ÓBUDAI EGYETEM
ÓBUDA UNIVERSITY

DOCTORAL (PhD) THESIS

ANNAMÁRIA KONCZ

Preliminary risk analysis of test laboratories

Supervisors: László Pokorádi, CSc, habil
Zsolt Csaba Johanyák, PhD, habil

DOCTORAL SCHOOL ON SAFETY AND SECURITY SCIENCES

Budapest, 2022

Examination Committee/Szigorlati Bizottság:

Head of Examination Committee/Elnök:

Prof. Dr. Berek Lajos

Participants/Tagok:

Dr. Lázár-Fülep Tímea

Dr. Kavas László

Date of examination/szigorlat időpontja:

24.02.2022

Defense Committee Members/Védési bizottság:

Head of Public Defence Committee/Elnök:

Prof. Dr. Berek Lajos

Secretary /Titkár:

Dr. Barányi István

Members / Tagok:

Prof. Dr. Kosztyán Zsolt

Dr. Kiss Imre

Dr. Drégelyi Kiss Ágota

Opponents / Bírálók:

Dr. Lázár-Fülep Tímea

Dr. Líska János

Date of defense/Nyilvános védés időpontja:

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“We can only see a short distance ahead, but we can see plenty there that needs to be done.”

Alan M. Turing

English mathematician, computer scientist [1]

ABSTRACT

In my thesis, a possible preliminary risk analysis process is identified and proposed for lithium-ion battery test laboratories. I have chosen this topic, because as a working professional, I have personal interest in risk and safety analysis of test processes. The suggested model (Hierarchical Overall risk Analysis-HORA) is suited for secondary lithium-ion battery testing laboratories, but it is applicable for other engineering testing facilities as well (with the modification of the defined rating catalogues). The new model completes and merges existing risk analysis method with considering more non-crisp factors. During practical work, a simple explosion and fire safety focused approach does not consider all of those aspects, that influence the possible test outcomes, and the traditional Failure Mode and Effect (FMEA) method is only applicable with shortcomings. Applied analyses in everyday work should cover the features of test samples and test processes, tolerable risk levels and cost considerations as well. The proposed model is based on a hierarchical fuzzy inference system that considers three main aspect groups. These influence the consequences of testing procedures: the risks of the product itself (represented by *Controllability* and *Occurrence* factors), the risks of the abuse testing process itself (represented by *Protection* and *Effectiveness* factors), and system-related risks (represented by the combined *System*/*Cost* factor).

INTRODUCTION

My motivation was combined whilst preparing this thesis. **Personal motivation and interest** came from my professional background: currently I am leading a lithium-ion battery-testing laboratory. In my own experience, safety comes first and careful planning saves excessive amount of time. The fundamental of a well-run test laboratory is a carefully prepared safety concept. At first, my aim was to create a concept that is complex, but easy to handle by the experts. Secondly, I intended to develop a method that is easy to adapt for the purposes of test laboratories under changing conditions. **Scientific motivation** came from the fact that previously I have moderated and taken part of Failure Mode and Effect Analysis (FMEA) meetings in the automotive industry. During this part of my professional career, I have experienced both the advantages and disadvantages of FMEA. According to my understanding, the main issues are the not definite logical connections, the lack of adaptability to the analysis of complex systems, the slight number of risk analysis factors. My goal was to create a new method, that solves the before mentioned vulnerabilities of traditional FMEA. (Although, the widely used conventional risk analysis concept of FMEA is useful for the purposes of manufacturing and product planning.)

Actuality of the topic

Since the 1980s the development of lithium-ion batteries is ongoing, with the improvements of researchers like Stanley Whittingham, John Goodenough and Josino Akira, who were awarded with the Nobel Prize in Chemistry in 2019 [2]. Their inventions revolutionized the market of portable energy source devices. Nowadays, lithium-ion batteries are inevitable parts of our lives: laptops, handheld tools, electrical devices, and even e-mobility devices: like e-bikes, e-scooters, hybrid and electric cars are equipped with them. The number of applied cells can be at least one in case of handheld tools, and it can reach even thousands in case of electric cars. Besides the excessive number of cells used for e-mobility purposes, the weight of the applications is significant as well. In Fig. 1 [3], a visual representation of Tesla model S lithium-ion battery weigh distribution can be seen. In comparison, the total weight of a Tesla model S is 2162 kg, and the battery itself weighs 480 kg. (Although it has to be stated, that the car itself contains not only one battery, in this case I am referring to the traction battery.)

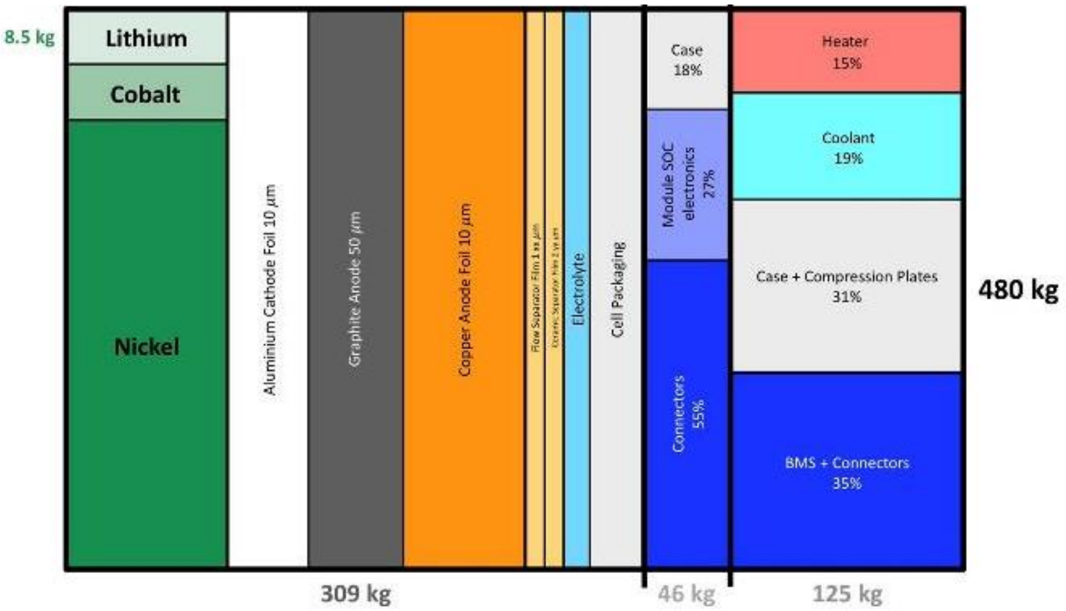


Fig. 1 The weight distribution of Tesla battery packs [3]

In Fig. 2 a Tesla model S standard 100 kWh battery can be seen. The battery itself is located in the floor of the car, although it is not part of the chassis.

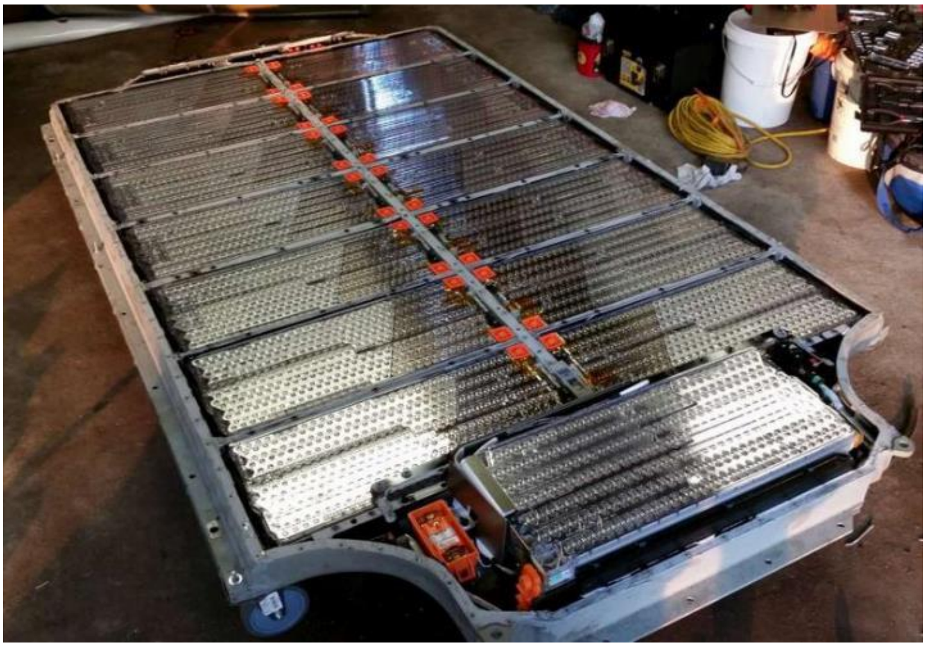


Fig. 2 Tesla Model S standard 100 kWh battery pack [4]

The demand for lithium-ion batteries is high as their application is widespread in the manufacturing sector. During the COVID 19 pandemic, the need for lithium-ion batteries increased as the shift to home office triggered household handicraft works, and the demand for portable electric devices, such as laptops, etc. In the following years, a shortage of lithium-ion battery supply is forecasted, due to material shortage (due to the excessive time of mining, and exploitation) [5].

The aforementioned technological and market aspects have a significant impact on battery testing facilities, as the demand for their services is not balanced; there are expansive peaks in workload. This accelerates the battery testing projects that leads to the decrease of preparation times. This way, the test intervals are approaching the technological time needs. Under these given circumstances, testing safety gains more and more importance, as lithium-ion battery tests are potentially hazardous and safety critical.

Formulation of the scientific problem

During my professional career, I have recognized the importance of risk analysis in the industry and in the service sector as well. FMEA, despite its shortcomings is an applicable method for risk assessment, but I have noted that with the development of traditional risk analysis methods new flexible ways of risk assessment can be created. I find this idea significantly important, because the current technological developments demand flexible and adaptable solutions. For the operation of lithium-ion testing facilities mandatory fire and explosion safety analysis are needed, but these does not cover the complexity of operational safety. Traditional FMEA uses only three factors (*Severity, Occurrence, and Detection*) which do not cover the influencing conditions. In other aspects, the specialty of this field is derived from the fact that a Process-FMEA itself is not enough to cover the risks, as the examined processes are abuse tests. There is high impact of uncertainty in accordance with Design FMEAs, as they are often missing from the manufacturer side. (Because in case of non-automotive batteries FMEA is not mandatory.) During the establishment of test facilities, the highest level of safety is a preliminary condition, but there are circumstances (lack of time or expertise) in which fast decisions are needed. The aim of my work is to establish a new method, which fits the purposes of practical work. With the usage of fuzzy logic, I have created a preliminary risk analysis approach that solves the aforementioned barriers of risk analysis methods.

Objectives of research

- Definition of input factors,
- Definition of rating catalogues,

- Definition of fuzzy systems/subsystems,
- Definition of system output,
- Validation of results.

Hypotheses of the research

- **Hypothesis 1 (H1)**: I assumed that a preliminary risk assessment would be required for standardized laboratory testing of lithium-ion batteries.

- **Hypothesis 2 (H2)**: I supposed that conventional FMEA-based analyses are not sufficient for a preliminary risk assessment of a lithium-ion battery-testing laboratory.

- **Hypothesis 3 (H3):** I assumed that by combining and developing existing risk assessment methods and developing appropriate assessment catalogues, a new method could be successfully developed for the preliminary risk assessment of lithium-ion batteries.

Research methods

During the preparation of my thesis, I have divided my research in three parts. In the first part, I have presented the basic structures and features of lithium-on batteries, the possible risks of lithium-ion batteries and the standardized lithium-ion battery tests. In the second part, I have examined specialized literature in terms of risk analysis methods, conventional FMEA and non-conventional FMEA methods. In the third part, I present the Hierarchical Overall Risk Analysis (HORA) method, which I have developed. The complex fuzzy logic based method was modelled with Matlab, and Taguchi's L_{75} 5^8 15^1 experimental design was used for the design of validation experiments.

Research limitations

In my thesis, I have taken into consideration the UN 38.3 [6] transport safety tests as a basis (on battery level). In my work, I did not analyze cell level tests and other standardized or customized tests. In the thesis I did not analyze the electrochemical risks, I have only represented a generalized level of risks. My thesis does not cover the aspects of automotive battery risk analysis. The suggested model is not for system optimization, but for preliminary risk analysis.

Structure of the dissertation

The thesis contains **six chapters**, as follows:

In **Chapter 1**, lithium-ion cells and batteries, and their standardized test methods are represented with outlining the potential hazards of lithium-ion battery abuse tests.

In **Chapter 2**, risk assessment methods according to IEC 31010:2019 [7], the traditional FMEA method, FMEA shortcomings and non-conventional FMEA methods are represented.

In **Chapter 3**, I present the suggested Hierarchical Overall Risk Analysis (HORA) model for the preliminary risk analysis of lithium-ion test laboratories.

In **Chapter 4**, I present the related approaches from specialized literature to HORA,

In **Chapter 5**, I summarize my findings.

In **Chapter 6**, I list the used references.

1 LITHIUM-ION BATTERIES AND THEIR STANDARDISED TEST METHODS

Lithium-ion batteries are part of our lives, and we all use their benefits. We cannot avoid them: they are built in our cell phones, laptops, handheld tools and even in our cars. To ensure the safety of these devices different types of tests are necessary (endurance tests, performance tests and transport safety tests). In this chapter, I give an outline of the standardized test methods of lithium-ion batteries and their possible risks. Lithium-ion battery tests simulate the non-intended use of batteries, and they might end up in hazardous technical events (e.g. electrochemical reactions such as thermal runaway).

1.1 Introduction to lithium-ion cells and batteries

Nowadays the usage of lithium-ion batteries as energy storage devices is unavoidable. Mobile phones, laptops, handheld tools and electric cars are equipped with them. Similar to their wide range of usage, even lithium battery cells and batteries have several types, depending on their material (different anode, cathode, separator, and electrolyte materials), their structure (pouch, cylindrical, prismatic, etc.) and their built-in safety options.

In the following, I provide an outline of their similarities and differences.

1.1.1 Different cell constructions

Lithium-ion batteries consist of lithium-ion cells. In the following section, I introduce the basic construction of lithium-ion cells, as they are the basis of the technology.

In Fig. 3 the typical consumer electronics cell designs can be seen (prismatic, pouch and cylindrical cells).

Lithium-ion batteries consist of the following parts:

- negative electrode (anode),
- positive electrode (cathode),
- electrolyte,
- separator,
- current collectors,
- and cell enclosures (cases and pouches).

Fig. 3 Typical consumer electronics lithium-ion cells [8]

Anodes are composed of a lithium intercalation compound that is coated with a metal current collector. The most common anode material is graphite, although there are different anode materials such as silicon, germanium and titanate.

Cathodes are mostly built of the following materials: lithium cobalt dioxide, lithium iron phosphate, lithium manganese oxide, mixed metals (containing cobalt, nickel, and aluminium), manganese oxides, nickel cobalt aluminate and nickel manganese cobaltite.

Electrolyte materials are commonly organic solvents (ethylene carbonate or diethyl carbonate).

Cell manufacturers apply a small number of additives to improve the performance characteristics of cells (cell stability, calendar life, cycle life and overcharge resistance, etc.). Separators are built from polypropylene, porous polyethylene, composite polyethylene or polypropylene films. Current collectors are commonly thin foils of copper and aluminium.

Cell enclosures are presented in Fig. 23 [1]: cylindrical, pouch and prismatic cells. The most common cell types are cylindrical cells (they are even parts of laptop and electric car batteries). (The identification of cell batteries is based on their size: e.g. type 18650, which refers to 18 mm diameter and 65.0 mm length [8].)

Lithium-ion batteries consists of lithium-ion cells, the most common consumer electronics batteries can be seen in Fig. 4 [8].

Fig. 4 Typical consumer electronics lithium-ion battery packs [8]

1.1.2 Common Li-ion cell and battery chemistries and their features

Lithium-ion batteries can be grouped based on their differing chemistry as well. The different materials and constructions result in different features, as it can be seen in Fig. 5 [9]. In the example Radar chart six different lithium ion battery chemistries are compered: $LiCoO_2$, LMO, LFP, NMC, NCA and NTA.

The six different features, which were taken into consideration, were the following:

- specific energy (capacity),
- cost,
- specific power,
- safety,
- performance,
- and life span [9].

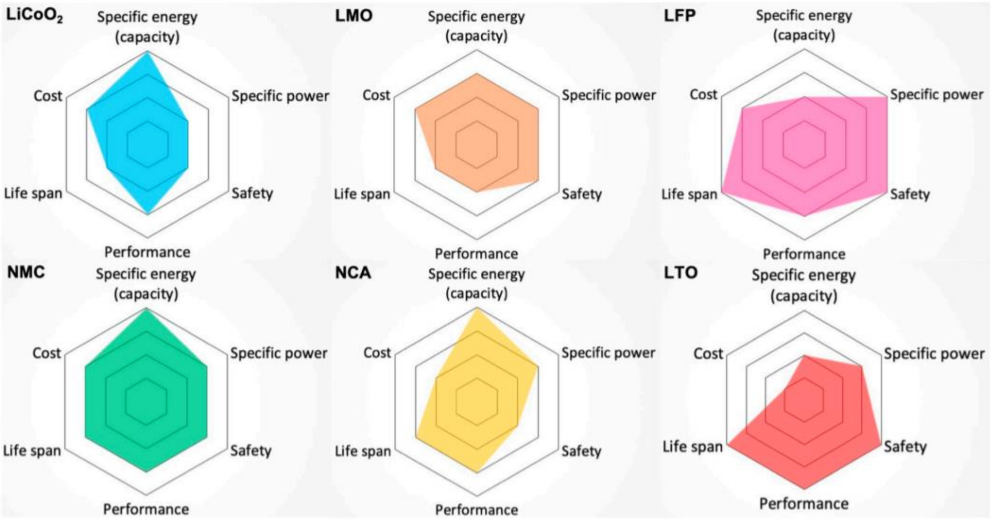


Fig. 5 Comparison of different types of Li-ion batteries used [9]

$LiCoO_2$ batteries were developed by Sony in 1991. Their advantages are high energy density, long lifecycle and the ease of manufacturing. In this case the positive electrodes are intercalation compounds from Li^+. They were used in personal electronics, such as laptops, tablets and cameras, etc. [9].

LMO (Lithium Manganese Oxide) batteries were the first lithium ion batteries. They were invented in the 1980's and after 15 years of development, they became available for commercial purposes. LMO batteries come with average specific energy levels (capacity), specific power and safety level. These batteries were the first to start the revolution of lithium ion based energy storage devices. (They are in the group of positive electrode batteries.) They are used in the automotive sectors as well, they are built-into cars such as Nissan Leaf, Chevy volt and BMWs [9].

LFP (Lithium Iron Phosphate) batteries were developed by the researchers of University of Texas in 1996. One advantage of this technology is that phosphate helps to prevent overcharging and provides higher tolerance to heat. LFP battery's positive features are high life span, safety and specific power levels. LFP batteries are in the positive electrode batteries as well. They are used by German automotive manufacturer companies [9].

NMC (Lithium Nickel Manganese Cobalt Oxide) batteries are in the group of positive electrode batteries. They possess high specific energy, which is a result of combining nickel and manganese. Their disadvantage comes with low stability. NMC batteries are mostly used for powertrains [9].

NCA (Lithium Nickel Cobalt Aluminium Oxide) batteries have been present since 1999. Their characteristics are high specific energy and power and long life span. Nowadays, Tesla is the only automotive manufacturers that uses them [9].

LTO ($Li_4Ti_5O_{12}$) batteries have negative electrodes with lithium-titanate. They were developed in the 1980s. They were commonly used in Mitsubishi and Honda electric vehicles. These batteries have positive features such as long life span, high safety and performance [9].

1.1.3 Safety options of lithium-ion batteries

In previous subsection, I have presented the different constructions of lithium-ion batteries, based on their construction and chemistry. In this subsection, I introduce the existing safety options of lithium ion batteries. These are important features of these devices, as they are potentially hazardous in the event of failure conditions.

Safety options can be the following:

- improved cathode materials,
- improved anode materials,
- thermally protective separators,
- flame retardants additives,
- safety fuses,
- safety vents,
- positive temperature coefficients,
- current interrupting devices,
- battery management systems (BMSs),
- battery thermal managements systems (BTMSs) [10].

The most common problem with lithium batteries is the phenomenon of thermal runaway. Thermal runaway is a sudden and unforeseeable process that results in the burning and explosion of batteries. Abuse conditions trigger the process. The aforementioned options are designed to prevent thermal runaway, the most hazardous thermal chain reaction. In the following section, I introduce the two most advanced safety solution for lithium ion batteries: BMS and BTMS.

Battery Management Systems (BMS) are system-aided solutions, which might improve the safety levels of batteries.

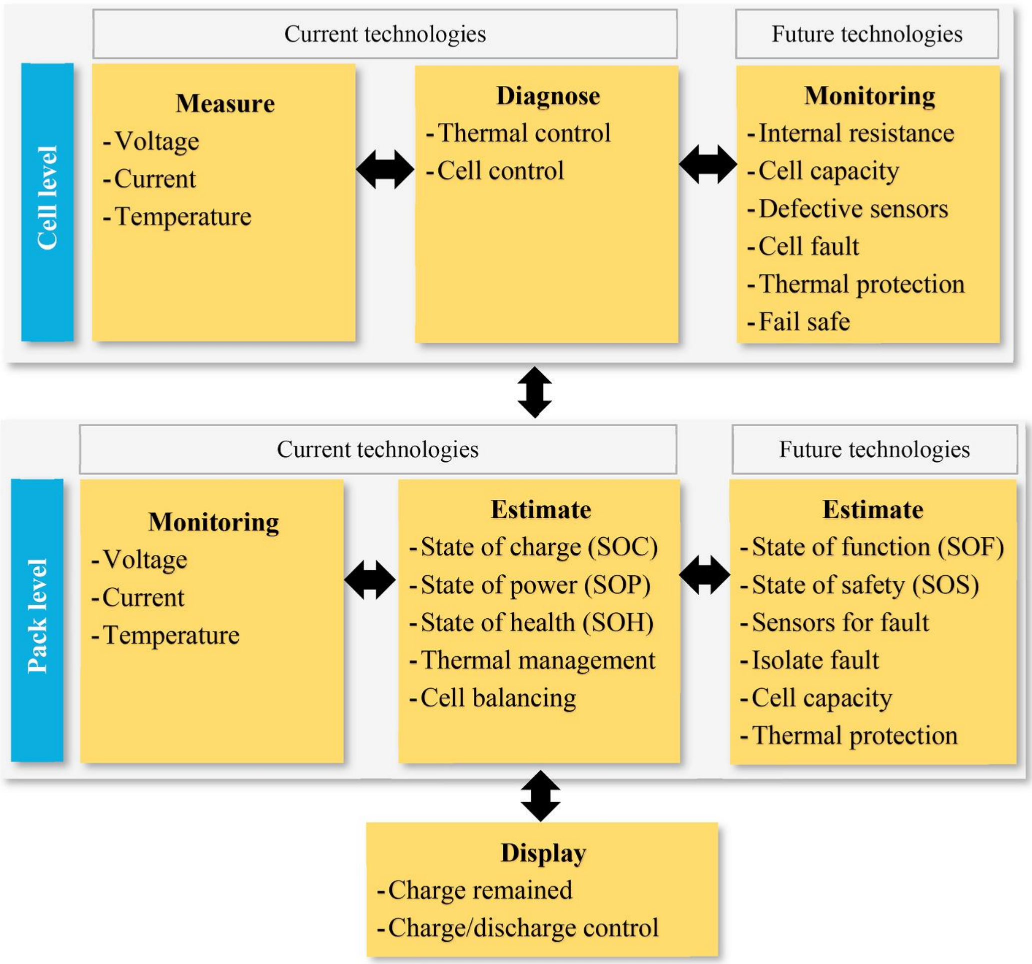


Fig. 6 Functions of the BMS in cell and pack level for the current and future technologies [10]

Battery Management Systems work both on the cell and battery level. Their task is to prevent battery overcharging and over-discharging. (These two processes might result in thermal runaway.) BMSs are designed as well to monitor SOC (State of Charge), state of safety, state of charge, state of health defective insulation, loose connection, short circuit and other battery faults. In Fig. 6, the different functions of BMS can be seen. The current BMS solutions on cell level work on the principle of voltage, current and temperature measurement (with the diagnosis of thermal control and cell control) and future solutions might work on the monitoring of internal resistance, cell capacity, defective sensors, cell fault, thermal protection and fail safe. On battery level the following solutions are present: monitoring of voltage, current and temperature, estimation of State of charge (SOC), State of power (SOP), State of health (SOH), Thermal management and cell balancing and the display of remained charge and charge/discharge control. Future solution might consist of State of function (SOF), State of safety (SOS), sensors for fault, fault isolation, cell capacity and thermal protection devices.

Another option to improve lithium-ion battery safety is the introduction of specific BTMS (Battery Thermal Management Systems). The function of BTMS is regulation of temperature within the battery packs, the establishment of temperature homogeneity and the keeping optimum operating temperature. There are different types of BTMSs, the most common types are shown in Fig. 7 [10].

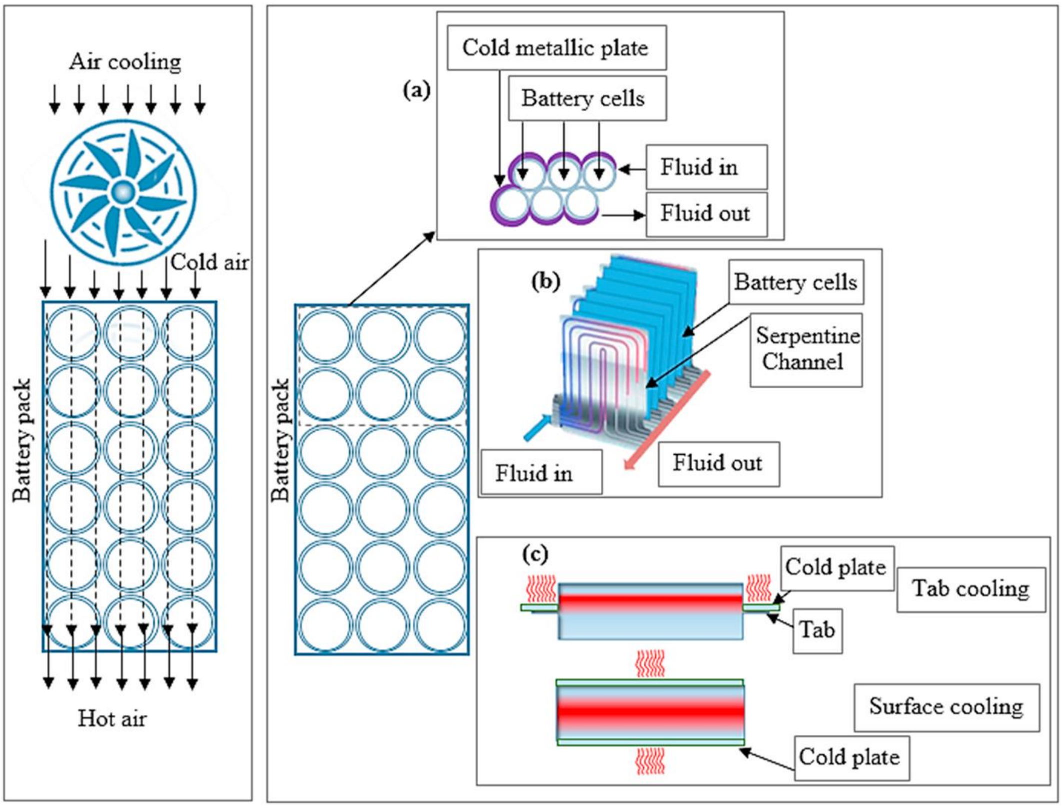


Fig. 7 Air and thermal management systems [10]

The conventional BTMs operate with air-cooling, but there are liquid cooling options available as well. In the automotive sector, the following models use air-cooling: Nissan LEAF (pouch cells), Toyota Prius (prismatic cells) and Volkswagen ID.3 (pouch cells). Indirect liquid cooling are used at these models: Tesla Model S (cylindrical cells), Porsche (pouch cells), Chevrolet Volt (pouch cells), Fiat 500e (Prismatic cells), BMW i3 (prismatic cells and Audi A3 e-tron (prismatic cells) [10].

