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Doctoral Thesis

Supply chain risk analysis

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Author:
István Mihálcz

Supervisor:
Prof. Dr. habil. Zsolt Tibor Kosztyán

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Date:
....

Supply chain risk analysis

Thesis for obtaining a PhD degree in the Doctoral School in Management Sciences
and Business Administration of the University of Pannonia

in the branch of Social Sciences on the subject of Management and Business Studies

Author: István MIHÁLCZ
Supervisor: Prof. Dr. habil. Zsolt Tibor KOSZTYÁN

Propose acceptance (yes/no) ....
Reviewer

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....
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Abstract

In order to address the rapidly increasing expectations of stakeholders and society, organizations have been required to devise strategies for intricate operations that are extremely responsive to both the external and internal factors within the firm. In order to ensure seamless functioning, it is imperative to comprehend the potential dangers and risks involved, as well as the measures taken to minimize them. Risk assessment is used in several domains and numerous frameworks and methodologies have been suggested in both practical applications and scholarly publications. Traditional methods of assessing risk fail to acknowledge the intrinsic complexity of modern organizational and process components such as supplier networks, as well as the interconnected repercussions of failures across different levels of a system. These methods are inadequate for addressing the ever-evolving demands placed on organizations. These circumstances require innovative strategies that propose versatile and adaptable ways for assessing risks, which can be adjusted to accommodate the organization's environment, quality, durability, environment, work safety, cyber security, and situational elements.

The purpose of this thesis is to extend conventional risk evaluation methodologies and provide a multi-level risk evaluation framework, that can handle the risk evaluation of the most complex systems, like on supply chain networks. This framework will facilitate the customization of risk evaluation and the successful integration of risk evaluation aspects. Risk-mitigation decisions in risk management systems usually rely on intricate risk indicators. Hence, aggregation plays a crucial role in the process of risk assessment. This thesis introduces various aggregation functions, analyzes their requirements, critiques the currently employed multiplication-based risk priority number, and proposes the utilization of a generalized aggregation function with a generalized output indicator which can be used in most complex systems, like supply chain networks. This function can be applied across different hierarchical levels within an organization.

Companies employ several management systems, such as those for quality, environment, energy conservation, and cyber security. However, the evaluation of risks associated with these systems is not consolidated. Decision makers lack a tool that can provide them with a comprehensive overview of the priority of risks across multiple management systems. This thesis also proposes a multi-level warning system that allows warnings to be established at different hierarchical levels, such as factors, processes, and departments of organizations. This increases the flexibility to combine risk evaluations from different areas, making it an important tool for decision makers.

The objective of this thesis is to provide a feasible application of the approaches mentioned earlier in the supply chain, which are often overlooked in terms of risk analysis. The research study presented here improves the current knowledge base by providing supply chain managers and decision makers with a practical tool to evaluate their procedures.

Keywords: FMEA; Supply chain risk; risk analysis; aggregation

Zusammenfassung

Um den schnell wachsenden Erwartungen der Interessengruppen und der Gesellschaft gerecht zu werden, müssen Unternehmen Strategien für komplexe Vorgänge entwickeln, die sowohl auf externe als auch auf interne Faktoren innerhalb des Unternehmens reagieren. Um ein reibungsloses Funktionieren zu gewährleisten, ist es unerlässlich, die damit verbundenen potenziellen Gefahren und Risiken sowie die Maßnahmen zu ihrer Minimierung zu kennen. Die Risikobewertung wird in verschiedenen Bereichen eingesetzt, und sowohl in praktischen Anwendungen als auch in wissenschaftlichen Veröffentlichungen wurden zahlreiche Rahmen und Methoden vorgeschlagen. Herkömmliche Methoden der Risikobewertung berücksichtigen nicht die Komplexität moderner Organisations- und Prozesskomponenten, wie z. B. Zulieferernetzwerke, sowie die miteinander verknüpften Auswirkungen von Fehlern auf den verschiedenen Ebenen eines Systems. Diese Methoden sind unzureichend, um den sich ständig weiterentwickelnden Anforderungen an Organisationen gerecht zu werden. Diese Umstände erfordern innovative Strategien, die vielseitige und anpassungsfähige Methoden zur Risikobewertung vorschlagen, die an das Umfeld, die Qualität, die Dauerhaftigkeit, die Umwelt, die Arbeitssicherheit, die Cybersicherheit und die situativen Elemente der Organisation angepasst werden können.

