM) standard is supported by ESD Association as ANSI/ESD ESD-STM5.3.1-1999 [12]. Presently, there are four CDM test standard (ESDA S5.3.1, JEDEC JESD22-C101, AEC-Q100-011 Rev. C, and JEITA ED-4701-300). Each require different test platform, testing, waveform, and calibration requirements [4]. The charged device model (CDM) event is associated with the charging of the semiconductor component substrate and package. The charging of the package occurs through direct contact charging, or field-induced charging process (e.g. the field-induced charge device model (FICDM)).

There is presently an effort to align the CDM standards between the ESD Association and the JEDEC organization, by establishing a joint ESDA/JEDEC standard. The ESDA/JEDEC joint standard (JS-002 2014) will replace existing CDM ESD standards JEDS22-C101 and ANSI/ESD S5.3.1. The new joint standard will preserve test systems in the field, and improve the waveform measurement process.

The charged device model (CDM) pulse is regarded as the fastest event of all the ESD events [4, 12–15]. Note that the CDM pulse waveform is influenced by the test platform and measurement metrology. The test platform is influenced by the field plate, field plate dielectric thickness and material type, and the probe assembly (e.g. test head, and ground plane). The metrology is influenced by the oscilloscope and verification module specifications.

First, the event is oscillatory. The CDM current pulse rise time is on the order of 250 ps, and with peak currents in the range of 10 A. The energy spectrum of the CDM pulse event extends to 5 GHz frequency. The CDM pulse waveform has a fast current pulse. The time scale of the CDM event is significantly lower than the thermal diffusion time; hence CDM events are in the "adiabatic regime" of a Wunsch-Bell power-to-failure curve [4].

In the calibration and verification procedure, the JEDEC standard requires a 1 GHz oscilloscope, whereas the ESDA standard requires 3 GHz [13]. Both standards today are bandwidth limited signal since the CDM waveform is faster that 1 GHz. These oscilloscopes were chosen based on availability at the time. It is well know that the energy spectrum of the CDM pulse waveform can extend into the 5 GHz frequency.

CDM event damage occurs in the semiconductor chip through the substrate. It can also occur through the power supply. Charge is stored on the package, and the substrate.; then the power supply rapidly discharges through the grounded pin. The CDM failure mechanism can be small "pin-hole" in a MOSFET gate structure; this can occur in receiver networks, as well as metal interconnects.

The current path for charged device model (CDM) in components is significantly different from other electrostatic discharge (ESD) events. In the case of the charged device model (CDM), the package and/or chip substrate is charged through a power or ground rail. The component itself is charged slowly to a desired voltage state. As a result, the current flows from the component itself to the grounded pin during ESD testing. This is significantly from other ESD tests that ground a reference, and then apply an ESD event to a signal or power pin. As a result, the current path that a CDM event follows is from inside the component to pin that is grounded during test.

To avoid CDM failures of the MOSFET gate structure, an additional charged device model (CDM) ESD network is used [3] The ESD network comprises of a first stage dual-diode network placed adjacent or in proximity of the signal pad. A second set of diodes (e.g. second stage network) are placed adjacent to the receiver circuit. A resistor is placed between the first and second stage. Three paths are possible for the CDM current from a charged ground rail (e.g. p-substrate) to the grounded receiver pin. For a positive charging of the substrate, the current flows from the substrate to any possible path that will reach the grounded signal pad node. A first path is through the n-channel MOSFET receiver circuit gate and to the second stage ESD diode. A second path is through the substrate to the second stage diode network. A third path is through the substrate to the first stage ESD network.

In the case of the first stage ESD protection circuit is far from the signal pad, the substrate resistance can be significant. For the third path, the total resistance from the grounded location to the grounded signal path is the sum of the substrate resistance and the ESD diode series resistance. In the case that the receiver network is adjacent to the second stage ESD network, the current will prefer to follow the second path instead of first path. When the impedance of the n-channel MOSFET receiver (e.g. Path A) is higher than resistance through the second path, the receiver gate structure can avoid rupturing of the MOSFET gate dielectric. To insure that the current flows through the second path through the second stage CDM ESD network, the circuit must be physically close to the receiver, and a low series resistance diode element.

3. Electrical overstress (EOS)

Electrical overstress (EOS) has been an issue in devices, circuit and systems for electronics for many decades, as early as the 1970s, and continues to be an issue today [1]. EOS failures are occurring at the device manufacturer, supplier, assembly and the field. In the electronic industry, many products and applications are returned from the field due to "EOS" failure. To make progress in addressing the electrical overstress (EOS) issue, it is important to provide a framework for evaluation and analysis of EOS phenomena.

Electrical overstress (EOS) sources exist from natural phenomena, and power distribution [1, 14–25]. Switches, cables, and other power electronics that can be a source of electrical overstress. EOS sources exist in devices, circuits and systems. In the following sections, these issues will be discussed [1].

3.1. EOS design issues

Many of the electrical overstress (EOS) issues can occur from the design of the semiconductor component, the system and its integration. Examples of EOS source design issues are as follows [1]:

- Semiconductor process - application mismatch.
- Printed circuit board (PCB) inductance.
- Printed circuit board (PCB) resistance.
- Latchup sensitivity [5].
- Safe operating area (SOA) power rating violation.
- Safe operating area (SOA) voltage rating violation.
- Safe operating area (SOA) current rating violation.
- Transient safe operating area - di/dt and dv/dt.

Figure 2 illustrates the safe operating area (SOA) of a semiconductor device. There is a current limit, and a voltage limit on the borders of the SOA. At the corner of the SOA, the limitation is a thermal limit, and a second breakdown limit. Thermal limit has to do with the thermal limit of a device. The second breakdown limit has to do with second breakdown or thermal breakdown limit.

Testing and test simulation of devices, components and systems are an important part of the evaluation to electrical overstress (EOS) [4]. EOS test simulation is valuable part of understand EOS failures. EOS testing provides [1, 4]:

- Root cause analysis.
- Replication of failure signature.
- Technology EOS hardness evaluation.
- Technology benchmarking.
- Component reliability qualification.
- System qualification.

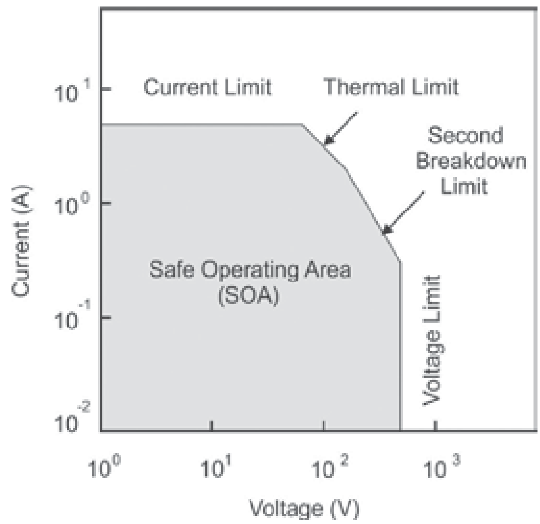

Figure 2. Safe operating area (SOA).

Field returns occur in all electronic components independent of the technology generation and period of time of evaluation. One of the key difficulties in the semiconductor industry is the ability to track, record and maintain a database of these field failures.

EOS events do not have a characteristic time response. EOS events are typically slower, and distinguishable from ESD events by having longer characteristic times. The time constant for EOS events range from sub-microseconds to seconds.

Electrical over-voltage (EOV), electric over-current (EOC), and electrical over-power (EOP) can lead to failure mechanisms; these can lead to melted packages, blown single component capacitors and resistors, ruptured packages, blown bond wires, cracked dielectrics, fused and melted metal layers, and molten silicon.

The failure analysis process can comprise of the following steps:

- Information gathering.
- Failure verification.
- Failure site identification and localization.
- Root cause determination.
- Feedback of root cause.
- Corrective action.
- Documentation reports.

3.2. EOS failure mechanisms

Visual external or internal inspection can be applied to evaluate EOS failure mechnanisms. Visual damage signatures can include the following:

- Package lead damage.
- Foreign material.
- Cracks.
- Package discoloration.
- Corrosion.

Visual damage can also be evaluated from internal inspection. For internal inspection, the following visual damage signatures are:

- Melted metallurgy.
- Cracked inter-level dielectrics.
- Molten silicon.

There are certain categories of failures that electrostatic discharge (ESD) does not typically cause, and EOS events do cause. Failures that typically are caused by EOS phenomena but not ESD are as follows [1]:

- Printed circuit board (PCB) damage.
- Package molding damage.
- Package pin damage.
- Wire bond damage.

Today, electrical overstress (EOS) is still an issue in today's electronic systems. To address electrical overstress in systems, electrical overstress (EOS) protection device are added to printed circuit boards (PCB), cards, and systems. The integration of EOS protection devices into systems.

3.3. EOS protection devices

Electrical overstress (EOS) protection devices are supported by a large variety of technologies. Although material and operation may differ between the EOS protection devices, their electrical characteristics can be classified into a few fundamental groups [16–25].

EOS protection networks can be identified as a voltage suppression device, or as a current-limiting device. The voltage suppression device limits the voltage observed on the signal pins or power rails of a component, preventing electrical over-voltage (EOV). The current-limiting device prevents a high current from reaching sensitive nodes, avoiding electrical over-current (EOC) [1].

Voltage suppression devices can also be sub-divided into two major classifications [1]. Voltage suppression devices can be segmented into devices that remain with a positive differential resistance, and those that undergo a negative resistance region. For positive differential resistance, these devices can be referred to as "voltage clamp" devices where dI/dV remains positive for all states; for the second group, there exists a region where dI/dV is negative. The first group can be classified as "voltage clamp devices" whereas the second group can be referred to as an "S-type I-V characteristic device", or as a "snapback device." In the classification of voltage suppression devices, the second classification can be associated with the directionality; a voltage suppression device can be "uni-directional" or "bidirectional."

The choice of electrical overstress (EOS) device to use in an application is dependent on the electrical characteristics, cost, and size. The electrical characteristics that are of interest are the breakdown voltage, and the forward conduction [1].

The types of voltage suppression devices used electrical overstress (EOS) are Transient Voltage Suppression (TVS) Diodes [22], Thyristor devices, Varistor devices [21], Polymer Voltage Suppression (PVS) devices, and Gas Discharge Tube (GDT) devices [23].

Current-limiting devices can be used in a series configuration for electrical overstress (EOS) protection. EOS current-limiting devices can be as follows [16–24]:

- Resistors.
- Resetting fuses.
- Non-resetting fuses.
- eFUSE.
- Positive temperature coefficient (PTC) devices.
- Circuit breakers.

The choice of the current-limiting EOS protection device is a function of the cost, size, rated current, time response, I^2t value, rated voltage, voltage drops, and application requirements.

Diodes are uni-directional type EOS structure, but can be utilized in a forward or reverse breakdown mode of operation for a voltage limiting EOS solution [1]. Schottky diodes are also commonly used uni-directional electrical overstress (EOS) protection device [1]. Schottky diodes have a forward conduction state, and reverse blocking state. Schottky diodes have a lower forward turn-on (e.g. 0.35 V) compared to standard silicon p-n junction (e.g. 0.7 V). For electrical overstress, Schottky diodes are mounted on printed circuit board (PCB) by soldering in the leads through vias, or surface mount. Schottky diodes are not as commonly used within components to provide electrostatic discharge (ESD) protection due to lack of availability. Schottky diodes are uni-directional type EOS structure, but can be utilized in a forward or reverse breakdown mode of operation for a voltage limiting EOS solution. Zener diodes are also used as a uni-directional electrical overstress (EOS) protection device [1].

Zener diodes are used for electrostatic discharge (ESD) protection for high voltage and power applications. Zener diodes are not used for ESD protection for low voltage CMOS applications. For electrical overstress (EOS) single component Zener diodes are mounted on printed circuit board (PCB) through vias, or surface mount. Zener diodes are uni-directional type EOS structure, but can be utilized primarily in reverse breakdown mode of operation for a voltage limiting EOS solution.

Zener diodes are used uni-directional electrical overstress (EOS) protection device. Zener diodes are typically used as a voltage clamping EOS protection device, and typically used in the breakdown state. Schottky and Zener diodes can both be integrated into a given application.

An EOS protection device used for high voltages is the varistor. A varistor is also known as a voltage dependent resistor (VDR). The varistor element behaves like a diode, forming a non-linear current-voltage (I-V characteristic).

Another EOS protection device is the metal oxide varistor (MOV) device; this is the most common varistor composition [1, 21]. Zinc oxide, combined with other metal oxides are integrated between two metal electrodes. Metal oxide varistors can also include bismuth, cobalt, and manganese. The operation of the MOV device is based on conduction through ZnO grains; current flows "diode-like" through the grain structures creating a low current flow at low voltages. At higher voltages, the current flow is dominated by a combination of thermionic emissions and tunneling. This diode-like behavior forms the diode-like characteristic provides the high resistance/low voltage state, and the low resistance/high voltage state. An advantage of the MOV structure is it has a high trigger voltage, making it suitable for EOS protection in power electronics (e.g. 120–700 V applications) [1, 21]. The disadvantage of these elements is that it has high capacitance, high on-resistance, high trigger voltage, and variability of the device response (e.g. on-resistance and clamping voltage) in the MOV device characteristics. Key device parameters of varistor are the energy rating, operating voltage, response time, maximum current and breakdown voltages.

Gas discharge tubes (GDT) devices can be used to avoid electrical overstress (EOS) in systems [1, 23]. Gas discharge tubes (GDT) are bidirectional, allowing for protection for both positive and negative EOS events. GDT elements are suitable from surge protection. GDT devices have high trigger voltages (unless used as a first stage followed by other low voltage secondary EOS solutions) [1].

Gas-filled tubes (GDT) utilize electrical discharge in gases. An applied voltage initiates the device by ionizing the electrical gas, followed by electrical glow discharge, and an electrical arc. With creation of an electrical arc, the GDT device becomes a low resistance shunt for EOS protection. These gas-filled tubes can contain hydrogen, deuterium, and noble gases (e.g. helium, neon, argon, krypton, and xenon). GDT devices can vary their electrical characteristics by choices of the gas type, pressure, electrode design, and spacings.

GDT devices undergo three states: (1) electrical breakdown, (2) glow discharge, and (3) electrical arc [1, 23]. The electrical breakdown is a high voltage low current state prior to triggering of the GDT device. A glow discharge region forms a second state which incorporates a low current high voltage state. Lastly, after full ionization of the gas, a low voltage high current state occurs with a low "on-resistance."

GDT devices have high trigger voltages suitable for LDMOS power electronic applications to HV LDMOS (e.g. 120 V), and UHV LDMOS applications (e.g. 600–700 V) [1, 23]. These devices are used in a number of high voltage switch devices, such as ignitrons, krytons, and thyratrons.

One of the disadvantages of the GDT devices is the slow turn-on times typically in the micro-seconds. An example of some of the electrical characteristics can exhibit d.c. breakdown from 75 to 600 V, with a single surge response of 40 kA in 10–20 s, or multiple surges of magnitude of 20 kA.

The electrical circuit breaker is used in industrial, commercial, and residential electrical systems for high currents. Electrical circuit breakers have issues of physical size, weight, cost, and time response. Circuit breakers can be used to protect household appliances, and large scale switchgear high voltage circuits. The circuit breaker is an electrical switch designed for the purpose of electrical over-current events, short circuits, or fault detection. Circuit breakers are typically "tripped" by the high current event, and can be manually reset. The concept of the circuit breaker was invented by Charles Grafton Page, in 1836 [17].

A class of circuit breakers is the thermal-magnetic circuit breaker [1]. Thermal-magnetic circuit breakers are used to avoid "short-circuit" currents. Thermal-magnetic circuit breakers are sensitive to temperature. Thermal-magnetic circuit breakers contain a bi-metal switch and an electromagnet. The bi-metal switch provides over-current protection. During current over-load, the bi-metal switch heats up, leading to bending of the element. The electromagnet responds to short-circuit currents [1].

Power controllers are used for low power and low voltage applications; power controllers typically are low voltage high efficiency products that can carry amperes of current per channel. Buck-converters use over-current protection logic and networks; over-current functions protect the switching converter from an output short by monitoring current flow in the application. Hence, in power applications, it is possible to integrate electrical over-voltage (EOV) and electrical over-current (EOC) within a component design. Many analog and power applications also contain thermal protection networks as well to avoid thermal runaway and EOS damage.

4. Challenges in the future

Future challenges exist in improve reliability and safety in components and systems due to electrostatic discharge (ESD) and electrical overstress (EOS). Challenges include the following:

- Achieving EOS and ESD standards protection levels in future technology generations.
- Maintaining chip and system level performance objectives without lowering of ESD and EOS protection levels.
- Electronic system failure from CMOS latchup in scaled future technology.
- Electronic system failure from overheating in handheld and portable devices.

5. Conclusions

In conclusion, ESD and EOS failures occur in devices, components and systems in electronics in the past, and in the future with the introduction of both single component to VLSI technology.

Significant advancements have been made in the understanding of failure mechanisms, as well as solutions to address them have been applied in semiconductor electronics.

Author details

Steven H. Voldman

Address all correspondence to: voldman@ieee.org

Institute of Electrical Engineering, IEEE fellow, United States of America

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Chapter 3

Vibration Strength of Pipelines

Muravieva Liudmila Victorovna

Additional information is available at the end of the chapter

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Abstract

Damage of offshore oil-and-gas pipelines results in significant pollution of the marine environment. Extent of pipeline damage during an earthquake depends on a number of factors: the seismic force and the seismic waves' propagation direction, the geological and groundwater conditions, the operation and process duties, the pipeline design and the joints, the pipeline material's characteristics, and the extent of pipeline wear. Requirements to the structural reliability of subsea pipelines are much stricter than those set to underground and overhead pipelines. An offshore pipeline is in the combined stressed condition. It is characterized by tension of the pipeline walls caused by pressure pulsations and cyclic bending due to the vibrations. This chapter tackles the vibration analysis issues. The main goal is to present to the industry specialists the principles of vibration assessment as applied to the offshore pipelines in seismic regions and to outline solutions of the vibration problems. The dynamic calculations of the offshore pipelines based on the natural frequency analysis are represented in the industrial construction standards only.

Keywords: marine subsea pipeline, stresses in the pipeline wall, pipeline vibration, the amplitude of offshore pipeline movements, seismic resistance of the offshore pipeline

1. Introduction

During operation of the offshore pipelines, the vibration processes occur as a result of pump plant running, activation of shutoff valves, emergency shutdowns, and external effects. Vibration protection issues are highlighted in the manual (design documentation), but during the design stage of the offshore pipeline system, these factors are not taken into consideration. Sea pipelines are new type of constructions in Russia. Only in VSN R 42-81 [8] are considered dynamic problem definition laying sea pipelines. All private oil-extracting companies are not interested in researches. A research of vibrations of pipelines demands the state researches.

The provisions [2–4] take into account the following stresses acting on the offshore pipeline: pressure of the product being transported, temperature exposures, and weight coating; however, dynamic nature of loading on the pipeline wall is not considered during the operation.

When calculations are made in regard of hazard assessment of the pipeline vibrations, criteria shall be used to determine the vibration behavior of the pipelines. Vibrations of the pipelines caused by external effects such as impact and earthquake can be described by a general integral of the forced vibration equation.

For example, in case of vibrations of the base plate to which a pipeline support is fixed (**Figure 1a** and **b**), the latter has a dynamic impact by which degree is determined by the support yield δ_A, $P = Y_0\delta_A \cos \omega t$.

It is highly important to have an opportunity to determine stressed condition of the pipelines subject to vibrations in the form of elastic curves, which occur during vibrations caused by external excitations.

Stresses in the pipeline wall can be regarded as criteria.

2. Vibration structure

It is used as a reliability factor of the structure under vibrations [1, 3]. Under harmonic vibrations, the vibration velocity can serve as a reliability criterion for the pipeline.

The harmonic vibrations are characterized by two parameters: frequency of vibrations and displacement amplitude:

$$y = Y_0 \sin \omega t \tag{1}$$

Vibration velocity and vibration acceleration are expressed as follows:

$$v_0 = \omega Y_0; \quad g_0 = \omega^2 Y_0 \tag{2}$$

3. Bending vibrations of the pipelines

Under bending vibrations of the pipelines, when distribution of stresses and vibration velocities is significantly different for various fixing conditions, factor *c* shall be determined individually for each case [3].

$$\frac{d^2y}{dx^2} + \frac{m\omega^2}{T} y = 0 \tag{3}$$

Form of the elastic curve of the pipeline is expressed by a sine wave.

$$y(z) = Y_0 \sin \frac{i\pi z}{L}, y(z) = Y_0 \bar{y}(z) \tag{4}$$

where Y_0 is an amplitude of vibrations.

Bending moment in the random location on the pipeline is equal to:

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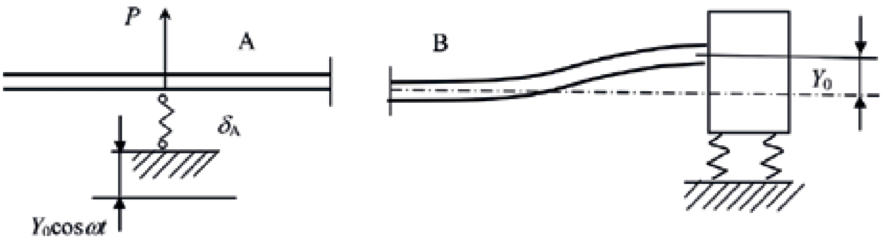

Figure 1. Force excitation of vibrations. (a) Excitation through an elastic support; (b) kinematic excitation of vibrations.

$$M(z) = EIy''(z) = -EI\frac{i^2\pi^2}{L^2}Y_0\sin\frac{i\pi z}{L} \tag{5}$$

where I is a moment of inertia.

Maximum stresses in the pipeline:

$$\sigma_{makc} = EI\frac{i^2\pi^2}{WL^2}Y_0, \tag{6}$$

then W is a moment of resistance in the pipeline.

At initial approximation, certain typical ideal forms of vibrations are used for vibration analysis. Then, the natural vibration frequency of the pipeline is expressed by the following formula:

$$\omega_i = \frac{i^2\pi^2}{L^2}\sqrt{\frac{EIg}{\rho F}} \tag{7}$$

where F is a square section of the pipeline.

According to [3, 5], the maximum vibration velocity is determined from the following equation:

$$\mathrm{V}_{\max} = v_{\mathrm{base}}\mathrm{K}\eta \tag{8}$$

where v_{base} is a vibration velocity of the base plate; η is a dynamic magnification factor; k is a form engagement factor: $k = \int_0^1 \overline{y}d\overline{z} / \int_0^1 \overline{y}^2 d\overline{z}$, $\overline{y}$, $\overline{z}$ are dimensionless forms of pipeline vibrations and current coordinate.

Expansion bends are regarded as vibration damping elements for the pipelines to ensure their vibration resistance. The expansion bends prevent the transfer of vibrations along the pipeline.

4. Analysis of pipeline vibrations

Stresses across the cross sections of the pipeline under natural vibrations can be determined from the following equation:

$$\sigma_k = \frac{ED}{2} C_k(\omega) \frac{\partial^2 y_k(z)}{\partial z^2}. \tag{9}$$

Stresses acting on the pipeline can be expressed as follows:

$$\sigma = Y_0 \frac{EI\overline{y''}}{W(z)},$$

where *EI* is bending rigidity of pipe, N·m^2.

Allowable amplitude of vibration equals to:

$$[Y_0] = \frac{[\sigma]W(z)}{EI\overline{y''}}, \tag{10}$$

where [σ] is a permissible stress in the pipe metal.

The analysis of pipeline vibrations is performed using root mean square of instantaneous vibration parameters over a period determined by the following formula [8]:

$$\overline{y} = \frac{1}{T} \int_0^T y^2 dt. \tag{11}$$

Measurement results of real pipeline vibrations show that such vibrations are of complex, and in some cases, they are of random nature. For the determination of stresses in the pipeline walls, the process loads P_p due to operating pressure of the product being transported, the effect of hydrostatic water head pressure shall be taken into consideration as well as time-variable loading on the pipeline such as pressure pulsations and seismic forces. It is effective to use spectral method during the analysis of the pipeline random vibrations [1, 3].

The internal pressure of the gas line generates random vibrations.

Elastic stress in the pipe walls can be expressed as follows:

$$\delta = \frac{F}{A} = \frac{\overline{p}_2 D}{2t}, \text{when } \overline{p}_2 = 2Et \frac{\Delta D}{D^2} = \frac{4Et}{D^2} d, \tag{11a}$$

where δ is a dynamic stres, N/m^2. Pressure changes in this manner $p \sin \omega t = \overline{\mathrm{p}}_2 + \overline{\mathrm{p}}_3$, in this case the balance between the elastic and internal force in the pipe wall shall be equal to:

$$\overline{\mathrm{p}}_1 = \overline{\mathrm{p}}_2 + \overline{\mathrm{p}}_3 = \frac{4E\mathrm{t}}{D^2} \mathrm{d} + \mathrm{t}\delta a$$

As displacement and acceleration, at a given frequency, are related by $-\omega^2$, the expression can be changed to:

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$$\overline{\mathrm{p}}_1 = +\left[\delta - \frac{4Et}{D^2\omega^2}\right]\mathrm{ta} \tag{12}$$

Or

$$\overline{\mathrm{p}}_1 = \left[\frac{4E}{D^2} - \omega^2\right]td \tag{13}$$

Combined stress in the axial direction due to pressure pulsations and vibration:

$$\sigma_t = \sigma_{\Delta pt} + \sigma_V \tag{14}$$

5. Spectral transforms

Spectral density corresponds to the spectral form of the internal pressure sinusoidal vibrations $u(t) = \sin \omega_0 t$. Periodic function spectrum $S_T(f)$ is determined by a direct Fourier transform of the time function

$$\begin{aligned} S_T(f) &= \int_{-\infty}^{\infty} s_T(t) e^{-j2\pi ft} dt = S(f)\cdot\frac{1}{T}\sum_{m=-\infty}^{\infty}\delta\left(f - \frac{m}{T}\right) \\ &= \frac{1}{T}\cdot\sum_{m=-\infty}^{\infty} S\left(\frac{m}{T}\right)\cdot\delta\left(f - \frac{m}{T}\right) = \sum_{m=-\infty}^{\infty} C[m]\cdot\delta\left(f - \frac{m}{T}\right) \end{aligned} \tag{15}$$

Complex weights of S-functions at frequencies multiple of 1/T. They represent expansion coefficients of the function (15) into a Fourier series as follows:

$$C[m] = \frac{1}{T}\cdot S\left(\frac{m}{T}\right)$$

Time function $s_T(t)$ and spectral function $C[m]$ of the impact are the main characteristics. They are interrelated by a complex Fourier series.