1.2 Test methods of lithium-ion batteries and their possible risks

Due to their hazardous nature, lithium-ion batteries need to be tested under failure conditions before their transport (in general). In the past, there were serious accidents during the transportation and application of lithium ion batteries. In Table 1 [11], I present a selection of lithium-ion battery related accidents that prove the inevitable necessity of battery tests.

Table 1 Lithium-ion battery failure related accidents in the recent years [11]

Classification	Date	Location	Accident
Mobile telephone	09.01.2018	Switzerland	An iPhone exploded when replacing the battery, which caused an injury and seven poisonings
Mobile telephone	10.01.2018	Spain	An iPhone exploded which caused thick smoke inside the store
Mobile telephone	30.12.2018	America	An iPhone XS Max self-ignited and burned the user
EV	01.05.2017	China	An EV bus self-ignited during charging
EV	24.03.2018	America	A Tesla Model S caught fire whilst stationary
EV	21.05.2018	China	An EV bus self-ignited during driving
Airplane	03.09.2010	The United Arab Emirates	A Boeing 787 crashed due to the battery catching fire, which caused two deaths
Airplane	07.01.2013	America	The battery pack caught fire and filled the cabin of a Boeing 787 with smoke
Airplane	16.01.2013	Japan	The battery pack caught fire during a Boeing 787 flight from Yamaguchi-Ube to Tokyo
Airplane	04.2014	Australia	A Boeing 737 caught fire due to the short-circuit of the battery inside a trunk

1.2.1 Standardized tests of lithium-ion batteries

Nowadays, there are many standards released in connection with lithium-ion batteries, thereby pointing out their hazardous nature as well.

Table 2 Examples of lithium-ion battery standards [12]

EN standards		IEC standards		UL standards	
Identification	**Description**	**Identification**	**Description**	**Identification**	**Description**
EN 60086-4	Safety of lithium batteries	**IEC 66281**	Safety of primary and secondary lithium cells and batteries during transport	**UL 1642**	Safety of Lithium-Ion Batteries - Testing
EN 62133	Safety requirements for portable sealed secondary cells	**IEC 61960**	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for portable applications - Part 3: Prismatic and cylindrical lithium secondary cells and batteries made from them	**UL 2054**	Household and Commercial Batteries
EN 61960	Specifies performance tests, designations, markings, dimensions and other requirements for lithium battery products	**IEC 62133**	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems	**UL 9540**	ANSI/CAN/UL Standard for Energy Storage Systems and Equipment
		IEC 61959	Secondary cells and batteries containing alkaline or other non-acid electrolytes - Mechanical tests for sealed portable secondary cells and batteries	**UL 9540A**	ANSI/CAN/UL Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems
				UL 1973	ANSI/CAN/UL Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications
				UL 1974	ANSI/CAN/UL Standard for Evaluation for Repurposing Batteries

These standards can be grouped based on either their purpose (endurance, performance and transport safety standards) or the releasing authority/commission (e.g. European

Union, United Nations (UN), International Electrotechnical Commission (IEC), European Committee for Standardization (CEN), Underwriters Laboratories (UL), Japanese Standards Association (JSA)) [13]. In Table 2, I present examples of relevant lithium-ion battery standards published by CEN, IEC and UL, to represent the variety of this field.

In addition to Table 2, the test criteria according to UN 38.3 (transport safety of lithium-ion batteries need to be mentioned, as they are a mandatory requirement for all lithium-ion battery products. The tests according to UN 38.3 simulate the upcoming conditions during the transport of batteries. These tests are so-called abuse tests, and their aim is to ensure that the batteries are not hazardous due to abuse conditions. The test procedure differs in case of cells, small batteries, large batteries and one-cell batteries.

The sequence of tests is described in the Manual and Test Criteria, provided by the United Nations Publication (according to the "United Nations Recommendations on the Transport of Dangerous Goods, Model Regulations"). The test list consists of electrical, mechanical and climate tests (Table 15) [6].

Transport safety testing according to UN 38.3 is the minimum criterion for portable lithium ion batteries; (there are different criteria for primary (non-rechargeable) and secondary (rechargeable) batteries in the regulation. In Table 3, the requirements for secondary battery tests are presented.

The UN 38.3 test differentiate between the batteries with the usage of the following categories (Table 15):

- cells not transported separately from a battery,
- cells,
- single cell batteries,
- small batteries,
- large batteries,
- batteries assembled with tested batteries ≤6 200 Wh or ≤500 g Li,
- batteries assembled with tested batteries >6 200 Wh or >500 g Li.

The test criteria of IEC 62281:2019 [14] are generally the same in case of batteries (Table 4), the differences are mainly related to test temperatures.

Table 3 UN 38.3 test sequence [6]

<table>
<tr><th colspan="11">Rechargeable cells and batteries</th></tr>
<tr><th colspan="2"></th><th>T.1</th><th>T.2</th><th>T.3</th><th>T.4</th><th>T.5</th><th>T.6</th><th>T.7[a]</th><th>T.8</th><th>Sum[d]</th></tr>
<tr><td rowspan="4">Cells not transported separately from a battery</td><td>first cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td><td rowspan="4">30</td></tr>
<tr><td>25th cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>first cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td>25th cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td rowspan="6">Cells</td><td>first cycle, fully charged state</td><td colspan="5">5</td><td></td><td></td><td></td><td rowspan="6">40</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">5</td><td></td><td></td><td></td></tr>
<tr><td>first cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>25th cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>first cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td>25th cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td rowspan="7">Single cell batteries[b]</td><td>first cycle, fully charged state</td><td colspan="5">5</td><td></td><td>4</td><td></td><td rowspan="7">48</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">5</td><td></td><td></td><td></td></tr>
<tr><td>first cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>25th cycle, 50% charged state</td><td></td><td></td><td></td><td></td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>first cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td>4</td><td></td></tr>
<tr><td>25th cycle, fully discharged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td>first cycle, fully charged state</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>10</td></tr>
<tr><td rowspan="2">Small batteries</td><td>first cycle, fully charged state</td><td colspan="5">4</td><td></td><td>4</td><td></td><td rowspan="2">16</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">4</td><td></td><td>4</td><td></td></tr>
<tr><td rowspan="2">Large batteries</td><td>first cycle, fully charged state</td><td colspan="5">2</td><td></td><td>2</td><td></td><td rowspan="2">8</td></tr>
<tr><td>25th cycle, fully charged state</td><td colspan="5">2</td><td></td><td>2</td><td></td></tr>
<tr><td>batteries assembled with tested batteries ≤6 200 Wh or ≤500 g Li</td><td>fully charged state</td><td></td><td></td><td colspan="3">1</td><td></td><td>1</td><td></td><td>2</td></tr>
<tr><td>batteries assembled with tested batteries >6 200 Wh or >500 g Li[c]</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>0</td></tr>
<tr><td colspan="11">[a] Batteries or single cell batteries not equipped with battery overcharge protection that are designed for use only as a component in another battery or in equipment, which affords such protection, are not subjected to the requirements of this test;
[b] Except for the T.7 Overcharge test, a single cell battery containing one tested cell does not require testing unless a change in cell design could result in the failure of any test;
[c] If the tested assembled battery is of a type that has been verified as preventing:
(i) Overcharge;
(ii) Short circuits; and
(iii) Over discharge between the batteries.
The sum represents the number of tests required, not the number of cells or batteries tested.</td></tr>
</table>

In addition to the aforementioned two requirements (UN 38.3 – transport safety, IEC 62281 –safety standard) IEC 62133-2 must be mentioned to get a wider understanding of lithium-ion safety tests. This standard involves stricter test requirements, since it introduces so-called fail-sample tests for the external short-circuit test steps.

Table 4 IEC 62281:2019 test sequence [14]

Tests	Cycles and discharge state	Cells	Single-cell batteries[a]		Multi-cell batteries	
			Small	Large	Small	Large
Tests T-1 to T-5	At first cycle, fully charged	5	5	5	4	2
	After 25 cycles, fully charged	5	5	5	4	2
Test T-6	At first cycle, at 50 % DOD	5	5	5	5 component cells	5 component cells
	After 25 cycles, at 50 % DOD	5	5	5	5 component cells	5 component cells
Test T-7	At first cycle, fully charged	N/A[b]	4[c]	2[c]	4[c]	2[c]
	After 25 cycles, fully charged	N/A[b]	4[c]	2[c]	4[c]	2[c]
Test T-8	At first cycle, fully discharged	10	10	10	10 component cells[d]	10 component cells[d]
	After 25 cycles, fully discharged	10	10	10	10 component cells[d]	10 component cells[d]
Total for all tests		**40**	**48**	**44**	**16 batteries and 30 component cells**	**8 batteries and 30 component cells**

a Single-cell batteries containing one tested component cell do not require re-testing unless the change could result in a failure of any of the tests, except for test T-7 where only batteries are tested.
b N/A = not applicable.
c See 5.2.
d Multi-cell batteries are considered to be protected against overdischarge of their component cells. Otherwise they would have to be tested as well.

Table 5 IEC 62133-2:2017+Amd. 1 test sequence [15]

Tests	Cell[a,d]	Battery
7.2.1 Continuous charge	5	-
7.2.2 Case stress	-	3
7.3.1 External short-circuit	5 per temperature	-
7.3.2 External short-circuit	-	5
7.3.3 Free fall	3	3
7.3.4 Thermal abuse	5 per temperature	-
7.3.5 Crush	5 per temperature	-
7.3.6 Overcharge	-	5
7.3.7 Forced discharge	5	-
7.3.8 Mechanical – 7.3.8.1 Vibration – 7.3.8.2 Mechanical shock	-	 3 3
7.3.9 Forced internal short[b, c]	5 per temperature	-
D.2 Measurement of the internal AC resistance for coin cells	3	-

[a] Excludes coin cells with an internal resistance greater than 3 Ω.
[b] Country specific test: only required for listed countries.
[c] Not applicable to coin and lithium ion polymer cells.
[d] For tests requiring charge procedure of 7.1.2 (procedure 2): 5 cells per temperature are tested

1.3 Possible risks of lithium ion battery abuse tests

The tests according to UN 38.3 simulate abuse conditions of lithium ion batteries. These abuse conditions are the following:

- electrical abuse (forced overcharge, over discharge, forced discharge, high C-rate),
- thermal abuse (external heating, overheat),
- and mechanical abuse (penetration, crash, drop, shock, vibration, immersion).

In Fig. 8 [10], I present possible negative outcomes of battery abuse conditions (abuse tests).

In case of electrical abuse tests, the possibility of thermal runaway processes is high. Electrical and thermal abuse might cause SEI decomposition, Anode-electrolyte reaction, electrolyte decomposition and generation of flammable gases.

Mechanical abuses might result in pressure built-up inside the battery, separator meltdown or cathode breakdown.

The above-mentioned conditions can start a chain reaction, which has the following stages: gas evolution, cracking of safety vents, fore ignition and explosion.

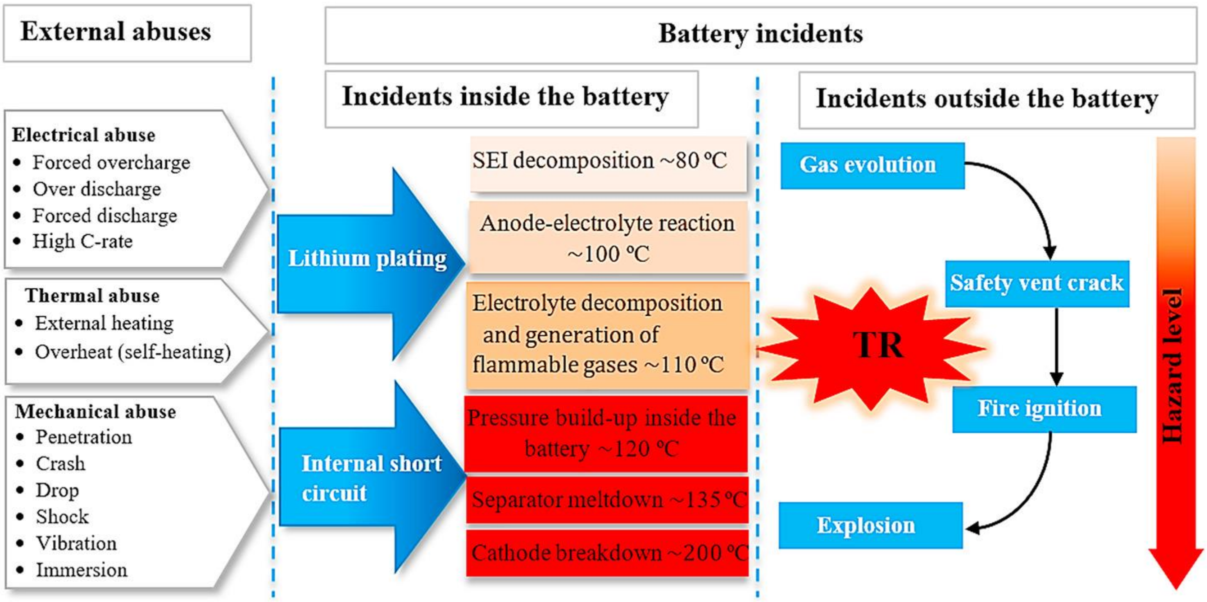


Fig. 8 Chain reactions due to abuse testing of lithium-ion batteries [10]

As the battery tests are done in accredited laboratories, the most important thing is to establish a safe environment. Lithium-ion battery events are potentially hazardous and the safety of laboratory personnel and laboratory set up is necessary.

Mostly lithium-ion battery testing facilities have to carry out explosion safety analyses, which gives the limits for the tests (in general in cell number and test type). These analyses always account for the worst-case scenario. For the laboratory personnel this improves safety as the laboratory equipment is selected based on the technical limits.

For internal use, the laboratory FMEAs (Failure Mode and Effect Analysis) might be a good solution if the test engineers want to decide whether the risks are tolerable in the given situation. The barrier of this solution is that the traditional FMEA only takes into consideration *Occurrence*, *Severity* and *Detection* factors, and it is hard to link the product features (Product FMEA) with the process itself (Process FMEA). (As the Design FMEAs of customers are often not available and are often differing).

According to my practical experience, and the described hazardous nature of lithium-ion batteries I state the necessity of preliminary laboratory risk analysis, because abuse testing aims to cause battery conditions which result in a possible technical event (smoke, fire or even explosion).

1.4 Chapter summary

The test sequence criteria represented in Table 21, 22, 23 outline the diversity of lithium-ion batteries (in construction) and the wide variety of tests. The mentioned test standards are valid and inevitable due to the hazardous nature of lithium-ion batteries (Table 19), preliminary risk analysis is definitely needed for the safety of test personnel and test environment (**H1**). In case of preliminary risk analysis of lithium-ion batteries, all test aspects are needed to be taken into consideration i.e.: numerous test standards and requirements. As there is a wide range of requirements, a not crisp, flexible evaluation is more suitable for the purpose of the preliminary risk analysis of lithium-ion batteries. FMEA is not the most proper solution for lithium-ion battery test processes as it is a too slow solution, and it does not provide a full overview for of the system itself, as often the linkage with the product side is missing (due to a missing Product-FMEA) (**H2**). For these reasons, I suggest the usage of the fuzzy based preliminary risk analysis method (**H3**).

2 RISK ASSESSMENT METHODS

Since Failure Mode and Effect Analysis (FMEA) was invented in the 1940's [16] it has approximately 70 years of history to look back on. The method was developed by the US military (MIL-P-1629 military standard, 1943) [17], and was used and implemented by the NASA as well [18].

Since the second half of the 20th century FMEA gained importance in design and process analysis as well, and nowadays it is an inevitable part of applied quality assurance/quality management systems.

The collection of applied risk analysis methods is summarized and detailed in the standard to IEC 31010:2019 [7]. The most relevant risk analysis methods are important to know, since they give a good overview about nowadays industrial practice.

In this chapter, first, I summarize traditional risk assessment methods; in subchapter 1, I describe the conventional FMEA, its types and barriers. In contrast to this, in the third subchapter I represent the main non-conventional FMEA types: FMEA based on Multi-Criteria Decision Making methods; Mathematical Programming approaches; Artificial Intelligence solutions and integrated approaches. The last subchapter summarizes my findings.

2.1 Risk assessment techniques according to IEC 31010:2019

The IEC 31010:2019 standard [7] covers the main risk assessment techniques, which are nowadays used in academia and in industrial practice. The main concept of the standard is to give a clear catalogue of the current existing methods. In Fig. 9 [7], the general process of risk assessment is defined. Risk assessment consists of five main steps:

- establishment of context,
- risk identification (core process),
- risk analysis (core process),
- risk evaluation (core process),
- risk treatment.

These process steps interact with the following additional steps: communication, consultation, monitoring, and review. The process involves constant feedback between the risk analysis participants, which is to insure clear understanding of the non-conformity and the suggested measures.

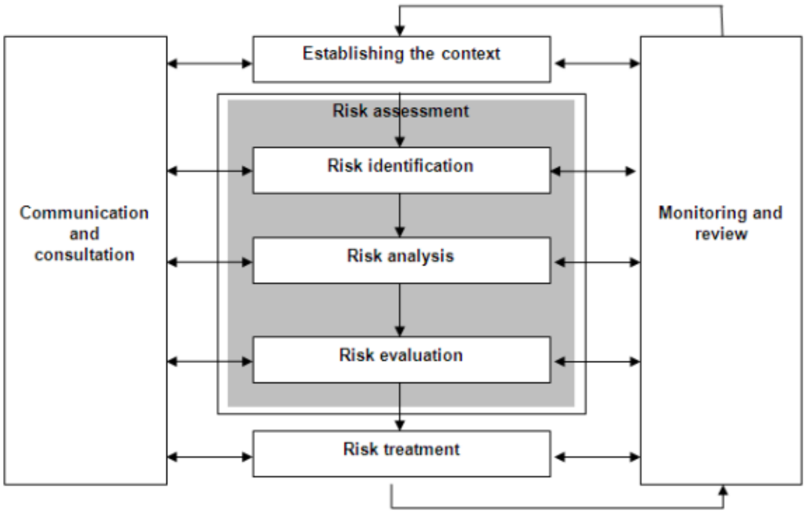


Fig. 9 ISO International Standard Risk Management Framework [7]

Table 6 Traditional risk assessment methods according to IEC 31010:2019 [7]

Risk assessment methods		**Abbreviation**
1	Brainstorming	-
2	Structured or semi-structured interviews	-
3	Delphi technique	-
4	Checklists	-
5	Preliminary hazard analysis	PHP
6	Hazard and operability studies	HAZOP
7	Hazard analysis and critical control points	HACCP
8	Toxicity assessment	-
9	Structured What-if technique	SWIFT
10	Scenario analysis	-
11	Business impact analysis	BIA
12	Root cause analysis	RCA
13	Failure modes and effects analysis, Failure modes and effects and critically analysis	FMEA, FMECA
14	Fault tree analysis	FTA
15	Event tree analysis	ETA
16	Cause-consequence analysis	-
17	Cause-and-effect analysis	-
18	Layers of protection analysis	LOPA
19	Decision tree analysis	-
20	Human reliability assessment	HRA
21	Bow tie analysis	-
22	Reliability centered maintenance	-
23	Sneak analysis, Sneak circuit analysis	SA, SCA
24	Markov- analysis	-
25	Monte Carlo simulation	MCS
26	Bayesian statistics and Bayes Nets	-
27	FN curves (*F* refers to events expected per year, *N* refers to the number harmed)	-
28	Risk indices	-
29	Consequence/probability matrix	-
30	Cost/benefit analysis	CBA
31	Multi-criteria decision analysis	MCDA

In Table 6, the main risk assessment methods are listed. The list covers the majority of the used risk assessment methods from the simplest to the more complex methods. The utilization of the methods depend on the issue to be solved.

The highlighted row 13 (Failure mode and Effect analysis and Failure Mode and Effect and Criticality Analysis) is in deep connection of this current thesis, as the main concept/idea is derived from the modified FMEA concept.

In addition to the aforementioned, Marhavilas et al [19] gives a wider overview to the practically used risk analysis and assessment methodologies (Fig. 10). According to their study, risk analysis and assessment methods can be grouped as the following: qualitative techniques, quantitative techniques, and hybrid techniques.

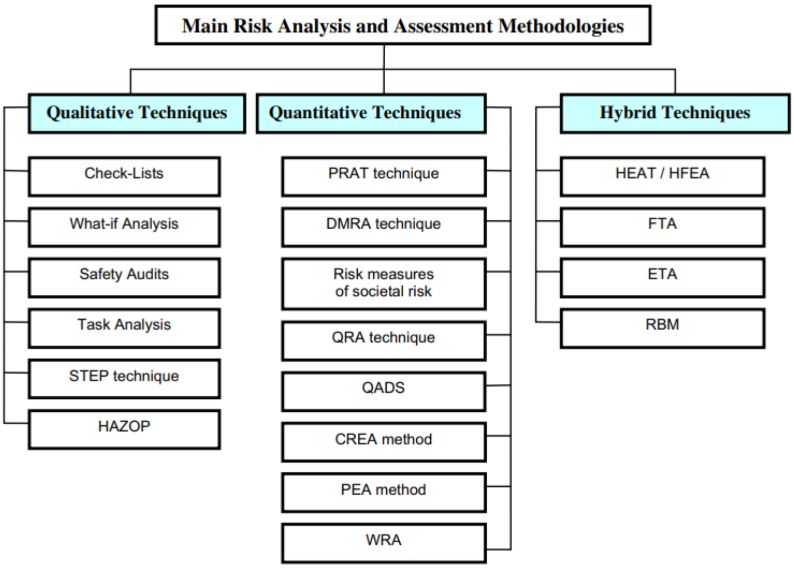


Fig. 10 Risk Analysis and Assessment methodologies [19]

Marhavilas et al [19] have listed novel approaches that are not listed in IEC 31010:2019 [7] PRAT technique, DMRA technique, CREA method, etc.

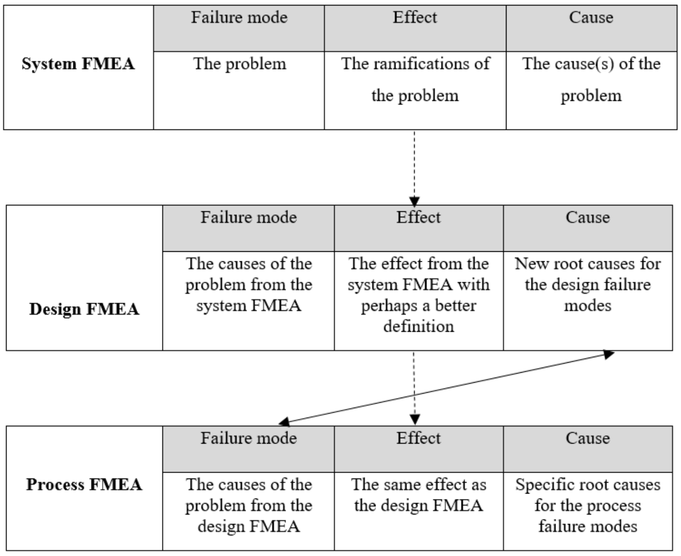
Several articles of several scientific fields focus on risk assessment, Marhavilas et al [19] gives an overview to construction industry. As a conclusion, it can be stated that risk assessment methods are developing, and each academic field, and each industry sector contributes to this evolution. In the following, I introduce to traditional FMEA and to non-conventional FMEA methods, as FMEA was the basis of my suggested preliminary risk analysis method (Hierarchical Overall Risk Analysis).

2.2 Traditional Failure Mode and Effect Analysis

The aim of the Failure Mode and Effect Analysis is to quantify the failure modes of a given system, product or process. FMEA has four basic types, which are the following: System FMEA, Product (Design) FMEA, Process FMEA and Service FMEA [18]. System FMEAs are often considered as general analyses, as they obviously do not contain all sub-FMEAs. Product FMEAs (Design FMEAs) focus on the product itself, divided into parts, which depend on the complexity of the products. According to the aforementioned, Product FMEAs can be grouped into Mechanical FMEAs (referring to the physical construction of the product), Electrical FMEAs (referring to the electrical connection of the product, electrical circuits) and Software FMEAs (referring to the SW of the product). These aspects give the complexity of a given product.

Process FMEAs in general are production related. They focus on the production process itself, and they are the basic quality management tools of manufacturers.

The main advantage of FMEA usage is that in case of an individual product a properly conducted FMEA chain (Product-, Design-, Process-FMEA) the failure effects and causes are linked to each other. In the end, this results in a complex analysis of even the most insignificant failure, with links to the effects on system level as well. According to Stamatis System-, Design- and Process FMEAs are linked through failure cause-failure mode connections, as it is shown in Figure **11**. This way, the design cause is related to the process failure mode failures [18].



	Failure mode	Effect	Cause
System FMEA	The problem	The ramifications of the problem	The cause(s) of the problem

	Failure mode	Effect	Cause
Design FMEA	The causes of the problem from the system FMEA	The effect from the system FMEA with perhaps a better definition	New root causes for the design failure modes

	Failure mode	Effect	Cause
Process FMEA	The causes of the problem from the design FMEA	The same effect as the design FMEA	Specific root causes for the process failure modes

Fig. 11 Connections between System-, Design- and Process FMEAs [18]

2.2.1 FMEA ratings

The failure modes are ranked according to their *Risk Priority Number* (RPN) [18], which is calculated by the following equation

$$\mathrm{RPN} = \mathrm{S} \cdot \mathrm{O} \cdot \mathrm{D} \tag{2.1}$$

where, *S* denotes *Severity*, *O* symbolizes *Occurrence*, and *D* stands for *Detection*. *Severity* measures the seriousness of the failure effect, while occurrence and detection ratings are related to the failure cause or the failure mode. Each factor is rated from 1 to 10 (or from 1 to 5). If all factors are rated with a maximum value of 10, the *RPN* is 1000.

Proper ratings are the basis of a precise FMEA. Therefore, a common rating catalogue is necessary for a consequent evaluation. Rating catalogues give a common understanding for the FMEA team when it comes to failure evaluation. In the following (Tables 7-9) a widely used FMEA catalogue is described for the three different risk criteria [20].