Ziel dieser Arbeit ist es, die konventionellen Risikobewertungsmethoden zu erweitern und einen mehrstufigen Risikobewertungsrahmen zu schaffen, der die Risikobewertung der komplexesten Systeme, z. B. in Lieferkettennetzwerken, ermöglicht. Dieser Rahmen wird die Anpassung der Risikobewertung und die erfolgreiche Integration von Risikobewertungsaspekten erleichtern. Entscheidungen zur Risikominderung in Risikomanagementsystemen beruhen in der Regel auf komplizierten Risikoindikatoren. Daher spielt die Aggregation eine entscheidende Rolle im Prozess der Risikobewertung. In dieser Arbeit werden verschiedene Aggregationsfunktionen vorgestellt, ihre Anforderungen analysiert, die derzeit verwendete, auf Multiplikation basierende Risikoprioritätszahl kritisiert und die Verwendung einer verallgemeinerten Aggregationsfunktion mit einem verallgemeinerten Ausgangsindikator vorgeschlagen, die in den meisten komplexen Systemen, wie z. B. Lieferkettennetzwerken, verwendet werden kann. Diese Funktion kann über verschiedene Hierarchieebenen innerhalb einer Organisation hinweg angewendet werden.

Unternehmen setzen verschiedene Managementsysteme ein, z. B. für Qualität, Umwelt, Energieeinsparung und Cybersicherheit. Die Bewertung der mit diesen Systemen verbundenen Risiken ist jedoch nicht konsolidiert. Den Entscheidungsträgern fehlt ein Instrument, das ihnen einen umfassenden Überblick über die Priorität der Risiken in mehreren Managementsystemen bietet. In dieser Arbeit wird auch ein mehrstufiges Warnsystem vorgeschlagen, das es ermöglicht, Warnungen auf verschiedenen hierarchischen Ebenen wie Faktoren, Prozessen und Abteilungen von Organisationen zu erstellen. Dies erhöht die Flexibilität bei der Kombination von Risikobewertungen aus verschiedenen Bereichen und macht es zu einem wichtigen Instrument für Entscheidungsträger.

Ziel dieser Arbeit ist es, eine praktikable Anwendung der oben genannten Ansätze in der Lieferkette zu ermöglichen, die bei der Risikoanalyse häufig übersehen wird. Die hier vorgestellte Forschungsstudie verbessert die aktuelle Wissensbasis, indem sie Managern und Entscheidungsträgern in der Lieferkette ein praktisches Instrument zur Bewertung ihrer Verfahren an die Hand gibt.

Stichworte: FMEA; Risiko der Lieferkette; Risikoanalyse; Anhäufung

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List of Abbreviations

AP	Action Priority, term used in the new FMEA
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
Cn	Controllability, factor
Co	Cost, factor
CRO	Chief Risk Officer
CSR	Customer Specific Requirement
D	Detectability, factor
EMS	Electronic Manufacturing Service or Environmental Management System
EnMS	Energy Management System
ERP	Enterprice Resource Planning
ESMS	Energy Saving Management System
FM	Failure Mode
FMEA	Failure Mode and Effect Analysis
HLS	High Lstructure Structure
ICE	Importance Criticality and Ease, effort or exposure
ISMS	Information Security Management System
ISO	International Standardization Organization
JDM	Joint Design and Manufacturing
MADM	Multi Attribute Decision Making
MCDM	Multi Criteria Decision Making
MFI	Mamdani Fuzzy Inference
MODM	Multi Oobjective Decision Making
MSR	Monitoring and System Response
NDA	Non- Disclosure Agreement
OEM	Original Equipment Manufacturer
O	Occurence, factor
QA	Quality Assurance
QMS	Quality Management System
PDCA	Plan Do Check Act
PM	Plastic Moulding
RAP	Risk Aggregation Protocol
REFS	Risk Evaluation Framework on Supply Chain
RFD	Risk Failure Deployment
RPN	Risk Priority Number