The function containing n vibrations is described by the following equations,

$$F(t) = \sin\omega_0 t \text{ at } 0 < \mathrm{t} < \frac{2\pi n}{\omega_0} \text{ and } F(t) = 0 \text{ at } 0 > \mathrm{t} > \frac{2\pi n}{\omega_0}.$$

Then amplitude spectrum is determined by the following expression:

$$S(\omega) = \left|\frac{2\omega_0 \frac{n\pi\omega}{\omega_0}}{\omega_0^2 - \omega^2}\right| \tag{16}$$

At small values of ω_0: $S(\omega) \approx \frac{1}{\omega}$.

Upon the completion of the vibration analysis according to the scheme of the single-degree-of-freedom system (which includes the reduced weight of the pipeline and its components, and elastic support action), stresses and deformations in the support elements shall be calculated.

Transfer function of the maximum stress relative to acceleration of the pipeline supports can be written as

$$|H_\sigma(\omega, z)| = \frac{C_k(\omega)\,\frac{ED}{2}\,y_k''(z)}{\sqrt{\left(\omega_0^2 - \omega^2\right)^2 + \left(2\beta\omega\omega_0\right)^2}}. \tag{17}$$

Spectral density of the pipeline response to random excitations will be equal to

$$\boldsymbol{\Phi}_{YY}(\boldsymbol{\omega}) = \frac{\boldsymbol{\Phi}_{QQ}(\boldsymbol{\omega})}{\left(\boldsymbol{\omega}_0^2 - \boldsymbol{\omega}^2\right)^2 + \left(\mathbf{2}\boldsymbol{\beta}\boldsymbol{\omega}\boldsymbol{\omega}_0\right)^4} \tag{18}$$

Considering the tensile strength and fatigue strength, the allowable amplitudes of stresses in the pipeline wall can be calculated from the following formulas:

$$\sigma_{\Lambda m} = \frac{\sigma_{-1}\beta k}{n_m\left(1 + \frac{\sigma_{-1}}{\sigma_B}\frac{1+q_r}{1-q_r}\right)}, \quad \sigma_{\Delta t} = \frac{\sigma_{-1}\beta k}{n_t\left(1 + \frac{\sigma_{-1}}{\sigma_B}\frac{1+q_t}{1-qr_t}\right)} \tag{19}$$

where $\boldsymbol{\sigma_B}$ is a tensile strength; $\boldsymbol{\sigma_{-1}}$ is a fatigue strength under symmetrical loading cycle; $\boldsymbol{\beta}$ is a coefficient that takes into consideration the effect of the pipeline surface finish on the fatigue strength: for new pipelines $\boldsymbol{\beta}$ **= 0.80–0.85**, for corrosion susceptible pipelines, this coefficient is reduced to $\boldsymbol{\beta}$ **= 0.5**; $\boldsymbol{k}$ is a stress concentration factor [1, 3, 4].

Stress ratio is shown as follows:

$$q_r = \frac{P_p - \Delta P}{P_p + \Delta P}, \quad q_t = \frac{P_p D/(2\delta) - \sigma_t}{P_p D/(2\delta) + \sigma_t},$$

During the installation of the pipeline system, the rated natural load shall be assumed as maximum* at the most probable sea condition for the time period under review, which is determined using (H_3, T_p), and applicable stream and wind conditions. Rated load is assumed as maximum at the most probable parameters of the natural environment (in other words, waves, stream, and wind- L_E), and equals to.

$$R(L_E) = 1 - \frac{1}{N}$$

where $R(L_E)$ is a probability distribution function L_E.

N is a number of loading cycles of minimum 3 h in length at a certain sea condition.

Note that the specific sea condition for the time period under review can be interpreted as a sea condition for an applicable location and period of pipe laying. Ordinary requirement is that the

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duration of the time period shall be long enough to consider all potential delays. Pipe laying period shall not exceed this time interval.

σ_{-1} value can be defined either using reference data or Manson formula [4]:

$$\sigma_{-1} = 1.75\sigma_B/N^{0.12}$$

here N is a number of loading cycles.

6. Pipeline vibration limiting

Pipeline vibration limiting regulations can be divided into the following categories:

- for pipeline soundness and quality
- for pipeline vibration resistance under exposure to external vibrations.

The requirements [design documentation] state that “the maximum allowable amplitude of vibrations of the process pipelines is 0.2 mm at vibration frequency of max 40 Hz” [2].

Offshore pipeline specifications do not provide either limitations for the pressure pulsations or vibration limitations.

Low-frequency vibrations of the pipelines under principal modes, when such vibrations are close to be harmonic, can be easily evaluated on the basis of the amplitude of vibration displacement since in this case they are proportional to the stresses induced in the pipelines and can be regarded as a strength factor of the pipelines.

We get the following expression for k-form of the vibrations using formula [5], for the root mean square value of vibrations:

$$\sqrt{\overline{\sigma_k^2}(z)} = \left[\int_0^\infty C_k(\omega)\frac{\Phi_{QQ}(\omega)d\omega}{\sqrt{\left(\omega_0^2-\omega^2\right)^2+\left(2\beta\omega\omega_0\right)^2}}\right]\frac{ED}{2}$$

In the event of random vibrations, the combined stress in the pipeline is the following:

$$\overline{\sigma^2}(z) = \sum_{k=1}^{N}\overline{\sigma_k^2}(z).$$

However, in the regulatory documents for offshore pipelines, there are not only restrictions on pressure pulsations but also restrictions on vibrations. Low-frequency oscillations of pipelines along lower forms, when these oscillations are close to harmonic, can be conveniently estimated from the amplitude values of the vibrational displacement because in this case they are proportional to the stresses arising in the pipelines and are indicators of the strength of the pipelines.

Vibration velocity can be written as:

$$V_l = \int_0^T a(t)dt = \int_0^T B_0 \sin\ \omega t dt = B_0 n / 2\pi f_K \tag{20}$$

where V_l is vibration velocity (mm/s); a is vibration acceleration (mm/s^2) with amplitude B_0; f_k is frequency of multiplicity factor k.

During the evaluation of the vibration strength, the maximum amplitude of equivalent vibration stresses shall be determined for each representative section of the pipeline. This amplitude is obtained as a result of various modal superpositions. Dimension of the transfer function depends on the type of disturbance and response against which the transfer function is determined.

When exposed to random vibrations, root-mean-square value of the maximum stress in the pipeline can be found using the transfer function for the maximum stress with respect to acceleration of the pipeline supports:

$$|H_\sigma(\omega, z)| = \frac{C_k(\omega)\frac{ED}{2}y_k''(z)}{\sqrt{\left(\omega_0^2 - \omega^2\right)^2 + \left(2\beta\omega\omega_0\right)^2}} \tag{21}$$

where D is outside diameter of pipe.

Pipeline response to broadband random vibrations can be defined as a combined effect of several narrowband random vibrations. The narrowband vibrations of the pipelines occur as a response to the broadband excitation under low damping. The mean frequency of the narrowband vibrations can be calculated from the Rice's formula:

$$\omega_0^2 = \frac{\int_{-\infty}^{\infty}\omega^2\Phi_{YY}(\omega)d\omega}{\int_{-\infty}^{\infty}\Phi_{YY}(\omega)d\omega} = \frac{R_y''(0)}{R_y(0)} = \frac{\sigma_{\dot{y}}^2}{\sigma_y^2} \tag{22}$$

Root mean square value of the pipeline movement to be subject to vibrations can be calculated from the following formula:

$$\sigma = \left[\int_{f_1}^{f_2} \eta_f^2 \Phi(f) df\right]^{1/2}, \quad \text{here } \sigma = \sqrt{\sum_{i=1}^{N} \eta_{f_i}^2 \Phi(f_i) \Delta f_i}. \tag{23}$$

where η_f is a dynamic response factor-relation between displacement amplitude of the anchor points for the pipeline and relative displacement amplitude of the pipeline sections at specified frequency; Φ(f) is a spectral density of the disturbed random vibration in the frequency band f_1 and f_2; Δf_i is an interval of the frequency band segmentation f_1, f_2; N is a number of intervals of the frequency band segmentation.

Development of the standardized vibration limits is complicated due to a wide variety of the requirements to the characteristics of the vibration capacity of various equipments.

However, for determination of the pipeline system reliability exposed to vibrations, it is required to consider the effect of vibrations on failures and malfunctions on the basis of certain assumptions regarding damage accumulation in the structures and failure occurrence. If stresses in the elastic elements of pipelines (supports) are considered failure criteria, the vibration strength of the supports shall be evaluated using calculation models of support structures. The private oil-extracting companies apply burying of pipelines. It is just concealment of a problem. In the seismic phenomena, vibrations arise in the thickness of the Earth.

During the analysis of the first fundamental forms of vibrations which lie within 20 Hz, vibration displacement is frequently used as a test parameter.

The following stages are included into the obligatory vibration tests of the pipeline: study of the operating conditions of the system and analysis of the dynamic loads acting on the pipeline; determination of the potential failure patterns; and selection of failure occurrence criteria due to vibrations.

According to the regulations of the Ministry of Gas Industry, emergency vibration level [2] is measured using vibration velocity V_e = 18 mm/s, and the warning vibration level is estimated by the exceedance V_e = 41 mm/s [9, 10].

During the pipeline vibration analysis, it is necessary to know rigidity characteristics of the system components. The rigidity of pipe of permanent round section is characterized by the following parameters: EI is bending rigidity, $N \cdot m^2$.

Up to the present moment, frequency ranges have not been yet defined for the offshore pipelines where one or another vibration parameter shall be used for vibration limitation purposes.

The allowable amplitude of vibrations is defined as follows:

$$\mathrm{V}_{\max} = v_{\text{base}} k\eta \, \mathrm{V}_{\max.}$$

Amplitude of vibration stresses at different frequencies is determined during calculation of the forced vibrations of the pipeline [8].

The main criterion of the pipeline vibration strength is detuning of natural frequencies f_j from discrete frequencies of the excitatory loads f_{ip}, defined as described in 2.2 [6].

Let us determine safe vibration velocity for the pipeline kinematically excited on the movable base plate. Amplitudes of vibration voltage at different frequencies are determined by the results of calculation of forced oscillations of the pipeline. The way to ensure the vibration resistance of the pipeline is to detune the natural frequencies fj of the structure [7].

Vibrations of marine pipelines with a protective coating to decrease the interaction of the pipeline with the coating result in cracking in the coating of corrosion and damage to the coating.

Example.

Vibration strength of pipelines.

Low-frequency vibrations of the pipelines under principal modes, when such vibrations are close to be harmonic, can be easily evaluated on the basis of the amplitude of vibration displacement because in this case they are proportional to the stresses induced in the pipelines and can be regarded as a strength factor of the pipelines.

σ_{-1} value can be defined either using reference data or Manson formula [4]:

$\sigma_{-1} = 1,75\sigma_B/N^{0.12}$, here ***N*** is a number of loading cycles.

Let us consider the following example of calculating the allowable stress amplitudes in the pipeline wall.

Researches were made for vibration speed (response characteristic: root mean square value of V_{max} = 0.0103 cm/s) and pressure pulsation amplitude of ΔP = 0.5 MPa for the landfall section of the offshore pipeline with rated pressure of 17.5 MPa. Outside diameter of the pipeline is D = 406 mm, wall thickness is 17.5 mm. Material grade is X52 (σ_B = 455 MPa, $\sigma_{-1} \approx$ 916 MPa, E = 0.20457·106MPa, σ_e = 358 MPa). Pipe section modulus is W = 0.00199 m^3.

$$Kt:=1$$

σBB·β·k=806.08

$$\mathrm{nm1} \cdot \left(1 + \frac{\sigma BB}{\sigma B} \cdot \frac{1 + rq}{1 - rq}\right) = 64.214$$

If length *l* of the pipeline section is 30 m, displacement y_0 is determined by the formula (7) and is equal to 0.026 m, considering the formula (9) v_{max} = 0.035 m

If pressure pulsation Δ*P* is 0.5 MPa and work pressure is 15.7 MPa (β = 0.8), stress variation on the pipeline wall is 6.386 MPa. Stress ratio (17) q_r is 0.938. Stress amplitude in the pipeline wall is equal to $\sigma_{\Delta q} = 12.553$ MPa considering steel tensile strength and fatigue strength (refer to **Table 1**).

Temperature fluctuations Δt = 5° result in stress variation of 12.36 MPa in the pipeline wall and are equal to r_t = 0.817 as shown in the formula (19). Allowing for tensile strength and fatigue

Name of the characteristics	**Steel**	
	X52∅406	**X65∅711**
Yield strength, MPa	358	448
Strength limit R_m, MPa	455	530
Permissible stresses in metal pipes σ, MPa	255.6	292.8

Table 1. The main physical characteristics of steel pipe [2].

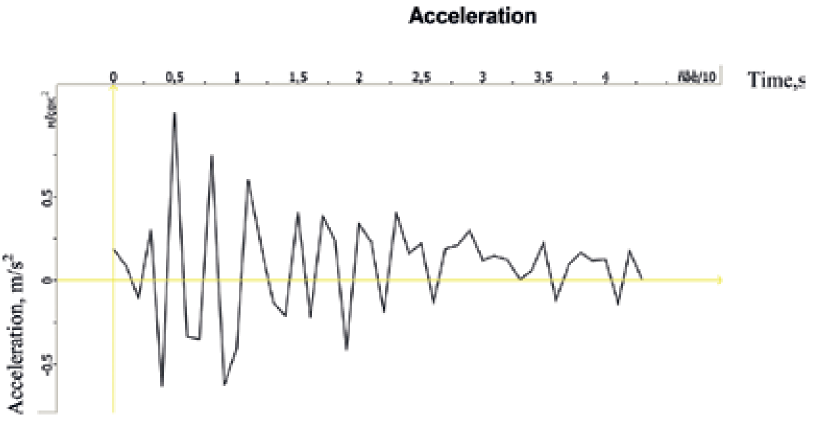

Figure 2. Accelerogram recording used during calculations.

strength of the pipeline steel (see **Table 1**), stress amplitude $\sigma_{\Delta t} = 38.322$ MPa in the pipeline wall. Fatigue strength factor of the pipeline shall be at least $n = 2.0$ [3].

Let us review the seismogram of seismic intensity 6 to MSK-64 scale for the vibration strength analysis of the landfall section of the offshore pipeline. The seismic impact is characterized by the following parameters: maximum acceleration $a_{max} = 0.94485$ cm/s^2 at t = 0.12 s (**Figure 2**).

We get the line spectrum of the signal consisting of the harmonics:

$$\Delta\omega = \frac{2\pi}{T_{min}} = \frac{2\pi}{N\cdot\Delta t}(\mathrm{rad/s})$$

where T_{min} is a minimum period.

Periodogram results can be interpreted as dispersed data at frequencies given in **Table 2** and **Figure 3**.

Ser.no.	Frequency	Period	Periodogram	Density	Spectral density in hamming window
0	0.00000		0.0	1488.55	0.035714
1	0.02174	46.0	2836.21	1828.18	0.241071
2	0.04348	23.0	1695.297	1839.68	0. 446429
3	0.06522	15.3333	1456.8	1528.67	0.241071
4	0.08696	11.5	1341.92	1355.41	0.035714
5	0.1087	9.2	1255.43	1258.18	
6	0.13044	7.66667	1174.63	1174.32	
7	0.15217	6.67143	1092.56	1091.35	
8	0.17391	5.75	1007.15	1005.84	
9	0.19585	5.11111	918.245	917.192	
10	0.21739	4.6	826.556	825. 941	

Ser.no.	Frequency	Period	Periodogram	Density	Spectral density in hamming window
11	0.23913	4.18182	733. 242	733.16	
12	0.26087	3.83333	639.703	640.204	
13	0.28261	3.53846	547.464	548.566	
14	0.30435	3. 28571	458.096	459.796	
15	0.32609	3.06667	373.16	375.439	
16	0.34783	2.875	294.168	296.99	
17	0.36957	2.70588	222.536	225.855	
18	0.3913	2.55556	159.563	163.32	
19	0.41304	2.42105	106.391	110.52	
20	0.43478	2.3	63.992	68.417	
21	0.45652	2.19048	33.139	37.781	
22	0.47826	2.09091	14.398	19.172	

Table 2. Vibration impact periodogram.

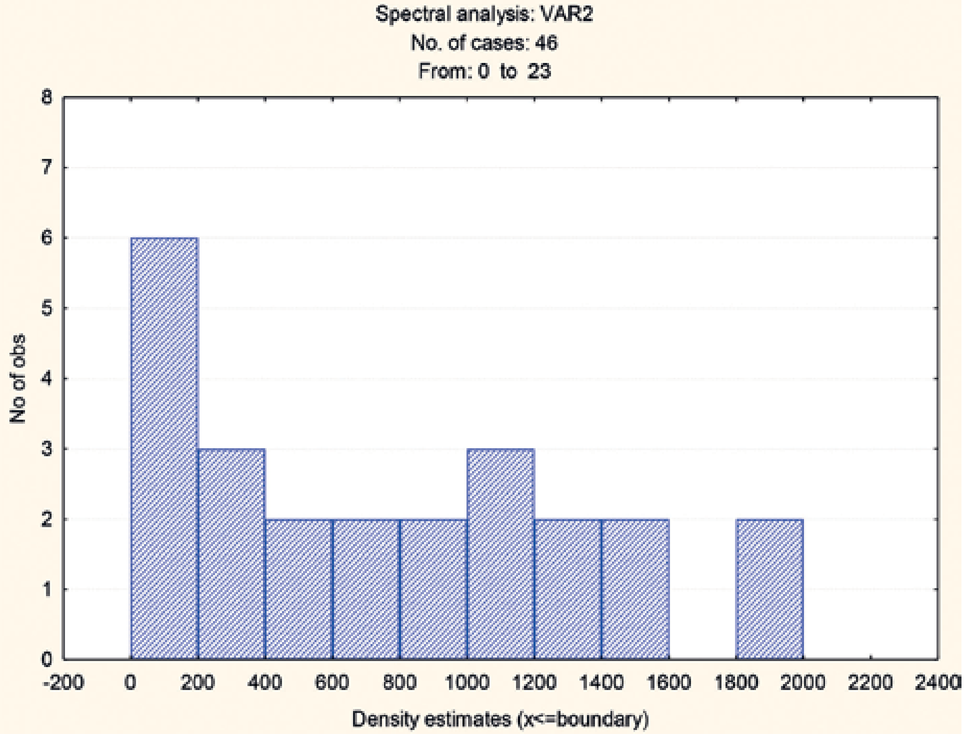

Figure 3. Vibration impact periodogram.

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Mean mathematic amplitude B_K over a period of observation T shall be written as:

$$B_0 = \frac{1}{T}\int_0^T B_K(t)dt, \tag{24}$$

where $B_K(t)$ is a behavior of *k*-x components of vibration spectrum.

Vibration velocity can be written as:

$$V_l = \int_0^T a(t)dt = \int_0^T B_0 sin\omega tdt = B_0 n/2\pi f_K \tag{25}$$

where V_l is vibration velocity (mm/s); *a* is vibration acceleration (mm/s^2) with amplitude B_0; f_k is frequency of multiplicity factor k.

According to the standards of the Ministry of Gas Industry [6], an emergency vibration level is equal to the vibration speed V_e = 18 mm/s, and an alarm vibration level exceeds V_e = 41 mm/s. For pipeline sections more than 0.5 m, the vibration displacement span is restricted to 0.5 mm (refer to the standards of the National Compressor Engineering Association "Souzcompressmach") [2].

Based on the allowable strength from [2], the allowable amplitude of vibrations is calculated for the pipeline of 408 mm diameter and 17.5 mm wall thickness, and allowable stress is 255.6 MPa. The effective span length of the pipeline section under review is 30 m. Amplitude of forced vibrations Y_0 is 0.061 m. Safe vibration speed of the pipeline, which is excited kinematically on the moving platform, is 0.035 m/s.

7. Conclusion

Offshore pipelines can be regarded as new constructions in Russia. Industry-Specific Construction Standard specifies dynamic vibrations of the pipeline.

None of the private oil companies is interested in studying vibration strength of the pipelines; they make references to the existing standards. Offshore pipeline vibration analysis is very important and requires government involvement. Such researches should be performed by the large scientific institutes.

Private companies use a pipe burial method. The pipelines can be buried; however, it is not a way to solve the problem. Seismic impacts come from under the ground.

Vibrations of marine pipelines with a protective coating to decrease the interaction of the pipeline with the coating result in cracking in the coating.

Author details

Muravieva Liudmila Victorovna

Address all correspondence to: rfludmia@yandex.ru

Saint Petersburg State Polytechnic University, St. Petersburg, Russian Federation

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Chapter 4

Probabilistic Methods for Damage Assessment in Aviation Technology

Józef Żurek and Ryszard Kaleta

Additional information is available at the end of the chapter

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Abstract

In this chapter, there has been presented destruction estimation models of construction elements of aircraft in different cases of the state of readiness. The following cases have been examined: when a diagnostic parameter indicating the state of readiness exceeds critical point; when unexpected failure occurs as a result of overload impulse; when a diagnostic parameter increases and as a result premature failure occurs; when damage can be indicated with a diagnostic parameter and an unexpected failure may occur. Differential calculus of Fokker-Planck type has been used in creating the model. Second part of the chapter includes a method of probability and risk evaluation of technical damage to functional-relief (redundant) systems using the Poisson model. The chapter raised the problem of diagnosis errors and erroneous usability evaluation, and describes the example of a real event of an aircraft landing without the released landing gear as a consequence of an erroneous diagnostics. The rescue process in a situation of an aviation accident hazard was described briefly.

Keywords: aircraft, probability, failure, protective systems, diagnostic

1. Introduction

In this chapter, the concept of a hazard in transport systems will be restricted and limited to the aviation technology. It is also assumed that these threats will be related to the possibility of the occurrence of catastrophic and signalled damage due to technical reasons caused by destructive processes, which appear during the aircraft operation. The current aircraft is characterised by a high level of reliability and durability. The reliability and durability tests of aviation technology are carried out in two different ways. The first way involves station tests of the selected units of objects and construction systems under simulated loads and operating conditions, while diagnosing the technical condition and recording data on the course of destruction processes.

The second way is to use an external central computerised system of monitoring and analysing the operation process of the entire set of objects, including a system of recording operational events and an information processing system. The system of recording information obtained during diagnostic checks and detected damage divided by types, symptoms, causes and effects is of particular importance. The recorded data are used for determination of the reliability and safety characteristics, and provide the opportunity to estimate a functioning resource.

2. Safety hazard due to sudden and developing damage in transport systems

Despite many efforts in the processes of designing and implementation of new aircraft constructions, the occurrence of not signalled (sudden) damage, the effects of which are serious, took place. They may occur in the process of operation for many reasons, and mostly due to the lack of complete recognition of many processes that take place during the aviation equipment operation. So far, there has been also a lack of methodology for optimal shaping of construction elements based on destruction models, which would take into account all possible types of their loads and assessment of the environmental impact effects in the long-term operation.

For example, it is possible to distinguish some causes of sudden (catastrophic) damage. They are as follows [1]:

- The loss of the volume strength of the element, which can be damaged as a result of the occurrence of excessive permanent deformations, the occurrence of an ad hoc crack, or a fatigue crack, which exceeded the critical value.
- The loss in material properties in the construction elements as a result of functioning of ageing processes.
- The loss of the element's usability as a result of the surface wear or the inclusions of foreign matters between the cooperating elements.
- The random increase in the concentration of vapours of chemicals and the occurrence of circumstances conductive to uncontrolled explosions.
- The random shortcuts in the electronic circuits.

All the causes leading to catastrophic damage are the subject of numerous experimental and theoretical considerations.

The occurrence of catastrophic damage to the aircraft equipment usually results in serious failures or catastrophes and large losses. Therefore, it is necessary to estimate the risk of incurring these losses.

The term of risk is understood as the probability of the occurrence of critical damage or an adverse event in case of the occurrence of losses. In our case, a negative phenomenon will include the occurrence of catastrophic damage to aircraft. The level of the accepted risk of negative events is determined by the frequency of their occurrence and costs. In **Figure 1**, a method for determination of the accepted risk range is presented.

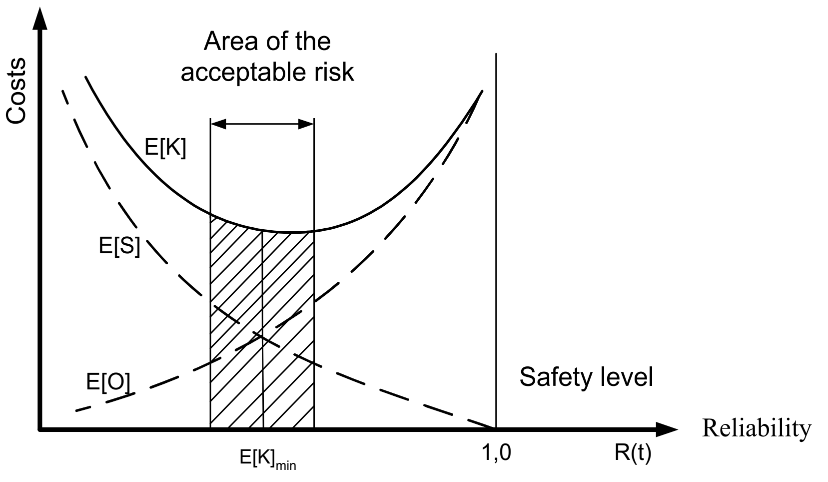

Figure 1. Diagram for determination of the acceptable range of the risk of losses.

where R(t)—probability of failure to the catastrophic damage occurrence.