The severity classification differentiates between 10 categories from the highest rating (Hazardous) to the lowest rating (None, No effect).

Table 7 *Severity* rating catalogue [21]

Effect	**Criteria: severity of effect**	**Rank**
Hazardous	Failure is hazardous and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations.	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards.	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable.	8
Major	Product performance is severely affected but functions. The system may not operate.	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair.	5
Low	Small effect on product performance. The product does not require repair.	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance.	2
None	No effect	1

In Table 8, the *Occurrence* levels are defined in 10 categories: the highest rating is 'Extremely high': where failure is almost inevitable and the lowest rating is the 'Nearly impossible' category.

Table 8 *Occurrence* rating catalogue [21]

Effect	Criteria: occurrence of failure cause	Rank
Extremely high: failure almost inevitable	≥1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2000	4
Low	1 in 15000	3
Remote	1 in 150000	2
Nearly impossible	≤ in 1500000	1

In practice, e.g. in the automotive industry the *Occurrence* ratings used to be chosen by their possible ppm values (in case of Process FMEAs).

In Table 9, the detection ratings are summarized in 10 categories. The lowest rating ('Almost certain') represents the highest chance of detection, and the highest rating ('Absolute uncertainty') represents the lowest chance of detection.

Table 9 *Detection* rating catalogue [21]

Detection	Criteria: likelihood of detection by design control	Rank
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode; or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	1

The rating catalogues are inevitably useful at FMEA meetings, as the experts of different fields (development, production, quality engineering, etc.) who are present at the FMEA meetings must have the same understanding of each category.

2.2.2 Shortcomings of Failure Mode and Effect Analysis

FMEA is a traditional method for risk analysis, which considers the aforementioned three factors during the analysis. Equations (1.2) are simple multiplications of these factors, which is often criticized by researchers [20]. In the following, the main shortcomings are listed and described.

If the relative importance of S, O, D factors are considered equal, it might occur that some combination of them results in lower RPN, but higher risk [21].

For example:

$$\mathrm{RPN}_1 = 8 \cdot 4 \cdot 3 = 96 \qquad (2.2)$$
$$\mathrm{RPN}_2 = 3 \cdot 4 \cdot 9 = 108$$

In this case *Severity* is 8 (hazardous effect), *Occurrence* is 4 (relatively low rate of occurrence) and *Detection* is 3 (high detection). This RPN_1 value is lower than the result of the following risk analysis.

The second case results in RPN_2, which is a multiplication of *Severity* 3 (minor severity), *Occurrence* 4 (relatively low rate of occurrence) and *Detection* 9 (very remoted detection) [21].Having RPN_1 lower than RPN_2 means that the seriousness of the failure is not consequent. The same problem occurs if different combinations of O, S and D may produce the same RPN value [20].

Concerning the rating catalogues the following issues might occur: the three risk factors are difficult to be precisely evaluated; the conversion of scores is different for the three risk factors; the RPN cannot be used to measure the effectiveness of corrective actions and RPNs are not continuous with many holes [20].

The method itself has the following shortcomings: the value of RPN might be the same, but their hidden risk implications may be very different and the interdependencies among various failure modes and effects are not taken into consideration [20].

According to Spreafico et al [16] there are four different categories of FMEA shortcomings besides the before mentioned. They classify four different categories of shortcomings: issues with applicability, issues with cause and effects connections, issues with risk analysis results, and difficulties in problem solving.

Applicability issues are the following:

- subjectivity (the focus of the analysis depends on the expertise of participants);
- time consuming activity (a proper analysis takes excessive amounts of work hours from several experts); lack of integration (not proper connection with databases);
- late application (delayed analysis conduction),
- info management problems (missing core information); staff problems (lack of preparation of team members), high expenses (expensiveness due to excessive number of resources needed).

According to Spreafico et al [16] the most cited issue in academia is the subjectivity of analysis, whilst industry faces excessive time consumption as the biggest disadvantage.

Cause and effect relation issues are the following:

secondary effects identification (difficulties in finding the logical connections in the failure net),

C-F chain representation model (lack of models),

level of details for effects description (lack of proper level of detailing: either too much or not enough information),

failure mode description (lack of precise guidelines of description: elements of failure net are often mixed up).

According to Spreafico et al [16] the most cited issue in academia and industry is the problem of secondary effects identification.

Problems of risk analysis are the following: subjectivity (improper definitions lead to unclear results), risk measurement (lack of specific criteria and quantification), risk reliability (inconsistent risk evaluation causes inconsistent decision-making).

According to Spreafico et al [16] subjectivity is the main issue in the fields of academia and industry as well.

Issues of problem solving are the following:

- result evaluation (difficulties of decision-making, lack or weak quantitative parameters);
- solution implementation (difficulties in decision making (lack of information about measure implementations);
- suitability for PS (FMEA concept is not proper for problem solving).

According to Spreafico et al [16], academia and industry find results evaluation the biggest issue in this group.

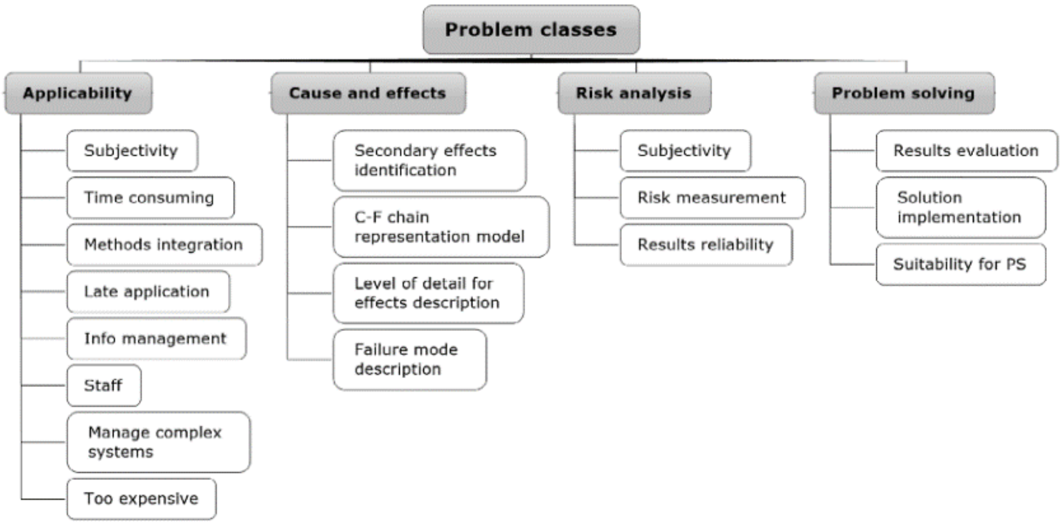
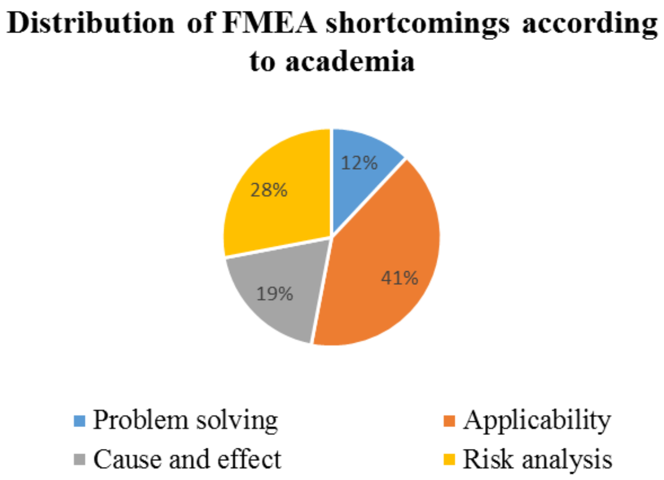
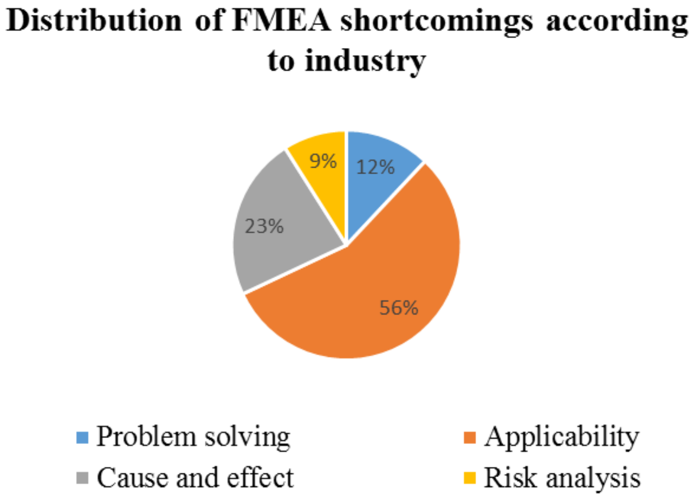


Fig. 12 Classification FMEA shortcomings [16]

In Fig. 13 Spreafico et al. [16] summarized their findings. The four problems groups were cited altogether 191 times in specialized literature (until 2015). Applicability was mentioned 86 times, cause and effect issues 38 times, risk analysis problems 45 times and problem-solving difficulties 22 times. Academia altogether mentioned FMEA shortcomings 148 times, and industry 43 times. The outcome of the FMEA issue distribution in case of FMEA is the following: problem solving (12%), applicability (41%), cause and effect (19%), risk analysis (28%). The results show similarities and differences in case of industry: applicability is the most significant issue (41%), problem solving has the same significance in both sectors (12%), cause and effect issues are considered to be important (academia 19%, industry 23%), whilst risk analysis issues are considered differently (academia 28%, industry 9%).



a, Distribution of FMEA shortcomings according to academia



b, Distribution of FMEA shortcomings according to industry

Fig. 13 Distribution of the problems and shortcomings for academia and industry [16]

2.2.3 Failure Mode and Effect Analysis shortcomings in the battery testing sector

Fantham and Galdwin [22] in their study represent the possible failure modes during battery testing under laboratory conditions. In the following, I represent failure net examples from their work (Table 10).

Table 10 FMEA carried out for battery testing processes [22]

System component	Potential failure mode(s)	Observed effect	Potential failure causes	*O*	*S*	*D*
Cell(s)	1.1 Over voltage	Heat generation and potential venting/fire	Over charge	Low	High	High
	1.2 Under voltage	Heat generation and potential venting/fire	Over discharge	Low	High	High
BMS	1.3 Stuck open	Tests cannot be performed	Coil/physical mechanism worn out	Low	Low	High
	1.4 Stuck open	Tests cannot be performed	Coil damaged from over voltage on coil input	Low	Low	High
Bi-directional Power supply	1.5 Power failure	Tests cannot be performed	Mains power loss Internal fault	Low	Low	High
	1.6 Communication failure	Supply could be stuck performing one sequence causing overcharge or over discharge	Poor installation of cable Software error Cable wear/failure	Med. Low	High High	High High
PC	1.7 Software bug	PC could send incorrect/no command to power supply resulting in limit being exceeded	Poorly written code	Med.	High	High
	1.8 Computer shutdown	No command sent to power supply meaning limit could be exceeded	PC component fails Loss of mains supply Computer self-updates so reboots	Med.	High	High

Fantham and Galdwin [22] collected the possible failure modes during lithium-ion battery testing, although the scope of the analysis is divided between product and process aspects. In case of failure modes 1.1 and 1.2 (system component cell) the failure modes are related to the test process itself and the failure effect comes from the product side. In case of failure modes 1.3-1.7 (system component Battery Management System) the failure modes and effects are related to the test process. The failure modes are relevant, but in practice the mixing of the scope of analysis causes confusion, as the inputs (Product FMEA) are differing from project from project, particularly in case of R&D projects, where the battery is only one component in the system itself.

Based on the conducted FMEA safety test setups are recommended, which are relevant for laboratory facility establishment (Fig. 8). As the outcome of their analysis, Fantham and Gladwin [22] identified safety relevant system components, which are represented in Fig. 14 fuses (in test setup), BMS, contactor (BMS controlled) and fire enclosure.

Generally, BMSs are responsible for voltage and temperature monitoring, and they forecast the balancing of cells and in case of an internal failure the battery cycling is ended, to prevent accidents.

(In my thesis, I am focusing on batteries and battery packs rather than cells, and their recommended setups are not applicable in every case, as not all batteries are equipped with BMS.)

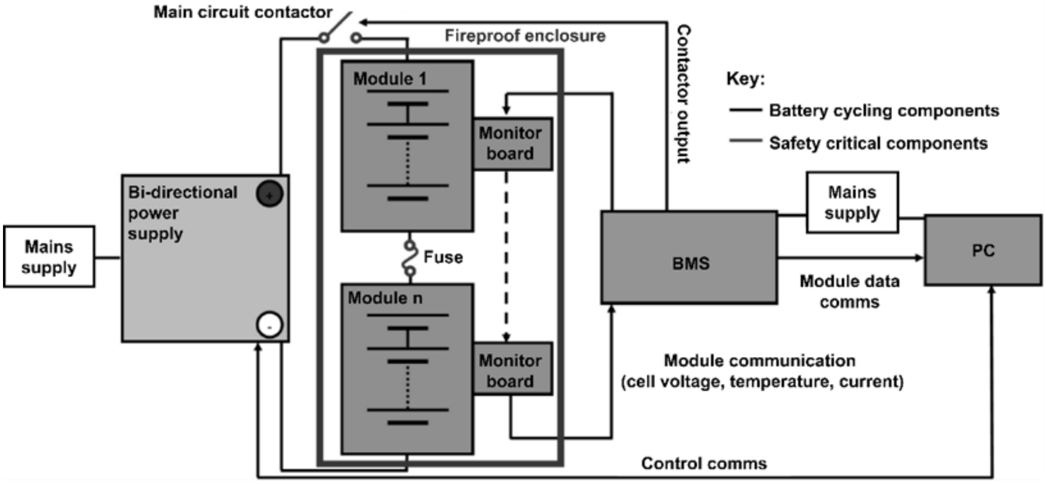


Fig. 14 System diagram for safe testing of battery packs, highlighting safety critical components [22]

In connection with the before mention, during my practical work, I have found the following comparable barriers of the conventional FMEA method to Sprecafico et al's [16] findings:

subjectivity (Applicability issue): as the inputs for analysis (Design FMEA) come from different sources (partners, customers) the level of method understanding is different, even in term of evaluation (*Severity*, *Occurrence*, *Detection* ratings). The differences in ratings cannot be avoided even if using standardized rating catalogues.

time consuming activity (Applicability issue): either the inputs are missing or excessive amount of time is needed to do the linkage of non-standard Design-FMEA (battery related) and Process-FMEA (laboratory related).

info management issues (Applicability issue): due to the fact that not all battery manufacturers are cell manufacturers as well, not all technical information are available.

For battery level tests the cell level IEC 62133-2 [15] certificate is needed. Unfortunately, not all technical information is available on the certificate sheet (product definition, manufacturer, ratings, type reference, trademark, factory locations are available). Relevant information can be gained from the Material Safety Data Sheets (MSDS) provided from the cell supplier. The electrolyte, anode and cathode material can be identified, but the BoM data, or detailed technical specification is not provided, often there is no information about cell level safety options. Based on this there is high level of uncertainty in case of battery testing, as there is no information available from the battery cells themselves.

management of complex systems (Applicability issue): as a battery is considered to be a complex system, in practice it often occurs that the mechanical, electrical and software aspect are handled in different analysis. The merging and providing of this information are insufficient in most cases.

high expenses (Applicability issue): both from manufacturer and both from service provider side the involved resources are outstanding, as there are no standardized methods. The time spent on analysis increases the time need of the tests, which influences the project expenses.

failure mode description (Cause and effect issue): due to the lack of guidelines, and standardized analysis activities the borders of failure modes and effects are blurred, which results in unclear analysis.

risk measurement (risk analysis issue): the lack of specific criteria is and common quantification result in non-comparable results in analysis outcomes, although the same laboratory Process FMEA needs to be linked.

results reliability (risk analysis issue): the planned countermeasures for risk reduction are often inconsistent for risk evaluation, and the deadlines of measure implementation are not synchronized in time.

After the comparison of Spreafico et al.’s [16] findings, I have collected those measures, which could improve the current existing risk analysis methods:

need for a developed hierarchical approach: instead of the providing the inputs from different sources, the whole laboratory concept is regarded as a whole system, which consists of product (battery) related and process (test process) related aspects,

need for new factors: instead of using the original factors (*Severity*, *Occurrence*, *Detection*) new and modified factors are needed to develop and fasten the analysis. In case of test laboratories, the level of *Protection* and the level of *Effectiveness* (Protection effectiveness) are relevant, as there are abuse tests ongoing. As well, in case of product to be tested modifications need to be made. The built-in safety options of batteries (e.g. BMS, BTMS, and safety vents) form a new factor (*Controllability*). *Occurrence* stands for the product related number of technical events (these can be defined from experience or from specialized literature). Following this logic, on System (laboratory) level the final factor is *Severity*/*Cost*. In this combined factor, the test consequences (HSE and laboratory environment related) are taken into consideration with the cost aspects. This helps to prioritize the ongoing and possible projects.

fuzzy method instead of crisp evaluation: with the usage of linguistic variables, the difficulty of risk calculation can be avoided.

2.3 NON-CONVENTIONAL FAILURE MODE AND EFFECT ANALYSIS TYPES

In terms of FMEA, there are multiple non-conventional approaches. According to Liu et al. [20] the following sub-groups can be identified: Multiple Criteria Decision Making applications, Mathematical Programming methods, Artificial Intelligence applications, Integrated approaches and Other (mixed) approaches. In our work, we focus on MCDM applications, Mathematical programming approaches and Artificial Intelligence solutions.

2.3.1 Multiple Criteria Decision Making applications

According to Massam [23] Multiple Criteria Decision Making applications (MCDM) are related to several decision making applications, as the following: Multi-Attribute Decision Making (MADM), Multi-Attribute Utility Theory (MAUT), Multi-Objective Decision Making (MODM) and Public Choice Theory (PCT).

They can be used for planning processes, if multiple decision alternatives are applicable [23], or at FMEA processes if multiple choices are applicable for each factor categories. MADM is applied if there are finite feasible sets of alternatives and the aim is to choose the best solution, in case of planning problems.

MCDM is used if the objective is to define a finite number of possible alternatives for a given problem (the problem is typically solved with mathematical programming). MADM and MODM are applied in case of single decision makers or unified opinions [23].

Table 11 Example of Fuzzy MCDM related applications used for FMEA and other approaches [20], [24]

Method	**Author(s)**	**Practical approaches/Practical FMEA applications**
Fuzzy ME-MCDM	Franceschini and Galetto [25]	risk analysis/several design and manufacturing purposes
Fuzzy evidence theory	Guo et al. [26]	comparison of technical products (cars)
	Li and Liao [27]	corporate risk analysis
	Wang et al. [28]	environmental impact assessment
	Xu et al. [29]	personal performance assessment
	Yang et al. [30]	car ranking
Fuzzy AHP/ANP	Hu et al. [31]	component risk analysis / Fuzzy FMEA of components
	Boral et al. [24]	manufacturing risk analysis / Fuzzy Process FMEA
Fuzzy TOPSIS	Boran et al. [32]	supplier selection (automotive, etc.)
	Taylan et al. [33]	risk assessment of construction projects
	Dagdeviren et al. [34]	weapon selection
	Braglia et al. [35]	production risk analysis / Fuzzy Production FMEA
Fuzzy Grey theory	Zhou and Thai [36]	failure analysis / Fuzzy FMEA for tanker equipment failure prediction
	Shi and Fei [37]	failure analysis / Combined Fuzzy FMEA method for medical service process
	Geum et al. [38]	failure analysis / Service specific Fuzzy FMEA (hospital service)
Fuzzy DEMATEL	Seyed et al. [39]	failure analysis / Product specific Fuzzy FMEA (turbocharger product FMEA)
	Govindan and Chaudhuri [40]	risk analysis of third-party logistics service
VIKOR	Liu et al. [41]	failure analysis / Fuzzy FMEA for medical processes
	Mete et al [42]	occupational risk assessment of a natural gas pipeline construction
COPRAS	Roozbahani et al. [43]	water transfer planning
SWARA/COPRAS	Zarbakhshnia et al. [44]	risk analysis of third-party logistics service
ELECTRE(-TRI)	Certa et al. [45]	Fuzzy FMEA / Alternative failure mode classification
	Liu and Ming [46]	Fuzzy FMECA / Fuzzy FMECA for smart product service
MULTIMOORA	Liu et al. [20]	Evaluation of failure modes / Fuzzy MULTIMOORA FMEA

In case of MAUT approaches the task is to evaluate the utilities of the given alternatives. As a result, the highest utility value is considered as the best possibility (in planning processes) [23]. PCT is applied if consensus is needed in a certain decision situation, as well in a case of a risk category selection.

In general, it can be stated that the MCDM method consists of three areas, which were previously isolated. These are the following: Solution generation via search, Solution selection via preference aggregation and trade-off, and Interactive visualization [23].

According to the three fields mentioned, the MCDM methods cover these main solutions of planning problems: well-distributed Pareto sets (Solution generation via search), Bayesian and Fuzzy decision-making techniques (Solution selection via preference aggregation and trade-off, and Interactive visualization) [23].

2.3.2 Integrated FMEA and FAHP (Fuzzy Analytic Hierarchy Process) for risk analysis

The integrated FAHP (Fuzzy Analytic Hierarchy Process) method is derived from the AHP (Analytic Hierarchy Process). AHP is a tool for determining the priority and relative importance of alternatives in a MCDM situation [31]. AHP was first introduced by Saaty [47]. In the following the integrated FAHP method will be introduced, which is closely linked to the traditional AHP method. According to Hu et al. [31], integrated FMEA and FAHP is an effective method for risk analysis. Their proposed solution corrects the disabilities of the traditional AHOP method, which manages uncertainty and imprecision of decision makers less effectively. In their study, they have analyzed the risk of green components and hazardous materials. According to Hu et al.'s approach [31] the integrated method consists of three sub-processes: definition of criteria and risk assessment with FMEA, definition of relative importance of factors, and utilization of integrated approach.

The outcome equation of Hu et al.'s approach is

$$RPN = W_{(O_1)}S_{(O_1)} + W_{(D_1)}S_{(D_1)} + W_{(S_1)}S_{(S_1)} + W_{(S_2)}S_{(S_2)} \tag{2.3}$$

where W is the weight of criteria of RPN, and S is the score of criteria of RPN.

2.3.3 Franceschini and Galetto’s Fuzzy ME-MCDM method

Bellman and Zadeh [48] introduced fuzzy sets within MCDM, which resulted later in the establishment of FCDM (Fuzzy Multicriteria Decision-Making). Due to the usage of linguistic variables FN (Fuzzy Numbers) are implemented. FN can be either Gaussian, trapezoidal or triangular [25].

$$\mathrm{RPC}(a_i) = \mathrm{Min}_j\,[\mathrm{Max}\{\mathrm{Neg}(\mathrm{I}(g_i)), g_j\,(a_i\,)\}, \qquad (2.4)$$

Where:

$\mathrm{RPC}(a_i)$: Risk Priority Code for the failure mode a_i

$\mathrm{I}(g_i)$: the importance associated with each criteria gi; gi is the evaluation criteria

$\mathrm{Neg}(\mathrm{I}(g_i))$ (S, O, D factors), j=1,…,n : the negation of the importance assigned to each decision-making criterion.

With the usage of fuzzy MCDM FMEA method the failure mode with the maximum risk priority code is defined as follows [25]:

$$\mathrm{RPC(a^*)} = \mathrm{Max}_{a_{i \neq A}}\,\{\mathrm{RPC}(a_i\,)\}, \qquad (2.5)$$

where *a* is the set of failure modes, *RPC* (a_i)is defined on a new 10-point ordinal scale as those values utilized for expressing index evaluations.

With the usage of Franceschini and Galetto’s method a different level of importance of *S, O, D* factors can be defined as follows [25]:

$$\mathrm{RPN(a^*)} = \mathrm{Max}_{a_{i \notin A}}[\mathrm{RPC}(a_1\,), \mathrm{RPC}(a_2\,), \mathrm{RPC}(a_3), \mathrm{RPC}(a_n)] \qquad (2.6)$$

The most important advantage of this method is that different importance levels can be given to each FMEA factors (*Severity*, *Occurrence*, *Detection*). This is important in terms of the FMEA’s purpose as well. In case of Design FMEA (Product FMEA) the severity values can have more importance, while in case of Process FMEA, the same applies for the *Occurrence* factor.

$$(\overline{\mathrm{ERS}})\,(\mathrm{FM}_n\,) = \frac{1}{2}\,(\mathrm{ERS}^{\mathrm{L}}\,(\mathrm{FM}_n\,) + \mathrm{ERS}^{\mathrm{U}}\,(\mathrm{FM}_n)), n = 1, \ldots, \mathrm{NERS}(\mathrm{FM}_n\,) \qquad (2.7)$$

2.3.4 Grey theory used for Fuzzy FMEA

The Fuzzy FMEA based on grey theory proposed by Zhou and Thai [36] is based on the assumption that with the fuzzification each risk criteria can be weighted (in contrast to the traditional method).

In the following, linguistic terms for each risk criteria are mentioned. In Table 12, the linguistic terms of *Occurrence* are presented. In this proposed example, 5 levels are mentioned, i.e. *VH* (Very High), *H* (High), *M* (Moderate), *L* (Low), and *R* (Remote) (Zhou and Thai, 2016):

Table 12 Linguistic terms of *Occurrence* (*factor O*) [36]

Rating	Probability of occurrence	Fuzzy number
Very high (VH)	Failure is almost inevitable	(8, 9, 10)
High (H)	Repeated failures	(6, 7, 8,9)
Moderate (M)	Occasional failures	(3, 4, 6,7)
Low (L)	Relatively few failures	(1, 2, 3,4)
Remote (R)	Failure is unlikely	(1, 1, 1,2)

In Table 13, the linguistic terms of *Severity* are presented. 10 different levels are differentiated in this example (*HWOW, HWW, VH, H, M, L, VL, MR, VMR, N*):

Table 13 Linguistic terms of *Severity (factor S)* [36]

Rating	Severity of occurrence	Fuzzy number
Hazardous without warning (HWOW)	Very high severity ranking without warning	(9,10)
Hazardous with warning (HWW)	Very high severity ranking with warning	(8, 9,10)
Very high (VH)	System inoperable with destructive failure	(7, 8,9)
High (H)	System inoperable with equipment damage	(6, 7,8)
Moderate (M)	System inoperable with minor damage	(5, 6,7)
Low (L)	System inoperable without damage	(4, 5,6)
Very low (VL)	System operable with significant degradation of performance	(3, 4,5)
Minor (MR)	System operable with some degradation of performance	(2, 3,4)
Very minor (VMR)	System operable with minimal interference	(1, 2,3)
None (N)	No effect	(1, 1,2)

In Table 14, the linguistic terms of Detection are defined (*AU, VR, R, VL, L, M, MH, H, VH, AC*).