S	**S**everity, factor
SCM	**S**upply **C**hain **M**anagement
SMS	**S**afety **M**anagement **S**ystem
TOPSIS	**T**echnique for **O**rder **P**reference by **S**imilarity to the **I**deal **S**olution
TREF	**T**otal **R**isk **E**valuation **F**ramework
TRPN	**T**otal **R**isk **P**riority **N**umber
WS	**W**arning **S**ystem

List of Symbols

μ	Fuzzy membership function
A	comparisom matrix
a_ij	judgement element in correlation matrix
CI	Consistency Index
Cr	Criticality factor
CR	Consistency Ratio
d_ij	element of decision matrix
f_i	risk factors
h_i	risk incident
k_ij	normalized element of correlation matrix
n	number of factors
N	warning level
P_i	performance score of element i
$(\mathbf{R}^{(N)}, \mathbf{W}^{(N)}, S)$	Risk aggregation protocol
RI	Random Consistency Index
$S(\mathbf{f}, \mathbf{w})$	risk aggregation function
S_i^+	ideal best Euclidean distance
S_i^-	ideal worst Euclidean distance
$\mathbf{T}$	Threshold vector
V_ij	normalized element of decision matrix
V_i^+	ideal best solution
V_i^-	ideal worst solution
w_i	weight value of factor f_i
$\mathbf{w}$	Vector of weights
W	warning rule

Chapter 1

Introduction

1.1 Motivation of the thesis

In today's globalized world, supply chains are the subject of increasing discourse, to the point where even average citizens are affected by them. The interconnectedness of the global community ensures that significant events occurring on the opposite side of the globe have an almost instantaneous impact on this side as well.

The news frequently reports on the events that precipitated the disaster, such as earthquakes, floods, and fires in enormous warehouses; agricultural catastrophes, conflicts, and more recent epidemics; and the products that were impacted by these calamities in the region.

Every individual is compelled to investigate causes and effects, but especially methods to prevent their consequences. Similarly, managers and purchasers of companies consider strategies to ensure a steady supply of basic materials for their organizations and to mitigate risks in light of the current economic climate. As a result, the discipline of risk analysis and management was established.

Numerous studies, analyses, and news reports have shown that contemporary supply chains are susceptible to much more dangers than their managers recognize (Yacob Khojasteh; Geske; Henke). As a result, supply chain vulnerability has emerged as a critical concern for numerous organizations. If not effectively managed, these risks, including natural disasters, cyber-attacks, terrorism, credit crunches, and pandemic situations, could result in significant declines in profitability, revenue, competitive advantage, and productivity, among other metrics. The potential for supply chain deformation in the event that one of the risks materializes raises the issue of supply chain reversion to its initial state. Consequently, organizations must enhance their comprehension of the ramifications of these risks throughout their supply chains. Publications related to risk analysis have increased at an exponential rate since the turn of the century (Huang et al., 2020). When taking into account the number of publications related to the most commonly used risk analysis methods and the implementation of FMEA in various domains, the supply chain will be placed towards the end of this list (Huang et al., 2020).

Risk analysis is a proactive and strategic approach to managing uncertainties in the supply chain. It helps organizations prepare for and respond to disruptions, ultimately contributing to the overall resilience and success of the supply chain.

Risk analysis is of the utmost importance in supply chain management for a variety of reasons (to name a few):

Suppliers selection: and rating is very important in the supply chain. The first rating system was made by Dickson in 1966 (Dickson, 1966), and this was updated by Cheraghi in 2011 (Cheraghi et al., 2011) presenting a very detailed literature review, and that was updated with a few related publications till 2020. As can be mentioned in conclusion, the importance of supplier selection, selection, and evaluation factors over time has changed. The rank is the same as published by Kara et al. (Kara and Ümit Oktay Fırat, 2018). Most important risk factors in evaluation of suppliers: late delivery, cost of risk, operational risk, quality, low customer service level.

Identification of Potential Threats: Supply chains are vulnerable to various risks, including natural disasters, geopolitical issues, economic downturns, information security, pandemic situations, and supplier failures (Henke; Rinaldi et al.). Conducting risk analysis helps in identifying potential threats that could disrupt the supply chain.