E[O]—expected value of the cost of developing the construction and reliability test (in order to eliminate catastrophic damage).

E[S]—expected value of the risk resulting from the frequency of the failure and losses as a result of the occurrence of catastrophic damage in the operation process.

E[K]—expected value of the total cost E[K] = E[O] + E[S].

Figure 1 shows the possibility of moving from the zero-risk policy of a threat to the 'acceptable' risk policy based on the principle 'as low the risk, as it is reasonably achievable'.

The basis for estimating the risk of threat is a forecast of the occurrence of negative phenomena during operation resulting in catastrophic damage.

In this chapter, the selected models, which can be used for estimating the reliability and risk of the occurrence of catastrophic damage in the accepted time period of the device operation, will be presented.

3. Types of damage causing threats and models for assessing the probability of their occurrence

3.1. Classification of construction systems and wear processes

By assumption, the aviation technology has high reliability requirements, which, in practice, are implemented through special inspection procedures and appropriate design solutions involving the introduction of excesses of structure, strength, power, information, etc. The structural excess is characterised by elements or functional systems, basic and reserve-protective ones. After damage to the basic system, the protection systems start functioning. It ensures a high safety level of aircraft flights, which is one of the most important issues in the air transport. Despite these protections and great efforts of technical services, the failures that cause accidents occur.

The protecting systems constituting the reserve of basic systems significantly increase the production costs and reduce the overall performance, such as capacity, range, fuel consumption, etc. They also require special treatment in the operation of aircraft, so that they have very high probability of correct functioning at the very low probability of use.

The accuracy of continuous or periodic identification of the state of usability is an important issue. The person stating the state of usability of basic and reserve technical systems can make two types of errors:

- an error of the first type consists of qualifying the usable device as unfit;
- an error of the second type consists of qualifying the unfit device as usable;

The result of the erroneous statement on the system activating the emergency release of the landing gear was the emergency landing of PLL LOT plane, Boeing 767-300ER, on November 1, 2011 at Warsaw Chopin Airport, which will be discussed in the further part of the chapter.

The wear and ageing processes of various elements are correlated with time or the functioning duration, or with calendar time in a varying degree. Generally, the construction elements and functional systems may be classified into three types:

- Elements having strongly correlated parameters determining the state of usability with the functioning duration or time, which can be identified with the existence of the memory related to the past.
- Elements having poorly correlated parameters of the state of usability with the functioning duration or time, which imply weak relationships of operating time with the technical condition change, wear and damage.
- Elements without correlation with the operating time, number of activation, or other measure of the functioning duration, with randomly occurring damage.

3.2. Elements strongly correlated with functioning time

In case of elements of the first group, it is possible to create the technical condition trajectory and to expect a moment of time, in which the limit state will occur. It is also possible to predict a moment of the element or unit secure taking out of service. In this case, a process of damage can be described with a suitably selected model for normal distribution, even with a small variance [2]. The suitable quantile of the random variable of functioning duration between damage can be a basis for developing a programme of diagnosing, maintenance and repairs. This group of elements can include slide bearings, gears, tyre treads of gear wheels, etc. A good model describing the time of the correct operation is normal distribution.

3.2.1. Normal distribution

The normal distribution sometimes constitutes limit distribution, to which many other types of distribution asymptotically approach in the operational processes of devices, together with an

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increase in the number of experiments. Based on operational tests, it can be concluded that the normal distribution provides an approximate (asymptotic) description of the random variable of T time of proper operation of the device's element to damage, and it can be used when the element's wear and ageing parameters create a continuous random process to achieve the limit state.

The random variable of T life time of tested objects has normal distribution, if its probability density is given by the following formula:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right] \tag{1}$$

where $m = E(T)$—expected value and $\sigma^2 = D^2(T)$—variance of the random variable are the distribution parameters.

The shape of $f(t)$ density function curve of normal distribution characterises the population of objects in terms of homogeneity. The homogeneity of the population of the same elements of devices in terms of their durability in operation is represented by the coefficient of variation $v = \sigma/m$ (**Figure 2**).

For v small values, it is possible to accurately predict the moment of time for achieving the limit state in the operating time interval $(0, t)$,

The reliability function value is calculated as follows:

$$R(t) = 1 - F(t) = 1 - \int_{-\infty}^{t} f(t)dt = \int_{t}^{+\infty} f(t)dt = \frac{1}{\sigma\sqrt{2\pi}} \int_{t}^{+\infty} \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right]dt \tag{2}$$

In order to simplify the calculations in practice, the so-called standardised variable is adopted:

$$u = \frac{t-m}{\sigma} \tag{3}$$

it indicates a number of average (standard) deviation in terms of which the random variable T_t being the implementation of life time of the particular i element differs from its expected value $m = E(T)$.

With $t = m + \sigma u$, taking into account that $dt = \sigma du$, the above formula is as follows:

$$f(t) = \frac{1}{\sqrt{2\pi}} \cdot \exp\left(-\frac{u^2}{2}\right) \tag{4}$$

However, the formula for the reliability function is as follows:

$$R(t) = \frac{1}{\sqrt{2\pi}} \int_{m+\sigma\cdot u}^{+\infty} \exp\left(-\frac{u^2}{2}\right)du \tag{5}$$

Due to the fact that the integral

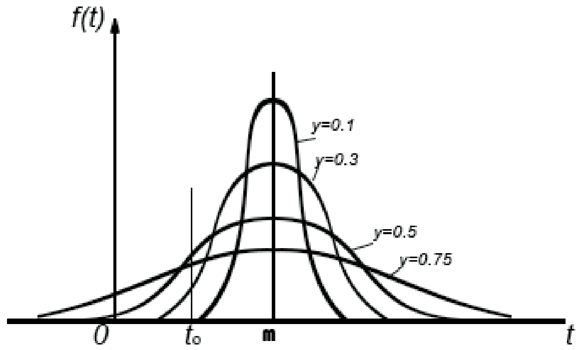

Figure 2. The probability density of normal distribution for different values of *v* coefficient of variation.

$$\frac{1}{\sqrt{2\pi}} \cdot \int_{-\infty}^{0} \exp\left(-\frac{u^2}{2}\right) du = 0.5 \tag{6}$$

and the function

$$\frac{1}{\sqrt{2\pi}} \int_{0}^{m+\sigma u} \exp\left(-\frac{u^2}{2}\right) du = \Phi(u) \tag{7}$$

are called the Laplace function (integral), the final form of the equation of the reliability function will be as follows:

$$R(u) = 0.5 - \Phi(u) \quad \text{and} \quad F(u) = 0.5 + \Phi(u) \tag{8}$$

The above presented formulas for normal distribution of life time of the aircraft elements provide the right accuracy of calculations at a high degree of homogeneity of a feature and tested objects, which is characterised by small deviation values and the standard one, that is, when the expected value $E(T) = m$, where $m >> \sigma$, $m > (2 \div 3)\sigma$ is practically accepted.

In these cases, for which $\frac{m}{\sigma} < 2$, it is recommended to use truncated normal distribution with the parameters of m, σ, for which the probability density function is as follows:

$$f(t) = \frac{1}{a\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right] \tag{9}$$

where m means the average life time of the object to damage, t means a current variable, $\sigma^2 = D^2(T)$ means a variance, while $\sigma > 0$ and $t > 0$, and a constant is determined on the basis of the following formula:

$$a = \frac{1}{F_0 \frac{m}{\sigma}} \tag{10}$$

The use of the truncated normal distribution in the reliability tests of technical objects has the following practical sense. The equation for the density function of the normal distribution applies for all t values, from $-\infty$ to $+\infty$. In the operational reliability tests of cars and their elements, there is always the relationship that $t > 0$, for which the density function is given by the above formula

$$f(t) = \frac{1}{a\sigma\sqrt{2\pi}} \cdot \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right] \tag{11}$$

however, $R(t)$ reliability function is provided by the following formula:

$$R(t) = \int_t^\infty f(t)dt = \frac{1}{a\sigma\sqrt{2\pi}} \int_t^\infty \exp\left[-\frac{(t-m)^2}{2\sigma^2}\right] dt \tag{12}$$

Because

$$\frac{t-m}{\sigma} = u \tag{13}$$

where

$$dt = \sigma du \tag{14}$$

substituting these figures, it is possible to obtain:

$$R(t) = \frac{1}{a\sigma\sqrt{2\pi}} \int_{m+\sigma u}^\infty \exp\left(-\frac{1}{2}u^2\right) du \tag{15}$$

The solution of the above integral includes the expression:

$$R(t) = \frac{F_0(u)}{F_0\left(\frac{m}{\sigma}\right)} \tag{16}$$

3.3. Elements poorly correlated with functioning time

The second group includes elements and structures operating in the variable conditions that are subject to the material fatigue, vibration, corrosion, etc. The process of damage to the other group's elements can be described by the models with variable parameters and high dispersion, such as: gamma, log-normal, Weibull and others [2]. The selection of operating programmes is very difficult, especially in cases of aviation technology, where the failure of a function of the object's construction system threatens the safety of people, the environment or causes significant material losses. In this case, it is important to apply the density of services, matching them to the damage threatening the safety or the most common ones.

With the development of the construction, it is important to mount the diagnosing systems for tracing (monitoring) the technical condition and signalling the pre-failure states in the units and functional systems. A certain way out of the situation involves monitoring of the course of induced forces with the use of a system of recorders adapted to record all relevant operational events, especially those threatening the safety of use. With the diagnosing and IT system for monitoring the state and the process of damage, it is possible to determine the area, in which the technical condition trajectory is placed, or to identify the durability resource.

3.3.1. Gamma distribution

In this distribution, it is assumed that for randomly selected moments of t time in the object, the energy with the same value of individually operating induced forces (external loads) is cumulated, and that after putting k number of induced forces, the object is damaged.

The density function of this probability is as follows:

$$f(t) = \begin{cases} \frac{1}{\Gamma(k)} \lambda^k t^{k-1} e^{-\lambda t} & for \quad t \geq 0 \\ 0 & for \quad t < 0 \end{cases} \tag{17}$$

where

k—number of events enforcing the ageing process, the cumulated effects of which cause the occurrence of damage in the object,

$\Gamma(k)$—gamma function is determined by the following formula:

$$\Gamma(k) = \int_0^{\infty} x^{k-1} e^{-x} dx \tag{18}$$

For total k, there is the relationship:

$$\Gamma(k) = (k-1)! \tag{19}$$

and the gamma distribution is called the Erlang distribution.

In this case, $F(t)$ distribution function has the following form:

$$F(t) = 1 - \sum_{n=0}^{k-1} \frac{(\lambda \cdot t)^n}{n!} e^{-\lambda t} \tag{20}$$

In **Figure 3**, the gamma distribution density for various values k and λ was presented. At the same time, it is characteristic that the individual induced force (load) action results in the aircraft ageing (or increase of the energy cumulated in it in a stepped manner). The individual increase of effects of such an induced force has a constant value. Furthermore, the probability of the occurrence of the aircraft ageing increases in the time interval (t, $t + \Delta t$):

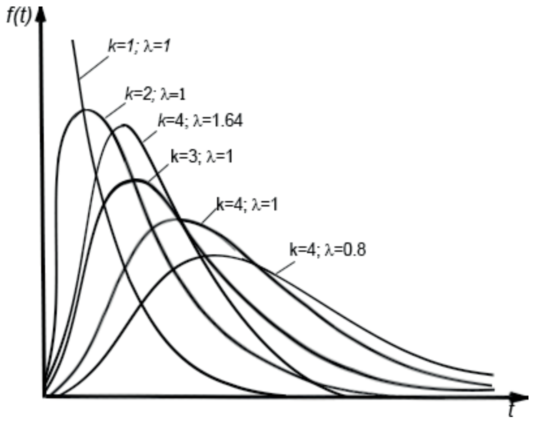

Figure 3. Gamma distribution density with different values k and λ.

$$p(t) = p = \lambda\Delta t + 0\Delta t \tag{21}$$

does not depend on the number of such increases, which occurred in time preceding t moment. In other words, the condition 'without consequences' that is significant for the simple Poisson's stream of damage is assumed. The above assumptions remain valid also for the normal distribution.

In case of the assumption that S_G is a maximum permissible level of cumulation of $n(t)$ stimuli, which result in ageing of a tested element of the aircraft and that for the number of stimuli

$$N(t) \geq S_G \tag{22}$$

this object becomes unfit for further correct operation in the system, k number of induced forces, the cumulated energy of which is necessary for causing its damage, is calculated from the following relationship:

$$k = \frac{S_G}{y} \tag{23}$$

where y means the value, by which the ageing takes place (e.g., wear) of the element in a stepped manner under the impact of a single stimulus. However, λ magnitude is characterised by the average intensity of the aircraft ageing:

$$\lambda = \frac{1}{y} = \frac{dE\{\eta(t)\}}{dt} \tag{24}$$

By using the formula for the function of $F(t)$ cumulated density of damage and $R(t) = 1 - F(t)$ relationship, the element's reliability function for the Erlang distribution will be expressed by the following formula:

$$R(t) = 1 - F(t) = \sum_{n=0}^{k-1} \frac{(\lambda \cdot t)^n}{n!} e^{-\lambda t} = e^{-\lambda t} \sum_{n=0}^{k-1} \frac{(\lambda \cdot t)^n}{n!} \tag{25}$$

The expected value $E(T)$, $D^2(T)$ variance and $v(T)$ coefficient of variation for this distribution is as follows:

$$E(T) = \frac{k}{\lambda}; \ \ D^2(T) = \frac{k}{\lambda^2}; \ \ v(T) = \frac{D^2(T)}{E(T)} = \sqrt{\frac{1}{k}} \tag{26}$$

3.4. Elements without correlation with operating time

The elements of the third group are subject to the exponential reliability law, in which the constant intensity of damage is assumed. The damage have a random nature and most often come from:

- manufacture errors (material and technological errors);
- overloads of a different nature;
- non-compliance with the instructions for use or operation technology.

The elements of the third group include bodies, glass housings and covers made of plastic, electronics components, etc.

3.4.1. Exponential distribution

If (T) time of correct operation to damage is recorded in a continuous manner and the intensity of damage $\lambda(t)$ is constant and does not depend on time in the entire interval (0, t), that is,

$$\lambda(t) = \lambda = const \tag{27}$$

the exponential distribution is used.

The $F(t)$ distribution function of this distribution of (T) time of the correct operation in the interval (0,t) is calculated on the basis of the following relationship:

$$F(t) = P\{T \le t\} = 1 - e^{-\lambda t} = 1 - \exp[-\lambda t] \tag{28}$$

and $f(t)$ function of distribution density for $t > 0$ is calculated on the basis of the relationship:

$$f(t) = \frac{dF(t)}{dt} = \lambda e^{-\lambda t} = \lambda \exp[-\lambda t] \tag{29}$$

where

$\lambda > 0$—means the distribution parameter (intensity of damage).

Moments of the exponential distribution are given by the following formula:

$$E(T) = \frac{1}{\lambda} \ \text{ and } \ D^2(T) = \frac{1}{\lambda^2} \tag{30}$$

The equality $E(T) = \frac{1}{\lambda}$ is true only for those elements of the device, for which the intensity of damage in the entire range of operation (0, t) is constant, and therefore, it does not increase or does not decrease with time of operation. The value of λ parameter affects the shape of the exponential distribution density curve presented in **Figure 4**.

When $t < 0$, the function is $f(t) = 0$,

When (T_k) time of proper operation to damage is treated discretely [3] (e.g., by $K-1$ number of activating the object without damage to the moment of K activation, during which the failure will occur). Then, the geometric distribution is used. The $F(t)$ distribution function of (T_k) time for proper operation is calculated in the following way:

$$F(t) = P\{T_k \le K\} = 1 - (1-p)^{k+1} \tag{31}$$

where

p—means the probability of damage to the unit at K activation, it can be also calculated from the relationship providing the approximate values:

$$F(t) = P\{T \le K\} = 1 - e^{\frac{K}{E(T)}} = 1 - \exp\left[-\frac{K}{E(T)}\right] \tag{32}$$

where

$E(T)$—expected value of time of proper operation to damage.

Therefore, for the purposes of operation, it is possible to use the following formula:

$$R(t) = \exp[-\lambda t] = \exp\left[-\frac{t}{E(T)}\right] \tag{33}$$

In relation to the fact that $F(t)$ distribution function is the complement to the reliability function unity:

$$R(t) + F(t) = 1 \tag{34}$$

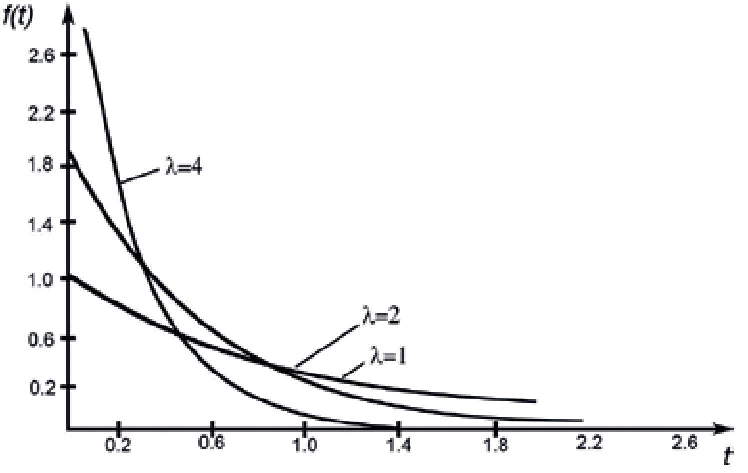

Figure 4. Example courses of the exponential distribution density for different values of the parameter λ.

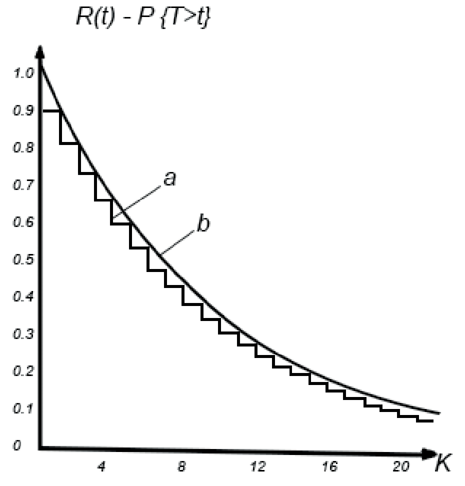

Figure 5. Reliability function courses; distribution: a—geometric, b—exponential.

then, $R(t)$ for the geometric distribution is:

$$R(t) = 1 - \left[1 - \exp\left(-\frac{K}{E(T)}\right)\right] = \exp\left[-\frac{K}{E(T)}\right] \tag{35}$$

and for the exponential distribution, $R(t)$ is:

$$R(t) = 1 - [1 - \exp(-\lambda t)] = \exp(-\lambda t) \tag{36}$$

In **Figure 5**, the reliability functions $R(t) = P\{T > t\}$ of the geometric distribution and the exponential distribution were presented. In the first case, the graph constitutes a step curve. However, the second graph constitutes a continuous curve. It was assumed that the parameters p and λ of both functions are the same, and their value is $p = \lambda = 0.1$.

Another way, which makes it possible to estimate the probability values of the occurrence of catastrophic damage in the aircraft devices, can include the use of models, including the limit state.

4. Estimation of the average number of the aircraft failure within a given period

A quantitative description and probability evaluation of damage to the basic and protection systems of the aircraft can be carried out in accordance with the postulates of the Poisson process [4].

Assuming that:

- probability of damage is directly proportional to the length of the concerned time period and the number of operated aircraft;
- proportionality factor identifying the risk of damage is constant;

The following system of equations is right:

$$\begin{aligned} P_0(t+\Delta t) &= P_0(t)\ \ (1-\lambda N(t)\Delta t) \\ P_1(t+\Delta t) &= P_1(t)\ \ (1-\lambda N(t)\Delta t) + P_0(t)\lambda N(t)\Delta t \\ &\vdots \\ P_n(t+\Delta t) &= P_n(t)\ \ (1-\lambda N(t)\Delta t) + P_{n-1}(t)\lambda N(t)\Delta t \\ &\text{for } n > 0 \end{aligned} \tag{37}$$

where

$P_0(t, t+\Delta t)$—probability of non-occurrence of damage to basic and protection systems in the time interval of Δt;

$P_i(t, t+\Delta t)$, (i = 1,…n)—probability of the occurrence of 'i' number of damage in the time interval of Δt;

$N(t)$—number of operated aircraft, in which the considered damage may occur;

λ—proportionality factor that represents the damage risk;

Δt—adopted time interval of aircraft operation (or the aircraft's flying time length).

By dividing Eq. (37) by Δt and going to the border with $\Delta t \to 0$, it is possible to obtain the following system of equations:

$$\begin{aligned} P_0' &= -\lambda N(t)P_0(t) \\ P_1' &= -\lambda N(t)P_1(t) + \lambda N(t)P_0(t) \\ &\vdots \\ P_n' &= -\lambda N(t)P_n(t) + \lambda N(t)P_{n-1}(t) \end{aligned} \tag{38}$$

For the system of equations (38), the initial conditions are as follows:

$$\left.\begin{aligned} P_0(0) &= 1 \\ P_n(0) &= 0 \end{aligned}\right\} \quad \text{for } n > 0 \tag{39}$$

Equation (38) is a linear differential equation and it is solved recursively. First, $P_0(t)$ is found. By having the knowledge of $P_0(t)$, then, $P_1(t)$ is determined, and so on.

The solution of the system of equations (39) takes the form of:

$$\begin{cases} P_0(t) = e^{-\lambda\int_0^t N(t)dt} \\ \vdots \\ P_n(t) = \dfrac{1}{n!}\left[\lambda\displaystyle\int_0^t N(t)dt\right]^n e^{-\lambda\int_0^t N(L)dt} \end{cases} \tag{40}$$

The probability that n damage requiring the launch of protection systems will occur in the time interval (0,t) is described with the Poisson distribution, whereas the role of the expression 'λt' is replaced with the following magnitude $\lambda \int_0^t N(t)\,dt$ due to the low frequency of the occurrence of this type of damage in the process of the aircraft operation.

The integral $\int_0^t N(t)dt$ can be replaced with the following total:

$$\int_0^t N(t)dt \leftrightarrow \sum_{i=1}^{N} t_i \tag{41}$$

where

N—number of aircraft operated within the considered time;

t_i—flying time of the aircraft within the considered time.

For a single aircraft, the probability of the damage occurrence during the considered t flying time will be:

$$q_1 = 1 - e^{-\lambda t} \tag{42}$$

where

$^q{}_1$—probability of damage in one aircraft;

t—aircraft's flying time.

Since λ risk of damage to both systems (basic and protection) that causes the failure is low, the expression $e^{-\lambda t}$ can be expanded into a power series.

Hence

$$e^{-\lambda t} \cong \quad 1 - \lambda t \tag{43}$$

By substituting Eq. (43) to (42), the following is obtained:

$$^q{}_2 \cong lt \tag{44}$$

With the relationship (44), it is possible to estimate the probability of the failure occurrence in a single aircraft.

The probability of correct aircraft functioning is expressed by the following relationship:

$$P_1 = 1 - \widehat{\lambda} t \tag{45}$$

In order to estimate the average number of failures during a given period for the operated aircraft park, the following relationship can be used:

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$$E[n] = \sum_{n=1}^{\infty} n P_n(t) = \widehat{\lambda} \sum_{i=1}^{N} t_i \tag{46}$$

where

t_i—flying time within a given period of i aircraft

N—number of operated aircraft.

We are often interested not only in the probability that n damage will occur for given flying time, but in the magnitude of λ coefficient characterising the intensity (risk) of the damage occurrence. In order to determine the estimator of λ parameter, a maximum likelihood method will be used. It should be supposed that we observed and recorded the occurrence of damage in several separate time intervals, when the aircraft's flying time was: t_1, t_2,…, t_i. As a result of the observation, the following was obtained:

- in the interval (0, t_1), n_1 of damage occurred;
- in the interval (t_1, t_2), n_2 of damage occurred;

⋮

- in the interval (t_{i-1}, t_i), n_i of damage occurred;

The probability of the occurrence of the said number of damage, that is, n_1+ n_2 +…+ n_i during operation with the intensity of their occurrence of λ is expressed by the relationship:

$$\begin{aligned} L &= \frac{(\lambda T_1)^{n_1}}{n_i!} e^{-\lambda T_1} \cdot \frac{(\lambda T_2)^{n_2}}{n_2!} e^{-\lambda T_2} \dots \frac{(\lambda T_i)^{n_i}}{n_i!} e^{-\lambda T_1} \\ &= \frac{\lambda^{n_1+n_2+\dots+n_i} T_1^{n_1} T_2^{n_2} \dots T_i^{n_i}}{n_1! n_2! \dots n_i!} e^{-\lambda(T_1+T_2+\dots+T_i)} \end{aligned} \tag{47}$$

where

$$T_i = t_i - t_{i-1} \tag{48}$$

The above recorded probability, considered as a function of λ variable, at defined n_1, n_2, …, n_i, T_1, T_2, …T_i is called the likelihood. Currently, such a value of λ, for which L likelihood adopts the greatest value, is found. For this purpose, relationship (47) is subjected to logarithms and a derivative in relation to λ, which is equated to zero, is calculated. By solving the obtained equation in this manner, it is possible to find the relationship for λ.

Hence

$$\widehat{\lambda} = \frac{n_1 + n_2 + \dots + n_i}{T_1 + T_2 + \dots + T_i} \tag{49}$$

With the help of the relationship (49), the estimator of λ coefficient with the use of the maximum likelihood method is determined.

Hence, relationship (47) takes the following form:

$$\widehat{q} = \widehat{\lambda} t \tag{50}$$

where

t—aircraft's flying time within the year.