Table 14 Linguistic terms of *Detection* (*factor D*) [36]

Rating	Severity of effect	Fuzzy number
Absolute uncertain (AU)	No chance	(9,10,10)
Very remote (VR)	Very remote chance	(8, 9,10)
Remote (R)	Remote chance	(7, 8, 9)
Very low (VL)	Very low chance	(6, 7, 8)
Low (L)	Low chance	(5, 6, 7)
Moderate (M)	Moderate chance	(4, 5, 6)
Moderately high (MH)	Moderately high chance	(3, 4, 5)
High (H)	High chance	(2, 3, 4)
Very high (VH)	Very high chance	(1, 2, 3)
Almost certain (AC)	Almost certainty	(1, 1, 2)

Finally, the *S*, *O*, *D* factors are de-fuzzified according to their membership functions:

$$K(x)=\sum_{i=0}^{n}(b_i-c)/\left[\sum_{i=0}^{n}(b_i-c)-\sum_{i=0}^{n}(a_i-d)\right] \tag{2.8}$$

where *K*(x) is the defuzzified crisp number, and n is the number of alpha levels. In case of the grey coefficient calculation, there is a correlation measure between x_i, y_i .

$$\text{For the set } \mathrm{X}=\{\mathrm{x_i} \mid \mathrm{i}\in \mathrm{I}, \mathrm{i}=0,1,2,...,\mathrm{m}\}, \mathrm{x_{i,s}y_i} \in \mathrm{X}\gamma(\mathrm{x_i},\mathrm{y_i}) \tag{2.9}$$

where $\Delta 0j(k)$ is the absolute difference between $x_0(k)$ and $x_j(k)$, x_0 contains standard series and, x_i contains comparative series. In this case, according to the above-mentioned definitions, the grey coefficient is calculated as follows:

$$\gamma(\mathrm{x_0(k)},\mathrm{x_i(k)})=[x(\min)+\zeta x(\max)]/[\Delta 0i(k)+\zeta x(\max)] \tag{2.10}$$

Where:

$$\mathrm{x(min)} = \min_{\mathrm{i}}\min_{\mathrm{k}}\Delta_{0\mathrm{i}}(\mathrm{k}) \tag{2.11}$$

$$\mathrm{x(max)} = \max_{\mathrm{i}}\max_{\mathrm{k}}\Delta_{0\mathrm{i}}(\mathrm{k}) \tag{2.12}$$

According to the principle of minimum ζϵ[0,1] is generally ζ=0.5. The degree of relation is defined as the value of grey relation coefficient:

$$\Delta_{0i}(k)=x_0(k)-x_i(k) \tag{2.13}$$

$$\gamma(x_0(k),x_i(k)),\ \ k=1,2,...,n \tag{2.14}$$

$$\gamma(x_0,x_i)=\frac{1}{n}\sum_{k=1}^{n}\gamma(x_0(k),x_i(k)) \tag{2.15}$$

As a conclusion, the following equation stands for the FMEA calculation:

$$\gamma(x_0, x_i) = \omega_0 \cdot \gamma(x_0(0), x_i(0)) + \omega_s \cdot \gamma(x_0(S), x_i(S)) + \omega_D \cdot \gamma(x_0(D), x_i(D)) \qquad (2.16)$$

Finally, Zhou and Thai propose a joint method of fuzzy and grey theory. Their method is separated into three main parts: the establishment of fuzzy rules and determination of linguistic terms and fuzzy membership function; the calculation of FRPN (Fuzzy RPN) by weighted geometric mean method and the defuzzification of *S*, *O*, *D* for obtaining a crisp number.

The advantage of the joint method is that the advantage of grey theory usage can be applied as well. Grey theory reflects on the nature of relative ranking which is fortunate if the evaluation information is not reliable, or incomplete [36].

2.3.5 Mathematical programming applications

Mathematical programming applications are relevant parts of the non-conventional FMEA methodology. There are three methods of the applications, summarized in Table 15: Fuzzy RPN method, Fuzzy DEA FMEA and Fuzzy Interval DEA FMEA. Fuzzy RPN method is used in cases of process and product level risk analyses, fuzzy DEA FMEA is used mainly for specific purposes (nuclear system risk analysis) as fuzzy interval DEA FMEA (system FMEA for fishing vessel construction).

2.3.1 Usage of fuzzy risk priority numbers (FRPNs)

According to Wang et al. [28] Risk Priority Numbers (RPNs) can be fuzzified and considered as FRPNs (Fuzzy Risk Priority Numbers). *FRPNs* are calculated as fuzzy weighted geometric means of *Severity* (S), *Occurrence* (O), and *Detection* (D) ratings. FRPNs can be defined with α-level sets and with linear programming. Defuzzification is done with centroid defuzzification method [20].

Table 15 Applications of Fuzzy Mathematical programming related to FMEA [20], [24]

Method	Author(s)	Practical approaches/Practical FMEA applications
Fuzzy RPN	Wang et al. [28], Gargama and Chaturvedi [49], Chen and Ko [50]	wide usage for both Design-, and Process FMEA
Fuzzy DEA FMEA	Garcia et al. [51]	example of nuclear system risk analysis
Fuzzy Interval DEA FMEA	Chin et al [52]	example of System FMEA for fishing vessel

Gargama and Chaturvedi [49] calculated FRPNs as well, but with using benchmark adjustment instead of linear programming [20],

Chen and Ko's [50] approach is a FRPN definition which is based on fuzzy ordered weighted geometric averaging of *S, O, D* factors [20]. They have defined fuzzy FMEA as the following:

$$(\widetilde{\mathrm{RPN}})_{\mathrm{j}} = \max(\widetilde{\mathrm{S}}_{\mathrm{r}} \cdot \widetilde{\mathrm{O}}_{\mathrm{s}} \cdot \widetilde{\mathrm{D}}_{\mathrm{t}})_{\mathrm{j}}, \ \mathrm{j} = 1,2,\ldots,\mathrm{J}, \tag{2.17}$$

Where $\tilde{S}_r, \tilde{O}_s, \tilde{D}_t$ are fuzzy subsets [0, 1]. Chen and Ko [50] introduced a FOWGA (fuzzy ordered weighted geometric averaging) operator. The FOWGA operator is used to aggregate m (>1) fuzzy sets.

$$\mathrm{f}(\tilde{\mathrm{a}}_1, \tilde{\mathrm{a}}_2, \ldots, \tilde{\mathrm{a}}_{\mathrm{m}}) = \prod\nolimits_{\mathrm{i}=1}^{\mathrm{m}} (\tilde{\mathrm{b}}_{\mathrm{i}})^{W_i} \tag{2.18}$$

$$\sum_{i=1}^{m} w_i = 1, w_i \in [0,1]$$

Where $\tilde{b}_i$ is the *i*th largest set of the $(\tilde{S}, \tilde{O}, \tilde{D})$, *w$_i$* is the weight of the $\widetilde{b_\imath}$ and FOWGA can be formulated as the following:

$$(\widetilde{\mathrm{RPN}})_{\mathrm{j}} = \mathrm{f}(\tilde{\mathrm{S}}, \tilde{\mathrm{O}}, \tilde{\mathrm{D}})_{\mathrm{j}} = \max\nolimits_{\mathrm{r,s,t}} \prod\nolimits_{1=1}^{3} (bi)_j^{w_i} \tag{2.19}$$

Where *w* is the weighting vector, $w = (w_1, w_2, w_3)^T$. *RPN* is defined with its membership function. The membership function is defined by deriving the lower and upper bounds of the α-cuts of *(RPN)$_j$* :

$$(RPN_j)_\alpha^L = \max\nolimits_{r,s,t} \prod\nolimits_{i=1}^{3} \left[(bi)_j^{w_i}\right]_\alpha^L \tag{2.20}$$

$$\left[RPN_j)_\alpha^U\right] = \max\nolimits_{r,s,t} \prod\nolimits_{i=1}^{3} \left[(bi)_j^{w_i}\right]_\alpha^U \tag{2.21}$$

After defining the membership function, the defuzzification is the following:

$$(RPN_j)' = \frac{\sum i \left\{ \dfrac{1}{2\left[(RPN_j)_{\alpha_i}^L + (RPN_j)_{\alpha_i}^U\right]} \right\} \cdot \overline{\mu i'}}{\sum i \overline{\mu i'} i} \tag{2.22}$$

Where μ_i' is the membership degree of $\frac{1}{2}\left[(RPN_j)_\alpha^L + (RPN_j)_{\alpha_i}^U\right]$

$$(\widetilde{\mathrm{Ri}}_{\mathrm{k}})_\alpha = \left[(Ri_k)_\alpha^L, (Ri_k)_\alpha^U\right] = \left[\sum\nolimits_{j=1}^{J} (RPN_j)' \cdot m(R'_{2,jk})_\alpha^L, \sum\nolimits_{j=1}^{J} (RPN_j)' \cdot m(R'_{2,jk})_\alpha^L\right] \tag{2.23}$$

The advantages of the method are that different combinations of *Severity*, *Occurrence* and *Detection* factors result in different FRPNs (unless the relative weights used are the same), and more risk factors can be used during the analysis [50].

2.3.2 Garcia et. al's fuzzy DEA FMEA

According to Garcia et al. [51] Risk Analysis evaluations are carried as a part of the Probabilistic Safety Analysis (PSA). In their research they have pointed out that that the different combinations of S, O, D factors produce the same value.

Garcia et al. states [51] this shortcoming can be solved with the modelling of RPN factors (*Severity*, *Occurrence*, *Detection*) as fuzzy sets. In case of this method, *Occurrence* and *Detection* factors are considered to have equal importance and *Severity* is considered to have more importance than O and D.

$$\mathrm{Max}\,\mathrm{h}_0 = \sum\nolimits_{\mathrm{j}=1}^{\mathrm{s}} u_j y_{j0} \tag{2.24}$$

$$\sum\nolimits_{i=1}^{r} v_i x_{i0} = 1 \tag{2.25}$$

$$\sum\nolimits_{\mathrm{j}=1}^{\mathrm{s}} u_j y_{j0} - \sum\nolimits_{i=1}^{r} v_i x_{ik} \le 0, \forall k \tag{2.26}$$

$$v_s - (v_0 + v_D) \ge 0 \tag{2.27}$$

$$u_j, v_i \ge \varepsilon \forall i, j \tag{2.28}$$

Where ε is a non-Archimedean figure, which should be as small as possible. ε should be defined as a number different from 0, if the ε=0 model defines one or more factors as not important. Regarding the disadvantage of the method, according to Chin et al. [52] Garcia et al.'s method [51] needs to be corrected, as it does not provide a complete evaluation for the failure modes. Due to Chin et al.'s approach the relative importance weights are taken into consideration, without subjective specification [20].

2.3.3 Chin et. al's fuzzy DEA FMEA

According to Chin et al.'s [52] model there are *n* failure modes, which need to be prioritized. These failure modes are evaluated with the selected *m* risk factors. Despite the traditional FMEA method (which equally considers *Severity*, *Occurrence*, *Detection* factors), in this case RPN is calculated as follows:

$$\mathrm{R_i} = \sum\nolimits_{\mathrm{j}=1}^{\mathrm{m}} \mathrm{w_j} r_{ij}, i = 1,...,n, \text{ which defines additive risks} \tag{2.29}$$

$$\mathrm{R_i} = \prod\nolimits_{\mathrm{j}}^{\mathrm{m}} = \mathrm{r}_{\mathrm{i}j}^{\mathrm{w_j}}, \mathrm{i} = 1,...,\mathrm{n}, \text{ which defines multiplicative risks} \tag{2.30}$$

If the maximum value of importance ratio is considered as 9, the ratio of maximum weight to minimum weight is defined between the range of 1 and 9.

$$1 \leq \frac{\max\{w_1,...,w_m\}}{\min\{w_1,...,w_m\}} \leq 9 \tag{2.31}$$

Chin et al [52] define *Occurrence* and *Detection* ratings on a scale of 1 to 10, while *Severity* is defined on a scale from 1 to 9 (as no importance has no point in this case).

$$\max\{\frac{w_j}{w_k} \mid j, k = 1, \ldots m; k \neq j\} \leq 9 \tag{2.32}$$

$$w_j - 9w_k \leq 0, j, k = 1, \ldots, m; k \neq j \tag{2.33}$$

According to the aforementioned, FMEA DEA models are defined as the maximum and minimum risks of each failure mode (additive failure modes), according to the following [52]:

$$R_0^{\max} = \text{Maximize} R_0 \tag{2.34}$$

Subject to:

$$(R_i \leq 1, \quad i = 1, \ldots, n,) \tag{2.35}$$

$$w_j - 9w_k \leq 0, \quad j, k = 1, \ldots, m; k \neq j \tag{2.36}$$

$$R_0^{\min} = \text{Minimize} R_0 \tag{2.37}$$

Subject to:

$$R_i \geq 1, \quad i = 1, \ldots, n, \tag{2.38}$$

$$w_j - 9w_k \leq 0, \quad j, k = 1, \ldots, m; k \neq j \tag{2.39}$$

The sum risk of each failure is defined with the following equation, which gives the geometric average of the maximum and minimum risk [52]:

$$\overline{R}i = \sqrt{(R_i^{\max} \cdot R_1^{\min})}, i = 1, \ldots, n \tag{2.40}$$

In case of defining multiple failure modes, the same equation can be used, but transformed to a logarithmic scale:

$$\ln R_0^{\max} = \text{Maximize} \ln R_0 \tag{2.41}$$

Subject to:

$$\ln R_i \leq 1, \quad i = 1,\ldots,n, \tag{2.42}$$

$$w_j - 9w_k \leq 0, \quad j,k = 1,\ldots,m; k \neq j \tag{2.43}$$

$$\ln R_0^{\min} = \text{Minimize} \ln R_0 \tag{2.44}$$

Subject to:

$$\ln R_i \geq 1, \quad i = 1,\ldots,n, \tag{2.45}$$

$$w_j - 9w_k \leq 0, \quad j,k = 1,\ldots,m; k \neq j \tag{2.46}$$

The geometric average risk is defined with exponential function:

$$Ri = \sqrt{(\text{EXP}(\ln R_i^{\max}) \cdot \text{EXP}(\ln R_i^{\min}\ )}, i = 1,\ldots,n, \tag{2.47}$$

The advantages are like Wang et al.’s approach [28], as more risk factors can be used during the analysis, and there is no need to use if-than rules.

2.3.4 Fuzzy Interval DEA FMEA

According to Chin et al. [52] the idea of an interval DEA FMEA is based on the team approach of the team method of FMEA. If the incomplete evaluation is transformed to an expectation interval, the maximum, minimum and the average risks are stated as intervals as well.

The geometric average risks are calculated as follows:

$$\begin{aligned}\left[\overline{R}_i^L, \overline{R}_i^U\right] = \Big[&\sqrt{EXP(\ln(R_i^{\max})^L) \cdot EXP(\ln(R_i^{\min})^L)}, \Big], \\ &\sqrt{EXP(\ln(R_i^{\max})^U) \cdot EXP(\ln(R_i^{\min})^U)}\Big], i = 1,\ldots,n\end{aligned} \tag{2.48}$$

This method is related to the minimax regret approach (MRA), implemented by Wang et al [28]MRA uses the maximum regret value (MRV) for comparing and ranking of interval numbers:

$$R(u_i) = \max[\max_{j \neq i}(u_j^U) - u_j^L, 0], i = 1,\ldots,N \tag{2.49}$$

2.3.5 Artificial intelligence approaches related to FMEA

Now, I would like to give a summary of the artificial intelligence approaches related to FMEA (Table 16), according to Liu et al [20]. Based on the grouping, there are four major groups of FMEA related solutions. These are the following: rule-base system [53] fuzzy rule-based system [54], fuzzy ART (Adaptive Resonance Theory) algorithm [55] and fuzzy cognitive map [56].

Table 16 Applications of artificial intelligence approaches related to FMEA

Method	Author(s)	Practical approaches/Practical FMEA applications
Rule base system	Sankar and Prabhu [53]	Process FMEA example of off-shore cooling plant example
Fuzzy rule-base system	Sharma and Sharma [54]	Process FMEA example for paper mill system
Fuzzy ART algorithm	Keskin [55]	Process FMEA for testing purposes
Fuzzy cognitive map	Peláez and Bowles [56], Gargama and Chaturvedi [49]	Design FMEA for water tank levelling system

2.3.6 Rule base system for FMEA

According to Sankar and Prabhu [53] the rule-based system for FMEA is carried out according to the following steps:

(1) Description of the part name, number, and function.

(2) Listing the possible failure modes

(3) Estimation of failure severity values

(4) Listing the potential failure causes

(5) Estimation of occurrence frequency of failures

(6) Description of failure detection methods

(7) Estimation of failure detection

(8) Evaluate the RPR (Risk Priority Rank)

(9) Recommendation of corrective actions

Step 8 is an addition to the traditional FMEA process with an implementation of a new risk priorisation scale. The suggested variable, RPR (Risk Priority Rank) can take up values from 1-1000, and is calculated with If-Then relations. In this case the rules are formulated in numerical form [53]. With the usage of the rules, we receive the RPR value, which differs from the traditional RPN that is the multiplication of the *Severity*, *Occurrence* and *Detection* factors. RPR indicates relative priority. For visualization purposes the outcome of the analysis is represented in an ordering matrix.

Table 17 Example of ordering matrix of a functional FMEA of a centrifugal pump [53]

Causes	**OR**	**DR**	**E1** **SR8** **FM1**	**E4** **SR7** **FM4**	**E2** **SR6** **FM2**	**E3** **SR5** **FM3**	**E5** **SR5** **FM5**
C4	9	5	784(360)	0	0	0	0
C6	6	7	759(336)	0	0	0	0
C29	8	3	754(192)	0	0	0	0
C17	8	5	0	754(280)	0	0	0
C27	7	8	0	739(392)	0	0	0
C14	7	5	0	732(245)	0	578(175)	0

In the ordering matrix the columns represent the following:

Causes (Cx): the identified failure causes in the failure net,

OR (Occurrence Rating): the value of failure cause occurrence (1-10),

DR (Detection Rating): the value of failure cause detection (1-10),

Ex (Effect): the identified failure cause effect,

SRx (Severity): the identified failure effect severity,

FMx (Failure Mode): the identified failure mode.

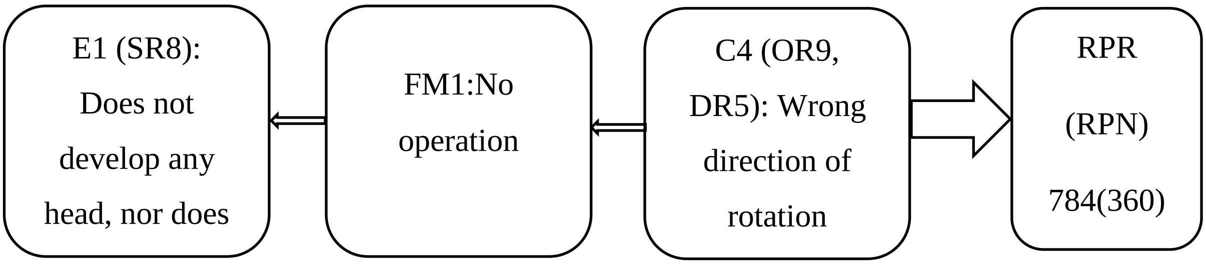


Fig. 15 Example of failure net (Functional FMEA of rotation pump) [53]

The ordering matrix can be understood as follows: each failure cause (*Cx*) is related to an occurrence (*OR*), detection (*DR*) and severity (*SR*) value (Fig. 15). The failure net consists of failure effects (Ex) and failure modes (*FMx*) as well, as in case of the traditional FMEA. RPN value is generated from the multiplication of *S*, *O*, *D* factors. The RPN values are placed in brackets. If there is no connection between a certain failure cause and a failure mode or failure effect, 0 is placed in the cell. This visual method helps to identify the potential problematic areas of a product or process [53]. According to the aforementioned the first row of Table 17 can be illustrated in a net as well.

The main advantage of this method is that it gives relative importance to each failure that helps to improve the numerical shortcoming of traditional FMEA, visualization is surplus solution as well, as it gives a good overview of the process or design. The proper definition of rules is essential in this case, since it has major influence of the sequence of failure importance.

2.3.7 Fuzzy rule-base system

Rule-based systems are implemented in fuzzy FMEA methods as well. According to Sharma and Sharma [54] shown in Fig. 10, fuzzy methodology (FM), root cause analysis (RCA) and FMEA can be merged in a common approach. *RCA* is tool for the comprehensive classification of cause into 4M's (4M stands for Machine, Method, Man and Material) [54]. In this integrated approach FMEA defines the input variables (*Of, S, Od*) that form RPN.

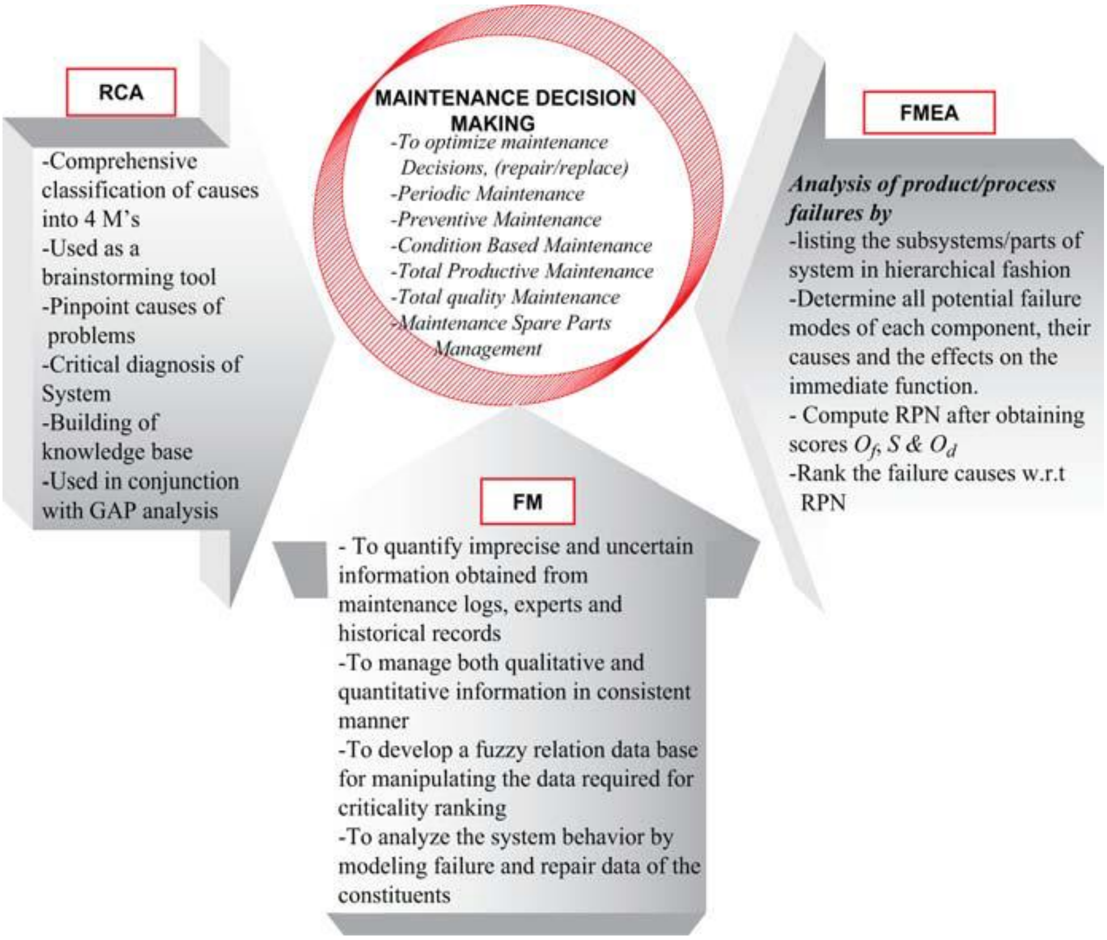


Fig. 16 Merged approach for maintenance decision making [54]

The third so-called tool is FM, that is responsible for the quantification of imprecise and uncertain information provided by the experts and their analysis. In Sharma and Sharma's example [54] maintenance decision-making is aided with this merged approach.

As shown in Fig. 16, the knowledge base is provided by data analysis and expert knowledge, that are evaluated with fuzzy rule-based analysis. The inputs of the integrated approach are *Of* (*Probability of occurrence of failure*), *S* (*Severity*) and *Od* (*likelihood of non-detection of failure*) factors. *Of* is determined as a function of mean time between failures, *Od* is estimated (for example as 0.5 % in case of visual inspection of operator's), and *S* is the numerical definition of failure effect on system performance.

This way, the fuzzified factors are the inputs of the fuzzy interference systems, that results in FRPNs after defuzzification.

For the determination of the FRPN variable, both triangular and trapezoidal membership functions were used). In Sharma and Sharma's example [54] five fuzzy sets were applied in case of each factor (*Of*, *S*, *Od*) and a total of 125 rules were used. For the interference system Petrinet models are used.

The main advantage and disadvantage of this solution is related to the same root (Fig. 17): information and data are gathered from three sub-systems, that makes the tool complex or even too complex for the analysts. All in all, the usage of this method provides a more realistic overview of industrial systems (modelling, predictions analysis) [54].

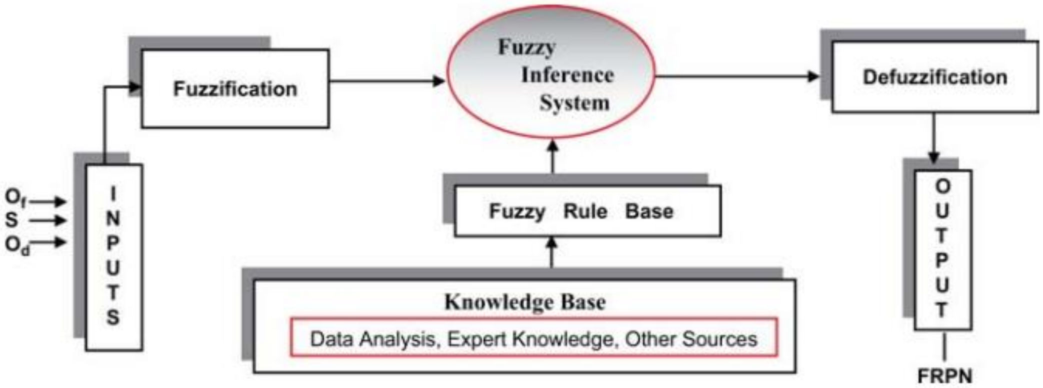


Fig. 17 Definition of fuzzy rule base system [54]

2.4 Chapter summary

In this chapter, I have represented the traditional Failure Mode and Effect Analysis method and the non-conventional FMEA types. According to my research, the traditional method lacks factors, it is time consuming, and it cannot manage and evaluate complex systems. The mentioned and described non-conventional analyses provide more flexible analysis solutions, but they do not provide a result oriented approach for the purpose of lithium-ion battery test laboratories. I assumed that a preliminary risk assessment would be required for standardized laboratory testing of lithium-ion batteries (**H1**).