Mitigation Planning: Once risks are identified, a proper risk analysis allows for the development of mitigation strategies (Yacob Khojasteh). This involves planning for alternative sources of supply, creating contingency plans, and establishing communication channels to respond effectively when a risk materializes.

Cost Reduction: By proactively identifying and addressing risks, supply chain managers can avoid costly disruptions (Su and Lei; Hu et al.). For example, having alternative suppliers or diversified sourcing strategies can help mitigate the impact of a supplier going out of business or facing production challenges.

Improving Resilience: Understanding potential risks allows organizations to build a more resilient supply chain (Sawik; Geske). This resilience is essential for adapting to unforeseen circumstances and maintaining business continuity during disruptions.

Compliance and Regulatory Considerations: In certain industries, there are strict regulations and compliance requirements (like sustainability (Rausch-Phan and Siegfried), information security (Melnyk et al.)). Failure to comply with these regulations can lead to significant disruptions and legal consequences. Risk analysis helps identify compliance-related risks and ensures that the supply chain is aligned with regulatory requirements.

Enhancing Decision-Making: Informed decision-making is critical in supply chain management (Wu and Pagell). Risk analysis provides valuable insights that can be used to make strategic decisions, such as selecting suppliers, determining inventory levels, and optimizing the overall supply chain structure (de Brito).

Customer Satisfaction: A resilient and well-managed supply chain ensures that products and services are delivered on time, even in the face of disruptions. This reliability contributes to customer satisfaction and helps maintain positive relationships with clients (Ellinger et al.; Omoruyi and Mafini).

Insurance and Risk Transfer: Understanding the risks involved in the supply chain allows organizations to assess the need for insurance coverage and risk transfer mechanisms. This can provide financial protection in the event of a disruption (Njegomir and Demko-Rihter; Freichel et al.).

Continuous Improvement: Regularly conducting risk analysis fosters a culture of continuous improvement within the supply chain. It allows organizations to learn from past experiences, update risk profiles, and refine mitigation strategies over time (Mayer et al.; de Brito).

Within this list, several things are connected in a hierarchical manner, where the attainment of certain goals is dependent on the attainment of other goals. Typically, these items are effectively managed by the organization, particularly if they have extensive experience in related business within the same industry, such as cost reduction, decision-making improvement, customer satisfaction, insurance and risk management, because these items are well-known or derived from lessons learned by organizations. However, there are some items that are entirely new, unforeseen, or demand greater attention, such as cyber-attacks, social engineering, spear fishing, unexpected disasters, pandemic situations, political factors, war, terrorist attacks, the implementation of new procedures, or regulatory changes.

The fact that Tier 1 or 2 suppliers may view their supply chains as proprietary and restrict visibility at the purchaser or integrating-manufacturer level should be emphasized. Certain non-disclosure agreements (NDAs) may also restrict the disclosure of the supply chain's identity. Notwithstanding these challenges, companies can nevertheless use systematic techniques to address identified risks. This method, along with the possibility of conducting thorough evaluations of suppliers through possible or regular audits, or the potential for suppliers to inaccurately assess themselves, is a risk that must be considered by any leader in supply chain management.

Consequently, the objective of the dissertation was to develop a risk assessment instrument that would be more user-friendly for decision makers in the supply chain.

This thesis focuses on the current state of risk assessment, specifically in the supply chain domain. Addresses the challenges associated with failure mode and effect analysis (FMEA), which is currently the most widely used method. The thesis also explores the issue of determining the appropriate number of factors for risk assessment, highlighting that two or three factors are not always sufficient for risk assessment. Additionally, it discusses the challenges related to aggregating functions in risk assessment. Furthermore, the thesis emphasizes the importance of implementing a warning system when performing analysis across multiple factors, departments, units, or management systems, such as quality, environment, energy savings, work-safety, or information security.

1.2 Research questions

Considering the issues and their relevance above, the current study seeks to answer the following research questions:

RQ1: In what ways can a risk evaluation framework tailored to supply chains be constructed to offer a more precise and straightforward estimation than the existing systems?