Relationship (50) makes it possible to estimate the probability of the damage occurrence in a single aircraft within a given time interval.

5. Catastrophic damage model of the device including the limit state

These models can be used for determination of the probability of the occurrence of various negative events in the devices for the following cases:

- when the parameter, specifying their state, will exceed the limit state;
- when a chance of the catastrophic damage occurrence is constant along the increasing parameter, which evaluates its state;
- when a chance of the catastrophic damage occurrence increases together with an increase in the parameter, which evaluates its state;
- when the parameters determining a chance of the damage occurrence constitute random variables.

It is assumed that:

- The device's technical condition is determined by one dominant diagnostic parameter. Its current value is determined by z.
- A change in the diagnostic parameter value occurs only during the aircraft flight:
- The parameter z is non-decreasing.

May $U_{z,t}$ mean the probability that in the moment of t, the diagnostic parameter value will be equal to z. For example, it can be assumed that z may mean, for example, the crack length or the surface wear value.

In order to describe an increase in the parameter value in the random basis, the following differential equation was adopted:

$$U_{z,t+\Delta t} = (1 - \lambda\Delta t)U_{z,t} + \lambda\Delta t U_{z-\Delta z,t} \tag{51}$$

where

Δz—increase in the diagnostic parameter value during one flight of the aircraft;

$\lambda\Delta t$—probability of the aircraft flight in the time interval of Δt, whereas $\lambda\Delta t \leq 1$;

λ—intensity of the aircraft flights.

Eq. (51) in the function notation adopts the following form:

$$u(z, t + \Delta t) = (1 - \lambda \Delta t)u(z, t) + \lambda \Delta t u(z - \Delta z, t) \tag{52}$$

where

$u(z, t)$—density function of the diagnostic parameter z at the time of t.

After taking into account the physics of the diagnostic parameter increase and appropriate transformation, the Fokker-Planck differential equation is obtained from Eq. (52). As a result of solving this equation, the following density function is obtained:

$$u(z, t) = \frac{1}{\sqrt{2\pi a t}} e^{-\frac{(z - bt)^2}{2at}} \tag{53}$$

where

b—average increase in the diagnostic parameter per time unit;

a—average increase square of the diagnostic parameter per time unit;

The probability of the catastrophic damage occurrence with the use of the relationship (53) can be presented in the following way:

$$Q(t, z_d) = \int_{z_d}^{\infty} \frac{1}{\sqrt{2\pi a t}} e^{-\frac{(z - bt)^2}{2at}} dz \tag{54}$$

where

z_d—diagnostic parameter value specifying the limit state.

The risk level of the catastrophic damage occurrence in the operating time function can be determined after transformation of relationship (54) as follows [5]:

$$Q(t)_{z_d} = \int_0^t f(t)_{z_d} dt \tag{55}$$

where

$$f(t)_{z_d} = \frac{z_d + bt}{2t} \frac{1}{\sqrt{2\pi a t}} e^{-\frac{(z_d - bt)^2}{2at}} \tag{56}$$

6. Assessment of a chance of the catastrophic damage occurrence with the constant level along the increasing diagnostic parameter value

In point 5, a case of the device operation, when the catastrophic damage occurred only after exceeding the limit state by the diagnostic parameter value, was considered. Currently, the next case is considered, when the opportunity of additional one (the second type of catastrophic damage), possible to be implemented in every moment of the aircraft operation, is added to the previous one.

Additionally, the intensity of the occurrence of this type of additional damage will be introduced:

$$\mu = \frac{P}{\Delta t} \Rightarrow P = \mu \Delta t \leq 1 \tag{57}$$

where

P—probability of the occurrence of this type of damage in a single aircraft flight;

Δt—time interval, in which the flight is to take place;

μ—additional damage intensity.

Other necessary parameters and magnitudes in this point will be the same as in point 4. The differential equation, in order to describe an increase in the value of the diagnostic parameter changes, adopts the following form (in the function notation):

$$u(z, t + \Delta t) = (1 - \lambda \Delta t)(1 - P)u(z, t) + \lambda \Delta t(1 - P)u(z - \Delta z, t) \tag{58}$$

From Eq. (58) after transformation, the following partial differential equation is obtained:

$$\frac{\partial u(z, t)}{\partial t} = -\mu u(z, t) - b(t)\frac{\partial u(z, t)}{\partial z} + \frac{1}{2}a(t)\frac{\partial^2 u(z, t)}{\partial z^2} \tag{59}$$

where

$b(t)$—average increase in the diagnostic parameter per time unit;

$$b(t) = \lambda(1 - P)\Delta z \tag{60}$$

$a(t)$—average increase in the diagnostic parameter's current value per time unit;

$$a(t) = \lambda(1 - P)\Delta z^2 \tag{61}$$

Δz—increase in the diagnostic parameter value during one flight (determined with the use of accuracy of changes in this parameter).

In Ref. [2], it was shown that the equation solution (59) adopts the following form:

$$u(z, t) = \mu e^{-\mu t}\overline{u}(z, t) \tag{62}$$

where

$$\overline{u}(z, t) = \frac{1}{\sqrt{2\pi A(t)}} e^{-\frac{(z - B(t))^2}{2A(t)}} \tag{63}$$

$$B(t) = \int_0^t b(t)dt \tag{64}$$

$$A(t) = \int a(t)dt \tag{65}$$

By using relationship (62), it is possible to determine the additional catastrophic damage occurrence within the range of $(0, t)$.

$$Q_1(t) = \int_0^t \mu e^{-\mu t} \left[\int_{-\infty}^{\infty} \overline{u}(z,t)dz \right] dt = 1 - e^{-\mu t} \tag{66}$$

Hence, it is possible to write the relationship for the total probability of the occurrence of both types of catastrophic damage in the time interval $(0, t)$:

$$Q(t) = \left(1 - e^{-\mu t}\right) + e^{-\mu t} \int_{z_d}^{\infty} \overline{u}(z,t)dz \tag{67}$$

The formula for the aircraft reliability adopts the following form:

$$R(t) = e^{-\mu t} \int_{-\infty}^{z_d} \frac{1}{\sqrt{2\pi A(t)}} e^{-\frac{(z-B(t))^2}{2A(t)}} \tag{68}$$

where $B(t)$ and $A(t)$ specific relationships (64) and (65).

7. Model outline of the catastrophic damage occurrence with the increasing chance of its occurrence together with the diagnostic parameter increase

In order to solve the problem, The Yule's process will be used by carrying out its modification. The method of this modification is provided in Ref. [6]. In this case, it is necessary to perform the diagnostic parameter value discretisation. The discretisation method is provided in **Figure 6**.

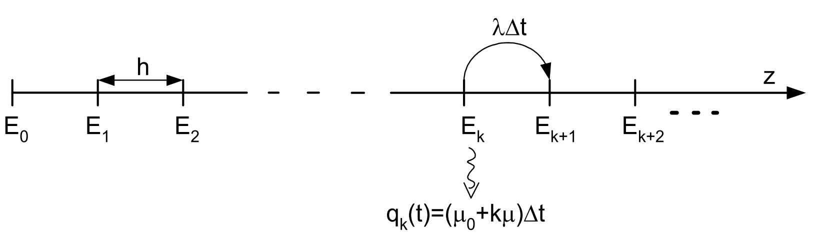

Figure 6. Discretisation diagram of the diagnostic parameter.

where

E_k—diagnostic parameter value states.

$\lambda\Delta t$—probability of the aircraft flight, as result of which a change in the state may occur.

$q_k(t)$—probability of the development process interruption (i.e., state changes). This probability depends on the state.

h—average value of the diagnostic parameter increase in time Δt (one flight).

May $P_k(t)$ mean the probability that in the moment of t, the diagnostic parameter value achieved the state E_k (where $k = 1, 2, \ldots$).

For these arrangements, it is possible to arrange the following system of the infinite number of equations:

$$\begin{aligned} &P_0(t+\Delta t) = P_0(t)\left[1 - \left(\mu_0 + \lambda\right)\Delta t\right] + 0(\Delta t) \\ &\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad \textit{for } \; k = 1, 2, \ldots \\ &P_k(t+\Delta t) = P_k(t)\left[1 - \left(\mu_0 + k\mu + \lambda\right)\Delta t\right] + P_{k-1}(t)\lambda\Delta t + 0(\Delta t) \end{aligned} \tag{69}$$

After division of both sides of k equation by Δt and transition to the border at $\Delta t \to 0$, the following system of equations is obtained:

$$\begin{aligned} &P_0^{'}(t) = -\left(\mu_0 + \lambda\right)P_0(t) \\ &\vdots \qquad\qquad\qquad\qquad\qquad\qquad\qquad \text{for } \; k = 1, 2, \ldots \\ &P_k^{'}(t) = -\left(\mu_0 + \lambda + k\mu\right)P_k(t) + \lambda P_k(t) \end{aligned} \tag{70}$$

The initial condition for each of these equations is as follows:

$$P_i(0) = \begin{cases} 1 & dla \;\; i = 0 \\ 0 & dla \;\; i \neq 0 \end{cases} \tag{71}$$

The system of Eq. (70) is solved recursively. Having the results of the solved system of equations, it is possible to determine the probability (reliability) that in the time interval $(0, t)$, the catastrophic damage will not occur. This relationship can be determined by adding up the obtained relationships $P_k(t)$. Hence

$$R(t) = \sum_{k=0}^{\infty} P_k(t) \tag{72}$$

The probability of the fact that to the moment of t, the catastrophic damage will occur, can be specified by the following relationship:

$$Q(t) = P\{T \le t\} = 1 - R(t) \tag{73}$$

After the adding up operation performance, the following form of the solution is obtained [6]:

$$Q(t) = 1 - e^{\frac{\lambda}{\mu} - \left(\lambda + \mu_0\right)t - \frac{\lambda}{\mu}e^{-\mu t}} \tag{74}$$

Hence, the time distribution density to the moment of the catastrophic damage occurrence.

$$f(t) = \left[\mu_0 + \lambda\left(1 - e^{-\mu t}\right)\right]e^{\frac{\lambda}{\mu}\left(1 - e^{-\mu t}\right) - \left(\lambda + \mu_0\right)t} \tag{75}$$

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8. Outline of the aircraft reliability assessment method taking into account signalled and catastrophic damage

8.1. Description of operation conditions and adoption of assumptions

It is assumed that the aircraft operation is done in such a way that the following arrangements and assumptions are correct:

1. In order to assess the technical condition, n diagnostic parameters are used. So the technical condition vector adopts the following form [7]:

$$x = (x_1, x_2, \dots, x_n) \tag{76}$$

2. Instead of the diagnostic parameter values in the reliability assessment, the following deviations are used:

$$z_i = x_i - x_{i\,nom} \quad (i = 1, 2, \dots, n) \tag{77}$$

where

x_i—i diagnostic parameter.

$x_{i\ nom}$—nominal value of i parameter.

3. Deviation values z_i (i = 1, 2,…, n) are positive.

4. The deviation limit values are z_i^d. If $0 \leq z_i < z_i^d \ \ (i = 1, 2, \dots, n)$, the aircraft is operational. When at least one deviation exceeds the limit value, the aircraft is considered to be unfit for operation.

5. It is assumed that $z_i \ \ (i = 1, 2, \dots, n)$ deviations are independent random variables, that is, a change in the value of one deviation does not change the value of other deviation.

6. The change in z_i deviation values occurs as a result of the aircraft operation, which is during the aircraft flight.

7. The speed of changes in the deviation values can be described with the use of the following relationship:

$$\frac{dz_i}{dN} = g(z_i, c_i) \tag{78}$$

where

z_i—diagnostic parameter deviation;

c_i—indicators characterising the local operating conditions of elements, which the increase in the diagnostic parameter's deviation value depends on;

N—number of aircraft flights.

By using relationship (78), it is possible to determine the deviation value during one flight:

$$\Delta z_i = g(z_i,\ \ c_i)\Delta N \qquad \text{for}\ \ \Delta N = 1 \tag{79}$$

8. The intensity of the aircraft flights λ is determined by the following relationship:

$$\lambda = \frac{P}{\Delta t} \tag{80}$$

where

Δt—is the time interval, in which the aircraft flight will take place with P probability. The time interval of Δt should be properly selected (depending on functioning of the aircraft operating system), for $\lambda\Delta t \le 1$.

By using the intensity of flights λ, it is possible to determine the number of performed flights of the aircraft to the moment of t in accordance with the following relationship:

$$N = \lambda t \tag{81}$$

9. It is assumed that the aircraft is operated. The task of the technical service is, among others, not to allow for the occurrence of signalled damage and to maximally limit the possibility of the occurrence of catastrophic damage, which is the cause of the aircraft failures and crashes.

10. It is assumed that the sets of signalled and catastrophic damage to the aircraft are separate. Hence, the aircraft reliability in this case can be written in the following form:

$$R(t) = R_1(t)R_2(t) \tag{82}$$

where

$R_1(t)$—probability of the fact that to the moment t there will be no catastrophic (sudden) damage in the aircraft.

$R_2(t)$—probability of the fact that to the moment t there will be no damage signalled in the aircraft.

Despite the attempts and great effort of technical services, currently, it is impossible to completely eliminate the risk of the catastrophic damage occurrence.

It is adopted that in case of a single flight of the aircraft, the probability determining the possibility of the catastrophic damage occurrence is Q. The progressive technical service of the aircraft is to prevent this probability increase together with an increase in operating time.

8.2. Aircraft reliability determination including signalled and catastrophic damage

Under the adopted probabilistic assumptions, a description of the deviation increase of diagnostic parameters in the function of the aircraft operating time can be considered separately for each diagnostic parameter. In view of the above, it is assumed that the process of deviation changes of i diagnostic parameter is considered.

May $U_{z_i,t}$ mean the probability of the fact that in the moment t, the deviation of i parameter is z_i.

For the adopted arrangements, the dynamics of changes (increase) of i deviation can be characterised with the use of the following differential equation [3]:

$$U_{z_i, t+\Delta t} = (1 - \lambda\Delta t)U_{z_i, t} + \lambda\Delta t \; U_{z_i - \Delta z_i, t} \tag{83}$$

where

$(1 - \lambda\Delta t)$—probability of the fact that in the time interval of Δt, the aircraft flight will not take place;

$\lambda\Delta t$—probability of the aircraft flight in the time interval of Δt.

Hence $(1 - \lambda\Delta t) + \lambda\Delta t = 1$

Eq. (83) expresses the following sense. The probability of the fact that in the moment of $t + \Delta t$, the deviation value of i diagnostic parameter will be z_i, if in t moment, it had this value and did not increase because of the lack of the aircraft flight or, in t moment, it had $z_i - \Delta z_i$ value and in the time interval of Δt, Δz_i increased, because the flight did not take place.

Differential Eq. (83), in the function notation, adopts the following form:

$$u(z_i, \quad t + \Delta t) = (1 - \lambda\Delta t) \quad u(z_i, t) + \lambda\Delta t u(z_i - \Delta z_i, t) \tag{84}$$

where

$u(z_i, t)$—deviation density function of i diagnostic parameter from the nominal value.

Differential Eq. (84) can be transformed to the partial differential equation, with the use of the following approximation:

$$\begin{aligned} u(z_i, \quad t + \Delta t) &= \quad u(z_i, t) + \frac{\partial u(z_i, t)}{\partial \; t} \; \Delta t \\ u(z_i - \Delta z_i, \quad t) &= \quad u(z_i, \quad t) - \frac{\partial u(z_i, t)}{\partial \; z_i} \; \Delta z_i + \frac{1}{2} \quad \frac{\partial^2 u(z_i, \quad t)}{\partial \; z_i^2} \; (\Delta \; z_i)^2 \end{aligned} \tag{85}$$

By substituting Eqs. (85) to (84), it is possible to obtain:

$$u(z_i, \quad t) + \frac{\partial u(z_i, t)}{\partial z} \; \Delta t = (1 - \lambda\Delta t) \;\; u(z_i, \quad t) + \lambda\Delta t \left[u(z_1, t) - \frac{\partial u(z_i, t)}{\partial z_i} \; \Delta z_i + \frac{1}{2} \frac{\partial^2 u(z_i, t)}{\partial z_i^2} (\Delta z_i)^2 \right] \tag{86}$$

Hence, after simplification, the following is obtained:

$$\frac{\partial u(z_i, t)}{\partial t} \; \Delta t = -\lambda\Delta z_i \Delta t \; \frac{\partial u(z_i, t)}{\partial z_i} \; + \frac{1}{2}\lambda\Delta t(\Delta z_i)^2 \quad \frac{\partial^2 u(z_i, \quad t)}{\partial z_i^2} \tag{87}$$

By dividing two sides of (87) equation by Δt, the following is obtained:

$$\frac{\partial u(z_i, t)}{\partial t} \; = -b_i(t) \quad \frac{\partial u(z_i, t)}{\partial z_i} \; + \frac{1}{2} \;\; a_i(t) \quad \frac{\partial^2 u(z_i, \quad t)}{\partial z_i^2} \tag{88}$$

where

$b_i(t) = \lambda \Delta z_i$—means the average increase of i deviation of the diagnostic parameter from the normal value per time unit;

$a_i(t) = \lambda (\Delta z_i)^2$—means the average increase square of i deviation from the normal value per time unit;

Δz_i—is determined by relationship (79) for $\Delta N = 1$.

The solution of the specific Eq. (88), which meets the following conditions, is searched for:

when $t \to 0$, the equation is convergent to the Dirac function, that is, $u(z_i, t) \to 0, \quad dla \quad z \neq 0$ $u(0, t) \to \infty$ but in a way that the integral of u function is equal to the unity for $t > 0$.

For such an adopted condition, the equation solution (88) adopts the form:

$$u(z_i, t) = \frac{1}{\sqrt{2\pi A_i(t)}} \quad e^{-\frac{(z_i - B_i(t))^2}{2A_i(t)}} \tag{89}$$

where

$$B_i(t) = \int_0^t b_i(t) dt \tag{90}$$

$$A_i(t) = \int_0^t a_i(t) dt \tag{91}$$

Relationship (90) determines the average value of the deviation, and relationship (91) determines the deviation variance.

By using relationship (89), the reliability in the aspect of the damage signalled for i diagnostic parameter can be written in the following form:

$$R_i(t) \cong \int_{-\infty}^{z_i^d} u(z_i, t) \, d \; z_i \tag{92}$$

By taking into account all the diagnostic parameters and adopted assumptions, the reliability formula adopts the following form:

$$R_2(t) = \prod_{i=1}^{n} R_i(t) \tag{93}$$

Now the relationship for the second component of $R_1(t)$ aircraft reliability is determined due to the catastrophic damage.

The catastrophic (sudden) damage is caused by incomplete control and knowledge of the aircraft technical condition.

It results from the aircraft operation that a group of damage occurs as a result of sudden changes in measurable and non-measurable parameters due to the inability to observe the changes of their values. The exceeding of the applicable limits also affects an increase in the risk of the aircraft catastrophic damage occurrence.

The damage intensity plays a basic role in the probabilistic description of the occurrence of this type of damage.

The intensity of damage is expressed by the following relationship:

$$\chi(t) = \lim_{\Delta t \to 0^+} \frac{P(t < T < t + \Delta t | T > t)}{\Delta t} \tag{94}$$

where

T—time random variable to the catastrophic damage occurrence;

t—aircraft operation time;

$P(\cdot)$—contingent event probability.

From relationship (94), after transformation, it is possible to obtain the following differential equation:

$$R_1'(t) + \chi(t) R_2(t) = 0 \tag{95}$$

Eq. (95), for the initial condition $R_1(t = 0) = 1$, has the following solution:

$$R_1(t) = e^{-\int_0^t \chi(t) dt} \tag{96}$$

If

$$\begin{aligned} &\chi(t) = \chi = const, \quad then: \\ &R_1(t) = e^{-\chi t} \end{aligned} \tag{97}$$

In order to use relationship (95), it is important to estimate χ parameter. Based on the observations of operation of a specific type of aircraft, it is possible to obtain the times of the occurrence of this type of damage t_k, where k = 1, 2,…, ω.

Time t_k is time for the occurrence of the first of this type of damage in k aircraft calculated from the beginning of operation.

In order to estimate χ parameter, a method of moments will be used. The comparison of the expected value of operating time calculated from the theoretical relationship, with the average value determined on the basis of the observation, will be made.

The theoretical average time of given operation to the moment of the catastrophic damage occurrence is:

$$E[T] = \int_0^\infty R_1(t) dt = \int_0^\infty e^{-\chi t} = \frac{1}{\chi} \tag{98}$$

The average value of the aircraft operating time (from the moment of the catastrophic damage occurrence) calculated on the basis of the observation will be:

$$\widehat{E}\,[T] = \frac{\sum_{k=1}^{\omega} t_k}{\omega} \tag{99}$$

Hence

$$\begin{gathered} \frac{1}{\chi^*} = \frac{\sum_{k=1}^{\omega} t_k}{\omega} \\ \chi^* = \frac{\omega}{\sum_{k=1}^{\omega} t_k} \end{gathered} \tag{100}$$

If the probability of the sudden damage occurrence during one flight is known, the intensity of this type of damage can be estimated by the following relationship:

$$\chi^* = \frac{Q}{\Delta t} \tag{101}$$

The relationship for estimation of $R_1(t)$ reliability will be:

$$R_1(t) = e^{-\chi^* t} \tag{102}$$

After taking into account relationships (93) and (102), the aircraft reliability formula will be:

$$R(t) = e^{-\chi t} \prod_{i=1}^{n} R_i(t) \tag{103}$$

8.3. Modification of the applied method for the aircraft reliability determination including sudden and signalled damage

By starting the modification of the applied method in point '8.2', the following additional assumptions are adopted:

- The aircraft catastrophic damage causes its withdrawal from operation;
- It is assumed that there is one dominant parameter among diagnostic parameters. Its dynamics of changes is the greatest, and due to its causes, the signalled damage is formed in the quickest manner.
- The probabilities associated with the aircraft flight frequency and the possibility of its withdrawal from operation constitutes separate, independent sets of events.

$$\lambda \Delta t + (1 - \lambda \Delta t) = 1 \tag{104}$$

$$\chi \Delta t + (1 - \chi \Delta t) = 1 \tag{105}$$

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For such specified probabilities, the following equation is right:

$$(1-\lambda\Delta t)(1-\chi\Delta t)+\lambda\Delta t(1-\chi\Delta t)+(1-\lambda\Delta t)\chi\Delta t+\lambda\Delta t\chi\Delta t=1 \tag{106}$$

But

$$\chi=\frac{Q}{\Delta t} \tag{107}$$

Hence

$$(1-\lambda\Delta t)(1-Q)+\lambda\Delta t(1-Q)+(1-\lambda\Delta t)\ \ Q+\lambda\Delta t\ \ Q=1 \tag{108}$$

$$(1-\lambda\Delta t)(1-Q)+\lambda\Delta t(1-Q)+\ \ Q=1 \tag{109}$$

The description of deviation changes in the dominant diagnostic parameter currently marked with z will be started. The variable z has the same meaning as z_i used in point '7.2' and the regularities of its increase are the same as z_i.

May $U_{z,t}$ mean the probability that in the moment t, the dominant diagnostic parameter deviation is z.

By using relationship (109) and assuming that z deviation increase is determined by first two components of this relationship, the differential Eq. (83) can be written in the following form:

$$U_{z,\,t+\Delta t}=(1-\lambda\Delta t)(1-Q)U_{z,\,t}+\lambda\Delta t(1-Q)U_{z-\Delta z,\,t} \tag{110}$$

Eq. (109) in the function notation adopts the following form:

$$u(z,t+\Delta t)=(1-\lambda\Delta t)(1-Q)u(z,t)+\lambda\Delta t(1-Q)u(z-\Delta z,t) \tag{111}$$

Eq. (111) is transformed into the partial differential equation with the use of the approximation (85) and relationship (109).

For greater transparency, $u(z,t)$ is added to and subtracted from the right side of Eq. (111).

After completing these operations, the following is obtained:

$$\begin{aligned}u(z,t)+\frac{\partial u(z,t)}{\partial t}\Delta t&=u(z,t)-u(z,t)+(1-\lambda\Delta t)(1-Q)u(z,t)+\\&+\lambda\Delta t(1-Q)\left(u(z,t)-\Delta z\frac{\partial u(z,t)}{\partial z}+\frac{1}{2}(\Delta z)^2\frac{\partial^2 u(z,t)}{\partial z^2}\right)\end{aligned} \tag{112}$$

Hence

$$\begin{aligned}u(z,t)-u(z,t)+\frac{\partial u(z,t)}{\partial t}\Delta t&=-((1-\lambda\Delta t)(1-Q)+\lambda\Delta t(1-Q)+Q)\,u(z,t)+\\&+\lambda\Delta\,t(1-Q)\left(u(z,t)-\Delta z\frac{\partial u(z,t)}{\partial z}+\frac{1}{2}(\Delta z)^2\frac{\partial^2 u(z,t)}{\partial z^2}\right)\end{aligned} \tag{113}$$

Finally, the following partial differential equation is obtained:

$$\frac{\partial u(z,t)}{\partial t} = -\chi\, u(z,t) - b(t)\frac{\partial u(z,t)}{\partial z} + \frac{1}{2}\ \ a(t)\frac{\partial^2 u(z,t)}{\partial z^2} \tag{114}$$

where

χ—intensity of the withdrawal of a specific type of aircraft due to the catastrophic damage occurrence:

$$\chi = \frac{Q}{\Delta t} \tag{115}$$

$b(t)$—average increase in the dominant parameter deviation per time unit:

$$b(t) = \lambda(1-Q)\Delta z \tag{116}$$

$a(t)$—average increase square of the dominant parameter deviation per time unit:

$$a(t) = \lambda(1-Q)\Delta z^2 \tag{117}$$

Δz—specified by relationship (79).

Eq. (114) is more general than the Fokker-Planck equation, written in the form of the relationship (88).

Eq. (114) has an additional element '-$\chi u(z,t)$'.