3 PROPOSED NEW METHOD FOR PRELIMINARY RISK ANALYSIS OF LITHIUM ION TEST LABORATORIES

The aim of the HORA model is to provide a practical option for the preliminary risk analysis of lithium-ion battery testing facilities. The proposed model's purpose is not to replace the mandatory explosion-safety risk analysis but to provide a practical, quick, and accurate tool for test engineers to foresee the effects of abuse tests. During the lithium-ion battery transport safety tests (according to UN 38.3 [6]) and the safety tests (e.g. according to IEC 62133-2 [15]) the batteries are tested under abuse conditions.

It has to be stated, that the traditional FMEA concept is the origin of the proposed method, but with some surplus logical considerations. At classical RPN (Risk Priority Number) calculation, three factors (*Severity, Occurrence* and *Detection*) are multiplied, and the basis of the analysis is either a construction (System-FMEA, Design-FMEA) or a process (Process-FMEA). These three factors do not cover necessarily the effect of all influencing factors, there is room for improvement in this area. In case of laboratory risk analysis, the focus is on handling the possible the technical events, not on the detection and probability of a given issue. The question in this case is simple: when will the battery related technical event happen? It is certain that in the case of battery abuse tests the probability of a technical event is inevitable. A risk analysis method, which relies only on *Severity, Occurrence* and *Detection*, is not appropriate for laboratory related risk analysis. The proposed model provides an alternative for this issue with the introduction of the following factors: protection, controllability and effectiveness.

During each analysis in the case of traditional FMEAs, failure nets are formed on all levels (system level, product level, and process level). Failure nets can be connected if e.g. the failure effects of the Design FMEA and the failure modes of the Process FMEA are linked to each other, thus the failure modes cause product-related effects as well the process-related ones. For laboratory-related risk analysis, the three levels of traditional FMEA analysis must be merged. The process level is related to the abuse testing process itself. At process level, I have used two factors: *Protection* (protective solution and devices in the laboratory) and *Effectiveness* (the effectiveness of safety solutions). The product level is related to the battery, which is tested during the standardized tests in the laboratory. I have identified two factors at this level: *Occurrence* (experience related number of events, or assumed occurrence of events) and *Controllability* (product level control of dangerous Li-ion battery events). The system level focuses on the whole measurement environment: product and process. At this level, I have introduced the combined *Severity/Cost* factor. The *Severity* factor stands for the seriousness of a possible event, and cost factor is related to the maintenance costs of the test environment (measurement devices and the laboratory itself). The proposed model eases the calculation as well as it is a fuzzy solution and saves time, which is an important aspect in practical, everyday engineering work. In the following, I present my published research results [P11].

3.1 Description of the Hierarchical Overall Risk Analysis (HORA) model

The proposed risk analysis method is based on the consideration that all levels of the traditional Failure Mode and Effects Analysis need to be involved but in a different manner (Fig. 18). It introduces a hierarchical point of view, an overall aspect of the test process.

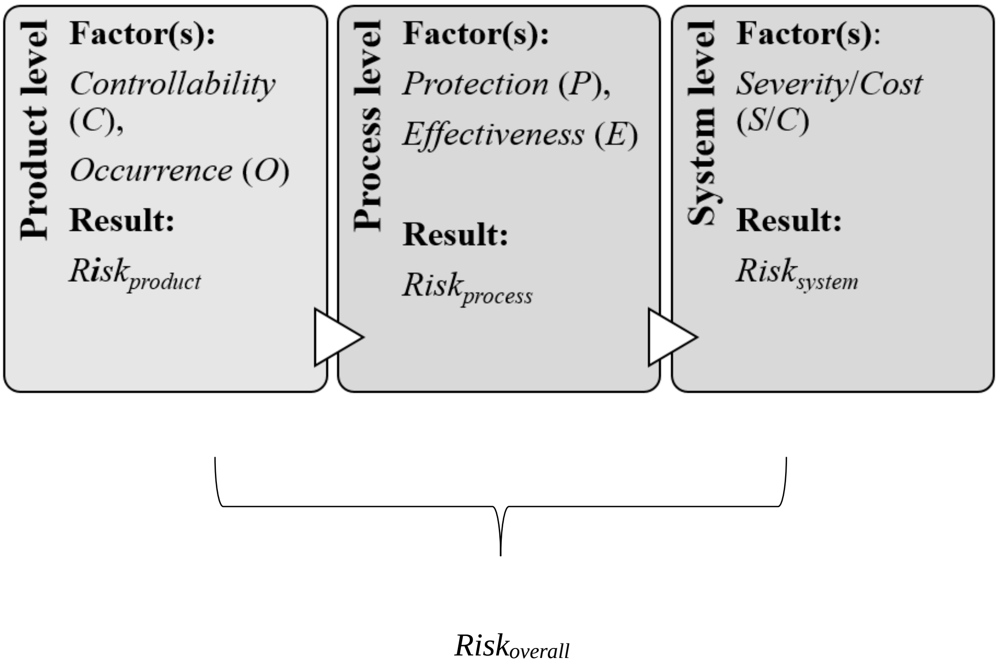


Fig. 18 Consideration of analysis levels

(*Edited by Author*)

With the usage of the traditional FMEA approaches analysis focuses on the system, design (product) or process level. In practice the connection between the analyses is created with the linkage of the higher level (e.g. design level) failure effects to the lower level failure modes (e.g. process level). This solution fits the purpose of those companies that develop, plan and manufacture the products. In case of those companies that offer engineering services such as the testing of batteries this linkage is not sufficient as the input (design –product- FMEA) is often missing or inappropriate. The other issue is that the process related analysis focuses on problems, which occur during the testing process, not on the structural risks.

The proposed method combines the advantages of design level and process level analysis, as the used factors are derived from different structural levels. Instead of using the original three factors: *Severity*, *Occurrence*, and *Detection* the new model uses five factors: *Controllability* (C), *Occurrence* (O), *Protection* (P), *Effectiveness* (E), and *System*/*Cost* (S/C).

In Fig. 19, I represent the basic concept of the HORA model. The model consists of three subsystems:

- Fuzzy subsystem$_1$: where the inputs are: *Controllability*, *Occurrence* and the output is $Risk_{product}$,
- Fuzzy subsystem$_2$: where the inputs are: $Risk_{product}$, *Protection*, *Effectiveness* and the output is $Risk_{process}$,
- Fuzzy subsystem$_3$: where the inputs are: $Risk_{process}$, *System*/*Cost* and the output is $Risk_{overall}$.

The Hierarchical Overall Risk Analysis model aims to analyze the risks of the Li-ion battery related abuse testing processes. The model assumes the existence and availability of the mandatory fire and explosion safety analysis. The causes of battery-related technical events are analyzed on levels: product level, process level and system level. Product level is considered as the cause level, process is considered as the failure mode level and system level as the effect level of the hierarchical system.

HORA combines the advantages of design level and process level analysis as the used factors are derived from different structural levels. The model uses five factors: *Controllability* (*C*), *Occurrence* (*O*), *Protection* (*P*), *Effectiveness* (*E*), and *System*/*Cost* (*S*/*C*). Severity and Cost factors are related to the battery-related technical event impacts. These two factors are interpreted together as every severity case has its cost-related effect as well. The basic concept of HORA is presented in Fig. 19.

The first fuzzy subsystem provides the causes, which are related to product behavior and construction. Its first input factor (*C*) scales the risks of built-in product controls. These product features help to protect the battery from potential hazardous behavior during abuse tests. The built-in control measures are as follows: low level controls (e.g. cell level protection), medium level controls (e.g. fuses, thermal fuses and safety vents) and high level controls (e.g. Battery Management System, Battery Thermal Management System). The second input factor is *O*, which has three levels: low, medium and high. The output is $Risk_{product}$ that summarizes and merges product level hazards and risks. The second fuzzy subsystem uses $Risk_{product}$, *P* and *E* as inputs. *Protection* and *Effectiveness* are related to the standardized abuse testing processes that are carried out in the test laboratory. This subsystem analyses the risks of the product and the process at once. The output of the second subsystem is called $Risk_{process}$. The third fuzzy subsystem takes product, process and system related aspects into account, as the inputs are $Risk_{process}$ and *S*/*C*. The outcome of HORA is numerical and can be defined as the acceptance criteria of the system.

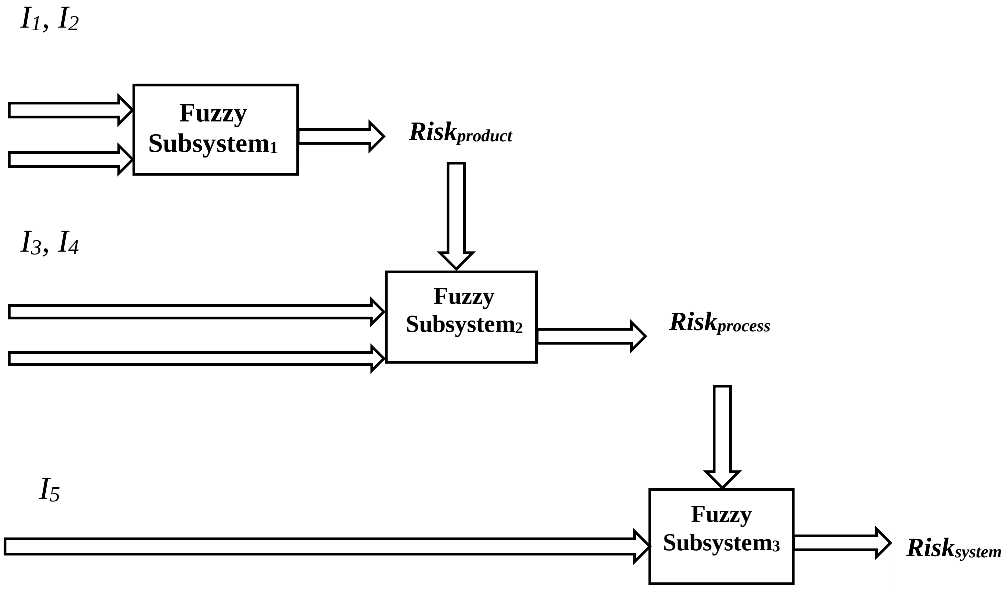


Fig. 19 Hierarchical Overall Risk Analysis (HORA) model explained

(*Edited by Author*)

The final outcome of the HORA method is numerical, which can be defined as the acceptance criterion of the system. The advantage of the HORA method is that the final acceptance criterion can be changed. It can be flexibly modified as the result of the present business conditions and new inquiries. In practice it means, that based on the existing laboratory safety options the test engineers can decide on the acceptable risk. In this case, the acceptable and tolerable risk is the risk source that does not affect personal safety and the lead-times of the parallel test processes.

3.1.1 Evaluation of *Controllability* and *Occurrence* criteria

Controllability and *Occurrence* refer to the product level; *Controllability* analyses the present control solutions of the test sample, Occurrence represents the possibility of hazardous effects (based on the type of the Lithium-ion cells used).

In Table 18, I present the classification catalogue of *Controllability* and *Occurrence* factors. For both factors, three levels are defined. Controllability may have three evaluation levels: *High* (which represents the ‘safest’ battery system constructions, e.g. BMS or BTMS included), *Medium* (simple safety solutions are represented in the sample, e.g. thermal fuse/fuse or safety vent) and *Low* (in this case, only cell level safety is present in the sample). For the definition of *Occurrence* level, I have used the same three level approach: *High* (if three or more tests result in technical events), *Medium* (if two tests out of ten result in technical events) and *Low* (if one or no tests result in technical events out of ten).

Table 18 *Controllability* and *Occurrence* rating catalogue (Edited by author)

Fuzzy s.	Parameters	*Controllability* (*C*)	*Occurrence* (*O*)
L	{1.00, 1.00, 5.50}	**HIGH:** high product level control, e.g. Battery Thermal Management System (BTMS) in sample and/or Battery Management System (BMS) in sample	**HIGH:** occurrence is considered high, if three or more test result in technical events out of ten occasions (in case of similar battery constructions).
M	{1.00, 5.50, 10.00}	**MEDIUM**: medium product level control, e.g. Thermal fuse/fuse or safety vent in sample	**MEDIUM:** occurrence is considered medium, if two tests result in technical events out of ten occasions (in case of similar battery constructions).
H	{5.50, 10.00, 10.00}	**LOW**: low product level control, e.g. only cell level protection	**LOW:** occurrence is considered to be low, if one or no test results in technical events out of ten occasions (in case of similar battery constructions).

As technical events are part of normal operation of battery testing laboratories, the laboratory environment have to be prepared for sudden abuse tests related/triggered events. Although, experience- and knowledge-based prediction of *Controllability* and *Occurrence* levels are useful for the laboratory personnel. There are cases in which the reconstruction/cleaning cost is not acceptable and the strict lead-times do not allow the stoppage of the tests due to a severe event.

To allow further differentiation between the three levels for the experts I have introduced the following numbering: low (1-2-3), medium (4-5-6) and high (7-8-9-10).

3.1.2 Evaluation of *Protection* and *Effectiveness* criteria

Protection (P) and *Effectiveness* (E) refer to the process level as they analyze the outcome of the testing process. *Protection* stands for the existing laboratory safety solutions, while *Effectiveness* stands for the effectiveness of the laboratory safety solutions. I have defined a three level scaling both for *Protection* and for *Effectiveness* (Table 19).

Table 19 Protection and Effectiveness rating catalogue (Edited by author)

Fuzzy s.	**Parameters**	***Protection* (*P*)**	***Effectiveness* (*E*)**
L	{1.00, 1.00, 5.50}	**HIGH**: several prevention actions exist (e.g.: explosion proof chamber, etc.)	**HIGH**: risks are clear and understood, proven effective protection devices are available.
M	{1.00, 5.50, 10.00}	**MEDIUM**: some prevention actions exist (e.g.: extinguishing system, gas detector sensors, etc.)	**MEDIUM**: unknown phenomenon can occur, prevention measures are existing, without proven result.
H	{5.50, 10.00, 10.00}	**LOW**: No/few prevention action or protective devices exist	**LOW**: Laboratory related risks are unknown, no proven effective protection devices are available.

Protection level (laboratory protection solutions to avoid battery related events) is scaled based on the following approach:

- Low: No/few prevention actions or protective devices exist,
- Medium: Some prevention actions exist (e.g. extinguishing system, gas detector sensors, etc.),
- High: Several prevention actions exist (e.g. explosion proof chamber, etc.)

Effectiveness (effectiveness of laboratory protection solutions) is scaled based on the following approach:

- Low: Laboratory related risks are unknown, no proven effective protection devices are available,
- Medium: Unknown phenomenon can occur, prevention measures exist, without proven result,
- High: Risks are clear and understood, proven effective protection devices are available.

To allow further differentiation between the three levels for the experts, I have introduced the following numbering: Low (1-2-3), Medium (4-5-6) and High (7-8-9-10).

3.1.3 Evaluation of *Severity/Cost* criteria

In this section, I introduce the recommended *Severity/Cost* criteria (rating catalogue). However, in advance the risk sources have to be represented as well. In my thesis, I have taken three standardized test sequences into consideration:

- UN 38.3 (United Nations manual on hazardous materials transport tests and standards, part3, section 38.3: current version: Seventh edition, 2019) ,
- IEC 62133-2 [15] (Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary lithium cells, and for batteries made from them, for use in portable applications - Part 2: Lithium systems, current version: IEC 62133-2:2017+AMD1:2021) ,
- IEC 62281 (Safety of primary and secondary lithium cells and batteries during transport, current version: IEC 62281:2019+AMD1:2021).

In Table 20, I compare the test steps of each aforementioned standard (both cell level and battery level). UN 38.3 is a mandatory requirement for transportation of batteries (similar requirements as IEC 62281), IEC 62133-2 is required for safety tests of portable Li-ion batteries.

As it can be observed there are three big test groups mentioned in the table: electrical tests (external short circuit, abnormal charge and forced discharge test), mechanical tests (crush, impact, shock, vibration, low pressure and drop test) and thermal tests (heating, temperature cycling and projectile test). The basic test setup is the same, only the test parameters differ in some cases.

Table 20 Comparison of UN and IEC test criteria [57]

Test criteria standard	**UN 38.3** [6]	**IEC 62133-2** [15]	**IEC 62281** [14]
External short circuit	•	•	•
Abnormal charge	•	•	•
Forced discharge	•	•	•
Crush		•	
Impact	•		•
Shock	•	•	•
Vibration	•	•	•
Heating		•	
Temperature cycling	•	•	•
Low pressure (altitude)	•	•	•
Projectile		•	
Drop		•	•
Continuous low-rate charging		•	

In Table 21, the detailed test processes (according to UN 38.3) are described. As the table above shows, the test processes intended to simulate abuse conditions. These can be caused either by the consumer (e.g. short circuit and overcharge test) or during transportation (e.g. altitude, vibration and shock test) (UN 38.3, 2019).

During these tests the laboratory personnel is subjected to hazardous environmental circumstances: to batteries that are prone to catch fire or even explode in the worst case. The main electrochemical process is related to the phenomena of thermal runaway. Thermal runaway is the result of electrical, mechanical and thermal abuse conditions. Thermal runaway has five major causes triggered by the abuse conditions; these are represented in Fig. 20.

Typical causes of thermal runaway:

- uncontrollable internal heat generation (side reactions happen due to oxygen release from cathode material),
- separator defects cause short circuits (chemical chain reactions occur with excessive heat transfer),
- electrolyte decomposition causes heat accumulation and release of oxygen (caused by the cathode and separator damage),
- local thermal abuse causes electromechanical side reactions,
- battery short-circuit and air penetration due to battery mechanical battery damage.

Table 21 UN 38.3 tests T.1 to T.8 for lithium cells and batteries prior to being transported [6]

Test steps	Test type	Specific procedures
Test T.1	**Altitude simulation**	Test cells and batteries stored at a pressure of 11.6 kPa or less for at least 6 h at ambient temperature (20 ± 5 °C).
Test T.2	**Thermal**	Rapid thermal cycling between high (75 ± 2 °C) and low (−40 ± 2 °C) storage temperatures, stored for at least 6 h at the test temperature, time interval between high and low test temperature change less than 30 min.
Test T.3	**Vibration**	The vibration is a sinusoidal waveform with a logarithmic sweep between 7 Hz (1 g_n peak acceleration) and 200 Hz (8 g_n peak acceleration) and back to 7 Hz; 12 times cycle, 3 mutually perpendicular mounting positions.
Test T.4	**Shock**	Subjected to a half-sine shock (150 g_n peak acceleration) and pulse duration (6 ms); 3 shocks cycling in the positive and negative directions for each of 3 mutually perpendicular mounting positions (total of 18 shocks).
Test T.5	**External short circuit**	Short circuit with a total external resistance of less than 0.1 Ω at (55 ± 2 °C), 1 h duration.
Test T.6	**Impact**	A 15.8-mm-diameter bar placed across the sample cell center, and a 9.1-kg mass is dropped from a height of (61 ± 2.5 cm) onto the sample.
Test T.7	**Overcharge**	Overcharging test should be conducted for 24 h with charge current (twice the manufacturer's recommended maximum) and minimum test voltage. The minimum test voltage is defined in two categories (a) when recommended charge voltage ≤18 V and (b) when recommended charge voltage >18 V: Both categories are further explained as: (a) the lesser of 22 V or 2 times the maximum charge voltage or, (b) 1.2 times the maximum charge voltage.
Test T.8	**Forced discharge**	Each cell is forced discharged by connecting it in series with a 12 V DC power supply at an initial current equal to the maximum discharge current specified by the manufacturer.

Amongst the aforementioned causes, short-circuits due to separator damage or electrical abuse and mechanical abuse are the main causes of Li-ion battery related accidents.

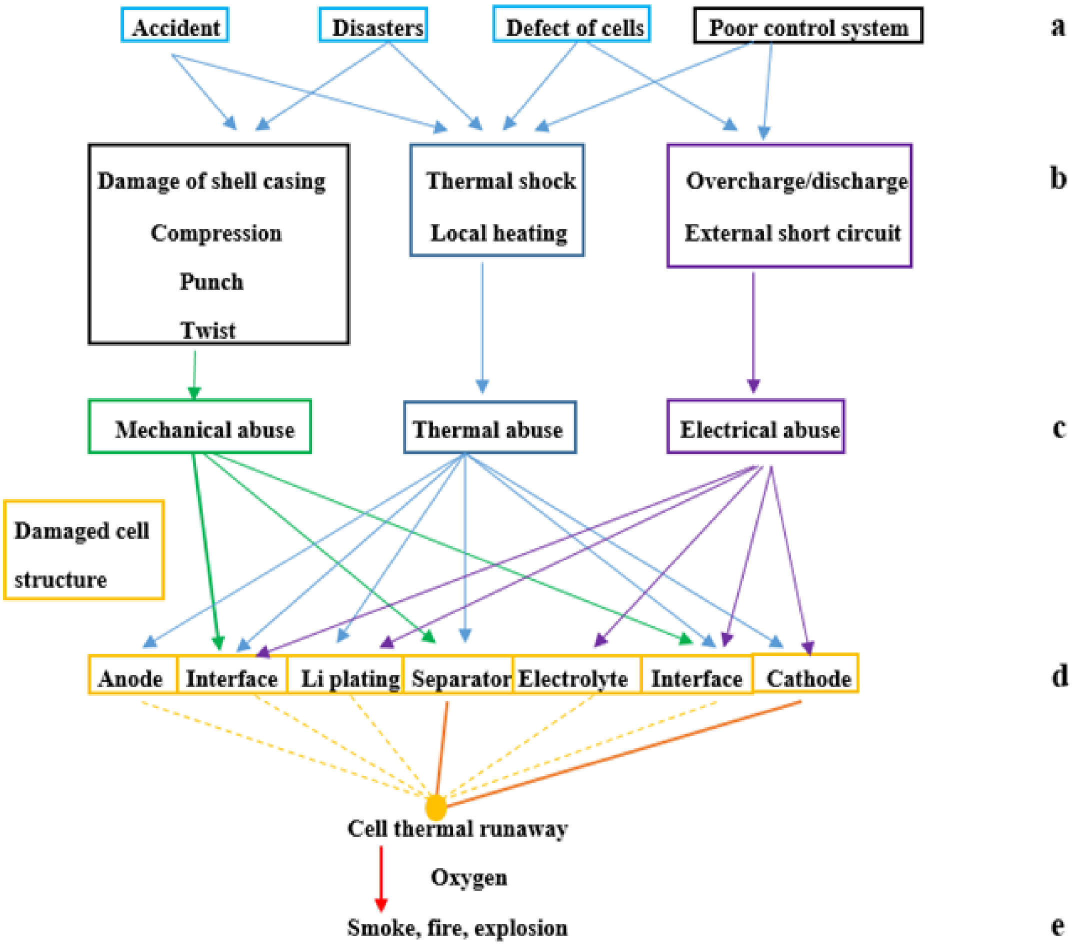


Fig. 20 Battery accidents related to accidents, disasters, and defect on cell level and poor control systems [58]

In Fig. 21, actual Li-ion battery related accidents are presented. In figure 1 (Fig. 32) the result of a collision related internal short-circuit can be seen (the vehicle caught fire). In picture 2 (Fig. 21) the vehicle fire was caused by overcharging of the battery (this resulted in thermal runaway). In picture 3 (Fig. 32), during the operation of the battery excessive heat occurred which stared the chain reaction of thermal runaway. In figure 4 (Fig. 32) the battery of the vehicle received thermal shock which resulted again in thermal runaway [58].

Mechanical abuse Electrical abuse

Thermal abuse Thermal shock

Fig. 21 Actual Li-ion battery related vehicle accidents [58]

As it can be seen in Fig. 21 abuse conditions, and even construction problems result in hazardous battery behavior. This is very spectacular in case of automotive batteries but in the case of handheld tools, mobile phones and notebooks the same phenomena occurs with similar hazardous consequences. Laboratory personnel are subjected to these hazards; therefore, it is inevitable that proper and customized preliminary risk analysis is one of the most important activities.

It is important to note that automotive Li-ion cells and batteries are subjected to other test sequences as well (besides UN 38.3) based on the following standards for example:

- SAND 2005-3123 (Electrical energy storage system abuse test, Manual for electric and hybrid electric vehicle applications),
- SAE J2464 (Electric and hybrid vehicle rechargeable energy storage system safety and abuse testing),
- GB/T31485 (Safety requirements and test methods for traction battery of electric vehicles),
- ISO 16750-2 (Road vehicles - environmental conditions and testing for electrical and electronic equipment - part 2: electrical loads),
- IEC62660–2 (Secondary Lithium Ion Cells for the propulsion of electric road vehicles – part 2:reliability and abuse testing),
- UL 2580 (Battery safety standards for electric vehicles),

- GM-Modified USABC (General motors battery test standard for electric vehicles),
- VW PV 8450 (Volkswagen battery test standards for electric vehicles) and
- SMTC9 N20011 (Electrochemical performance test specification of electric vehicles for lithium-ion battery) [59].

During these tests the laboratory personnel is subjected to hazardous environmental circumstances. For example, batteries are prone to catch fire or even to explode in a worst-case-scenario. These scenarios are mainly due to the thermal runaway phenomenon (a complex electrochemical effect). Thermal runaway is the result of electrical, mechanical and thermal abuse conditions.

The suggested approach for severity and cost rating is presented in Table 22. Supposing triangle shaped membership functions the parameters of the sets associated to the individual levels are given as well. In case of this catalogue three aspects have to be considered together because probable accidents have consequences in three different aspects: (a) laboratory environment related effects due to standardized tests ($S_{laboratory}$); (b) laboratory personnel related effects ($S_{personnel}$); and (c) the cost of damages (*Cost*). The combined *S*/*C* catalogue can be adjusted based on the existing laboratory setup and safety solutions.

Table 22 Severity/Cost catalogue (Edited by author)

Fuzzy s.	**Parameters**	$S_{laboratory}$	$S_{personnel}$	***Cost***
NE	{1.00, 1.00, 2.29}	No effect in the testing environment.	No effect in the testing environment, no health effect.	No effect in the testing environment, no costs occur.
VL	{1.00, 2.29, 3.57}	Melted plastic parts in chamber, cleaning necessary.	Potential effects on respiration, health hazards	Chamber cleaning required, cleaning costs occur.
L	{2.29, 3.57, 4.86}	Release of excessive internal pressure from a cell or battery in a manner intended by design to preclude rupture or explosion; excessive amount of melted plastic parts in chamber, cleaning necessary	Effects on respiration, heat hazards.	Chamber cleaning required, cleaning costs occur, service downtime.

Fuzzy s.	**Parameters**	$S_{laboratory}$	$S_{personnel}$	***Cost***
ML	{3.57, 4.86, 6.14}	Unplanned, visible escape of liquid electrolyte; minor gas leakage in the environment; smoke in the test environment	Long-term effects on respiration, heat hazards.	Cleaning of test environment is required, service downtime.
M	{4.86, 6.14, 7.43}	Major gas leakage in the environment; smoke in the test environment	Long-term effects on respiration, effects on vision, heat hazards.	Cleaning of test environment is required, possible damaged test equipment in the room, excessive service downtime.
MH	{6.14, 7.43, 8.71}	Mechanical failure of a cell container or battery case induced by an internal or external cause, resulting in exposure or spillage but not ejection of materials; fire in the test environment	Potential burn hazard.	Possible damaged test equipment in the room, dust accumulation, excessive service downtime.
H	{7.43, 8.71, 10.00}	Emission of flames from a cell or battery; fire, flying parts in the test environment	Burn hazard, cut injuries.	Damaged test equipment in the room, dust accumulation, excessive service downtime.
VH	{8.71, 10.00, 10.00}	Cell container or battery case opens violently and major components are forcibly expelled; explosion in the test environment	Worst case scenario: death.	Purchase of new test chamber is necessary, dust accumulation, excessive service downtime.