RQ2: In the supply chain, risks must be mapped and estimated for several areas/domains. What method can be used to bring these alarm levels together?

RQ3: Which aggregation method is the optimal for supply chain?

The structure of the dissertation is as follows. Chapter 1 provides a brief background on the motivation of this thesis, while Chapter 2 focuses on reviewing the literature, including related works and conclusions. Chapter 3 provides an exposition of the mathematical foundation and the theoretical framework of implemented risk analysis. Chapter 4 introduces the approaches used for designing implementation, provides application examples of these methods, and compares them. Chapter 5 explores the topic, while Chapter 6 confirms the accuracy of the findings. Chapter 7 provides a summary, while Chapter 8 examines the constraints of this study and offers guidance for future endeavors

Chapter 2

Literature review

2.1 What is the risk?

Risk is a concept that appears in various contexts, and its definition can vary depending on the field and perspective. However, common to most definitions of risk are uncertainty and undesirable outcomes.

The concept of risk assessment has origins in ancient times, although it was not necessarily structured or methodical. Was proclaimed as the divine revelation. More than 3200 years ago, the people known as Asipu, residing in the Tigris-Euphrates valley, used their expertise in evaluating risk to inform decision makers (Covello and Mumpower). Around 2400 years ago, the Athenians utilized their ability to evaluate risk in order to assist decision makers by relying on recorded material, observations, inferences, and presumptions (Kloman). This can be regarded as a risk assessment with a single element.

Risk analysis began to gain prominence in the financial sector, specifically inside insurance companies and banks' lending operations, in the early 1900s (Kloman). This is the initial endeavor to utilize the mathematical foundation of 2-factor analysis to assess uncertainty and severity or effect.

Three crucial phases might be stated here:

1. Harry Markowitz authored an article titled "Portfolio Selection" in the Journal of Finance (Markowitz) in 1952, and he was awarded with the Nobel Prize in for this achievement in 1990. This article explores the analysis of return and variation in an investment portfolio, which is used to create advanced metrics of financial risk that are commonly used today. Douglas Barlow, the insurance risk manager at Massey Ferguson in Toronto, introduced the concept of "cost-of-risk" in 1962 (Kloman). This concept involves comparing the total of self-funded losses, insurance premiums, loss control costs, and administrative costs to revenues, assets, and equity.

2. Mehr and Hedges in 1963 (Wood et al.) and Williams and Hems in 1964 (Hall et al.) wrote the first academic publications on pure risk management, and since then the technological risk management model has been developed. Risk management became a corporate affair in the late 1990s. The major orientation decisions in firms' management policy (and monitoring) are now made by the board of directors. Most often, the audit committee monitors these decisions, although some large

financial institutions have put risk management committees in place. The position of Chief Risk Officer, or CRO, emerged. (Dionne). From a business point of view, the risk is a probability or threat of damage, injury, loss, or any other negative occurrence caused by external or internal vulnerabilities, something that may be avoided through preemptive action.

Up until now, the risk was only characterized by two characteristics: severity $*$ probability $=$ primary risk indicator or expected value.

3. In 1940, the United States Military pioneered a technique to minimize sources of variation and the associated risk of failures in the manufacturing of missiles. This event is regarded as the inception of FMEA. The Ford Motor Company adopted this approach in the mid-1970s for safety and regulatory reasons, and it was later copied by other car makers in the US and Europe. These dates are highly significant, as they mark the inception of risk management in manufacturing processes, coinciding with the recognition of three key components in risk management. In short time the FMEA became the most popular risk analysis tool in production, especially in automotive. In 1993 the Automotive Industry Action Group (AIAG) first published the FMEA Reference Manual for the automotive industry. The last, 4th edition appeared in 2008 (Chrysler LLC), and the new edition will appear in 2025.