In order to present the equation solution (114), the equation solution (88) will be used. If the equation solution (88) constitutes the relationship (89), then, the equation solution (114) constitutes the following function:

$$\overline{u}(z,t) = \chi e^{-\chi t}\ \ \overline{u}(z,t) \tag{118}$$

where

$\overline{u}(z,t)$—is the equation solution (88) and is presented by the relationship (89). In this solution, in the integrals (90) and (91), it is important to use the relationships (116) and (117).

In order to justify that the function (118) is the equation solution (114), the following transformation is presented:

A derivative after the relationship time (118) is calculated.

$$\begin{aligned}
\frac{\partial u(z,t)}{\partial t} &= \chi^2 e^{-\chi t}\overline{u}(z,t) + \chi e^{-\chi t}\frac{\partial \overline{u}(z,t)}{\partial t} = \\
&= \chi u(z,t) + \chi e^{-\chi t}\left(-b(t)\frac{\partial \overline{u}(z,t)}{\partial z} + \frac{1}{2}a(t)\frac{\partial^2 \overline{u}(z,t)}{\partial z^2}\right) = \\
&= \chi u(z,t) - b(t)\frac{\partial u(z,t)}{\partial z} + \frac{1}{2}a(t)\frac{\partial^2 u(z,t)}{\partial z^2}
\end{aligned} \tag{119}$$

Hence, it can be observed that the function (118) is the equation solution (114).

Function (114) has the density function characteristics, because:

$$\int_{-\infty}^{\infty}\int_{0}^{\infty} u(z,t)dz\ \ dt = \int_{0}^{\infty}\left[\int_{-\infty}^{\infty} u(z,t)dz\right]dt = 1 \tag{120}$$

By using relationship (118), the aircraft unreliability is determined

$$Q(t) = \int_{0}^{t} \chi e^{-\chi t}\left[\int_{-\infty}^{z_d} \overline{u}(z,t)dz + \int_{zd}^{\infty} \overline{u}(z,t)dz\right]dt = 1 - e^{-\chi t} \tag{121}$$

Thus, it is possible to write that:

$$Q(t) = \overline{Q}_1(t)\overline{R}_2(t) + \overline{Q}_1(t)\overline{Q}_2(t) \tag{122}$$

where

$\overline{Q}_1(t)$—unreliability caused by the aircraft catastrophic damage;

$\overline{Q}_2(t)$—unreliability caused by the deviation increase of the dominant parameter above the limit value.

$\overline{R}_1(t)$—aircraft reliability referring to the catastrophic damage;

$\overline{R}_2(t)$—aircraft reliability referring to the dominant parameter;

Thus, the aircraft reliability will be:

$$R(t) = \overline{R}_1(t)\cdot\overline{R}_2(t) \tag{123}$$

Hence

$$R(t) + Q(t) = 1 \tag{124}$$

Thus, the aircraft reliability formula will be:

$$R(t) = e^{-\chi t}\int_{-\infty}^{z_d} \frac{1}{\sqrt{2\pi A(t)}}\ e^{-\ \frac{(z-B(t))^2}{2A(t)}}dz \tag{125}$$

where

B(t) and A(t) are determined by relationships (90) and (91).

The above method applies to the cases, in which the effects of action of destructive processes cumulate, that are correlated with the aircraft operating time and this process is disrupted by the possibility of the occurrence of the sudden damage caused by, for example, overload pulses, hard landings, etc.

This method may allow to estimate durability, due to individual diagnostic parameters. The data obtained in this way can be used in order to improve the technical service. The sequence of diagnostic controls adequately spread over operating time allows to prevent the signalled damage occurrence.

Therefore, it can be assumed that:

$$R_2(t) = \prod_{i=1}^{n} \int_{-\infty}^{z_d} u_1(z_i, t)dz_i \approx 1 \tag{126}$$

The aircraft reliability, including the technical service, can be estimated by the following relationship:

$$R(t) = e^{-\chi^* t} \tag{127}$$

The presented methods for determining the relationships for the aircraft reliability are conditioned by the adopted assumptions. They can be modified in accordance with the assumptions. The more accurately the adopted assumptions will reflect the actual conditions, the more precisely the aircraft reliability will be estimated. The methods can be adapted to specific cases for determination of the catastrophic damage probability values, including the physics of occurring phenomena and operating conditions. The aircraft reliability forecasts can be used for consideration of specific problems with the reliability assessment and durability of elements, units and devices.

9. Reliability incorrect assessment results in air systems

9.1. Analysis of errors of diagnosing and stating the usability state of technical systems

The reliability of diagnostic equipment and the ergonomics of technical systems affect the errors made by the operator. The chapter raised the problem of diagnosis errors and erroneous usability evaluation and describes the example of a real event of the aircraft landing without the released landing gear, as a consequence of erroneous diagnosing. The rescue process in a situation of an aviation accident hazard was briefly described in this chapter. A person equipped with diagnostic equipment can make two types of errors, whose measurements are the occurrence probabilities marked with symbols α and β.

α—means an error of the first type, which consists of qualifying the usable device as unfit;

β—means an error of the second type, which consists of qualifying the unfit device as usable.

Making the first type error in the identification process of the aircraft's usability may cause losses due to unplanned downtime and repeated inspection. In case of making the second type error, more dangerous consequences with the possibility of an aviation accident are often caused;

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Three factors determining identification errors can be mentioned:

- monitoring susceptibility of the object: it shows the extent, to which the object is adapted to the inspection, and a way in which the inspection procedures identify the actual state, as well the percentage of features not subject to the inspection;
- technical equipment of the operator inspecting the state of the object and procedures of interpreting the results
- predispositions of the operator, his or her qualifications, personal characteristics;
- circumstances of the inspection, climatic conditions, time stress, information stress, etc.

As it results from the above considerations, the identification error is a parameter of the systemic nature. The object designer, the designer of diagnostic equipment, the operator equipped with diagnostic equipment of sufficient quality and the training of the operator conducting identification are responsible for the object state identification error. Despite the fact that the identification error depends on many factors, it is the person conducting the identification who is legally and morally responsible for the effects resulting from the identification error. The removal of responsibility from the operator follows the specified tests conducted by the specially appointed expert teams. These teams often include also experts from scientific and research institutions. These teams determine the causes of the erroneous qualification of the object condition. It results in a stressful situation for the operator, who does not always understand the essence of various sources of misidentification, blaming himself or herself for adverse events. The problem of the first and second type errors during the identification of the usability state has a legal-moral, economic and technical aspect.

The source of the error is sometimes unreliability of diagnosing units equipped with the necessary equipment and procedures of stating the usability state. With regard to the object, on which the condition is identified, it can be said that there are the following events on it:

A_{01}—The event involving the fact that the object is in the state of usability and it will keep this state during the identification. The probability of such an event is marked with P_{01}.

A_{02}—The event involving the occurrence of damage detected in the identification process in the object until or during identification. The probability of such an event is q_{02}.

A_{03}—The event involving the occurrence of damage not detected during the identification in the object until or during the identification process. The probability of such an event is marked with q_{03}.

These probabilities meet the condition:

$$P_{01} + q_{02} + q_{03} = 1 \tag{128}$$

The diagnosis process may include the following events:

A_{11}—The event involving the fact that the diagnosis is correctly carried out and the object state statement is flawless. The probability of such an event is P_{11}.

A_{12}—The event involving the fact that the object was considered unfit regardless of its state. The probability of such an event is q_{12}.

A_{13}—The event involving the fact that the object was considered usable regardless of its state. The probability of such an event is q_{13}.

A_{14}—The event involving the fact that the object was considered unfit, whereas, in fact, it is usable, and the object was considered usable, whereas, in fact, it is unfit. The probability of such an event is marked with q_{14}.

These probabilities meet the condition:

$$P_{11} + q_{12} + q_{13} + q_{14} = 1 \tag{129}$$

The probability of an event involving the fact that the object considered unfit, in fact, is usable, that is, making the first type error is given by the following formula:

$$\alpha = 1 - \frac{P_{01}}{1 - \frac{q_{02}(P_{11} - q_{14})}{P_{11} + q_{13}}} \tag{130}$$

The probability of an event involving the fact that the object will be considered usable, whereas it is, in fact, unfit, that is, making the second type error is given by the following formula:

$$\beta = 1 - \frac{1}{1 + \frac{P_{01}}{1 - P_{01} + q_{02}\frac{P_{11} - q_{14}}{q_{12} - q_{14}}}} \tag{131}$$

The impact of possible events is the process of diagnosis on the values of the first and second type errors results from the provided formulas.

9.2. Shaping of the first and second type errors by the operator teaching method

Figure 7 shows the course of function α_m of reducing the error of the first type as a result of m repetition of action performed by the operator or diagnosing team for different values of the experimentally determined coefficient $C(\alpha)$.

These errors in the function of the number of m tests are given by the following formulas:

$$\alpha_m = \alpha[1 - \alpha \ C(\alpha)]^{m-1} \tag{132}$$

$$\beta_m = \beta[1 - \beta \ C(\beta)]^{m-1} \tag{133}$$

The intensity of learning has a significant impact on the reduction of the first and second type errors. As a result of the training, the operator learns using the controls, reading instrument indications and interpretation of symptoms of the object's usability and unfitness. For the purposes of teaching the operator, the specific states are modelled. As a result of conducted research and analyses, $C(\alpha)$, $C(\beta)$ coefficients characterising the quantitative progress of the training and the intensity of reducing the first and second type errors are determined.

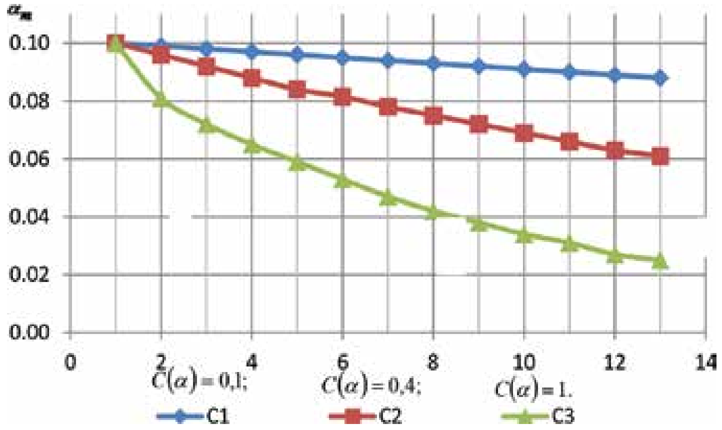

Figure 7. The course of α_m function for $C(\alpha)$ various values for $\alpha = 0, 1$.

9.3. Example result of erroneous diagnosing

The fact of a certain error in diagnosing can be stated on the example of the above-mentioned emergency landing of the PLL LOT plane, Boeing 767-300ER, on November 1, 2011 at Warsaw Chopin Airport. It should be reminded that the Boeing 767-300 plane of the Polish airlines LOT departed from the Newark airport (USA) after midnight on November 1, 2011. Thirty minutes after the takeoff from Newark, the crew of the Polish plane signalled a failure of the central hydraulic system. The machine had another system, the emergency and electrical one, which could retract the landing gear. After the departure, the plane was filled with fuel and despite the failure it would not be justified to fly around over the U.S. territory for many hours because only after fuel consumption, it would be possible to check the operation of the system extending the landing gear and to try to land. The captain decided to continue the flight, although he could not be sure as to the emergency system usability, and he intended to verify the operation in the territory of Poland. Over Warsaw, it occurred that the usability of the entire landing gear control system was evaluated erroneously because its extension failed, although the flaps had extended. Then, the decision on emergency landing was made. The result of the incorrect evaluation of the situation described above was the plane failure, which is a rare event in the aircraft operation.

The members of the government committee investigating the circumstance of the emergency landing showed that the emergency system was efficient but the aircraft crew did not use it because one of the key fuses, which secured several aircraft's systems, including the emergency landing gear extension system, was disabled. If the fuse had been enabled, the dramatic landing at the Warsaw's Okęcie would not have happened.

9.4. Rescue process of the critical situation

In the considered flight, an event involving consideration of the activating element as usable, regardless of its state, occurred, and it was not subject to diagnosing [2]. The unaware classification of the unfit device as usable without diagnosing is a systemic error of the second type.

In the model representing the situation of the emergency landing on November 1, 2011, it is possible to distinguish the following elements (**Figure 8**): protected object—landing gear extension system, protecting object—emergency landing gear extension system and the activating element.

In **Figure 8**, the probabilistic characteristics of the implementation time of the security task and available time were marked.

T_{OB}—random variable of the security task implementation time,

$F_{OB}(t)$—distribution function of the random variable of the security task implementation time,

t_{OB}, —random variable implementation: time of the flight over the airport and search for the solution,

T_D—random variable of available time: time of the flight limited by fuel residues,

$F_D(t)$—distribution function of the random variable of available time,

t_D—implementation of the random variable of available time: maximum time of the flight limited by fuel residues.

The available time determines the reasonable time necessary to prevent a dangerous situation. In general, this time may be determined by, for example, a fuel resource, a resource of an active substance or any other type of energy extending the system operation.

The analysis of the situation and taking activities at available time can be described as follows:

- receiving information about the hydraulic system leak;
- making the decision to continue the flight;
- initiation of the landing procedure;
- receiving information about a faulty protection system (electrical system);
- analysis of the obtained information and search for a solution;
- making the decision about the emergency landing on the aircraft fabric covering;
- implementation of the made decision;
- inspection of the made decision.

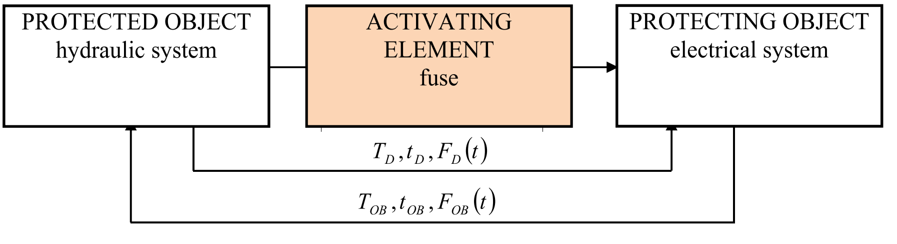

Figure 8. Relief system model with the protection system.

After receiving the information about a defective protection system (electrical system) and inability to release the landing gear, there was the search for solutions, which had to take place at the available time—$T_{D.}$ After recognition of the erroneous evaluation of the emergency system, the only solution left was the use of a different emergency protection system in the form of the fuselage designed for this purpose. Owing to the pilot's wise action, great skills and precise operation, the implementation of the made decision on the emergency landing was successful. This type of situation can be described with the salvage equation, which designates the probability of the danger defuse at the available time through the convolution of distribution functions of random variables of the available time and implementation time of the rescue task.

$$P(T_{OB} < T_D) = \int_0^\infty F_D(t+\tau)dF_{OB}(t) \tag{134}$$

The probability distribution of the available time depends on the type of event. For example, for a survivor at sea, it will be the time of survival dependent on circumstances (temperature of the water and his or her own equipment); for the aircraft, the remained flight persistence; for a parachutist, remaining height, etc. The probability distribution of the implementation time of an intervention task also depends on many factors—the type of the task, the degree of the rescue team or system's readiness, action efficiency.

In the cited example, making the right decision and the precise landing proved to be the right action preventing from crash. The implementation of random variables in the considered event in the relationship, ($t_{OB} < t_D$) fulfilled the salvage condition.

The presented analysis of the diagnosis errors and the rescue process model were presented in a shortened version due to the limited scope of the chapter.

Author details

Józef Żurek* and Ryszard Kaleta

*Address all correspondence to: jozef.zurek@itwl.pl

Air Force Institute of Technology, Warsaw, Poland

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Section 3

Exploring Purposes

Failures in a Critical Infrastructure System

David Rehak and Martin Hromada

Additional information is available at the end of the chapter

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Abstract

The purpose of this chapter is to provide a comprehensive overview of a critical infrastructure system, of failures and impacts that occur within it and of the resilience, which effectively reduces the risk of these impacts spreading on to dependent subsystems. The chapter presents a basic description of a critical infrastructure system and of the hierarchic arrangement of its subsystems and linkages between them. Critical infrastructure system failures, including their causes and impacts on dependent subsystems and on society as a whole, are presented in the following section. Particular focus is given to the propagation of impacts in a critical infrastructure system and the current approaches to their modeling. The chapter concludes by expounding on the resilience of critical infrastructure subsystems and its impact on the minimization of failures in critical infrastructure subsystems in circumstances involving emergencies.

Keywords: critical infrastructure, system, disruption, failure, impacts, resilience

1. Introduction

Society has traditionally depended on a broad variety of services as much as on the infrastructures providing them. Over time, some of these infrastructures, or rather their elements considered to be of vital importance to society, began to be regarded as critical. At present, these infrastructures constitute the critical infrastructure system [1], which consists of individual subsystems, i.e., sectors, subsectors, and elements. There are dependencies between critical infrastructure subsystems which can, due to a disruption in the functionality of one subsystem, spread to dependent subsystems, and thereby escalate the impacts from emergencies on society.

2. Critical infrastructure system description

The issue of critical infrastructure protection began to be addressed in the United States in response to a terrorist bombing on a federal building in Oklahoma City in 1995 [2]. Over the following years, other countries also started tackling these problems, e.g., from 1998 in Canada and from 1999 in the United Kingdom, Germany, Sweden, and Switzerland. Following the September 11, 2001 attacks, the majority of European countries proceeded to define "Critical Infrastructure" and began to take actions aimed at its protection [3].

The US Department of Homeland Security (DHS) currently defines a critical infrastructure as "*systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters*" [4]. A critical infrastructure at the European Union level is specified in a Council Directive [1], defining a critical infrastructure as "*an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact in a Member State as a result of the failure to maintain those functions*."

The hierarchic arrangement of a critical infrastructure system has three levels that constitute a vertical classification [3]: system level, sector level, and element level (see **Figure 1**). The system level is the basic classification of a critical infrastructure according to its functions. This level comprises two areas, namely the technical infrastructure and the socioeconomic infrastructure. The technical infrastructure includes sectors producing and providing specific

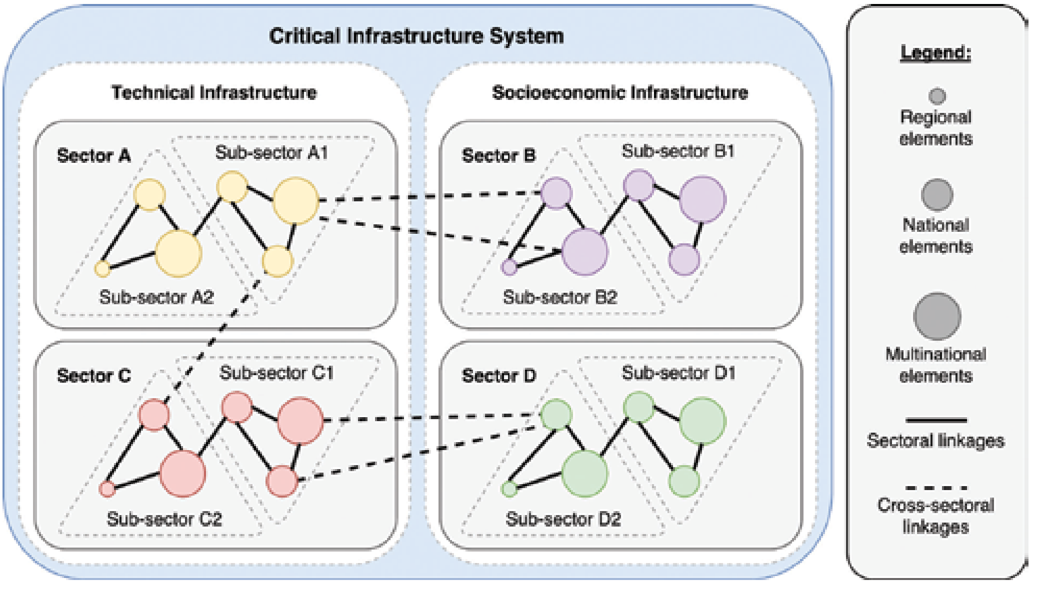

Figure 1. Hierarchic arrangement in a critical infrastructure system.

commodities (e.g., energy and water supply) or sectors providing technical services (e.g., transport or ICT systems). The socioeconomic infrastructure is composed of sectors that provide social or economic services (e.g., health care, financial and currency markets, emergency services, and public administration). There are significant dependencies between two types of critical infrastructure [5]. For instance, all of the socioeconomic sectors require the unrestricted availability of commodities produced by the technical infrastructure sectors, whereas the technical infrastructure, by contrast, fully depends on the socioeconomic sectors, especially in crisis situations.

The sector level is composed of the individual sectors and subsectors of a critical infrastructure. This level represents the classification of specific sectors and their mutual linkages. The transportation sector, for example, is made up of five subsectors, namely road transport, rail transport, air transport, inland waterways transport, and ocean and short-sea shipping and ports [1]. The individual elements that form the element level are the basic building blocks of the critical infrastructure system. These elements reach different degrees of relevance within the system, depending on the extent of the impact that their disruption or failure can potentially produce.

It is imperative that a critical infrastructure system be viewed in a comprehensive manner, taking into account its networked arrangement where individual subsystems are interlinked via various types of linkages. The basic structure of these linkages arises from their character and includes one-way linkages, which represent an influence or dependency, and two-way linkages involving interdependency. Rinaldi et al. [6] have classified interdependencies in more detail as physical, cybernetic, geographic, and logical in nature and noted that interdependencies increase the risk of failures or disruptions in multiple infrastructures. Pederson et al. [5] have subsequently further classified these linkages for lower levels of detail.

3. Impacts of critical infrastructure system failures on dependent subsystems and society

Like any other complex system, a critical infrastructure system includes a multitude of elements with different levels of importance, categorized into several levels and interconnected by linkages of various types and intensity. Such a structural arrangement leads to a broad correlation between individual subsystems, which determines the manner and intensity of propagation of impacts from critical infrastructure system failures on dependent subsystems and society.

3.1. Critical infrastructure system failures

The functioning of a critical infrastructure system is constantly being threatened by a wide range of security threats. These threats can be generally categorized into five basic groups [7]:

- climatological threats (including natural disasters such as floods, tornadoes, heavy snowfall, or extensive fires);

- geological threats (e.g., earthquakes, volcanic activity, landslides);
- biological threats (e.g., pandemics);
- technological threats (including technological emergencies such as radiation emergencies, hazardous chemical spills, flooding caused by damage to hydraulic structures, widespread disruptions to engineering networks, public water supply emergencies or major road, rail, or air traffic accidents); and
- criminal threats (e.g., terrorism, criminal activity, armed conflicts).

The effects produced by these threats on a critical infrastructure system or its subsystems can cause adverse events, which can in turn lead to disruptions or in extreme cases, failures of different subsystems. This involves, in particular, disruptions to functional parameters causing a decline in the performance of specific elements (see **Figure 2**) where the decline is directly proportional to the intensity of the emergency and the degree of resilience of the respective critical infrastructure element.

Depending on the category of threats, three types of emergencies, that subsequently generate individual failures, can occur in a critical infrastructure system. These include intentional anthropogenic events (i.e., terrorism and criminal activity), unintentional anthropogenic events (i.e., technological emergencies), and natural events (i.e., climatological, geological, and biological threats). Once generated, the failures can propagate further within a critical infrastructure system and produce negative impacts of different character, intensity, and effect. Rinaldi et al. [6] were the first to define the basic types of failure propagation in a critical infrastructure system:

- A cascading failure occurs when a disruption in one infrastructure causes the failure of element in a second infrastructure, which subsequently causes a disruption in the second infrastructure (e.g., electric power failure could create disruption in other infrastructures).
- An escalating failure occurs when an existing disruption in one infrastructure exacerbates an independent disruption of a second infrastructure, generally in the form of increasing the severity or the time for recovery of the second failure (e.g., disruption in ICT network may escalate to disruption in a road transport network).
- A common cause occurs when two or more infrastructure networks are disrupted at the same time: elements within each network fail because of some common cause (e.g., action of natural disaster to all local infrastructures).

Over the following years, numerous scholarly papers and studies attempting to elaborate on and tackle the issue of failure propagation within a critical infrastructure system from different viewpoints were published based on the work of Rinaldi et al. [6]. These include Visualization of Critical Infrastructure Failure [8], Cascading Effects of Common-Cause Failures in Critical Infrastructures [9], Analyzing Critical Infrastructure Failure with a Resilience Inoperability Input–Output Model [10], or Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures [11] to name a few.

3.2. Impacts of critical infrastructure system failures

Critical infrastructure system failures subsequently produce negative impacts. These impacts can propagate further not only within the critical infrastructure system (between dependent subsystems), but also outside the system where they can specifically affect society, including national interests such as state security, the economy, and basic human needs [1].

The intensity and propagation of the impacts from critical infrastructure system failures is affected by several external and internal factors of the system concerned. While the external factors include, in particular, resilience of society and the character, and the scope and duration of an emergency; the principal internal factors include the type and scope of the failure inside the system [6], subsystem linkages, and subsystem resilience. The nature of the impacts is characterized by the scope, structure, intensity, duration, and effect of the emergency (see **Figure 3**) [3].

In the event of a disruption to a critical infrastructure system, the impacts spread into two basic areas. The first instance involves impacts within the system where the failure of one critical infrastructure subsystem causes a failure of another subsystem in what is known as a cascading effect [6]. In the second instance, the impacts exert influence outside the system, specifically, on society, producing negative effects on national interests such as security, the economy, and basic human needs [3].

In both of the above-mentioned cases, the impacts may be classified as direct or indirect from a structural point of view. The immediate effect of a disrupted subsystem on another subsystem or directly on society is considered to be a direct or primary action. In contrast, indirect effects of impacts occur vicariously through any critical infrastructure subsystem, regardless of whether or not they affect another subsystem or society as a result. Indirect effects of impacts may be secondary (through one subsystem) or multi-structural (through several subsystems) in character [3].