If we are representing Li-ion battery hazard categories, we cannot dismiss EUCAR hazard scaling. EUCAR (European Council for Automotive R&D) is a council in which the heads of research and development of the members companies are represented. Members are: Volvo Group, BMW Group, CNH Industrial, DAF, Fiat Chrysler Automobile, Ford, Honda, Hyundai, Land Rover, Jaguar PSA Renault Groupe, Toyota and Volkswagen [60].

Since nowadays EVs (electric vehicles) are using Li-ion batteries, there is strong focus on their safety as well. EUCAR implemented its own severity catalogue [61]. This severity catalogue uses eight levels from 0 to 7. The severity categories are the following: No effect, Passive protection activated, Defect/damage, Leakage Δ<50%, Venting Δ>50%, Fire and flame, Rupture and Explosion.

As it can be seen, there is strong connection between the IEC and UN 38.3 severity categories, the difference being at level 1 (passive protection activated instead of deformation) and at level 3 (Leakage Δ<50%) and at level 4 (Venting Δ>50%), where there is threshold given.

Table 23 EUCAR hazard levels [61]

Hazard level	**Description**	**Classification criteria and effects**
0	No effect	No effect, no loss of functionality
1	Passive protection activated	No defect, no leakage, no venting, fire or flame, no passive protection rupture, no explosion, no exothermic reaction or thermally activated runaway. Cell reversibly defected. Repair or protection device needed.
2	Defect/damage	No leakage, no venting, fire or flame, no rupture, no explosion, no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ<50%	No venting, fire or flame, no rupture, no explosion. Weight loss <50% of electrolyte weight (electrolyte=solvent + salt)
4	Venting Δ>50%	No fire or flame, no rupture, no explosion.
5	Fire and flame	No rupture, no explosion (i.e., no flying parts)
6	Rupture	No explosion, but flying parts of the active mass
7	Explosion	Explosion (i.e., disintegration of the cell)

3.1.4 Fuzzy Membership Functions

The universe of discourse of all input and output variables is [1, 10], and the membership functions are triangular shaped described by the general equation (3.1)

$$\mu = \begin{cases} \max\left(\dfrac{x-a}{b-a}, 0\right), & x \le b \\ \max\left(\dfrac{c-x}{c-b}, 0\right), & otherwise, \end{cases} \tag{3.1}$$

where a, b, and c are the abscissa values of the breakpoints conform Fig. 22.

The linguistic terms and the parameters of the membership functions of the variables *C*, *O*, *P*, *E*, and *S*/*C* are presented in Tables 18, 19, and 22, respectively. The variables $Risk_{product}$, $Risk_{process}$, and $Risk_{system}$ have identical partitions with the variable *C*. The two types of fuzzy partitions are represented in Fig. 23**232323**.

3.1.5 Risk Assessment Matrices of Fuzzy subsystems

In the HORA model, the rules were defined based on the expertise of specialists that had been working on this field for several years. All fuzzy subsystems use Mamdani type inference, and centroid type defuzzification was applied. The rules of the fuzzy subsystems are presented in Tables 24, 25, and 26, respectively.

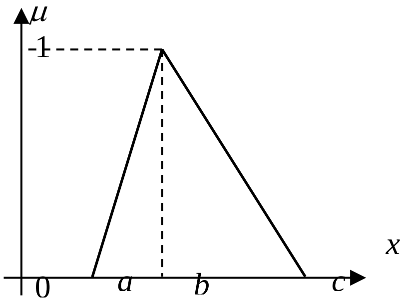


Fig. 22 Triangle shaped membership function and its parameters

(*Edited by Author*)

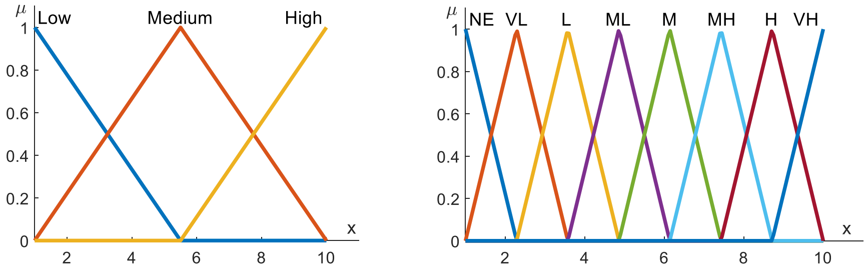


Fig. 23 Fuzzy partitions (*Edited by Author*)

Table 24 Risk Assessment Matrix of the first fuzzy subsystem (*Edited by Author*)

$Risk_{product}$	***Occurrence***			
Controllability		HIGH	MEDIUM	LOW
	HIGH	MEDIUM	MEDIUM	LOW
	MEDIUM	HIGH	MEDIUM	MEDIUM
	LOW	HIGH	HIGH	MEDIUM

Table 25 Risk Assessment Matrix of the second fuzzy subsystem (*Edited by Author*)

$Risk_{product}$ **HIGH**	**Effectiveness**			
		HIGH	MEDIUM	LOW
Protection	HIGH	MEDIUM	MEDIUM	HIGH
	MEDIUM	MEDIUM	HIGH	HIGH
	LOW	HIGH	HIGH	HIGH

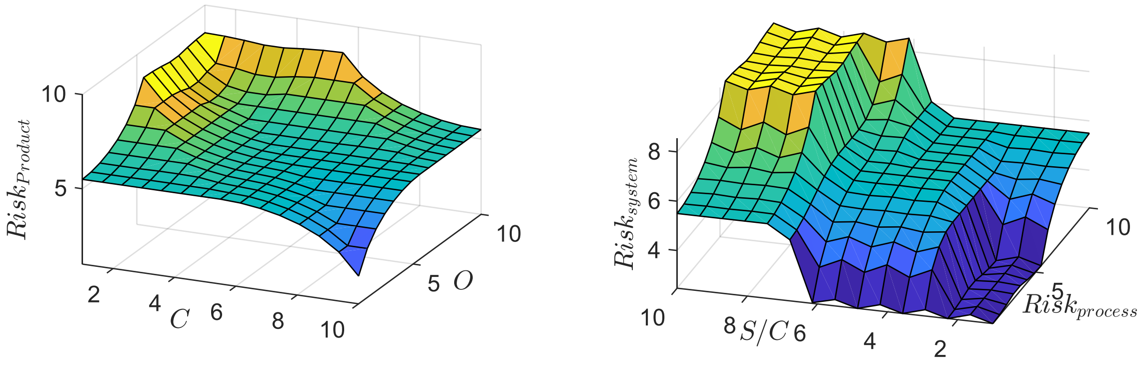
$Risk_{produc}t$ **MEDIUM**	**Effectiveness**			
		HIGH	MEDIUM	LOW
Protection	HIGH	MEDIUM	MEDIUM	MEDIUM
	MEDIUM	MEDIUM	MEDIUM	HIGH
	LOW	MEDIUM	HIGH	HIGH

$Risk_{product}$ LOW	**Effectiveness**			
		HIGH	MEDIUM	LOW
Protection	HIGH	LOW	LOW	MEDIUM
	MEDIUM	LOW	MEDIUM	HIGH
	LOW	MEDIUM	MEDIUM	HIGH

Table 26 Risk Assessment Matrix of the third fuzzy subsystem (*Edited by Author*)

	Severity/Cost								
		VERY HIGH	HIGH	MEDIUM-HIGH	MEDIUM	MEDIUM-LOW	LOW	VERY LOW	NO EFFECT
$Risk_{process}$	H	H	H	H	H	M	M	M	M
	M	H	H	H	M	M	M	L	L
	L	M	M	M	L	L	L	L	L

The hierarchical HORA model was implemented in Matlab using the Fuzzy Logic Toolbox. The output of the subsystems in function of the input values can easily visualized by a surface in case of the first and the third ($Risk_{product}$ and $Risk_{system}$) subsystems (Fig. **24** (a) and (b)).



(a) (b)

Fig. 24 Visualization of the output of the first (a) and third (b) fuzzy logic subsystems (*Edited by author*)

In case of the second subsystem (*Risk*$_{process}$) the results are shown on a different type of graph. As a 4D approach is not possible, the value of the output is calculated, and the colour of the dots represent the value of the output (Fig. 25).

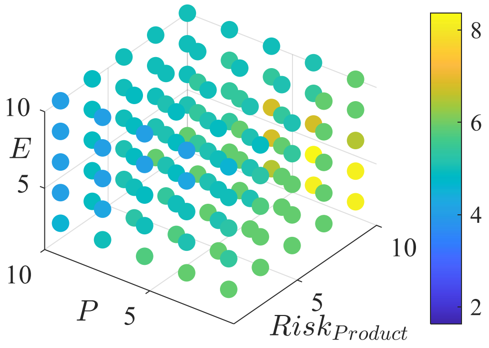


Fig. 25 Visualization of the output of the second fuzzy logic subsystems (*Risk*$_{process}$) (*Edited by author*)

For the better understanding of HORA I present the membership values associated to the scores in case of the *Controllability*, *Occurrence*, *Risk*$_{product}$, *Protection*, *Effectiveness*, *Risk*$_{process}$ and *Risk*$_{system}$ variables and the membership values associated to the scores in case of the *Severity*/*Cost* variable in Annex I.

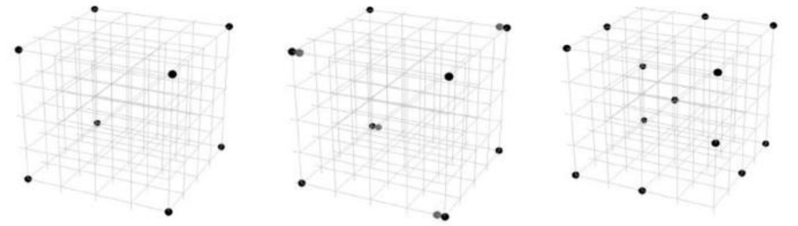
3.1.6 Validation of the HORA model

For the validation of the HORA model, I have used a DoE (Design of Experiment approach). DoE was primarily invented for agricultural purposes [62] but this statistical approach is widely used nowadays. DoE analyses factors and levels, it is a tool for validation (instead of straightforward identification of design).

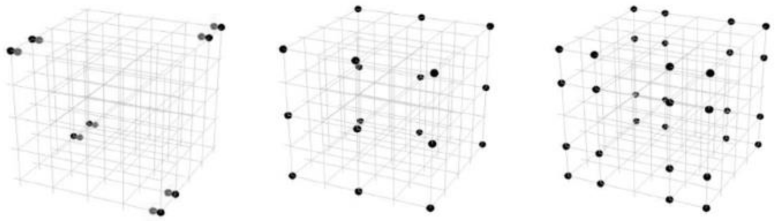
There are different DoE methods existing:

- Taguchi design (TD)- the applied approach in our study,
- Placket Burman design (PBD) – third-level resolution designs, which considers only the main effects,
- Definite screening design (DSD) - which introduces third, middle level for continuous factors,
- Central-composite design (CCD) - used for narrowing down factors,
- Box-Behnken design (BBD) - similar to CCD, but requires lee experimental runs,
- and Full-factorial design (FFD) - consists of all possible combination of factors and levels (Fig. 26) [62].

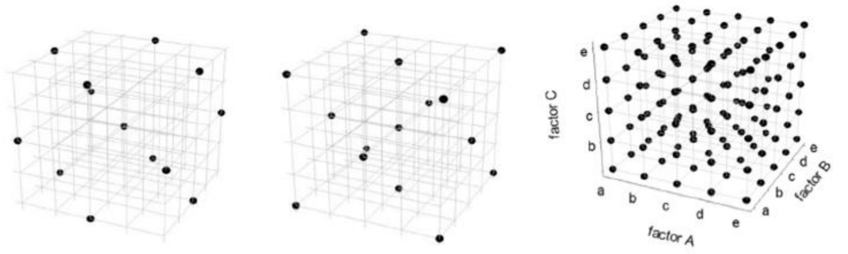
In my work, I have used the Taguchi method for DoE. The Taguchi design earned a divided reception in the scientific community but it is indeed a practical approach for experimental design. Its advantages are orthogonal arrays. The factors levels are balanced, which reduces the factor levels. This helps to optimize the required number of experimental runs.



Taguchi 2Lx3F (L8) Placket Burman design (PBD) Definitive screening design (DSD)



Taguchi 2L+4Lx2F (L16) Taguchi 2L+3Lx2F (L18) Taguchi 2L+4Lx2F (L32)



Box–Behnken design (BBD) Central-composite design (CCD) Full-factorial design (FFD)

Fig. 26 Different Design of Experiment (DoE) approaches [62]

During the validation of the HORA model, I have used DoE (Design of Experiments) considerations. I have carried out the validation with the usage of Taguchi's orthogonal array design (OA). The reason of choice is that the OA is compact "with the least number of combination it delivers the same result as full factorial" Taguchi's approach is an optimized solution, where the degree of freedom is directly proportional to the level of parameters.

In this given case I have used L_{75} 5^8 15^1 experimental design (Annex II). For the three-set variables I have targeted 5 values for the 8-set variables (values between the current peak point and values between them).

3.1.7 Model validation

The validation of the HORA model was done by the help of experienced Li-ion battery test engineers. First, in case of each factor several values were selected for later trial. Five levels were determined for the factors *Controllability*, *Occurrence*, *Protection*, and *Effectiveness* as well as fifteen levels for *Severity*/*Cost*, respectively. The key idea was to include values with maximal membership value in a fuzzy set as well as values at the intersection of two neighbouring membership functions. Considering these values there are in total 9 375 possible arrangements, which would mean a too high number of evaluations for the human experts. Therefore, the design of experiments approach developed by Taguchi [62] was applied to select the lowest possible number of arrangements for actual evaluations. The design $L_{75}\ 5^8\ 15^1$ [63] fitted best the current task. It contains 75 experiments and allows the investigation of at most eight factors with five levels and one factor with fifteen levels. In course of the validation process for each of the 75 value tuples the involved test engineers compared their own $Risk_{system}$ evaluation with output of the system and gave improvement suggestions in questionable cases. Four typical examples are presented in Table 27.

Table 27 Risk evaluation examples (*Edited by author*)

	Controllability	***Occurrence***	***Protection***	***Effectiveness***	***Severity/Cost***	***$Risk_{system}$***
Example 1	1	1	1	1	1	7
Example 2	3	3	10	8	2	3
Example 3	6	3	8	6	9	8
Example 4	8	6	3	10	10	10

Example 1 takes the following case into consideration. The *Controllability* is characterized by low product level control, the *Occurrence* is low, the *Protection* is low, the *Effectiveness* is low, and the *Severity*/*Cost* can be evaluated as no effect and no costs. In this case $Risk_{system}$ is considered to be 7, as *Controllability*, *Protection* and *Effectiveness* have the lowest value, although *Occurrence* and *Severity*/*Risk* level is low.

Example 2 examines the following case. The *Controllability* is low, the *Occurrence* is low, the *Protection* level is good as several prevention actions exist, the *Effectiveness* is characterized by risks are clear and understood, proven effective protection devices are available, and *Severity*/*Cost* is evaluated as deformation or cleaning costs occur. In this case $Risk_{system}$ is considered to be 3 as *Occurrence* level is 3, and the technological events have only *Severity*/*Cost* 2 value.

Example 3 takes the following case into consideration. The *Controllability* level is medium, the *Occurrence* is low, the *Protection* is characterized by the existence of several prevention actions, the *Effectiveness* is evaluated as 6 because unknown phenomenon can occur, the *Severity*/*Cost* level is increased owing the explosion possibility and in worst case scenario death can also occur. In this case $Risk_{system}$ is considered to be 8, because although the *Occurrence* level is 3, the *Severity*/*Cost* value is considered to be 9.

Example 4 examines the following case. The *Controllability* is high, the *Occurrence* is medium, the *Protection* level is low with no/few prevention actions, the *Effectiveness* is high as risks are clear and understood and proven effective protection devices are available, and finally the *Severity*/*Cost* is also high owing to possible explosion in the test environment and in worst case scenario death can also occur. Purchase of new test chamber is necessary, dust accumulation, excessive service downtime is probable. In this case $Risk_{system}$ is considered to be 10, due to medium level of *Occurrence* and high level of *Severity*/*Cost*.

3.2 Chapter summary

During my research, I constructed a new model for the preliminary analysis of lithium-ion battery test laboratories **(H3)**. The model adapts the existing approaches for fuzzy based risk analysis and develops the traditional Failure Mode and Effect analysis.
HORA provides a practical and complex solution for the preliminary risk analysis of Li-ion battery test laboratories **[P11]**. With the introduction of the hierarchical solution and with the implementation of new factors (*Controllability*, *Protection* and *Effectiveness*) a more flexible and reliable risk analysis solution is created.

4 RELATED APPROACHES IN SPECIALIZED LITERATURE

During my research, I have developed and combined different existing analysis methods from specialized literature. The proposed method is a hierarchic fuzzy FMEA approach, based on Ványi and Pokorádi's [64] hierarchic FMEA method, Bona et al.'s Total risk priority number approach [65], Zlateva's [66] fuzzy based risk assessment method, Takács's [67] multilevel fuzzy approach and Soares et al's [68] Risk analysis of stationary Li-ion batteries. Therefore, I review these methods in the following sections.

4.1.1 Ványi and Pokorádi's hierarchical FMEA method

Ványi and Pokorádi introduced the hierarchic FMEA (H-FMEA) approach [64]. Ványi and Pokorádi's method is based on the hierarchic structuring of FMEA with the usage of multidisciplinary elements (hardware-software-mechanical aspects). The aim of this model is to provide a general understanding of system modelling with the proposal of specific system elements. The highest level of analysis the system elements are taken into consideration and they are connecting to lower-level design elements. The proposed model is based on the automotive R&D approaches and uses special characteristics to define the specific factors with high importance (e.g., safety critical components). The middle analysis elements are connected to the hardware and mechanical analysis.

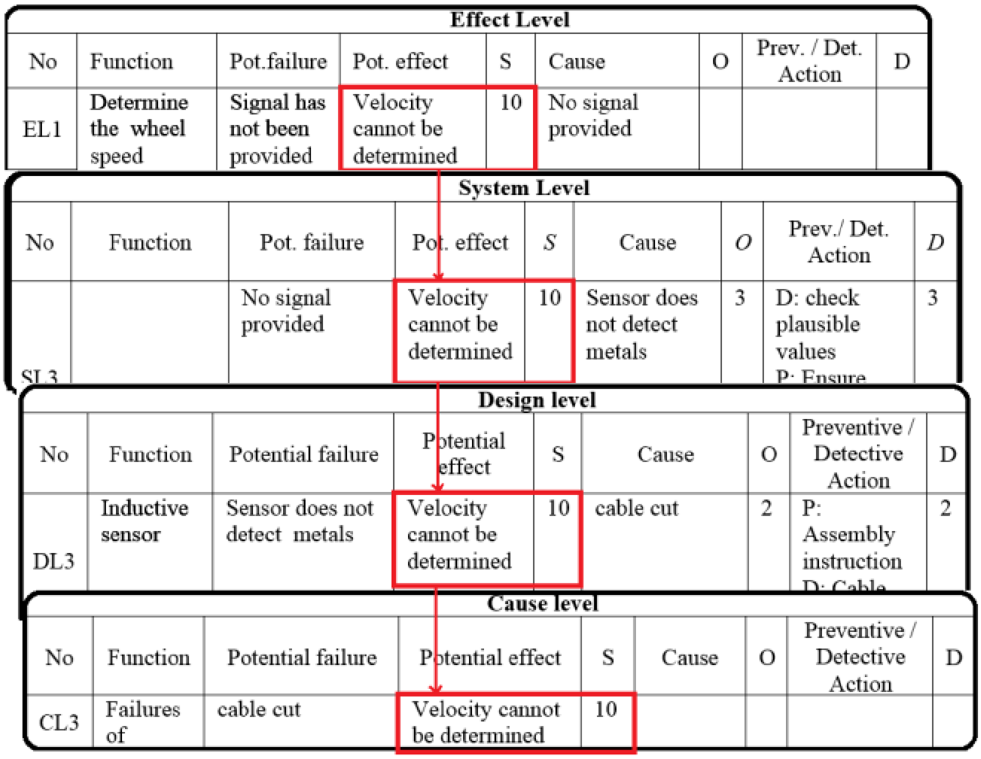
In my thesis, I have taken Ványi and Pokorádi's [64] consideration of hierarchical FMEA into consideration as my suggested model uses the hierarchy of FMEA. System level is the highest, product level is the middle and process level is the lowest part of the hierarchy. System level stands for the laboratory environment, process level refers to the Li-ion battery test process and product level is the battery sample to be tested.

In Fig. 27, the connection of four different levels is shown (hardware-software-mechanical aspects). The H-FMEA consists of different levels (EL: Effect level, SL: System Level, DL: Design Level, CL: Cause Level). The example shows the following failure net of the automotive ABS (Anti-Braking System) risk analysis:

- EL1: Tire speed determination (function) - Speed cannot be determined (effect) (10),
- SL3: Generation of a periodic signal based on wheel rotation (function) - Speed cannot be determined (10),
- DL3: Inductive sensor(function) - Speed cannot be determined (10),

- CL3: Inductive sensor failure- Speed cannot be determined (10) [64].

During the hierarchic FMEA the main restriction is that appears of different levels carry the same meaning and severity in the whole analysis. In this case, it means that the failure mode refereed at the hierarchy level is connected with the net represented by the lower-level failures. (Failure net: failure effect-failure mode-failure cause).



Effect Level

No	Function	Pot.failure	Pot. effect	S	Cause	O	Prev. / Det. Action	D
EL1	Determine the wheel speed	Signal has not been provided	Velocity cannot be determined	10	No signal provided			

System Level

No	Function	Pot. failure	Pot. effect	S	Cause	O	Prev./ Det. Action	D
SL3		No signal provided	Velocity cannot be determined	10	Sensor does not detect metals	3	D: check plausible values P: Ensure	3

Design level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
DL3	Inductive sensor	Sensor does not detect metals	Velocity cannot be determined	10	cable cut	2	P: Assembly instruction D: Cable	2

Cause level

No	Function	Potential failure	Potential effect	S	Cause	O	Preventive / Detective Action	D
CL3	Failures of	cable cut	Velocity cannot be determined	10				

Fig. 27 Ványi and Pokorádi's hierarchical FMEA approach [64]

The aim of Ványi and Pokorádi's H-FMEA model is to minimize the risks of a certain product. The idea's novelty lays in the schematization and the inheritance of risk priority numbers (Table 28).

Ványi and Pokorádi use a qualitative analysis method with fault-tree analysis, and proposes a sensitivity investigation to improve the traditional FMEA approach. For softening of the original FMEA the Action Priority categories are used during the analysis.

Table 28 Evaluation of Action Priority on Design FMEA level VDA [64]

S	O	D	AP	AP justification
9-10	6-10	1-10	H	High priority is given due to safety and / or regulation Effects, which have high or very high occurrence.
9-10	4-5	7-10	H	High priority is given due to safety and / or regulation Effects, which have moderate occurrence.
5-8	4-5	5-6	H	High priority is given due to safety and / or regulation Effects, which include the loss or reduced operation of basic or comfort functions, which have moderate occurrence and moderate detection.
5-8	4-5	1-4	M	Moderate priority is given due to safety and / or regulation Effects, which include the loss or reduced operation of basic or comfort functions, which have moderate occurrence and low detection.
2-4	4-5	5-6	M	Moderate priority due to measurable quality features (appearance, sound, heptics), with moderate occurrence and moderate detection.
2-4	4-5	1-4	L	Low priority due to measurable quality features (appearance, sound, heptics), with moderate occurrence and low detection.
1	1-10	1-10	L	Low priority due to undetectable effect.

In the Action Priority catalogue (Table 28), 7 different levels are taken into consideration. Three categories defined as High Risk levels (S: 9-10, O:6-10,D:1-10; S:9-10,O:4-5, D:7-10; S: 5-8, O: 4-5,D: 5-6), two categories defined as Moderate Risk levels (S: 5-8, O: 4-5, D:1-4; S: 2-4, O: 4-5, D: 5-6) and two categories defined as Low Risk levels (S: 2-4, O:4-5, D:1-4; S:1, O:1-10, D:1-10) (Ványi, G. and Pokorádi, L., 2018) .

In the proposed model, I have taken Ványi and Pokorádi's hierarchical FMEA method into consideration. I have created a modified H-FMEA method, in which three different levels are considered: System level (the test environment and the test personnel regarded as a system), Product level (the battery to be tested) and Process level (Li-ion battery UN38.3 transport safety testing). During the analysis, the whole UN38.3 transport safety battery testing process or partial test evaluation can be taken into consideration, and each analysis level carries the same understanding of failures. The usage of Action Priority (AP) categories in Ványi and Pokorádi's approach is similar to the fuzzy approach of my proposed model.

Ványi and Pokorádi's [64] idea's novelty lies in the schematization and the inheritance of risk priority numbers. In our paper, Ványi and Pokorádi's [64] approach of hierarchical FMEA has been taken into consideration, as the HORA model uses the hierarchical structure of FMEA. The difference between Ványi and Pokorádi's [64] approach and the HORA model lies in the fact that the aim of our method is to provide a laboratory related preliminary analysis, not a product level safety analysis.

4.1.2 Bona et al.'s Total risk priority number (TERPN) approach

Bona et al.'s [65] method is an improvement of the traditional FMEA method, as it uses significant number of influencing factors and it is easy to apply and provides accuracy in risk analysis.

Bona et al.'s [65] proposed method combines the complex SIRA (Safety Improve Risk Assessment) method with the FMECA (Failure Mode, Effect and Criticality Analysis) method and with the AISS method.

The SIRA method is a type of analytic hierarchic analysis. In this case the decision making-problem consists of n alternatives ($A_1, \ldots, A_n$) and m criteria ($C_1, \ldots, C_m$). The model uses a pairwise comparison where the result is $c_{(ij)}$, that is defined as the dominant factor. The dominant factor represents an estimate *a* criterion, *i* compared to *j* ($i, j=1, \ldots m$)). The relevant importance between the elements is to provide the pairwise comparison [65].

In Fig. 28 the visual interpretation can be seen. There are three different categories of Detection measures in this case: *E1* (immediate actions), *E2* (risk awareness), *E3* (possibility of intervention).

With the usage of the matrix (Fig. 29) during the calculation, the absolute priority weights (vector w) are defined.