4. The initial standard addressing supply chain security and resilience was introduced in 2007, known as ISO28000 Security management systems. The most recent version (2nd) appeared in 2022 and adheres to the high level structure (HLS) of ISO standards. The standard especially focuses on the evaluation and management of security risks that pertain to the organization and its stakeholders. For a comprehensive analysis of the advantages of this standard, Wong Huei Ing refer to the detailed literature evaluation. Curiously, this criteria is absent from the Customers Special Requirements of automotive OEMs/IATF (last check 21.07.2024), which is why it is not commonly utilized. This page contains the CSR of following companies: BMW Group, Ford Motor Company, Geely Group, General Motors, IVECO Group, Jaguar Land Rover Limited, Mercedes-Benz Group AG, Renault Group, Stellantis (ex FCA), Stellantis (ex PSA), Volkswagen AG, and Volvo Group. The automotive industry acknowledged this inadequacy and initiated the development of its own auditing standard, known as VDA6.8 Supply Chain Process Audit, to mitigate supply chain risks. This standard is expected to be introduced at the end of 2024 or the beginning of 2025.

Given that Failure Mode and Effects Analysis (FMEA) is the most commonly employed approach for assessing risks, I will commence the following part by discussing the FMEA and its benefits and drawbacks.

2.2 Shortcomings of FMEA

According to Huang et al. (2020), the analysis of keywords in the risk-related literature over the past 20 years confirms that the FMEA remains the most commonly utilized tool for evaluating risks. In their study, Liu et al. (2013a) analyzed 75 publications published between 2000 and 2010 on the topic of risk evaluation. They reached the same conclusion, emphasizing that currently, the FMEA is employed in conjunction with other evaluation methodologies (Liu et al., 2013a; Huang et al., 2020).

The shortcomings of FMEA have been presented by several authors Liu et al. (2013a); Lolli et al. (2015); Malekitabar et al. (2018); Wu and Wu (2021). A summary can be seen in the table below (Table 2.1).

TABLE 2.1: Shortcomings of old FMEA (based on Wu and Wu (2021)), and comparison with the new FMEA (AIAG).

The shortcoming of the traditional FMEA	**Improvements and representative articles**	**Comparison with new FMEA**
1. The relative importance between O, S and D was not considered. It is assumed that these three factors are of equal importance, but this may not be the case when considering the practical application of FMEA.	Weights are assigned to three factors based on various weighting methods, such as OWA (Chang and Cheng), IFWA (Liu), BWM (Rezaei), and FWE (Park et al.).	Solved with the introduction of an AP (action priority) level matrix, based on factors level
2. Different O, S and D rating sets may produce exactly the same RPN values, but their hidden risk implications may be completely different. This issue may result in wasted resources and time, or, in some cases, high-risk failure modes were not widely known.	The introduction of factor weights reduces and avoids the confusion caused by the same RPN results in different failure modes.	The RPN removed, instead appears AP levels (Low, Medium, High).
3. RPN calculation considers only three risk factors, mainly safety, and ignores other important factors such as quality and cost.	Cost (Tazi et al.), quality (Nguyen et al.), and other factors (Jahangoshai Rezaee et al.) are added to improve the theoretical basis of the RPN evaluation.	Not improved; still consider just 3 factors (O, S, and D)
4. The RPN approach does not consider the direct/indirect relationship between failure modes and is flawed for systems with many subsystems and components. When one failure causes several other failure modes, that failure should be prioritized for corrective action.	The FTA (Peeters et al.), Bayesian network (Kabir and Papadopoulos), and other methods are used to present the interactions and relationships of various failures.	AP levels are a bit better, level H requires corrective action, level M requires corrective action or justification why no action is needed, and L means that no action is needed.
5. The three risk factors O, S, and D are evaluated on a discrete ordinal scale. However, the multiplication is not meaningful on the ordinal scale. Thus, the results obtained are not only meaningless, but also in fact misleading.	Few articles discuss the ordinal scale and multiplication issues. Alternatively, MCDM methods, such as TOPSIS (Vahdani et al.) and DEMATEL (Liu et al.), are used to prioritize failure modes directly.	Still not improved
6. The three risk factors are often difficult to determine accurately. Members of the FMEA team often provide different types of assessment information for the same risk factor, and some of the assessment information may be inaccurate, uncertain, and incomplete due to time constraints, inexperience, and insufficient data.	Introduce uncertainty assessment methods, such as fuzzy theory, rough theory, evidence theory, and probability theory into the FMEA analysis (see Section 2.2).	Still not improved
7. The mathematical form used to calculate the RPN is very sensitive to changes in the assessment of risk factors.	Few articles discuss this issue	Still not improved
8. The rating transitions for the three components of FM are different. The relationship between the probability table for O and O is nonlinear, whereas the relationship between the probability table for D(S) and D(S) is linear.	Few articles discuss this issue	Still not improved
9. The results of RPNs are discrete, and many holes are there.	Few articles discuss this issue	Instead of RPN are used 3 levels

The aforementioned deficiencies are applicable to all aggregation methods that are dependent on multiplication, not just FMEA.