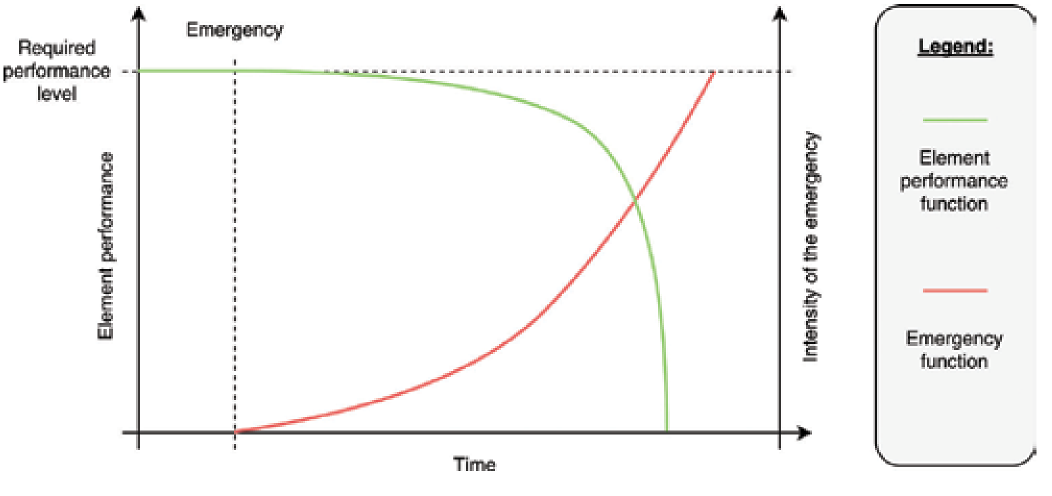

Figure 2. Disruption to an element in a critical infrastructure system.

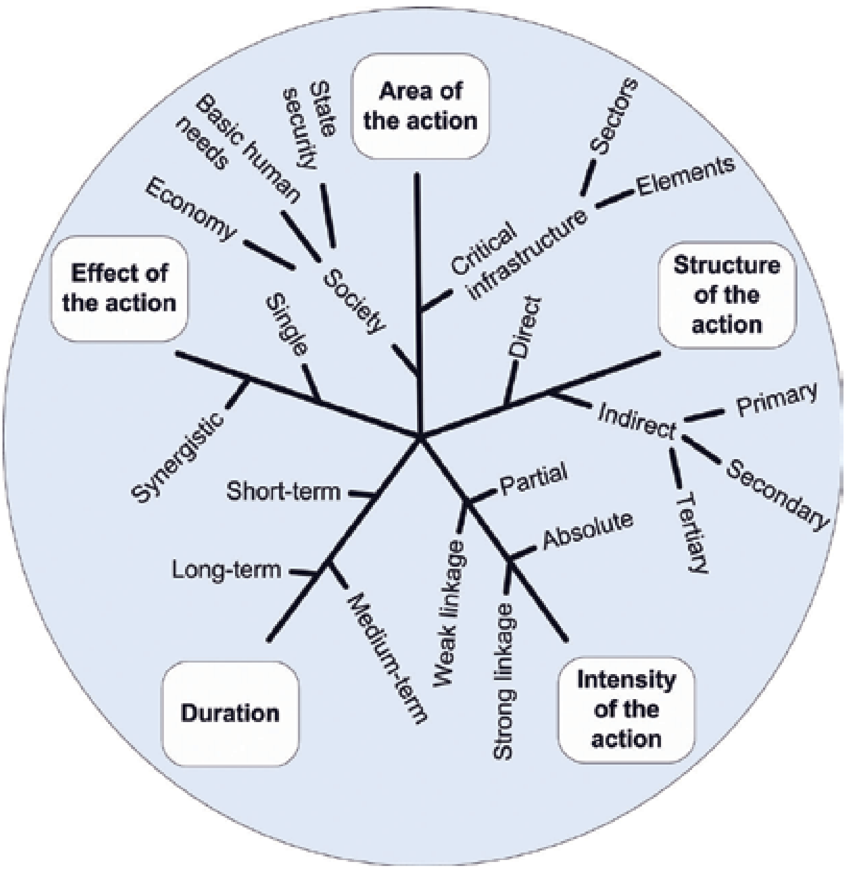

Figure 3. Aspects that create the character of impacts in a critical infrastructure system [3].

Other important factors determining the character of impacts are their intensity and duration. The impact intensity depends on the extent of a failure in a subsystem, that in turn affects another critical infrastructure subsystem, as well as on the level of their linkage. If the linkage is weak, the impact intensity is low and the subsequent impact on the affected subsystem is limited. However, if this linkage is strong, the impact intensity is high and the impact on the affected subsystem can be devastating or absolute. The impact duration, which may be short-term, medium-term, or long-term, represents an important variable with respect to the impact intensity. Ouyang et al. [12] present the typical time progression of a critical infrastructure disruption, dividing it into prevention, propagation, damage, assessment, and recovery periods [3].

Another key factor determining the character of impacts is the effect of their action. If the impacts of a disrupted subsystems act on another subsystem or society in one way only, the impact effect can be regarded as a single impact. However, if the impact effects are multi-way (e.g., through the combination of direct and indirect impacts) and occur concurrently in real-time, then the effects are considered to be synergistic [3].

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3.3. Propagation of impacts in a critical infrastructure system

The above-mentioned aspects, shaping the character of impacts, also significantly contribute to the propagation of these impacts in a critical infrastructure system. At the core of their propagation lie critical infrastructure system failures caused by the negative effects of security risks (i.e., causes of disruptions or failures of a critical infrastructure), which can be either external or internal in nature. Such impacts can then exert a direct influence on society (i.e., direct impacts), spread further across the critical infrastructure, and cause other failures, which lead to additional impacts (i.e., cascading impacts) or they can, due to a cascading effect, act jointly on a single target (i.e., synergistic impacts). See **Figure 4** for a graphical representation of all the potential ways in which impacts can propagate within a critical infrastructure system.

Direct impacts are impacts caused by the disruption or failure of a critical infrastructure subsystem, which act directly on society. The effects of a security threat (e.g., a terror attack) to a component of a critical road infrastructure of international importance (e.g., a major freeway bridge) can be used as an example. These negative effects result in the disruption to the functional parameters of the freeway, which has a direct impact on society (in this instance on passengers and freeway network operators).

Cascading impacts are impacts caused by the disruption or failure of a critical infrastructure subsystem, which spread further across the critical infrastructure, resulting in failures in dependent subsystems that in turn lead to an escalation in other impacts. The effects of a security threat (e.g., a gale) to a component of a critical electric energy infrastructure of national importance (e.g., 110 kV distribution system) can be used as an example. These negative effects result in the disruption to functional parameters of the distribution system, which cascades into dependent subsystems (e.g., a railroad signaling system). The disruption to a distribution system then results in a cascading impact on society due to nonfunctioning railroad transport.

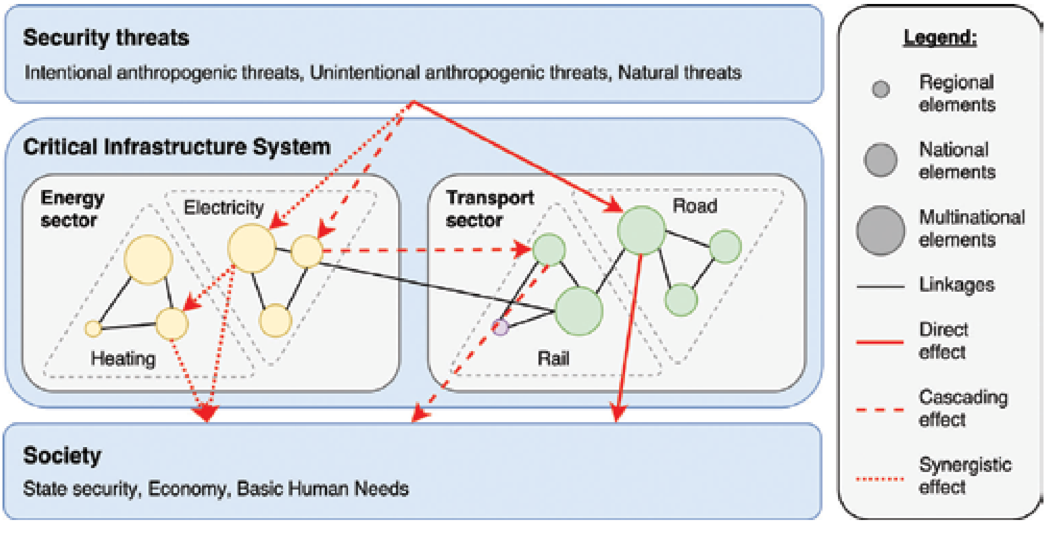

Figure 4. Ways of impact propagation in a critical infrastructure system.

Synergistic impacts are impacts caused by the disruption or failure of two or more critical infrastructure subsystems which occur concurrently, thereby exacerbating their impacts on society [3, 9]. The effects of a security threat (e.g., a technological accident) to element of a critical electric energy infrastructure of international importance (e.g., a nuclear power plant) can be used as an example. These negative effects result not only in direct impacts on society (i.e., large-scale power outages), but also in the impacts cascading to dependent subsystems (e.g., heat production and distribution), the disruption of which produces additional impacts on society. This situation brings about a synergistic effect, consisting of the added effect of joint impacts on society, and increasing their mere sum [3].

3.4. Modeling of impacts of critical infrastructure system failures

Modeling the anticipated propagation of impacts constitutes an important approach contributing to their minimization in a critical infrastructure system. However, it involves a complex process which should be based on mathematical modeling as well as on the integration of innovative approaches to analyze the critical infrastructure system. The basis for this process should include, in particular [13]:

- early indication of impacts using a bottom-up approach;
- harmonization and transformation of cross-cutting criteria at the regional level;
- European critical infrastructure risk and safety/security management; and
- implementation of a preferential critical infrastructure risk assessment.

An early indication of impacts through the application of a bottom-up approach should be based on the determination of resilience disruption indicators in interconnected critical infrastructure subsystems. It is a holistic approach to assess the resilience of a critical infrastructure based on a comprehensive perception of specific political, economic, social, technological, legislative, and ecological environments. The essence of this approach is a systematic approach consisting of a cross-sectoral evaluation based on a research into the mutual linkages between individual critical infrastructure subsystems. It factors in the propagation of cascading impacts and synergistic effects in a critical infrastructure system. The referenced system solution should be applied using a progressive bottom-up approach, which is based on a critical infrastructure evaluation from the lowest level (city, region) upwards and has already been implemented in a number of developed countries (e.g., Switzerland and the Netherlands). This approach can be viewed as the logical continuation of the ongoing research into critical infrastructure security in terms of integrating the research results, via identifiers describing the critical infrastructure status, into a composite resilience indicator (see **Figure 5**) [13].

The application of the bottom-up approach is closely related to the need to harmonize and transform cross-cutting criteria at the regional level. Individual Member States of the European Union have already set the cross-cutting criteria values for national critical infrastructure elements. However, the vast majority of states have failed to disclose these values, making the follow-up research into the modeling of the impacts on society particularly

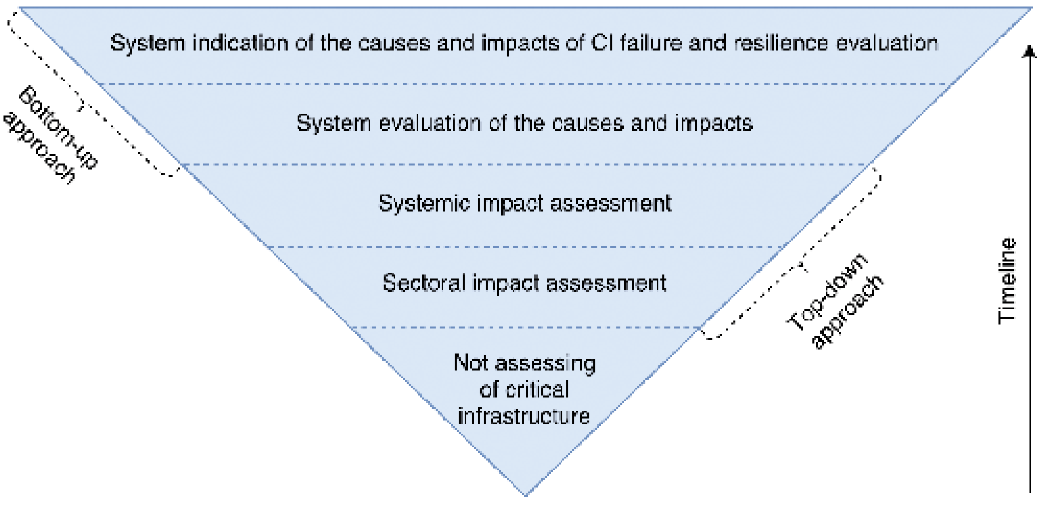

Figure 5. Development of the approach to a critical infrastructure research [14].

challenging. For this purpose, it is possible to use the results of the international RAIN project [15] undertaken as part of the EU's 7th Framework Programme. Based on recommendations arising from a European Union directive [1] and a regulation on the criteria for determining critical infrastructure elements adopted by the government of the Czech Republic [16], the following cross-cutting criteria were defined for a wider international debate within the RAIN project [15]:

- health impacts—the number of victims with a threshold value of more than 25 fatalities or more than 250 individuals hospitalized for a period exceeding 24 hours per 1 million inhabitants within the region under review;
- economic impacts with an economic loss threshold value of over 0.5% of gross domestic product; and
- impacts on the public with a threshold value of more than 12,500 individuals per 1 million inhabitants within the region under review affected by extensive restrictions in the provision of essential services or by other major disruptions to everyday life.

A provisional transformation of national criteria could form the basis for the setting of cross-cutting criteria values at the regional level (note: however, this method of setting regional values is not ideal in terms of applying the bottom-up approach as it is more akin to the top-down approach due to the transformation of national criteria). The transformation involves the dynamic conversion of threshold values for national cross-cutting criteria to regional criteria. This ratio is mainly applied as a proportion of the population of a given state to the population of the region concerned, and of the threshold values of national cross-cutting criteria to those of regional cross-cutting criteria. In principal, static threshold values are converted to dynamic values not only due to the varying population sizes in different regions, but also due to the different levels of gross domestic product generated in these regions [17].

European critical infrastructure risk and safety/security management comprises an important aspect of modeling the impacts of critical infrastructure failures. In adopting this approach, risks are recognized at an early stage, allowing for a timely indication of impacts on independent critical infrastructure subsystems. The following methodologies should be employed with a view to optimize the risk and safety/security management system and comply with the requirements for crisis preparedness plans applicable to critical infrastructures entities, as an equivalent to the Operator Security Plan:

- Methodology for selected CIs system resilience element evaluation [18]; and
- Methodology for ensuring the protection of CIs in the production, transmission, and distribution of electricity [19].

Implementation of a preferential critical infrastructure risk assessment provides another important basis for the modeling of impacts produced by critical infrastructure failures [20]. This allows the assessor to introduce subjective conditions into an otherwise objective process of risk assessment, providing the assessor with an option to partially influence the assessment process by preferring certain factors over others. The significance of this phase of the assessment process lies in the fact that different entities perceive certain risks from different points of view, which creates a conducive environment for discussion of all stakeholders, ensuring the most appropriate safety/security actions are taken. Moreover, a preferential critical infrastructure risk assessment also provides an important basis for the modeling of impacts of critical infrastructure failures as its results determine vulnerabilities enabling the propagation of impacts throughout the critical infrastructure system [13].

4. Resilience of critical infrastructure subsystems

The purpose of each critical infrastructure subsystem is to deliver services to recipients. It is therefore essential to ensure that each subsystem is fully functional and that appropriate steps are taken to minimize its failures and curtail the propagation of any potential impacts on society or any other dependent critical infrastructure subsystems. According to existing scientific knowledge, the best and most effective way of minimizing the impacts of critical infrastructure system failures is to reach the highest possible level of resilience with respect to all of its subsystems.

4.1. Definition of resilience

The term resilience was first defined in connection with the resistance and stability of ecological systems where two types of system behavior were identified [21]. The first type, stability, is the ability of a system to return to an equilibrium state after a temporary disturbance and the more rapidly it returns, the more stable it is. The second type of system behavior, known as resilience, is a measure of the ability of a system to absorb impacts without significant changes to the system status. Over time, this perspective was expanded to include the sphere of sociology, which then led to resilience being explored in socio-ecological systems. Based on the achieved results, the research into resilience gradually spread to other disciplines such as psychology, economy, and engineering.

In 2001, Holling shed light on understanding the complexity of economic, ecological, and social systems with the publication of a definition based on two fundamental components of each system, namely hierarchy and adaptive cycles [22]. Together they form panarchy according to Holling. Panarchy can be defined as a structure in which systems of nature and humans are interlinked in never-ending adaptive cycles of growth, accumulation, restructuring, and renewal.

The research into the resilience of socio-ecological systems also sparked an interest in research focused on resilience in society. The resilience of a society is dependent on its ability to respond to a stress factor and can be defined as "*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management*" [23].

Resilience gradually began to be defined in general terms for any system, including engineering. Resilience was first described in connection with a critical infrastructure in a document entitled Critical Infrastructure Resilience Final Report and Recommendations [24], where it is defined as the ability to absorb, adapt to, and/or rapidly recover from a potentially disruptive event. By contrast, the critical infrastructure resilience strategy [25] defines critical infrastructure resilience as the ability to reduce the magnitude and/or duration of a disruptive event. These definitions clearly show what constitutes resilience, or rather what characteristics enhance the resilience of a system. For example, Chandra [26], based on his study of socio-ecological systems, includes the following attributes in engineering systems resilience: redundancy, adaptability, flexibility, interoperability, and diversity.

As research into the resilience of critical infrastructures has since been pursued by numerous leading research workers and institutions, the definition of resilience has been repeated over and over again without any added value. However, the different approaches to determining their attributes/aspects/components/properties/characteristics/capacities/abilities/assets/parameters may be worth mentioning. Below are some examples of the different approaches:

- Ehlen et al. [27]—absorption, adaptation, and recovery.
- Keeping the country running [28]—the ability to anticipate, absorb, adapt, and/or rapidly recover. For the system to function as a whole, it must incorporate four assets or elements: resistance, reliability, redundancy, response, and recovery.
- Carlson et al. [29]—the form of linkages between six aspects (anticipation, resistance, absorption, ability to respond, adaptability, and recovery), which according to the author define resilience, and four parameters (preparedness, mitigation, response, and recovery), which characterize the process of enhancing the resilience capacity of a system.
- Béné et al. [30]—three basic aspects: absorptive capacity (the ability to cope with the impacts of adverse changes and shocks), adaptive capacity (the ability of a system to adapt to changes), and transformative capacity (the ability to create a fundamentally new system).

- Presidential Policy Directive—Critical Infrastructure Security and Resilience [31]—the ability to prepare, resist, and rapidly recover.
- Hromada et al. [32]—preparedness and adaptability as the basis for the fulfillment of the resilience function. Key indicators: robustness, preparedness, ability to respond, recoverability.
- Eid et al. [33]—the ability to anticipate, resist, absorb, respond, adapt, and rapidly recover from a disruption.
- Ortiz De La Torre et al. [34]—prepare, prevent, and protect (before the disruption), mitigate, absorb and adapt (during the disruption), and respond, recover and learn (after the disruption).
- Bologna et al. [35]—the overall activities of modeling, and analysis of critical infrastructure system aimed to evaluate the ability to prevent, absorb, adapt, and recover from a disruptive event, either natural or man-made.
- Nan and Sansavini [36]—ability of the system to withstand a change or a disruptive event by reducing the initial negative impacts (absorptive capability), by adapting itself to them (adaptive capability), and by recovering from them (restorative capability).

Some experts consider critical infrastructure resilience to be the primary national policy framework and a vital criterion for the future sustainability of cities or infrastructures as such, and argue that, from a broader perspective, resilience is indispensable in terms of population protection and crisis management [33, 37].

4.2. Concept of critical infrastructure resilience

Based on the accepted definitions, resilience can be said to represent the level of internal preparedness of critical infrastructure subsystems for emergencies or the ability of these subsystems to perform and maintain their functions when negatively affected by internal and/or external factors. Strengthening resilience (e.g., Action Plan for Critical Infrastructure [38] or Labaka et al. [39]) minimizes the vulnerability of subsystems, which in turn curtails the occurrence, intensity, and propagation of failures and their impacts in a critical infrastructure system and society.

Understanding and clear definition of resilience represent the cornerstone of resilience assessment and strengthen with respect to critical infrastructure subsystems. In fact, critical infrastructure system resilience must be understood as a cyclic process based on continual strengthening of resilience of individual subsystems (see **Figure 6**). The crucial phases of this process are prevention, absorption, recovery, and adaptation.

The first phase of the critical infrastructure resilience cycle is prevention. In individual critical infrastructure subsystems, this is determined by permanent preparedness and protection of each subsystem. Prevention is provided on a continuous basis until a subsystem disruption occurs, at which time it is suspended, and for the duration of the emergency, replaced by absorption.

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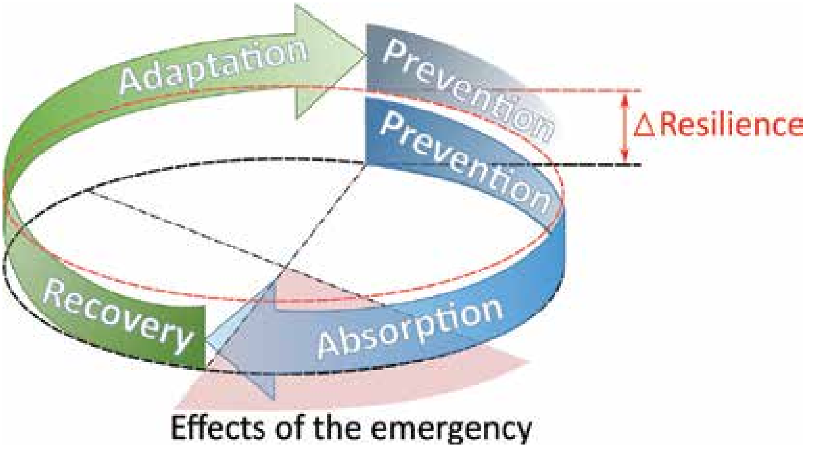

Figure 6. Cycle of critical infrastructure resilience.

Absorption, the second phase of the resilience cycle, is initiated if a subsystem is disrupted due to an emergency and is determined by the critical infrastructure subsystem robustness. Accordingly, robustness is determined by the ability of a critical infrastructure element to absorb the effects of an emergency. In a critical infrastructure system, two types of robustness are recognized, namely structural and security robustness. Structural robustness is determined by the progress in the decline of a function and the level of redundancy, while security robustness is based on the level of protective measures, detection, and ability to respond.

The recovery phase starts after the effects of an emergency have worn off. This phase is characterized by recoverability, which is the capacity of a subsystem to recover its function to the required level of performance after the effects of an emergency no longer exist. The success of recovery is determined by the available resources and the time required to complete the recovery process.

The final phase of the critical infrastructure resilience cycle is adaptation, which is essentially the ability of an organization to adapt a subsystem to subsequent effects of an emergency. It represents the dynamic long-acting ability of an organization to adapt to changes in circumstances. Adaptation is determined by the internal processes of an organization focused on the strengthening of resilience, i.e., risk management and innovation/education processes. However, strengthening of the resilience of a subsystem already occurs during the recovery phase of its performance.

4.3. Resilience assessment in a critical infrastructure system

The Resilience Assessment and Evaluation of Computing Systems compilation monograph [40] was the first comprehensive overview study exploring critical infrastructure resilience assessment in the field of information and communication technology. Another important monograph, Critical Infrastructure System Security and Resiliency [41], introducing a practical methodology for the development of an efficient system of critical infrastructure protection, was published a year later. This methodology focuses both on the prevention of emergencies and the mitigation of its consequences. The same year saw the publication of the Resilience Measurement Index: An Indicator of Critical Infrastructure Resilience study [42], whose main objective is to measure the ability of a critical infrastructure to reduce the magnitude and/or duration of impacts from disruptive events.

In 2013, the European Commission published a working document on a new approach to the European Programme for Critical Infrastructure Protection: Making European Critical Infrastructures more secure [43]. This document clearly emphasized the importance of resilience and interdependencies in a critical infrastructure as well as the need to develop tools and methods for their assessment.

In addition, the issue of measuring critical infrastructure resilience has long been explored by the Swiss Federal Institute of Technology in Zurich (Eidgenössische Technische Hochschule Zürich). The institute presents the results of its risk and resilience research in the form of scientific reports, with the issue of resilience measurement addressed in detail in the SKI Focus Report 8: Measuring Resilience [44] and the SKI Focus Report 9: Measuring Critical Infrastructure Resilience [45].

There are also several major international projects dealing with critical infrastructure resilience assessment at present, including SMART RESILIENCE: Smart Resilience Indicators for Smart Critical Infrastructures, IMPROVER: Improved Risk Evaluation and Implementation of Resilience Concepts to Critical Infrastructure, RESILIENS: Realizing European Resilience for Critical Infrastructure, or RESILIENCE 2015: Dynamic Resilience Evaluation of Interrelated Critical Infrastructure Subsystems.

In 2016, a comprehensive approach based on the results of leading research projects was published in the Guidelines for Critical Infrastructures Resilience Evaluation document [35]. This approach has its basis in the evaluation of individual indicators constituting resilience, the resulting composite indicator being a function of indicators in technical (i.e., prevention, absorption, adaptation, and recovery), personal, organizational, and cooperative dimensions.

Additional significant approaches to evaluate resilience have been presented, for example, in an interim report of the project RESILIENS D2.2: Qualitative, Semi-Quantitative and Quantitative Methods and Measures for Resilience Assessment and Enhancement [34]. The second part of the document presents a critical infrastructure resilience assessment tool (CI-RAT), which has been developed as part of this project and is based on a semi-quantitative methodology for CI resilience assessment, and on a CI resilience management concept.