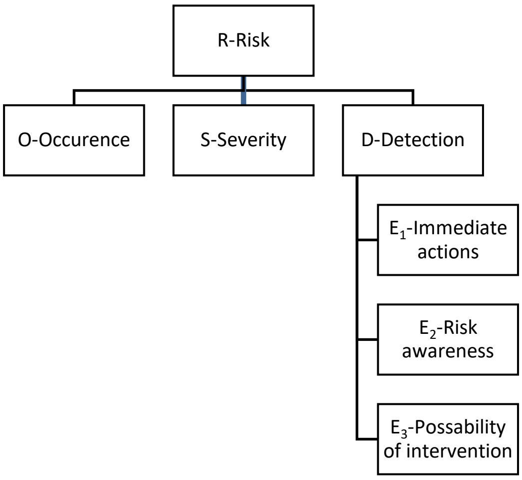


Fig. 28 AHP (Analytic Hierarchy Process) model for risk assessment [65]

$$\begin{bmatrix} 1 & A_{12} & A_{13} & \dots & \dots & \dots & \dots & A_{1n} \\ 1/A_{12} & 1 & \dots & \dots & \dots & \dots & \dots & \dots \\ 1/A_{13} & \dots & 1 & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & 1 & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & 1 & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & 1 & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & 1 & \dots \\ 1/A_{1n} & \dots & \dots & \dots & \dots & \dots & \dots & 1 \end{bmatrix} \begin{vmatrix} w_1 \\ w_2 \\ w_3 \\ \dots \\ \dots \\ \dots \\ w_n \end{vmatrix} = \mathrm{A\ W}$$

Fig. 29 Matrix for SIRA method [65]

With the usage of the method, R (risk) can be calculated with the following equation:

$$\mathrm{R} = \mathrm{w_d}\,\mathrm{D} + w_f \mathrm{F} + w_e \mathrm{E} \tag{4.1}$$

where w_d, w_e,w_f are weights relating to D, E and F.

During the analysis, the calculation is done for each lower level. The synthetic risk index for each hazard and for each source of danger is calculated in this manner.

The aim of the aforementioned model is to compare the various parameters to help identifying choices and actions based on set priorities. The SIRA method has been used for the evaluation of computer virus spread (stochastic model, Amador, 2014), environmental risk assessment of E –waste (modified SIRA method, Hameed et al., 2020), occupational health and safety in construction industry (modified SIRA method, Khan et al., 2019), etc.

The advantages of the SIRA model are that it provides integration between objective and subjective factors with the usage of hierarchical risk assessment (distribution of point values are used). The disadvantages are difficulties in application and the strong link between result and hierarchical structure.

The disadvantages are to be solved with the integration of the FMECA method, although Kanzode et al. considered it as a biased proactive approach. In Bona et al.'s [65] model this is solved by the usage of several factors. The critical point of applying FMECA is the choice of corrective actions for the reduction of the highest RPN values. This issue can be solved with the usage of Fleischer et al.'s proposed approach (cost-effectiveness curve), that focuses on prevention instead of protection [65].

Bona et al.'s [65]method consists of the following steps:

- Step 1: Identification of risk areas (focusing on tasks, machines, products),

- Step 2: Identification of risks (related to safety and health of workers, management organizational aspects, product quality),
- Step 3: FMECA evaluation (for each area of analysis, P: *Probability*, S:*Severity*, D: *Detection*):

$$1 \leq O_{task} \leq 10,\ 1 \leq S_{tasks} \leq 10,\ 1 \leq D_{tasks} \leq 10$$
$$1 \leq O_{machines} \leq 10,\ 1 \leq S_{machines} \leq 10,\ 1 \leq D_{machines} \leq 10$$
$$1 \leq O_{products} \leq 10,\ 1 \leq S_{products} \leq 10,\ 1 \leq D_{products} \leq 10 \qquad (4.2)$$

Evaluation of RPN indexes for the area of analysis:

$$RPN_i = O_i * S_i * D_i; \quad i = 1 \ldots n$$
$$RPN_j = O_j * S_j * D_j; \quad j = 1 \ldots m$$
$$RPN_k = O_k * S_k * D_k; \ k = 1 \ldots h \qquad (4.3)$$

- Step 4: Evaluation of ERPN (Efficient Risk Priority Number) index for each area of analysis

$$ERPN = \frac{S \cdot O \cdot D \cdot P \cdot E}{C} = \frac{RPN \cdot P \cdot E}{C} \qquad (4.4)$$

Where:

- S: *Severity,*
- O: *Occurrence,*
- D: *Detection,*
- P: *Protection,*
- E: *Effectiveness,*
- C: *Cost.*

- Step 5: Evaluation of the global TRPN index

$$\mathrm{TERPN_{tasks}} = \sum_{i=1}^{n} \mathrm{ERPN_i}$$
$$\mathrm{TERPN_{machines}} = \sum_{j=1}^{m} \mathrm{ERPN_j}$$
$$\mathrm{TERPN_{products}} = \textstyle\sum_{k=1}^{k} \mathrm{ERPN_k} \qquad (4.5)$$

- Step 6: Evaluation of the Global TRPN index for the whole company

$$\mathrm{TERPN}_{\mathrm{global}}=\mathrm{TERPN}_{\mathrm{tasks}}+\mathrm{TERPN}_{\mathrm{machines}}+\mathrm{TERPN}_{\mathrm{products}} \qquad (4.6)$$

- Step 7: Identification of corrective values (with the adoption of chosen corrective actions)

$$\mathrm{TERPN}^{*}_{\mathrm{global}}=\mathrm{TERPN}^{*}_{\mathrm{tasks}}+\mathrm{TERPN}^{*}_{\mathrm{machines}}+\mathrm{TERPN}^{*}_{\mathrm{products}} \qquad (4.7)$$

- Step 8: Identification of Cost of Intervention

$$\text{Total Cost of Intervention } C^{*}\mathrm{global}=(C^{*}_{\mathrm{tasks}}+C^{*}_{\mathrm{machines}}+C^{*}_{\mathrm{products}})\leq \mathrm{SafetyBudget} \qquad (4.8)$$

- Step 9: Identification of Improved Risk Priority Number (IRPN)

$$\mathrm{IRPN}^{*}_{global}=\frac{\mathrm{TERPN}_{\mathrm{global}}-\mathrm{TERPN}^{*}_{\mathrm{global}}}{\mathrm{TERPN}_{\mathrm{global}}}\ [\%] \qquad (4.9)$$

We have used Di Bona et al.’s [65] considerations, as they have defined several factors in their analysis (*Severity*, *Occurrence*, *Detection*, *Prevention*, *Effectiveness*, and *Cost*). For our practical problem (lithium-ion battery testing purposes) the usage of multiple factors is favourable, as it aides multilevel analysis. In contrast to their proposed method, HORA is a hierarchical fuzzy approach, not a quantitative method. Nevertheless, Di Bona et al. [65] uses *Prevention* as a related factor. In our paper, we have re-placed *Prevention* factor with *Protection*, combined with *Effectiveness* (related to Fuzzy subsystem$_2$, Risk$_{\mathrm{process}}$). With the replacement, my aim was to provide a complex process-level analysis.

4.1.3 Zlateva et al.’s fuzzy based risk assessment

Zlateva et al.’s approach [66]focuses on the estimation of social risks from natural hazards in Bulgaria. The problem itself is defined as a multi-criterial task and it evaluates several input variables, such as indicators for natural hazards and social vulnerability. The modelling was done in Matlab (Fuzzy Logic toolbox and Simulink), with the creation of a fuzzy logic system, that uses five inputs and one output. Zlateva et al.’s [66] aim was to develop a risk management approach for the analysis of natural disasters (their system is a part of the Web Integrated Information System of Bulgaria) [66].

In Fig. 30, the five inputs are defined as follows: *Input₁* (Extreme temperatures), *Input₂* (Floods), *Input₃* (Seismic hazard), *Input₄* (Population density) and, *Input₅* (Socio-economic status). The system uses linguistic variables, five indicators and three intermediate variables. The model uses three fuzzy membership functions: Low, Middle and High. The membership functions of the model are trapezoid, and are assessed in the interval [0, 10]. The membership functions are represented in Fig.31. The first level of the model includes one fuzzy logic subsystem, the second level consists of two fuzzy logic subsystems, and the third level includes one subsystem. The outputs of the system are identified as follows: Output_1 (Climatic risk), Output_2 (Environmental risk), Output_3 (Social vulnerability), Output_4 (Social risk).

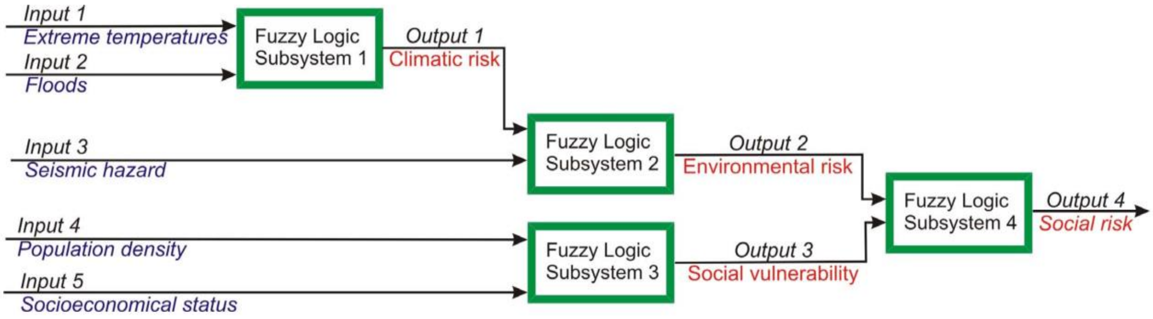


Fig. 30 Three-level hierarchical fuzzy system [66]

The fuzzy logic system's output is considered as a complex risk value while the output partitions contain five fuzzy membership functions: Very low, Low, Middle, High, and Very High. The five fuzzy membership functions are triangular, and the output (social risk from natural disasters) is evaluated in the interval of [0,100]. The triangular output membership functions are shown in Fig. 31.

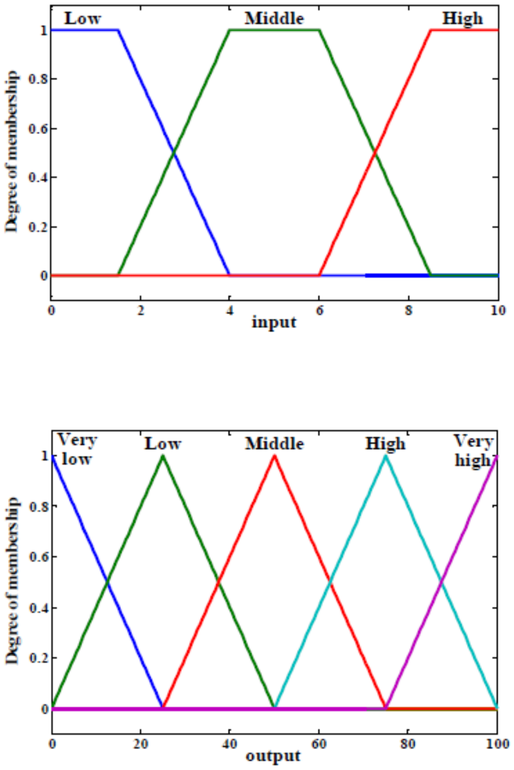


Fig. 31 Membership functions of the fuzzy model [66]

The system uses 9 rules. The fuzzy logic subsystems are Mamdani type ones.

Zlateva et al.'s [66] model evaluates six different geographical locations: Blagoevgrad, Simitli, Kresna, Strumyani, Sandanski and Petrich. According to their analysis, region Kresna was identified as the most problematic area with the highest climatic risk. The result of the analysis is shown in Table 29.

Table 29 Input data and results of Zlateva et al.'s analysis [66]

Criterion	*Blagoevrad*	*Simitli*	*Kresna*	*Strumyani*	*Sandanski*	*Petrich*
Input 1 Extreme temperature	*1*	*2*	*6*	*7*	*10*	*10*
Input 2 Floods	2	8	10	6	1	3
Climatic risk	1.4	5.4	8.6	5.9	4.8	6.7
Input 3 Seismic hazard	6	8	10	7	3	1
Environmental risk	4.9	7.5	8.5	6.1	4.1	2.8
Input 4 Population density	10	3	1	1	5	7
Input 5 Socioeconomical status	*9*	*3*	*3*	*3*	*6*	*6*

Zlateva et al. [66] created a three-level fuzzy approach for social risk estimation. The input parameters can be divided into ecological (climatic, environmental) and social (social vulnerability) parameters. These factors can be considered as either system or process related, in contrast to HORA's multilevel (system, product, process level) approach.

4.1.4 M. Takács's multilevel fuzzy approach of risk and disaster management

M. Takács [67] describes a hierarchic fuzzy approach for risk and disaster management with the usage of a hierarchical structure that is comparable to the methodology of the HORA model. According to M. Takács, the risk management model is built up as a hierarchical risk factors, actions and directions. In case of fuzzy-based risk management systems the factors are fuzzified due to their linguistic representation. In case of risk and disaster systems the inputs are factors and the actions are defined by the IF-THEN rules (Fig. 32). The input risk factors are grouped by the Fuzzy Risk Measure Sets (FRMS). They can be defined as 'low' (low risk), 'normal' (standard risk), and 'high' (high risk), etc. The fuzzy sets represent the systems parameters in this case [67].

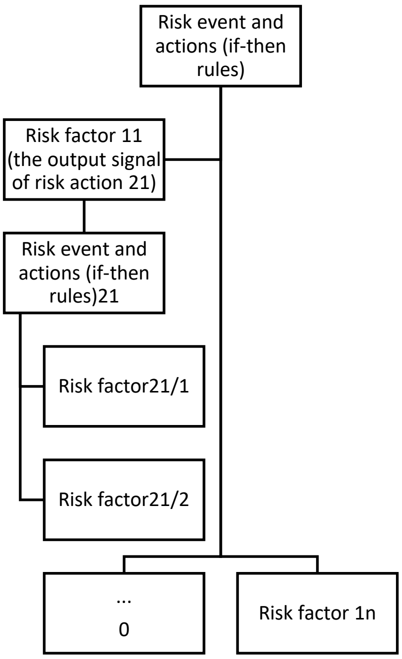


Fig. 32 Hierarchical risk management construction [67]

In M. Takács's [67] paper, a case study of disaster management is represented. In this case study, the risk or disaster factors are the inputs (fuzzified inputs) of the system and hierarchically constructed rule system is used (Fig. 33). According to the model, the inputs of one fuzzy subsystem give the outputs of the next level of the decision chain.

The advantage of this method is the easy addition of surplus factors while only the affected subsystem changes its complexity. If a given subsystem is more important than the others are, an importance number can be introduced (from the range of [0, 1]).

In the case study introduced in Fig. 33, the risk factors are classified as follows:

- unintended events
    - industrial accidents,
    - transport or telecommunication accidents,
    - economic crises
- willful events [67].

The risk and disaster factors can be divided to human- and nature-based groups as well.

The effects of the above mentioned disasters are represented by their relative frequency, and the fuzzy rule use membership functions like: ‘never’, frequently’, ‘never’, etc. The model uses triangular or trapezoidal membership functions. The inputs of the system are crisp.

The decision-making system in the case study uses Mamdani type approximate reasoning (min and max operators) for decision making and the rule base system is hierarchically structured [67].

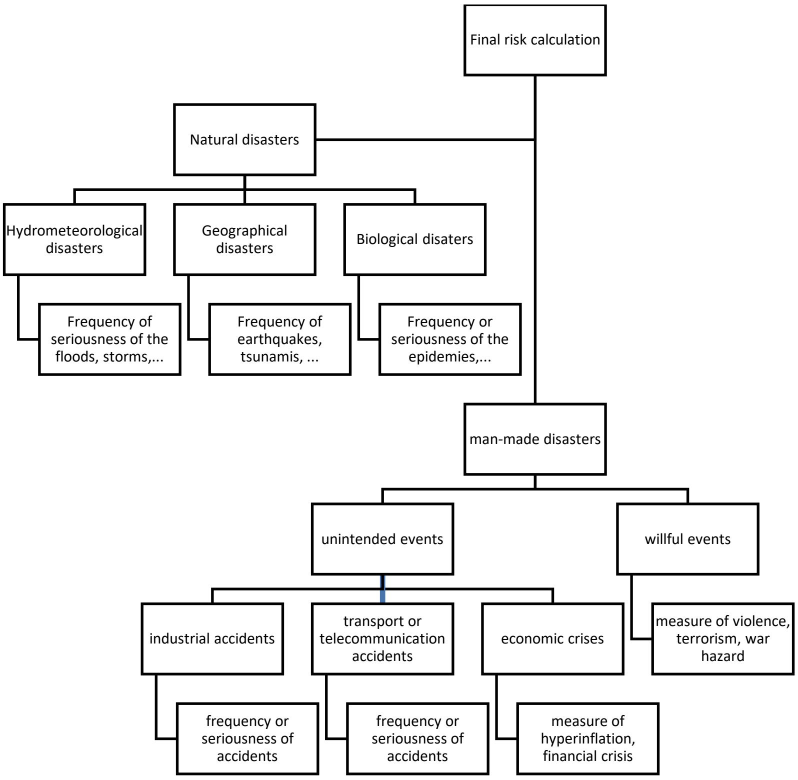


Fig. 33 Hierarchical constructed rule base system [67]

The system structure of the hierarchical multilevel analysis is represented in Fig. 34. The example model uses three fuzzy sub-systems, and triangular membership functions [67].

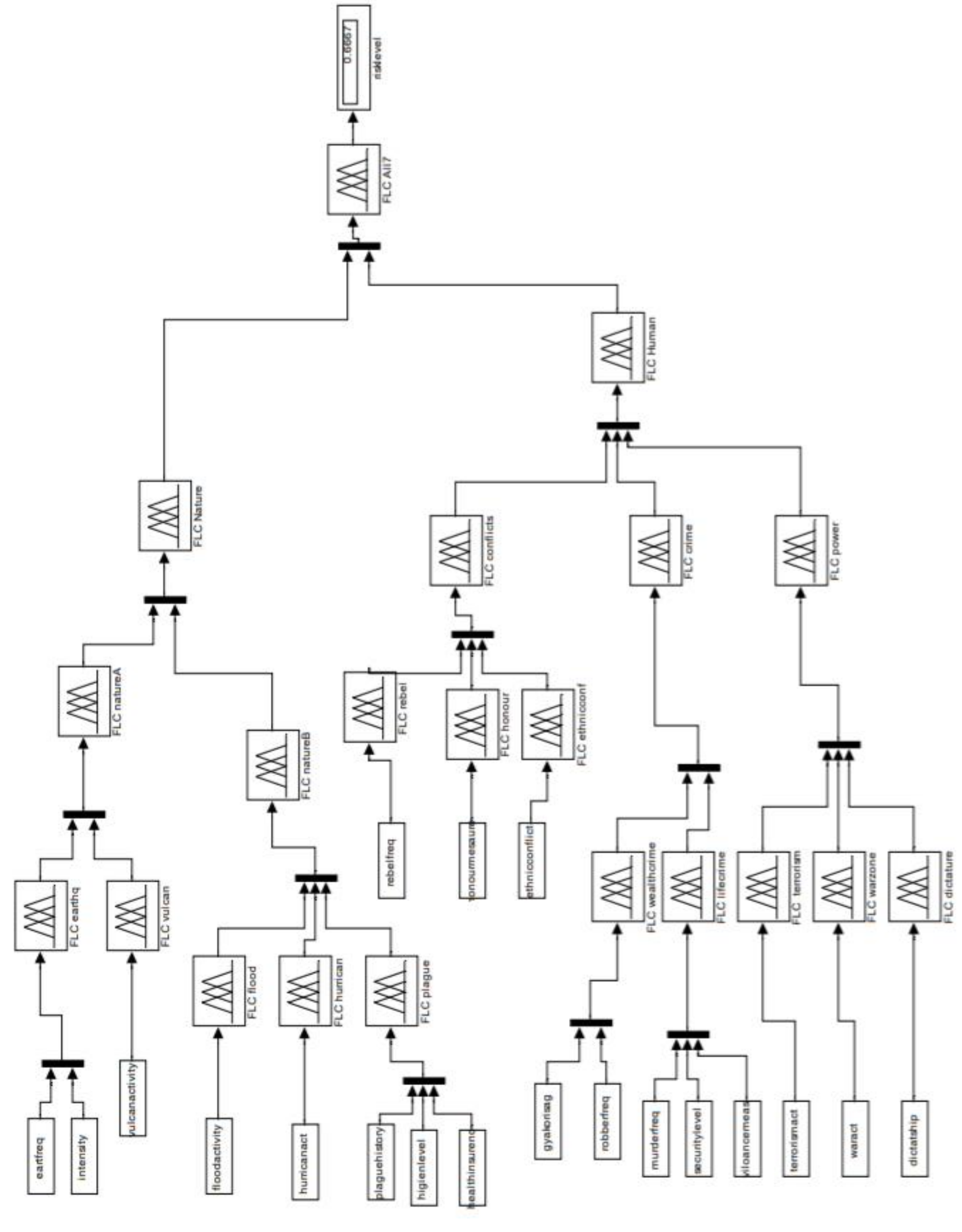


Fig. 34 System construction of disaster effects [67]

Unlike HORA, M. Takács [67] suggested the usage of fuzzy Analytical Hierarchy Process (AHP) as well, for the pairwise comparison of objectives, criteria, constraint and alternatives. In our case, we do not take factor decrease in account, as the fixed number of factors allow us to create an ‘overall’ aspect.

4.1.5 Risk analysis of stationary Li-ion batteries for power system analysis (STABALID project)

Soares et al.'s [68] model brings a risk analysis perspective to Li-ion batteries. The described approach provides a possible solution to lithium-ion battery risk analysis of power system applications. The basic thought behind Soares et al's [68] approach is the hazardous nature of lithium-ion cells, the basic elements of lithium-ion batteries. According to their description the risk of Lithium-ion batteries can involve by either an internal or external event.

The model uses seven subcategories of risks (Fig. 35):

- mechanical risks (vibrations, noise, etc.),
- chemical risks (flammable substances, combustions, etc.),
- electrical risks (high voltage, high current, etc.),
- thermodynamic risks (source of high/low temperature, high pressure, etc.),
- radiations (infra-red and ultra-violet radiations),
- biological risks (viruses and bacteria, etc.),
- environmental risks (humidity, rain, etc.) [68].

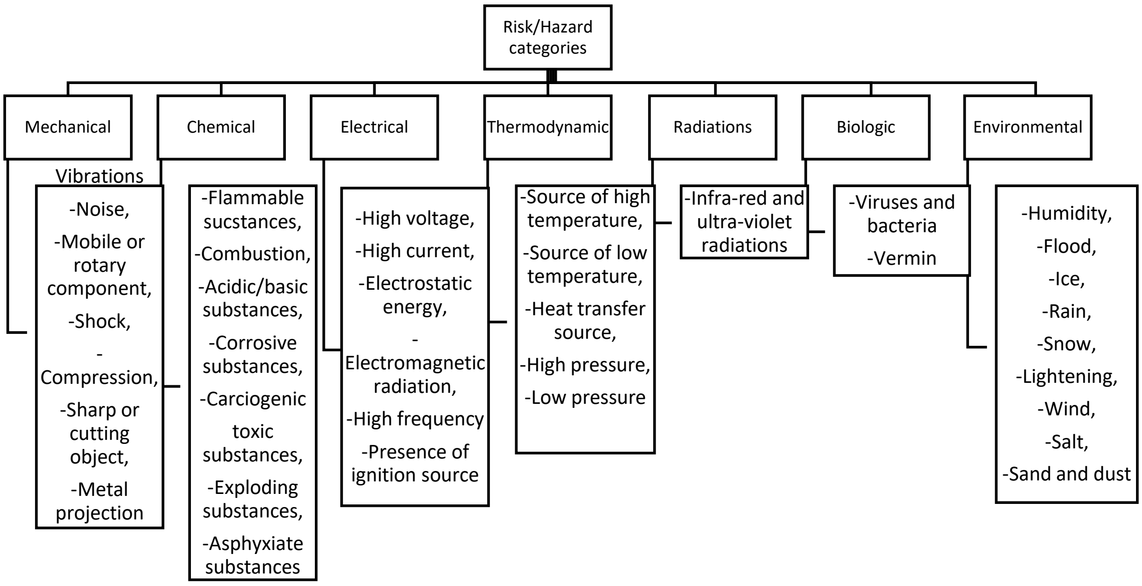


Fig. 35 Risk/hazard categories of lithium-ion cells and batteries [68]

Table 30 Battery-cycle life hazard map [68]

Production	**Storage**		**Transportation**		**Installation/ Decommissioning**		**Operation**		**Maintenance/ Inspections**	
Internal problem analysis	**Internal problem analysis**	**External peril analysis**	**Internal problem analysis**	**External peril analysis**	**Internal problem analysis**	**External peril analysis**	**Internal problem analysis**	**External peril analysis**	**Internal problem analysis**	**External peril analysis**
Weakened cell structure	Sharp or cutting objects	Vibrations	Flammable substances	Vibrations	Sharp or cutting objects	Vibrations	Mobile or rotary component	Vibrations	Mobile or rotary component	Shock
Overall production quality	Flammable substances	Shock	Acidic or corrosive substances	Shock	Flammable substances	Shock	Sharp or cutting objects	Shock	Sharp or cutting objects	Sharp or cutting objects
Bad assembly	Acidic or corrosive substances	Sharp or cutting objects	High temperature or heat transfer source	Stress, compression	Acidic or corrosive substances	Sharp or cutting objects	Flammable substances	Sharp or cutting objects	Flammable substances	Metal projection
Bad conception regarding constructive aspects	Carcinogenic substances	Metal projection	High pressure	Sharp or cutting objects	Carcinogenic substances	Metal projection	Acidic or corrosive substances	Metal projection	Acidic or corrosive substances	Electrostatic energy
	Toxic substances	High voltage (>120V)		Metal projection	Toxic substances	Electrostatic energy	Carcinogenic substances	High voltage	Carcinogenic substances	High temperature
	Asphyxiating substances	High current		Electrostatic energy	Asphyxiating substances	High temperature	Toxic substances	High current	Toxic substances	Vermin and other animals
	High voltage (>120V)	Electrostatic energy		High temperature or heat transfer source	High voltage (>120V)	Vermin and other animals	Asphyxiating substances	Electromagnetic radiation	Asphyxiating substances	Humidity, condensation
	High current	High temperature		Humidity, condensation	High current	Humidity, condensation	High voltage (>120V)	Electrostatic energy	High voltage (>120V)	Rain
	High temperature	Vermin and other animals		Rain	High temperature	Rain	High current	High temperature or heat transfer source	High current	Sand and dust
	High pressure	Humidity, condensation		Salt	High pressure	Sand and dust	High temperature or heat transfer source	Vermin and other animals	High temperature or heat transfer source	
		Flood		Sand and dust			High pressure	Humidity, condensation	High pressure	
		Rain					Overheat	Flood		
		Salt					Internal short circuit	Rain		
		Sand and dust					Overcharge	Lightning		
							Recharge of an over discharged cell	Salt		
							Loss of cell tightness	Sand and dust		
							External short circuit			
							Fire			

Soares et al. [68] conducted a risk mapping of hazards during the whole battery cycle life (Table 30). The hazard mapping described six different stages of battery life: production, storage, transportation/removal, installation/decommissioning, operation, maintenance/inspections. In case of the stages after production, internal and external peril analysis was conducted, for instance during operation, one internal problem might be high temperature or heat-transfer source presence and one external problem might be humidity/condensation.