5. Conclusion

The chapter entitled "Failures in a Critical Infrastructure System" presents a comprehensive overview of a critical infrastructure system, which may be regarded as the basis for ensuring the functional continuity of society from both the economic and social perspectives. The introductory part of the chapter is designed as a historical framework, defining critical infrastructures in relation to legislative, normative, and institutional processes involved in addressing the issues concerned. The described framework formulates the basis, approaches, and logic of a hierarchical system arrangement in connection to interdependencies and linkages between elementary elements. Infrastructure failures have been classified in terms of their sources and causes because the potential impacts of failures in selected dependent systems can have profound effects on the functioning of society as a whole. It was argued that the impacts of failures in dependent systems increase the occurrence of cascading and synergistic effects, which fundamentally affect the resilience of individual elements and the general function of the system. This led to establishing the relationship between system resilience and failures with respect to critical infrastructure network elements.

Based on these facts, the impacts of failures and their propagation were described in the context of the necessity to model such impacts. In this regard, the significance and applicability of top-down and bottom-up approaches in relation to the exploration of mutual linkages was further compared as one of the identifiers describing the critical infrastructure status. The significance of identifying and labeling critical infrastructure elements is, therefore, also viewed from the perspective of the need for a more objective setting of cross-cutting criteria values, equally applicable at the regional level. As already mentioned, element resilience exerts a substantial effect on the overall impacts of potential failures. That is why a resilience framework for critical infrastructure subsystems was established with a view to defining resilience, formulating a resilience concept, and setting up a resilience evaluation process in a critical infrastructure system. The presented facts are based on the Ministry of the Interior of the Czech Republic Security Research project—RESILIENCE 2015: Dynamic Resilience Evaluation of Interrelated Critical Infrastructure Subsystems and form a resilience knowledge base as the ability of a system, community, or society exposed to adverse events to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and recovery of its essential basic structures and functions through risk management.

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Author details

David Rehak[1] and Martin Hromada[2]*

*Address all correspondence to: hromada@fai.utb.cz

1 Faculty of Safety Engineering, VŠB - Technical University of Ostrava, Czech Republic

2 Faculty of Applied Informatics, Tomas Bata University in Zlín, Czech Republic

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Chapter 6

Dealing with Complexities and Uncertainties in a System-of-Systems: Case Studies on Urban Systems

Datu Buyung Agusdinata

Additional information is available at the end of the chapter

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Abstract

Dealing with complexities and uncertainties in the design and planning of human-engineered systems such as urban systems is crucial. When the stakes are so high and consequences of alternative actions are so uncertain, a systematic consideration of complexities and uncertainties is warranted. This chapter describes a system-of-systems (SoS) framework to represent the interdependencies and dynamics among human and engineered systems. The framework comprises a set of tools including network theory, system dynamics, and exploratory modeling and analysis. Based on the framework, three case studies are presented. The first case analyzes urban systems' vulnerabilities to climate change using the context of the 2004 hurricane in South Florida, USA. The second case is a comparison of the performance of two design options for natural-gas powered electricity power plant. The third case is a system analysis for supporting an economic revival in the US Midwest City. The applications reveal information about (1) critical infrastructure nodes, (2) robustness of decisions under uncertainty, and (3) dynamics relevant to support decision-making.

Keywords: urban systems' vulnerabilities, urban economic revival, infrastructure investment decision, robust performance, failure modes

1. Introduction

Urban systems are increasingly under strain as about 54% of the world's populations currently are city inhabitants [1]. A growing trend of population growth and urbanization will increase this proportion to 66% by 2050. In urban systems, infrastructures constitute the physical framework within which our economy and society operate [2]. Disruptions in infrastructure, therefore, pose considerable threats to some of the very pillars of modern life. Infrastructures including energy, food, water, transportation, manufacturing, and telecommunications are key components in enabling modern society to function.

From a conceptual point of view, urban infrastructure can be considered as a couple human-engineered system. An engineered system (ES) is *a combination of technological components that work in synergy to collectively perform a useful function* [3].

Recent structural changes, such as deregulation in the energy sector, have revealed infrastructure's vulnerabilities. Public dissatisfactions began to surface as the lack of capacity, reliability, and vulnerability of such provisions become increasingly prevalent causing politicians to take serious considerations. At the same time, many infrastructures have appeared to be inert to change because these infrastructures have long technical life time and are deeply interwoven in our social, economic, and political structure. Lack of systematic knowledge in addressing uncertainties may contribute to ad hoc political decisions, which may block timely adaptation and discourage further investment in the infrastructure system [4].

A system-of-systems (SoS) perspective is an attempt to structure the complexity of human-engineered systems by taking a broader view than just the physical design (i.e., traditional system engineering view) and operational aspect, to include commercial and financial, economic, social, and policy aspects couched within multiple levels. The goal is to improve analysis for decision-making.

A system-of-systems (SoS) consists of multiple, heterogeneous, distributed systems embedded in networks at multiple levels that evolve over time. Complexity in an SoS stems primarily from the heterogeneity of its constituent systems, the distributed nature of these systems. The complexity brought by the system heterogeneity exists both within a domain (e.g., power generation) and across domains (e.g., power generation, energy service economics, and governmental policy/regulation).

The chapter first describes a generic SoS conceptual model that characterizes the interdependencies among SoS constituents. Next, a model of uncertainty space evolution over time is presented. Three case studies are then presented to illustrate the framework. In the last section, the added values of SoS framework are discussed.

2. Conceptual model

2.1. Characterization of SoS interdependencies

An SoS consists of constituent systems that include individual engineered and actor system (**Figure 1**). An engineered system (ES) represents the performance and capabilities of relevant physical/technological systems. An actor system (AS) represents the development and operation of resources by an actor and, possibly, the management of other actor behavior residing either horizontally at the same SoS level or vertically across level.

The model is described using system model elements that are central to the policy analysis approach [5]. Policies (P) are the set of instruments within the control of the decision makers

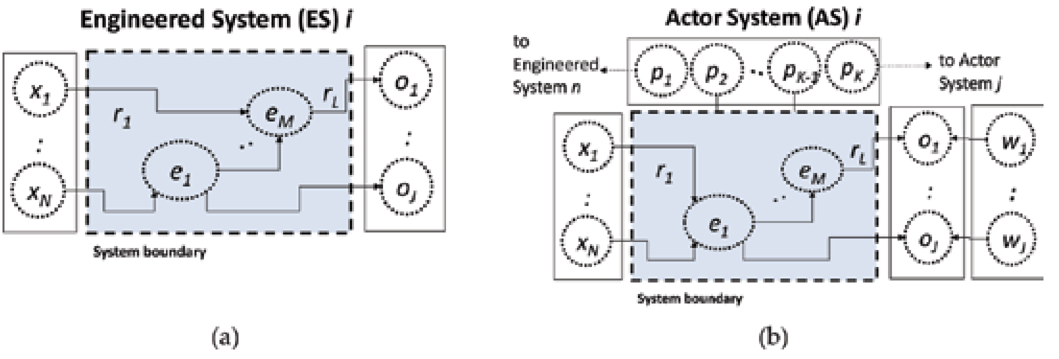

Figure 1. System-of-systems constituents: (a) engineered system and (b) actor system.

that can change the system. External forces (X) refer to factors that are not controllable by the decision maker but may influence the system significantly. The structure of an actor system can be specified as a set of endogenous factors (I) together with relationships (R), which may include functional, behavioral, or causal ones. The results of these interactions, the model outputs, are called outcomes of interest (O). The value systems (W) of decision makers and stakeholders reflect their goals and preferences. Notice that an engineered system is devoid of policy instruments and has no value systems.

An SoS of urban systems can then be constructed via assemblage of some ES and AS systems in a structure resembling the nested system in **Figure 2**. Each element represents an ES, which resides at the lowest level (α level) and an AS, which resides at the β level and above.

Based on the framework, several terms can be defined:

- A scenario is a single realization of one set of external forces (X).
- System structure is the configuration of E and R.
- Uncertainty space, **S** covers the entire scenarios, system structure, and value systems (XERW).

The different types of interdependencies within an SoS are given in **Table 1**. The system model variables in an SoS interact with one another, creating a network of interrelationships. These interdependencies are bidirectional. In one direction, the interdependency can manifest in a form of influence.

2.2. Dealing with uncertainties in a system-of-systems

To deal with uncertainties in a system-of-systems, a computational approach called exploratory modeling and analysis (EMA) has been proposed [6, 7]. EMA is founded on the idea of exploring multiple hypotheses about the SoS of interest by varying the assumptions underlying the system model. EMA is used to explore the implications of multiple hypotheses about the system by means of computational experiments. A computational experiment is a single computer run of the system model using one set of assumptions.

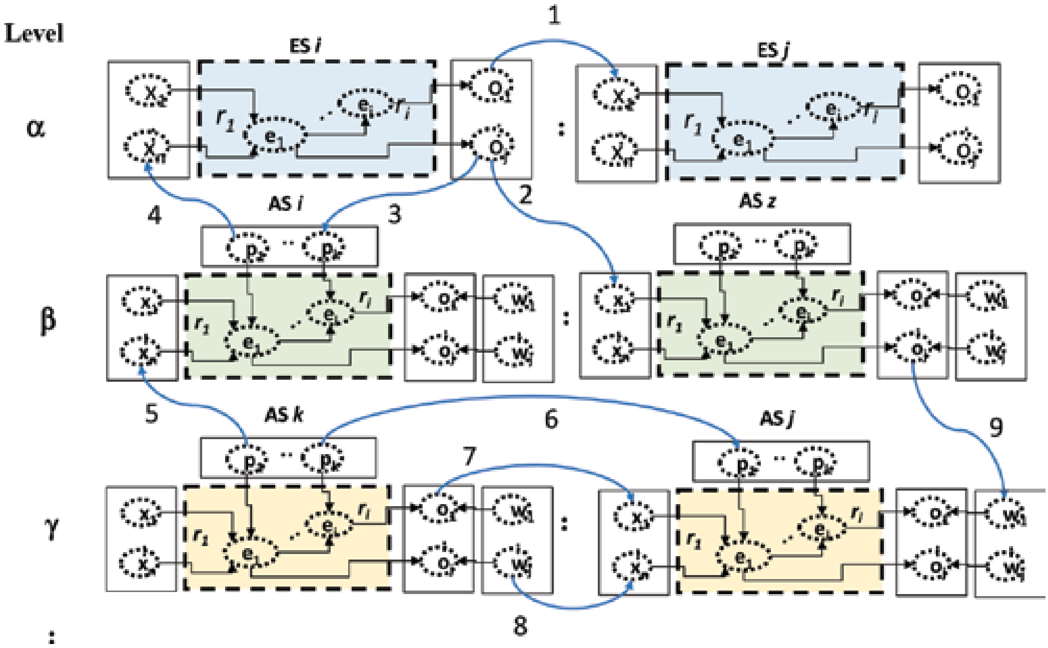

Figure 2. A system-of-systems consisting of engineered (ES) and actor systems (AS).

Linkage of interdependencies	Formalism
An outcome of an ES is an external factor for another ES	$\mathbf{o}_{ES\,i} = \mathbf{x}_{ES\,j;i\neq j}$
An outcome of an ES is an external factor for an AS	$\mathbf{o}_{ES\,i} = \mathbf{x}_{AS\,i}$
An outcome of an ES influences actor decision	$\mathbf{p}_{AS\,i} = f(\mathbf{o}_{ES\,i})$
An actor's decision is an external factor for an ES	$\mathbf{p}_{AS\,i} = \mathbf{x}_{ES\,i}$
An actor's decision is an external factor for another actor	$\mathbf{p}_{AS\,i} = \mathbf{x}_{AS\,j;i\neq j}$
An actor's decision influences another actor's decision	$\mathbf{p}_{AS\,i} = f(\mathbf{p}_{ASj;i\neq j})$
The realization of an outcome of interest of an actor affects the decision of another actor	$\mathbf{p}_{AS\,i} = f(\mathbf{o}_{AS\,j;i\neq j})$
A value system of one actor becomes an exogenous factor of another	$\mathbf{x}_{AS\,i} = \mathbf{w}_{AS\,j;i\neq j}$
The outcomes of one actor system affect the value system of another actor	$\mathbf{w}_{AS\,i} = f(\mathbf{o}_{AS\,j;i\neq j})$

Table 1. Interdependencies among SoS elements.

2.2.1. Characterization of the evolution of SoS uncertainty space over time

Figure 3 shows an 'uncertainty space funnel' that models how the future realizations of the model variables will unfold in a time horizon of n periods. In a future of multiple discrete time periods, one unique realization in the first period leads to multiple possible realizations

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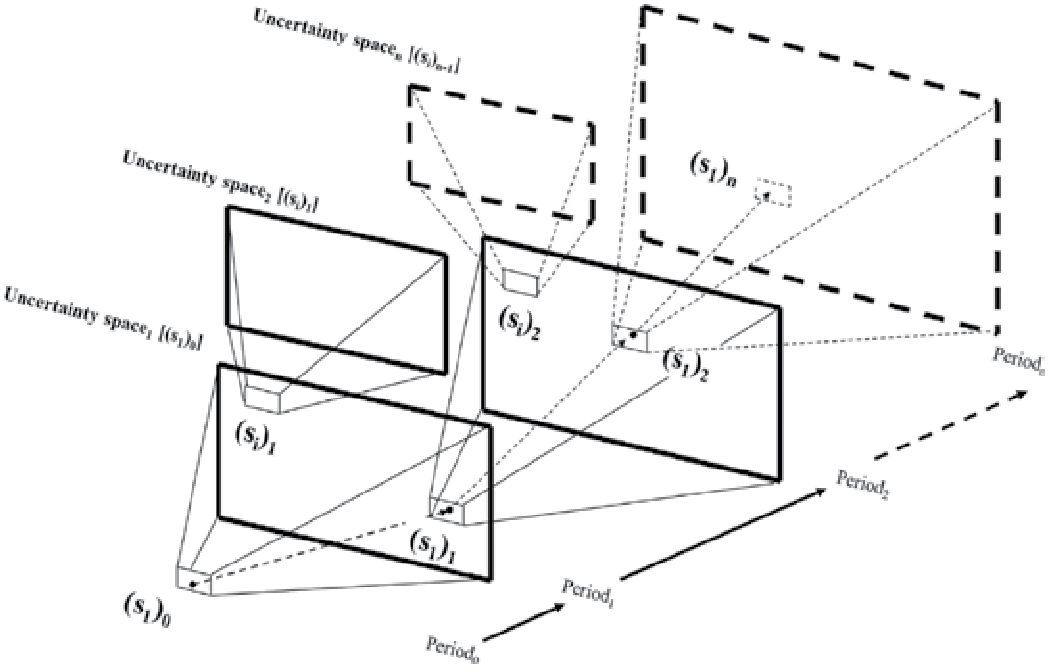

Figure 3. The evolution of SoS uncertainty space.

in the second period, each of which will then lead to multiple possible realizations in the third period, and so on until the last period is reached.

Uncertainty spaces at one particular period can be modeled in different ways. For example, the *uncertainty space*$_1$ $[(s_1)_1]$ and the *uncertainty space*$_2$ $[(s_2)_1]$ can have exactly the same nature (i.e., the *X, E, R*, and *W* elements) and the same size (i.e., the choice of range of the *X, E, R*, and *W* elements). When a structural change occurs, however, the nature and size of one uncertainty space may be totally different with the other.

Three main characteristics of SoS uncertainty space are described as follows:

1. The degree and scope of uncertainty increases as the time period progresses. This is a default characteristics since the longer the time span the greater the uncertainty.
2. The degree and scope of uncertainty actually decreases as time progresses. This occurs, for example, in case the threshold market share of a certain technology is reached, which reduces the range of the share of other technologies (i.e., *lock-in effect*).
3. The nature of the uncertainty space in one period is different from that in the subsequent period, which may also depend on the realization preceding it. For example, when a structural change (I, R) occurs, some of the variables become irrelevant and new ones need to be added. Also, the value system of decision makers and stakeholders may change over time. Future decision makers may have different decision criteria or put different weights on the criteria.

This way of characterizing SoS uncertainty space highlights its path dependency nature. Suppose that $(s_1)_0$ is the realization of the uncertainty space in period_0 (i.e., the initial condition). In period_1, the uncertainty space that is path dependent on the initial condition $(s_1)_0$ is the uncertainty space_1 $[(s_1)_0]$. The evolution of uncertainty space progresses over time until the end of analysis' time horizon, $Period_n$. In $Period_n$, there will be a set of uncertainty spaces, each originated from the realizations of all the preceding periods (i.e., uncertainty space_1 $([(s_i)_{n-1}],\ldots, [(s_i)_2], [(s_i)_1], [(s_i)_0])$. One future path (illustrated by the dashed arrows), for example, can be represented by $(s_1)_0 \rightarrow (s_1)_1 \rightarrow (s_1)_2 \ldots \rightarrow (s_1)_n$.

3. Case study 1: vulnerabilities of urban systems

An urban system is a complex system comprising an infrastructure-actor network, whose complexity is confounded by their close physical proximity and functional interdependencies. An understanding of its complexities can support policymakers to maintain quality of life amidst perturbations, growth and decay, discontinuities, and stress in the system. Building upon [8], we aim to establish the level of influence and vulnerability of a network of multiple infrastructure-actor networks in urban systems.

3.1. A typology of urban system complexities

An overall urban system comprises several individual systems such as energy, water, telecommunication, and transportation. We develop a typology for classifying different types of system interdependency (**Figure 4**), which is based on (1) whether the network accounts for the connectivity within an individual system (i.e., intrasystem) or across systems (i.e., intersystem) and (2) whether the context of such connectivity takes place in an emergency condition (i.e., with drastic service discontinuities) or in a non-emergency one.

To a certain extent, each of the resulting quadrants has a different focus of inquiry and hence policy implications in terms of actors' actions and coordination. For instance, the first quadrant (Q1) focuses on connectivity within a single sector (e.g., transportation) in a non-emergency condition. An example of inquiry in this sector may revolve around the issue of reducing traffic congestion. By contrast, in the third quadrant (Q3), the inquiry considers interdependencies among multiple sectors (e.g., a city as a whole) and addresses broader issues (e.g., impacts of extreme weather events). In this chapter, we focus on the fourth quadrant.

3.2. Network theory perspective and the network model

Network theory is employed to obtain measures that can illuminate the degree of infrastructure influence and vulnerability within an urban system. We consider a particular infrastructure as a node. A directional link between two nodes means that the failure in the source affects the end node. This formulation implies that fewer links among nodes are actually desirable. We use and interpret sample data from [9] to model the (inter)dependencies among infrastructure and the repair team for the urban systems in Florida during the 2004 hurricane season. The resulting network model of infrastructure-actor connectivity is depicted in **Figure 5**. To generate some network measures, we employ the UCINET software [10].

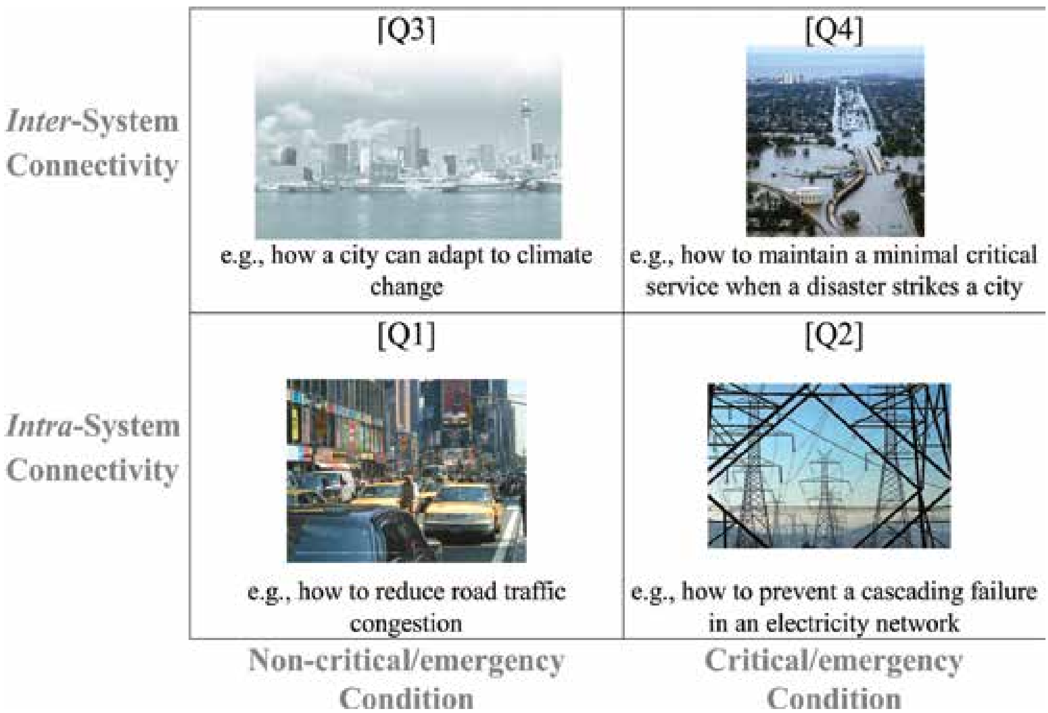

Figure 4. A typology of urban system complexities.

3.3. Results and implications

A summary of the network measures is given in **Table 2**. Each of the measures and its implication is described later.

3.3.1. Centrality degree

It counts the number of outgoing (i.e., influence) and incoming (i.e., dependence) links. For the case study, road infrastructure exerts the most influence to others, whereas (waste) water plant and electricity transmission receive most influence from others and hence are most vulnerable. This insight can inform prioritizing infrastructures that need to be decoupled from other.

3.3.2. Betweenness centrality

This measures node importance in terms of its role as an 'intermediary' in a failure path. The electricity plan appears to play the most dominant role. Consequently, urban system needs to be disconnected with electricity plant by, for example, having own backup power.

3.3.3. Eigen-vector centrality

It measures the importance of an infrastructure not only by the number of nodes it affects but also the importance of the nodes to which it affects. It appears that the supervisory control and data acquisition (SCADA) system is the infrastructure with the highest score because it affects three very important nodes such as electricity transmission, electricity plant, and phone/Internet infrastructure.

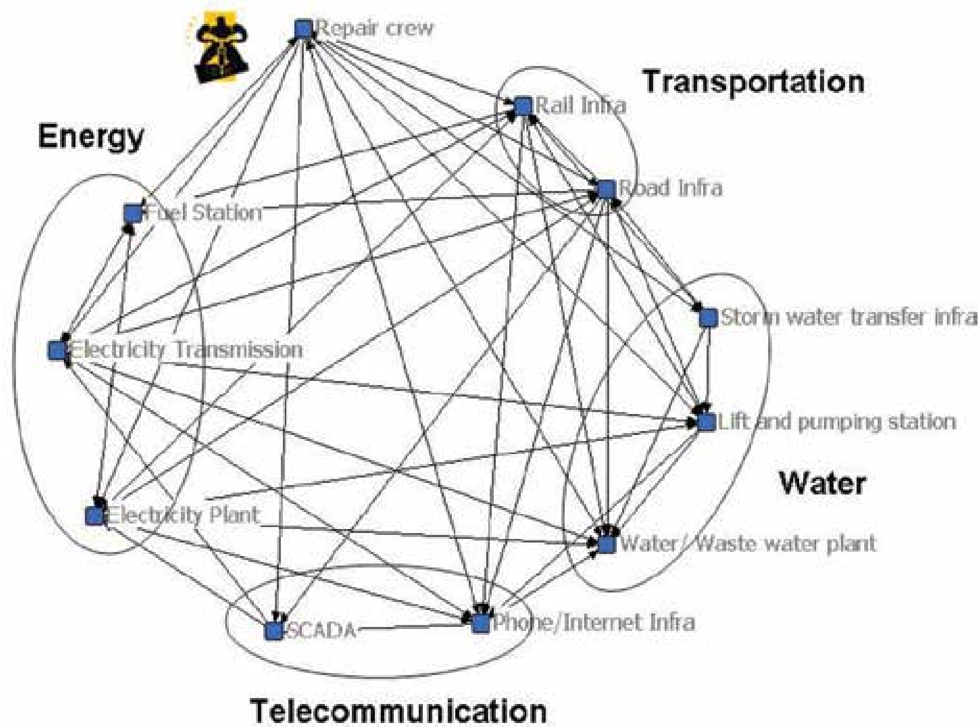

Figure 5. Infrastructure-actor network in the context of Florida urban systems.

Infrastructure-Actor Elements	Centrality degree (out)	Centrality degree (in)	Betweenness Centrality	Eigen vector centrality
Electricity Plant	6	7	12.167	0.179
Electricity Transmission	6	8	7.250	0.297
Fuel Station	3	5	1.700	0.319
Phone/Internet Infrastructure	5	7	7.367	0.275
SCADA	2	3	0.200	0.404
Water/ Waste Water Plant	2	8	0.667	0.348
Water Lift and Pumping Station	6	6	2.533	0.270
Storm Water Transfer infrastructure	4	3	0.250	0.343
Road Infrastructure	9	5	7.167	0.279
Rail Infrastructure	7	5	3.833	0.322
Actor: Repair Crews	10	5	9.867	0.213

Table 2. Summary results of network analysis of urban infrastructure systems.

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Our initial work employs network theory to establish the degree and influence and vulnerability of infrastructure-actor interdependency in urban systems. The insight obtained from the work can potentially be used to set priority of actions and to find a balance between vulnerability and performance.

4. Case study 2: investments in energy infrastructure

Uncertainties abound in making investment decisions in energy infrastructure such as electricity power plant. There are some major uncertainties they have to deal with in liberalized energy markets ([11]). It is difficult to predict the future electricity demand price as well as the price of input fuels. In addition, there are several structural uncertainties. These include regulation on price mechanisms (e.g., price cap) and environment (e.g., cooling water, emissions, and waste), the developments in the natural gas industry (e.g., the extraction of gas through fracking), and the unbundling of the energy industry into separate electricity generation, transmission, and distribution function.

4.1. SoS model of investment in energy infrastructure

An SoS model for electricity power plant investment is given in **Figure 6**. It consists of two engineered (power plant and house building technologies) and three actor systems (utility companies, household consumers, and public utilities commission).

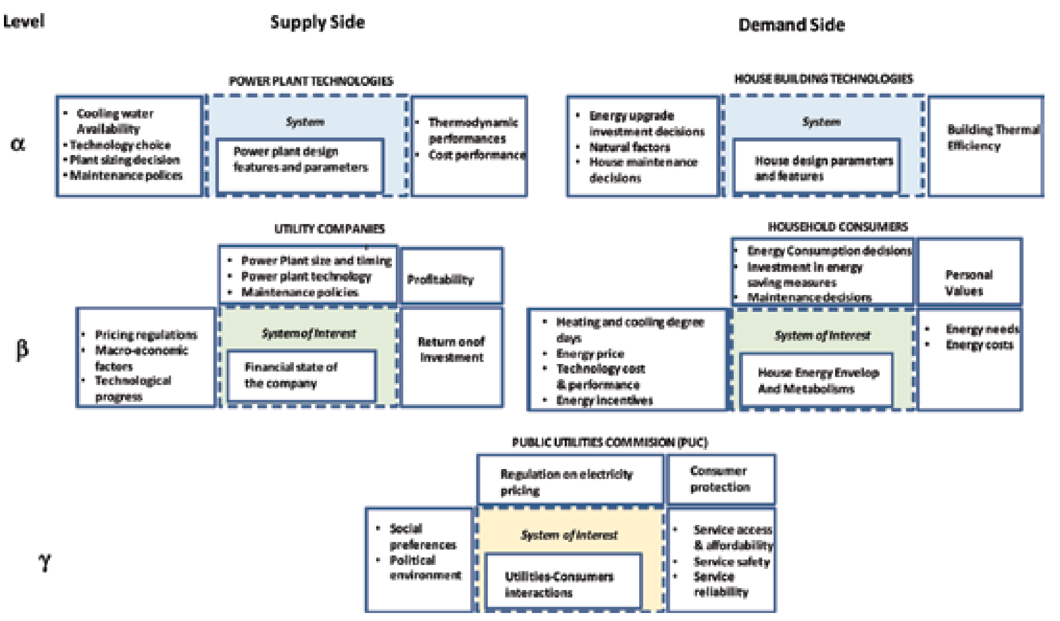

Figure 6. SoS model for electricity power plant investment.

Some of the main elements of system-of-systems model are described as follows:

- Policies (P): At the beta level, policy variables for utility companies involved: the size of the plant, the timing of plant construction, and maintenance policies. These are the actions that would become external forces to the power plant technologies at the alpha level. For the household consumers, their decisions are mainly associated with energy consumption and investments in energy saving measures, which in turn affect house building technologies (at alpha level).
- External forces (X): At the beta level, the utility companies would be concerned and uncertain factors such as electricity pricing regulations, macroeconomic variables, and technological options. The household consumers would be uncertain about natural gas price, electricity demand, and electricity price. At the gamma level, the public utilities seemingly would face uncertainties about political climate and dynamics in societal values.
- Endogenous factors I: For utility companies, they are the variables that determine the cash flow of the investment: (1) installed and used capacity, (2) costs: construction (sunk cost), fixed and variable operations costs, and fuel, and (3) revenues.
- Outcome of interest (O): Profitability is one key outcome for utility companies, which will be measured in net present value (NPV). For public utilities commissions, one outcome they want to monitor is the level of service reliability and affordability.
- The relationships (R): For utility companies, the relationships involved include: (1) revenue functions, (2) cost functions, and (3) functions that translate the costs, revenues, and discount factors (i.e., interest rate) into NPV.
- The value system of the decision makers (W): Utility companies are driven to maximize profitability. In contrast, the utilities commissions are mandated to promote and protect public interests.

4.2. Computational model of electricity power plant investment

Based on the abovementioned definition of SoS, a simple computational model of electricity infrastructure investment was developed. In response to these uncertainties, utility companies may choose not to invest in capital intensive, long lead-time generating technologies such as large nuclear- or hydropower plants or in technologies with relatively high pollution such as coal plant. Instead, they may opt for cheaper, smaller, and less polluting plants that have shorter lead times to build [12].

The model compares the performance of two alternative investment decisions. *Investment1* builds a power plant with a production capacity of 563 MW, whereas *Investment2* constructs a smaller plant of 264 MW. Both power plants use natural gas fueled combined cycle plant technology. The complete model is described in [6].

The uncertainty space for the investment decisions spans a period of 20 years and is discretized into an interval of 10 years. Major uncertainties of future conditions over the time span include several factors. First is electricity demand of which an annual growth rate range between −5 and 5% was taken. Second is the change in electricity price that was assumed to grow between −20 and 20% per 10 year. Lastly, the volatility of natural gas price is modeled using a binomial method [13]. The gas price change follows a 'random walk' pattern with specific upward (up) and downward (down) movement factor.

To assess the success of investment decisions, three decision criteria are used: net present value (NPV), regret, and robustness criterion. A regret value represents the difference between the NPV of a decision compared to the NPV of the *best alternative* in a particular scenario. Based on the NPV and regret criteria, an investment is considered to be successful if it has a positive NPV and has 'no' (NPV difference: 0—$0.09 million) or 'mild' (0.1—$14.9 million) regret. On the other hand, an investment is considered to fail, if it has 'a lot' (15—$99.9 million) and 'overwhelming' (greater than $100 million) regret even though the NPV is positive. Failure also includes all regret outcomes with negative NPV.

A robustness score represents the ratio of the number of successful scenarios with the total number of scenarios. Four categories of robustness can be specified. The robustness falls into Category I if the score is between 1 and 0.75 and Category II for the score between 0.5 and 0.74. A decision is considered robust if it has Category I and II score. Decision makers should then compare the robustness of decision alternatives and choose a decision with maximum robustness.

4.3. Results and analysis

Computational experiments were performed across the uncertainty space. The resulting regret category and robustness score of *Investment1* and *Investment2* is given and compared in **Figure 7**. For Investment1, a mapping of regret category is illustrated for a scenario at Period1 (i.e., year 1–10), in which electricity demand grows by 5%, the gas price moves upward, and electricity price increases by 20%. Compared to *Investment2*, at the end of Period2 (i.e., year 20), *Investment1* ends up largely successful. This is indicated by 44 scenarios (out of 50) with 'no' and 'mild' regret. This performance is aggregated into a single robustness score of 0.88 (i.e., 44 divided by 50), which falls into robustness Category I. The same calculation is repeated for all other scenarios (a total of 2500).

In a multiple period decision problem, the robustness score can be further aggregated by taking score average. In this way, the path dependency of decision performance can be traced back to the time when the decision is made (i.e., Period0). The nested robustness score for *Investment1* and *Investment2* is 0.16 and 0.42, respectively. Based on these results, *Investment2* should be chosen because it performs better in more scenarios than *Investment1*.

4.4. Seeking failure modes: future conditions that might turn a robust decision into a failure

Decision makers are also interested in knowing other conditions that will make their seemingly promising decision fail. To illustrate sensitivity, analysis was performed on the interest rate, which has been held constant at 5%. **Figure 8** shows that the ranges of interest rate that will make Investment1 fail. For example, when the interest rate reaches 11%, the Investment1 is no longer robust across some of the most favorable conditions in period1 because all the robustness scores fall into Categories III and IV.

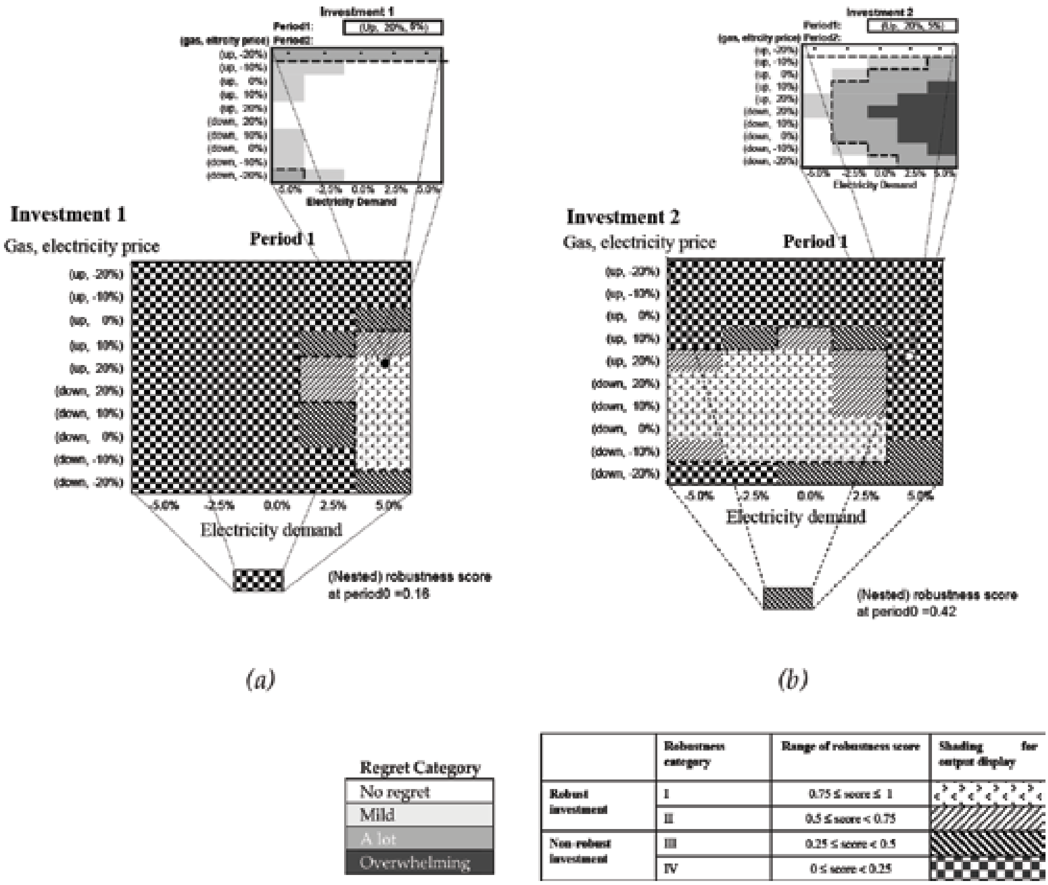

Figure 7. Investment robustness outcomes (a) Investment1 (563 MW) and (b) Investment2 (264 MW).

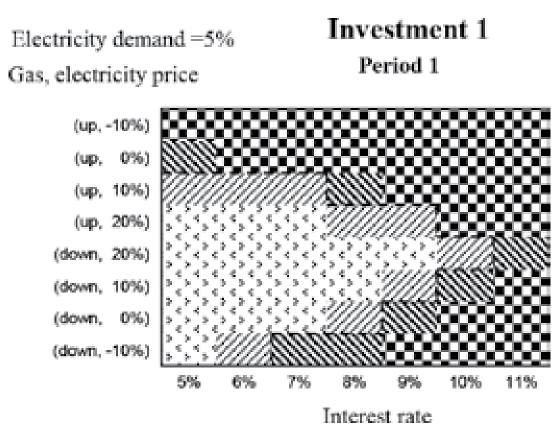

Figure 8. Sensitivity of favorable scenarios to interest rate.

5. Case study 3: informing economic revival initiatives in the northern Illinois region

5.1. Introduction

The economy of the Northern Illinois Region, USA with Rockford as its largest city has suffered since the late 1980s as a result of the decline of manufacturing industry. Currently, a diverse initiative has been launched by various agencies to try to reverse the trend.

The case study presents a development of a decision-support tool to inform policymakers and stakeholders to revive the region's economy. To this end, the proposal will implement a holistic system approach. The approach used will be a combined system dynamics and SOS perspective. The issues that will be addressed include the interactions between the city quality of life factors and investment decisions.

5.2. SoS conceptualization

The combined SOS perspective and system dynamics have a capability to model economic decisions at three different levels such as city, company, and individual. **Figure 9** shows the multi-level decision making occurring within a macroeconomic context.

5.3. System dynamics approach

System dynamics is an approach to understand the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire

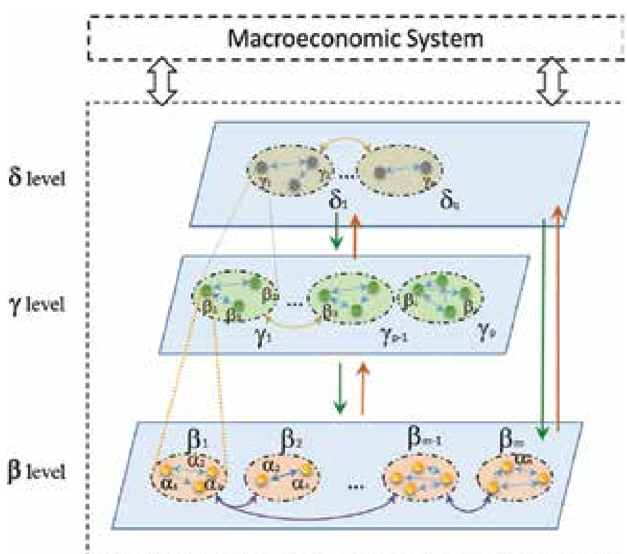

Figure 9. SoS for urban systems.

system. It employs a causal loop and a stock and flow model to represent the change and accumulation of system variables (**Figure 10a**, **b**, respectively).

5.4. Dynamics at macroeconomic level

At the macroeconomic level, the approach captures the relationships between key economic factors of production (labor, land, capital, and technology) and economic output (e.g., production and GDP) (**Figure 11**).

At this level, several causal and feedback loops can be identified. We can identify, for example, two loops associated with migration. An increase in net migration will add to work force, and availability of work force will in turn reduce the rate of net migration (Loop 1). In the same way, an increase in migration will increase the competition for housing (reduced house availability) and availability of housing will make the city more attractive (increased net migration) (Loop 2).

5.5. Dynamics at city level

For the greater Rockford area, for instance, much efforts have been put in to increase the attractiveness for companies to invest (Source). The efforts focus on industrial infrastructure but also on factors contributing to the quality of life (school quality, housing, safety, health care, recreation facilities and parks) (**Figure 12**). They clearly want exploit the positive feedback in which companies expect quality workers, who in turn is attracted by improved quality of life.

5.6. Dynamics at company level

At company level, an issue of interest is how investment decisions affect the production capacity and company's hiring (**Figure 13**).

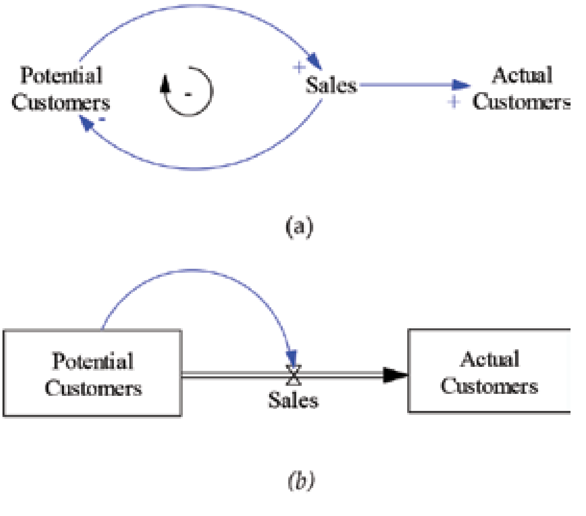

Figure 10. System dynamics main building blocks (a) causal loop and feedback diagram. (b) Stock and flow diagram.

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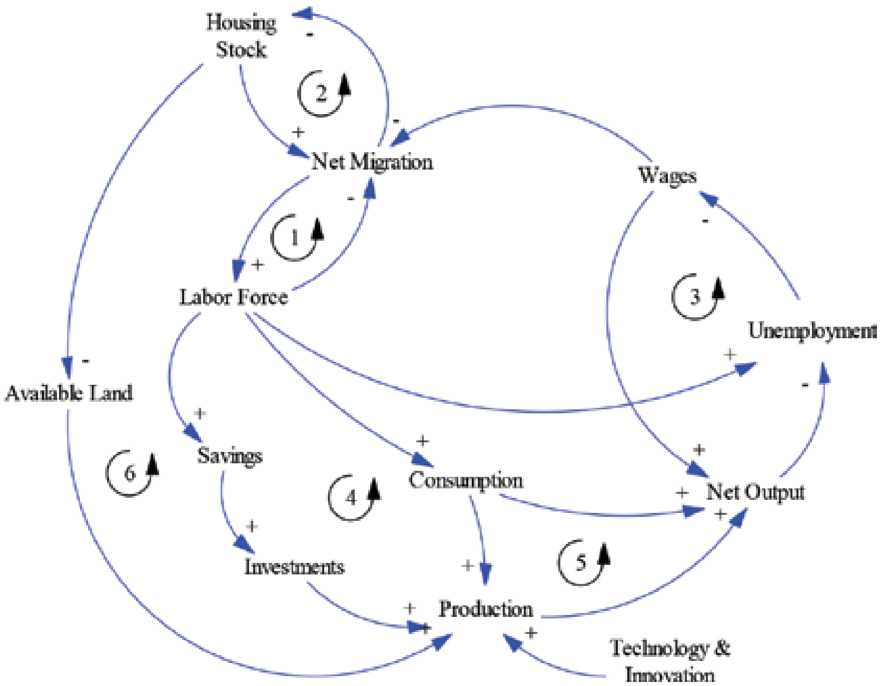

Figure 11. A macroeconomic view of urban system interdependencies.

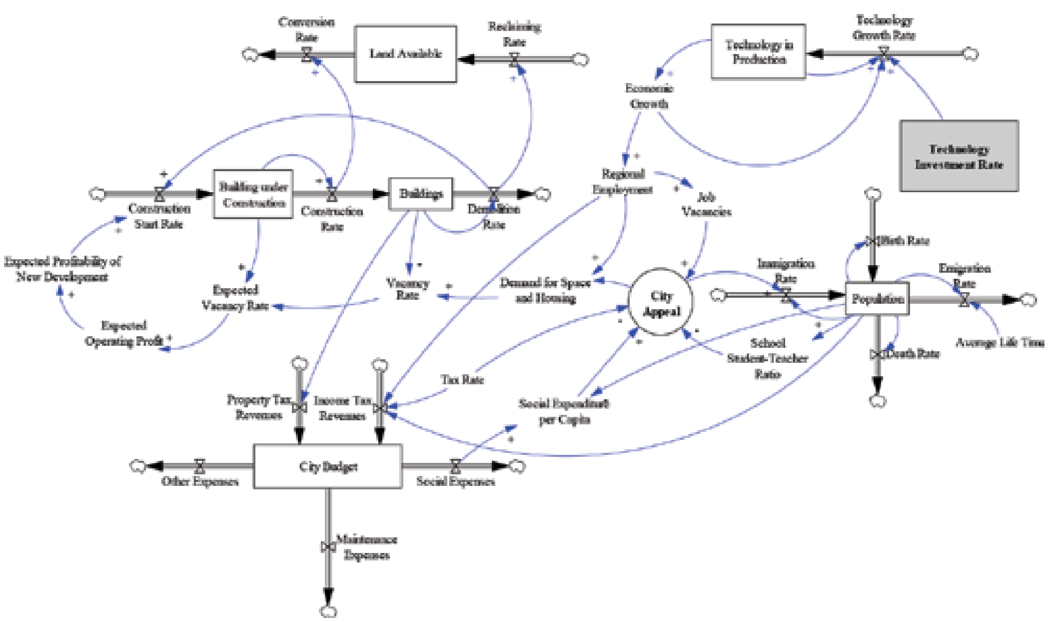

Figure 12. Interrelationships between investment decisions and city attractiveness.

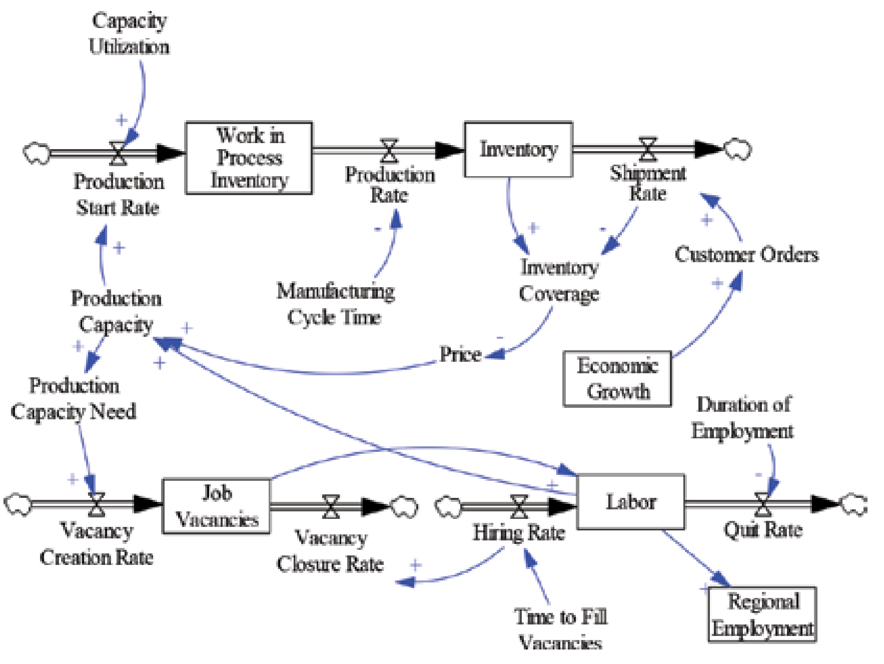

Figure 13. Company's hiring mechanism as a response to customer orders.

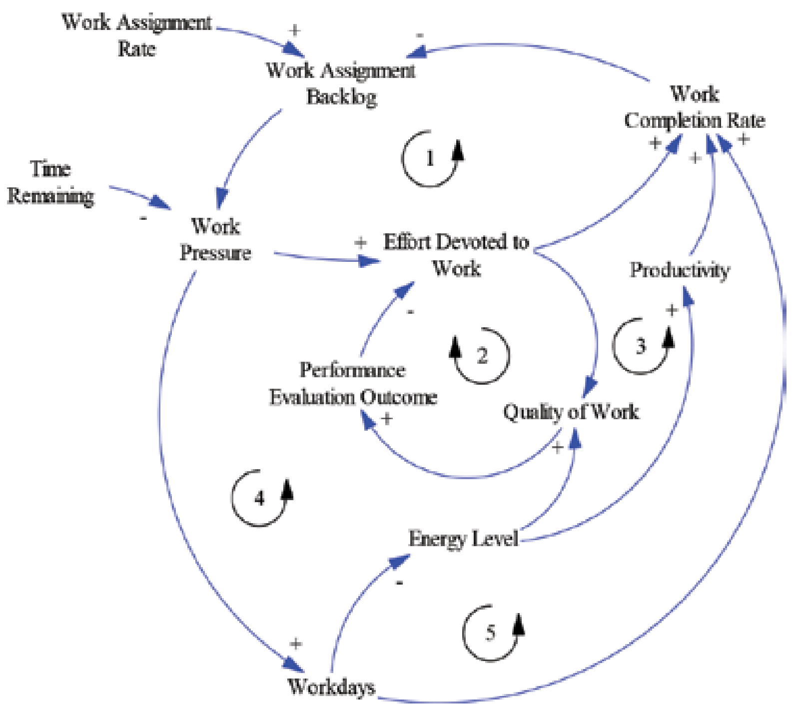

Figure 14. Worker's motivation and work accomplishment dynamics.

The level of regional employment (at macroeconomic level) depends on the number of job vacancies at companies. The demand for workers will be driven by the need to fill production capacity, which in turn depends on customers' orders as they are influenced by how well the economy is doing (i.e., economic growth at macroeconomic level).

5.7. Dynamics at individual level

At individual motivational level, research has suggested psychological behavior that can be best captured using system dynamics [14]. **Figure 14** illustrates factors that are affecting workers' motivation at work and their accomplishments. For instance, quality of work will depend on the effort devoted, which in turn depends on work pressure.

6. Concluding remarks

Urban systems are facing pressures from population growth, urbanization, and climate change. Keeping the status quo could lead to failures in the systems. Given these challenges, better understanding of various elements of urban systems and their interdependencies is needed to inform decisions to improve the systems.

The chapter presents a system-of-systems (SoS) framework to structure complexity of urban systems. A way to deal with future uncertainties within urban system SoS is described. As a whole, SoS forms a network of decision makers and engineered systems at various levels. Over time, the elements of SoS and their relationships will evolve. Their uncertainties can be handled using a computational approach called exploratory modeling and analysis (EMA).

The framework described in the chapter is applied to three case studies. Each case study highlights a unique aspect of urban systems. Different tools were employed to generate insights relevant for decision-making. The first case study looked at the vulnerabilities of urban system under perturbations and disruptions. It uses data related to urban infrastructure in Florida, USA that was devastated by hurricane. Network theory was applied to identify nodes of infrastructure that are influential in causing system failures and are critical for recovery.

The second case study assesses the performance of alternative investment decisions on electricity power plant. EMA is applied to define and explore uncertainty space in terms of measures of regret and robustness of each investment alternative. Once a preliminary robust decision has been identified, EMA can reveal a set of circumstances that may cause the decision to fail. The last case study conceptualizes the dynamics of urban economic revival within a larger macroeconomic environment. A system dynamics tool was employed to represent the context of an economic region in Midwest, USA. Detailed causal loop and stock-and-flow models were developed to specify factors and their relationships across individual, company, and city level.

Author details

Datu Buyung Agusdinata

Address all correspondence to: bagusdin@asu.edu

School of Sustainability, Arizona State University, Tempe, AZ, USA

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This book provides the application of praxises in the field of engineering safety by learning from previous system failures. And it addresses the most recent developments in the theoretical and practical aspects of these important fields, which, due to their special nature, bring together in a systematic way, many disciplines of engineering, from the traditional to the most technologically advanced. The authors of these chapters are involved in using the system thinking and system engineering approaches at the scale of increased complexity and advanced computational solutions to such systems. The chapters cover the areas such as failure assessment in aeronautical engineering, seismic resistance of offshore pipeline engineering, electrical engineering, critical infrastructure failure, and system of system theory.

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