According to Soares et al.'s [68] methodology, Lithium-ion battery related risk analysis has the following steps: risk identification, risk evaluation (internal problem analysis, external peril analysis), recommended mitigation measures and risk re-evaluation (Fig. 36).

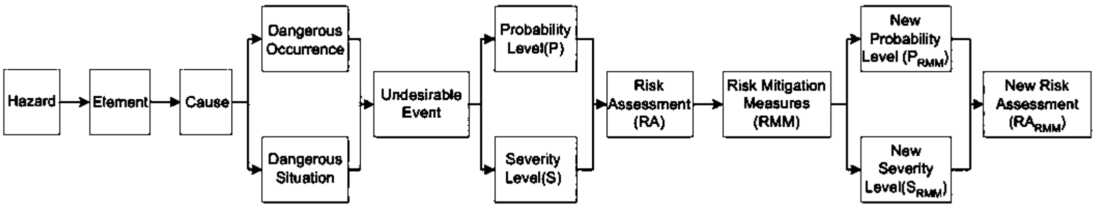


Fig. 36 The process of risk analysis according to Soares et al. [68]

During risk evaluation the probability levels (Table 31), severity levels (Table 32) and severity/probability levels are defined (Table 33).

Soares et al. [68] gives four probability categories (Table 31): improbable event ($P \leq 10^{-9}$/h), remote event ($10^{-9} < P \leq 10^{-7}$/h), occasional event ($10^{-7} < P \leq 10^{-5}$/h) and probable event ($P > 10^{-5}$/h).

Table 31 Probability levels (P) of events [68]

Probability levels (P)	
Level	**Probability**
1	$P \leq 10^{-9}$/h → improbable event
2	$10^{-9} < P \leq 10^{-7}$/h → remote event
3	$10^{-7} < P \leq 10^{-5}$/h → occasional event
4	$P > 10^{-5}$/h→ probable event

During the evaluation of risks, four different severity levels are defined (Table 32):

- minor severity level (which represents slight degradation of battery performance, etc.),
- major severity level (which represents considerable degradation of battery performance, etc.),
- hazardous severity level (which represents that the battery is out-of-service),
- catastrophic severity level (which represents that the battery is out-of-service, major damage on the battery) [68]

Table 32 Severity levels [68]

Level	Severity	Description
1	**Minor**	Slight degradation of battery performance → the owner can still use the battery Maintenance operation is advisable, but not mandatory → limited cost impact Low risk for user or operator → small reduction in safety conditions
2	**Major**	Considerable degradation of battery performance → the owner can still use the battery but a quick maintenance is requested Low risk for user or operator → important reduction in safety conditions
3	**Hazardous**	The battery is out-of-service → possibility of significant damage on the battery Immediate maintenance is mandatory → significant intervention cost Low risk for user or operator (possible injury) →large reduction in safety conditions
4	**Catastrophic**	The battery is out-of-service → major damage on the battery Significant risk for user or operator (significant or fatal injury) or important environmental degradation

Soares et al [68] defines the risk levels based on the connection of *Probability* and *Severity* levels (Table 32). According to their approach, e.g. P level 1 and *Severity* level 1 stands for *Acceptable risk* level, and P level 4 and *Severity* level 4 stands for *Intolerable risk level*.

In Table 33, the so-called decision matrix is defined. Similarly to the defined HORA approach, the risk level is scaled. In case of the HORA approach, the fuzzy rules provide qualification for the risk factors. The novelty of the defined model is that the expert can self-judge whether the risk is acceptable or not acceptable based on the given conditions.

Table 33 Risk assessment based on the P and S levels [68]

RA		**S**			
		1	2	3	4
P	1	Acceptable	Acceptable	Acceptable	Tolerable
	2	Acceptable	Acceptable	Tolerable	Intolerable
	3	Acceptable	Tolerable	Intolerable	Intolerable
	4	Tolerable	Intolerable	Intolerable	Intolerable

The key message of Soares et al.’s [68] model is represented in Fig. 37: batteries, as potential hazardous products have a strong impact on the surrounding environment, but indeed environmental conditions are strongly influencing its risk level.

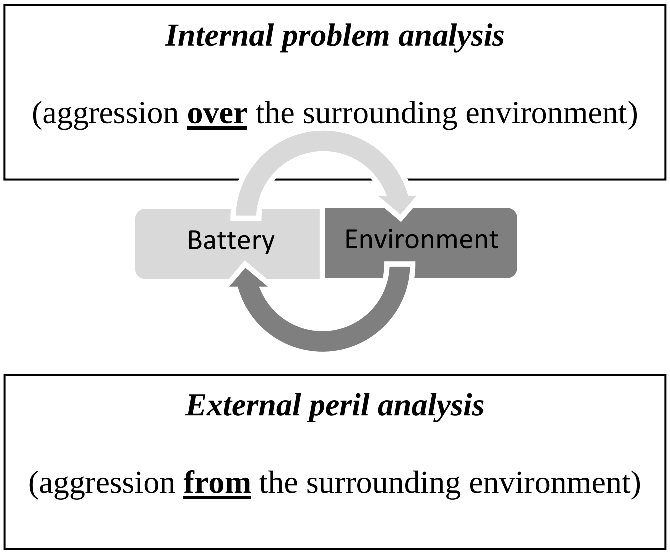


Fig. 37 The nature of Lithium-ion battery risk analysis [68]

Soares et al. [68] defines Risk Mitigation Measures (RMM) in their paper. The implementation of these measures results in new probability (PRMM) and severity (SRMM) levels, as the methods is based on continuous improvement. In case of HORA (Chapter 3), the application purpose differs, since it is used for decision-making support in case of standardized tests with the preliminary assumption that proper laboratory environment is present (based on existing fire and explosion safety analysis).

4.2 Chapter summary

In this chapter, I have summarized those methods [64], [65], [66], [67] and [68], which I have merged and developed whilst creating my own preliminary risk analysis method (HORA).

In this chapter, I have suggested a new preliminary analysis method (HORA method) in which I intend to solve the above-mentioned shortcomings (**H1**).

As I have demonstrated the high level of uncertainty in case of lithium-ion battery tests, I state there is certain need for preliminary risk analysis with the development of current risk analysis methods (**H2**).

5 SUMMARY

In my thesis, I have presented a new method for preliminary Li-ion battery test laboratory risk analyses. The approach is novel, as in most cases the risk of battery utilization is taken into consideration (e.g. EUCAR hazard catalogue [61]). During battery abusive testing, hazardous battery behaviors are created by purpose. These point out the necessity of a carefully selected risk analysis method. FMEA the most traditional risk analysis method is only partially applicable in this case, as the usage of only process-related analysis has its shortages because it does not take product and system level approaches into consideration. In manufacturing, the direct linkage of Product- and Process FMEAs can be a useful method but not all batteries are provided with FMEAs during the everyday operation of the laboratory; and even so, the FMEAs cannot be standardized as each manufacturers handle FMEAs in different ways. This gives the idea of implementing a hierarchical FMEA solution, as it takes the whole laboratory (system level), testing process (process level) and product types (product level) into consideration. The fuzzification of the hierarchical approach eases its usage since, engineers do not have to statistically analyse each case to come to a decision about the feasibility of tests based on pre-evaluated risk levels. One more advantage of the recommended method is that the thresholds of each factors (including $Risk_{overall}$) can be flexibly adjusted for individual laboratories with differing test and safety setups. This relates to the rating catalogues as well, *Occurrence* catalogues can be modified based on the experience of test engineers, while process-related (*Protection*, *Effectiveness*) catalogues can be described based on the existing safety solutions.

5.1 Hypotheses of the research

In Table 34, I check my formulated hypothesis, that I have determined in the Introduction section. My research hypotheses were proven during my research, as follows:

Table 34 Hypotheses of research (*Edited by author*)

HYPOTHESES	RESULTS
H1: I assumed that a preliminary risk assessment would be required for standardized laboratory testing of lithium-ion batteries.	**PROVEN**
H2: I supposed that conventional FMEA-based analyses are not sufficient for a preliminary risk assessment of a lithium-ion battery-testing laboratory.	**PROVEN**
H3: I assumed that by combining and developing existing risk assessment methods and developing appropriate assessment catalogues, a new method could be successfully developed for the preliminary risk assessment of lithium-ion batteries.	**PROVEN**

5.2 New scientific results

The aim of my research was to determine a flexible, new preliminary risk analysis method for lithium-ion battery test laboratories. Based on my practical experience, a traditional fire and explosion-safety laboratory analysis is not sufficient in most cases. Those analyses focus on cell-based limitations due to worst-case scenarios. During practical work, test engineers should be aware of realistic probable outcomes of abuse tests to predetermine effects, which helps them to prioritize battery test projects. As the incoming information is not sufficient in case of small batteries (lack of information about battery safety options, cell material, etc.), a standardized Failure Mode and Effect Analysis is not suitable. Missing Design FMEAs render impossible the linkage of existing laboratory Process FMEAs. Let me emphasize that my research was limited to small size batteries, automotive approaches were not considered.

Therefore, my new scientific results are as follows:

- **Thesis (T1)**: *I have **verified** that a preliminary risk assessment is required for standardized laboratory testing of lithium-ion batteries.*

Based on my practical experience, during my research I have analyzed my hypothesis 2 (H2). By summarizing the variety of Li-ion batteries and the wide range of test processes in Chapter 2, I have demonstrated the necessity of a preliminary risk analysis method, which is a practical tool to predetermine system related effects. The foreseeable test-related effects help test engineers to prioritize their test projects. Therefore, my **T1** thesis is proved by my results of my scientific research process that is supported by my publications **[P7]**, **[P8]** and **[P11]**.

- **Thesis 2 (T2)**: *I have* ***proven*** *that conventional FMEA-based analyses are not sufficient for a preliminary risk assessment of a lithium-ion battery-testing laboratory.*

Based on my professional experience, and the findings stated in specialized literature, I have evaluated my hypothesis 1 (H1), and published my results. During the literature review investigation, I have found proof about the shortages of the traditional Failure Mode and effect Analysis, according to Spreafico et al. [16], presented in Chapter 1. I have aligned the results of Spreafico et al. with the findings of Fantham and Gladwin [22]. With the comparison and review of a specialized Li-ion battery test process FMEA [22], I have identified gaps in the usage of the traditional FMEA method.

Therefore, my **T2** thesis is proved by my results of my scientific research process that is supported by my publications **[P7]**, **[P8]** and **[P11]**.

- **Thesis (T3)**: *I have developed a new preliminary risk assessment method called Hierarchical Overall Risk Analysis (HORA).*

During the literature review process, I have identified those existing approaches (Chapter 1), that can be successfully merged to create a new method, with surplus considerations. In Chapter 1, I have detailed the similarities and differences of the existing methods and the suggested model, HORA.

Based on my research, and the outlined shortages of current preliminary risk analysis methods, and the basis of them, I have constructed a new preliminary risk analysis method (Chapter 3) according to my hypothesis 3 (H3), which considers the test processes and product features to be a whole system. As it is a fuzzy logic-based approach, it eases usage, and covers the shortages of information at product side. Therefore, I have proven my **T3** thesis by my results of the new established model, and I have supported by my publication [**P11**].

- **Thesis (T3a)**: *I have* ***proven*** *the accurate operation of the system by involving experts (test engineers).*

For the validation process, I have used DoE considerations (according to Taguchi) [62], [68]. (The orthogonal array L75 58 151 was the most fitting design [68].) The validation process was done with the help of experienced lithium-ion battery test engineers. According to their feedback, the model provides valid predictions. Therefore, I have proven my T3a thesis by my results of the new established model, and I have supported by my publication [**P11**].

- **Thesis 3b (T3b)**: *I have* ***determined*** *the factors required for the preliminary risk analysis.*

Whilst developing the HORA model, I have introduced the factors *Occurrence, Controllability, Protection, Effectiveness,* and *Severity* /*Cost*. These factors are interpreted at different levels of the model. *Occurrence* and *Controllability* belong to Fuzzy subsystem$_1$ (Risk$_{\text{product}}$), *Protection* and *Effectiveness* belong to Fuzzy subsystem$_2$ (Risk$_{\text{process}}$), and *Severity*/*Cost* belongs to Fuzzy subsystem$_3$ ($Risk_{system}$).
Therefore, I have proven my **T3b** thesis by my results of the new established model, and I have supported by my publication **[P11]**.

- **Thesis 3c (T3c)**: *I have* ***introduced*** *a combined Severity / Cost factor that can be used for the complex evaluation of technological events.*

Besides the technically related factors, factor *Severity*/*Cost* combines the battery test related effects from both the technical and economical side. During practical projects, the cost related considerations influence project priority as well.
Therefore, I have proven my **T3c** thesis by my results of the new established model, and I have supported by my publication **[P11]**.

- **Thesis 4 (T4)**: *I have created customized rating catalogues to evaluate each factor (Occurrence, Controllability, Protection, Effectiveness, Severity / Cost) ensuring further adaptiveness of the proposed method.*

For the proper identification of each factor level, I have implemented rating catalogues (Chapter 3). With the help of the rating catalogues, the experts can determine the input factors with ease. Besides using linguistic variables, crisp values are represented in the rating catalogues as well as its comparison with the traditional Failure Mode and Effect Analysis method.

Therefore, I have proven my **T4** thesis by my results of the new established model, and I have supported by my publication **[P11]**.

5.3 Recommendations for future usage

Further research will consider the applicability fuzzy signatures [69], solutions inspired by fuzzy control theory [70], cognitive maps [71], and rule base simplification techniques [72]. One possible future step is to create a decision-making (DM) application [73] in which the HORA model is expanded on. The aim of this future approach is to provide a highly efficient DM application with flexible thresholds. With the usage of a customised DM approach the preliminary analysis can be combined with a system-built decision-making tool that decreases time spent on project preparation tasks.

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[P3] **A. Koncz**, L. Pokorádi, Zs. Cs. Johanyák: Fuzzy logic in automotive engineering, Gradus, 5 : 2, pp. 194-200. , 7 p. (2018)

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[P6] **A. Koncz**, L. Pokorádi, Zs. Cs. Johanyák: Risk analysis in the automotive industry, Repüléstudományi Közlemények, 31: 3 pp. 119-124., 6 p. (2019)

[P7] **A. Koncz,** L. Pokorádi, Zs. Cs. Johanyák: Compared risk analysis of automated and manual safety solutions for transport safety testing of Li-ion batteries**,** 20th IEEE International Symposium on Computational Intelligence and Informatics (CINTI) Proceedings (2020), pp. 145-150.

[P8] **A. Koncz**: Transport safety testing of lithium-ion batteries and their risk concerning laboratory environment during tests, Proceedings of the 16th MINI Conference on Vehicle System Dynamics, Identification and Anomalies, Budapest, Hungary, Budapest University of Technology and Economics, *manuscript accepted* (2020)

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[P12] **A. Koncz**: A 8D problémamegoldó technika, Repüléstudományi Közlemények, XXVII., 3 pp. 7-17, 11 p. (2015)

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6.3 List of presentations at conferences

[P14] *A Hibamód- és Hatáselemzés alkalmazása napjaink autóiparában*, Óbuda University, International Engineering Symposium at Bánki, IESB 27.11.2017, Budapest, Hungary

[P15] *Failure Mode and Effect Analysis Types in the Automotive Industry*, 16th Mini conference on Vehicle System Dynamics, Identification and Anomalies (VSDIA, 2018), 11.05.2018, Budapest, Budapest University of Technology and Economics

[P16] *Fuzzy logic in automotive engineering*, AGTEDU conference, John von Neumann University, 15.11.2018, Kecskemét, Hungary

[P17] *A Toyota Termelési Rendszer bemutatása és gyakorlati alkalmazásai*, International Engineering Symposium at Bánki (IESB 2018), 21.11.2018, Budapest, Óbuda University, Budapest, Hungary

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[P20] *Non-conventional risk analysis methods specified for battery transport safety testing*, AGTEDU conference, John von Neumann University, 11.12.2020, Kecskemét, Hungary

[P21] *Műszaki laboratórium előzetes fuzzy alapú kockázatértékelése*, SZAFARI conference (Szimpózium a Fuzzy alapú Mérnöki Rendszerekről), Óbuda University, 17.05.2021, Budapest, Hungary

LIST OF ABBREVIATIONS

ABS:	Anti-Braking system
AC:	Almost certain
AHP:	Analytic Hierarchy Process
AP:	Action Priority
ART:	Adaptive Resonance Theory
AU:	Absolute uncertain
BBD:	Box-Behnken design
BIA:	Business impact analysis
C:	Cost
CAS number:	Chemical Abstracts Service Number
CBA:	Cost/benefit analysis
CCD:	Central-composite design
CEN:	European Committee for Standardization
CL:	Cause level
D:	Detection
DL:	Design level
DMRA:	Decision-Matrix Risk Assessment
DoE:	Design of Experiments
DSD:	Definite screening design
E:	Effectiveness
EL:	Effect level
ERPN:	Efficient Risk Priority Number
ETA:	Event tree analysis
EU:	European Union
FAHP:	Fuzzy Analytic Hierarchy Process
FFD:	Full-factorial design
FMEA:	Failure Mode and Effects Analysis
FMECA:	Failure Mode, Effects and Criticality Analysis
FN:	Fuzzy numbers
FOWGA:	Fuzzy Ordered Weighted Geometric Averaging
FRMS:	Fuzzy Risk Measure Sets

FRMS: Fuzzy Risk Measure Sets
FRPN: Fuzzy Risk Priority Number
FTA: Fault tree analysis
H: High
HACCP: Hazard analysis and critical control points
HAZOP: Hazard and operability studies
HRA: Human reliability analysis
HWOW: Hazardous without warning
HWW: Hazardous with warning
IEC: International Electrotechnical Commission
IRPN: Identification of improved risk priority number
JSA: Japanese Standards Association
L: Low
LFP: Lithium Iron Phosphate)
LMO: Lithium Manganese Oxide)
LOPA: Layers of protection analysis
M: Moderate
MADM: Multi-Attribute Decision Making,
MAUT: Multi-Attribute Utility Theory
MCA: Monte Carlo simulation
MCDA: Multi-criteria decision analysis
MH: Moderately high
MODM: Multi-Objective Decision Making
MR: Minor
MRA: Minimax regret value
MRV: Maximum regret value
N: None
NCA: Lithium Nickel Cobalt Aluminium Oxide)
NMC: Lithium Nickel Manganese Cobalt Oxide)
O: Occurrence
Od: Likelihood of non-detection of failure
Of: Probability of occurrence of failure
P: Probability
PBD: Placket Burman design

PCT:	Public Choice Theory
PHP:	Preliminary hazard analysis
PS:	Problem solving
PSA:	Probabilistic Safety Analysis
R:	Remote
RCA:	Root cause analysis
RPN:	Risk Priority Number
RPR:	Risk priority rank
S:	Severity
SA:	Sneak analysis
SCA:	Sneak circuit analysis
SIRA:	Safety Improve Risk Analysis
SL:	System level
SOC:	State of Charge
SOF:	State of function
SOH:	State of health
SOP:	State of power
SOS:	State of safety
SWIFT:	Structured What-if technique
TD:	Taguchi design
TRPN:	Total Efficient Risk Priority Number
TRPN:	Total risk priority number
UL:	Underwriters Laboratories
UN:	United Nations
VH:	Very high
VL:	Very Low
VMR:	Very minor
VR:	Very remote

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ANNEXES

ANNEX I.

Table A1 Membership values associated to the scores in case of the *Controllability*, *Occurrence*, *Risk$_{product}$*, *Protection*, *Effectiveness*, *Risk$_{process}$*, and *Risk$_{System}$* variables

Score											
		1	2	3	4	5	6	7	8	9	10
Fuzzy set	L	1.00	0.78	0.56	0.33	0.11	0.00	0.00	0.00	0.00	0.00
	M	0.00	0.22	0.44	0.67	0.89	0.89	0.67	0.44	0.22	0.00
	H	0.00	0.00	0.00	0.00	0.00	0.11	0.33	0.56	0.78	1.00

Table A2 Membership values associated to the scores in case of the *Severity/Cost* variable

Score											
		1	2	3	4	5	6	7	8	9	10
Fuzzy set	NE	1.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	VL	0.00	0.78	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	L	0.00	0.00	0.55	0.67	0.00	0.00	0.00	0.00	0.00	0.00
	ML	0.00	0.00	0.00	0.33	0.89	0.11	0.00	0.00	0.00	0.00
	L	0.00	0.00	0.00	0.00	0.11	0.89	0.33	0.00	0.00	0.00
	MH	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.55	0.00	0.00
	H	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.78	0.00
	VH	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	1.00

ANNEX II.

Table A3 L_{75} 5^8 15^1 (Taguchi) experimental design

Controllability	*Occurrence*	*Protection*	*Effectiveness*	*Severity/Cost*	*Risk$_{System}$*
0.00	0.00	0.00	0.00	0.00	4.73
0.00	0.00	0.00	10.00	0.71	1.92
0.00	0.00	7.50	5.00	1.43	1.63
0.00	2.50	5.00	5.00	2.14	4.38
0.00	2.50	7.50	10.00	2.86	5.00
0.00	2.50	10.00	0.00	3.57	5.00
0.00	5.00	2.50	7.50	4.29	5.00
0.00	5.00	5.00	10.00	5.00	5.00
0.00	5.00	10.00	5.00	5.71	5.00
0.00	7.50	2.50	2.50	6.43	5.63
0.00	7.50	5.00	7.50	7.14	8.34
0.00	7.50	10.00	2.50	7.86	8.08
0.00	10.00	0.00	7.50	8.57	8.32
0.00	10.00	2.50	0.00	9.29	8.08
0.00	10.00	7.50	2.50	10.00	8.34
2.50	0.00	2.50	10.00	8.57	8.37
2.50	0.00	5.00	2.50	9.29	8.08
2.50	0.00	10.00	5.00	10.00	8.37
2.50	2.50	2.50	0.00	0.71	4.59
2.50	2.50	2.50	2.50	0.00	2.76
2.50	2.50	10.00	7.50	1.43	1.63
2.50	5.00	0.00	2.50	3.57	5.00
2.50	5.00	7.50	7.50	2.14	4.38
2.50	5.00	10.00	0.00	2.86	5.00
2.50	7.50	0.00	7.50	5.71	5.04
2.50	7.50	5.00	10.00	4.29	5.00
2.50	7.50	7.50	0.00	5.00	5.06
2.50	10.00	0.00	5.00	7.86	8.08
2.50	10.00	5.00	5.00	6.43	5.63
2.50	10.00	7.50	10.00	7.14	8.37
5.00	0.00	2.50	7.50	7.86	8.08
5.00	0.00	7.50	7.50	6.43	5.63
5.00	0.00	10.00	0.00	7.14	8.37
5.00	2.50	0.00	7.50	10.00	8.34
5.00	2.50	5.00	0.00	8.57	8.23
5.00	2.50	7.50	5.00	9.29	8.08
5.00	5.00	0.00	10.00	1.43	1.63
5.00	5.00	5.00	2.50	0.71	3.21
5.00	5.00	5.00	5.00	0.00	1.63
5.00	7.50	0.00	2.50	2.86	5.00
5.00	7.50	2.50	5.00	3.57	5.00
5.00	7.50	10.00	10.00	2.14	4.38
5.00	10.00	2.50	10.00	5.71	5.04
5.00	10.00	7.50	0.00	4.29	5.00
5.00	10.00	10.00	2.50	5.00	5.06
7.50	0.00	0.00	5.00	5.00	5.53
7.50	0.00	5.00	0.00	5.71	6.15
7.50	0.00	10.00	2.50	4.29	5.00
7.50	2.50	0.00	2.50	7.14	8.20
7.50	2.50	5.00	10.00	7.86	7.96

Controllability	***Occurrence***	***Protection***	***Effectiveness***	***Severity/Cost***	***Risk$_{System}$***
7.50	2.50	10.00	10.00	6.43	5.63
7.50	5.00	2.50	10.00	10.00	8.37
7.50	5.00	7.50	2.50	8.57	8.34
7.50	5.00	10.00	7.50	9.29	8.08
7.50	7.50	2.50	0.00	1.43	4.63
7.50	7.50	7.50	5.00	0.71	2.08
7.50	7.50	7.50	7.50	0.00	1.76
7.50	10.00	0.00	0.00	2.14	4.68
7.50	10.00	2.50	5.00	2.86	5.00
7.50	10.00	5.00	7.50	3.57	5.00
10.00	0.00	2.50	2.50	2.14	4.38
10.00	0.00	5.00	7.50	2.86	4.96
10.00	0.00	7.50	10.00	3.57	4.89
10.00	2.50	0.00	5.00	4.29	5.00
10.00	2.50	2.50	7.50	5.00	5.05
10.00	2.50	7.50	2.50	5.71	5.04
10.00	5.00	0.00	0.00	6.43	5.88
10.00	5.00	2.50	5.00	7.14	8.34
10.00	5.00	7.50	0.00	7.86	8.08
10.00	7.50	0.00	10.00	9.29	8.08
10.00	7.50	5.00	0.00	10.00	8.23
10.00	7.50	10.00	5.00	8.57	8.37
10.00	10.00	5.00	2.50	1.43	2.76
10.00	10.00	10.00	7.50	0.71	1.92
10.00	10.00	10.00	10.00	0.00	1.63

ACKNOWLEDGEMENT IN HUNGARIAN

Munkámat a családomnak, barátaimnak és kollégáimnak ajánlom, akik inspiráltak,
hittek bennem és támogattak a tanulmányaimban.

I dedicate my doctoral dissertations to my family, friends and colleagues who inspired,
believed and supported me through my learning journey.

ACKNOWLEDGEMENT

I would like to thank my supervisors – Dr. László Pokorádi and Dr. Zsolt Csaba Johanyák– for their valuable help at all stages of my PhD research. Without their support, this thesis would not been created.

I would additionally thank the management, lecturers and staff of the Doctoral School on Safety and Security Sciences of Óbuda University for their advice, professional suggestions and work in helping me with my research activities.

I would like to thank my managers at my workplace, as well my direct colleagues from the staff of TÜV Rheinland InterCert Ltd. who supported the fulfilment of my study obligations in all respects.

NYILATKOZAT

Nyilatkozat a munka önállóságáról, irodalmi források megfelelő módon történt idézéséről

Alulírott **Koncz Annamária** kijelentem, hogy a

PRELIMINARY RISK ANALYSIS OF TEST LABORATORIES

című benyújtott doktori értekezést **magam készítettem**, és abban csak az irodalmi hivatkozások listáján megadott forrásokat használtam fel. Minden olyan részt, amelyet szó szerint, vagy azonos tartalomban, de átfogalmazva más forrásból átvettem, egyértelműen, a forrás megadásával megjelöltem.

Budapest, 2022.04.03

Koncz A

…………………………………..

(**Koncz Annamária**)

szerző

STATEMENT

For the independence of work, literature resources of the quote in an appropriate way

As the author, **Ms. Annamaria KONCZ** takes an official statement as follows:

a) Firstly, this ” **PRELIMINARY RISK ANALYSIS OF TEST LABORATORIES**” doctoral dissertation is my own fully exclusive work;

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written by:

Koncz A

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(**Ms. Annamária KONCZ**)

author