In 2019 was published the new FMEA (AIAG), called AIAG-VDA FMEA 1st edition.

Changes:

- The RPN (Risk Priority Number) was eliminated and replaced with Action Priority level defined in related Table,
- Use a seven steps approach (planning, structure analysis, function analysis, failure analysis, risk analysis, optimization and documentation of results),
- Use as a measurable of the FMEA effectiveness and efficiency,
- Higher emphasis on error-proofing,

- Appears a new chapter: Monitoring and System Response.

The Severity (S), the Occurrence (O), and the Detection (D) scale remain, which means the team should evaluate them as in the case of old Monitoring and System Response (MSR). Now instead of RPN, the Action Priority level is used, which can be Low, Medium, or High, according to S, O, D factors value from an Action Priority Table defined. The standard recommends a table for AP levels based on factors (S, O, D) values, but that can be modified in function of the area of usage. In this way from the FMEA team is not requested to make actions based on RPN number, which based on Table B.1 (see in Appendix B) not always highlights the real risk level, they should do actions based on AP level: for Low level no action is required, for Medium if no action is taken, that should be justified, and for High level it is mandatory to take action to reduce the risk.

Regrettably, the AP's introduction cannot be utilized for risk level comparison due to its inadequate "compression" into three levels. Therefore, a numerical or ordinal representation corresponding to the RPN is necessary to aid risk assessors in comprehending which hazards are substantial.

Several deficiencies exist in the FMEA methodology; these remain unresolved in the 2019 FMEA publication (AIAG), see Table 2.1's last column.

2.3 Risk factors

The methods developed in the literature presented above define the degree of risk depending on a fixed number of factors. In the traditional FMEA method, the risk value is calculated based on the occurrence, severity, and detectability parameters (Liu et al., 2013a; Fattahi and Khalilzadeh, 2018). The Fine Kinney method calculates risk depending on the likelihood of occurrence, exposure, and consequence parameters (Kinney and Wiruth, 1976). Some extensions of the number of risk factors have been introduced in the literature. Karasan et al. (2018) extends the number of factors, calculating risk based on severity, probability, frequency, and detectability values. In addition, Salah et al. employs a risk assessment comprised of four factors: severity, occurrence, detection, and dependency. This underscores the significance and efficacy of the extended system, namely of FMEA. Ouédraogo et al. (2011) increased the factors to 5: risk perception, impact of hazard, research specificities, hazard detectability and probability of occurrence of accident, or Wan et al. (2019) using as factors the likelihood, consequence of time/delay, consequence of additional expense, consequence of damage to quality, and visibility. In the last case, commonly used variables were assessed, namely Visibility and Consequence, with the latter being determined by the provider's delay, the cost associated with the supplier, and the quality of the given components. Maheswaran and Loganathan (2013a) proposed four risk factors including severity, occurrence, detection, and protection. Yousefi et al. (2018) considered two additional factors including cost and duration of treatment in addition to severity, occurrence and detection. The article

(Braglia et al.) demonstrates the consideration of risk factors in two steps. Firstly, the FMEA method is used, which involves analyzing common factors such as severity (S), detectability (D), and occurrence (O). Then, the RFD (Risk Failure Deployment) method is employed, which utilizes matrices to identify and quantify failure modes, root failure causes, failure mode relationships, and ICE (Importance, Criticality, and Exposure) matrix, which provides a clear plan for addressing each root cause by determining the necessary corrective measures. This second part takes into account the economic impact, the costs associated with eliminating each root cause, and the feasibility of implementing improvement activities. The presented methodology basically utilizes six elements, albeit the last three are taken into account throughout the assessment.

These methods, however, are limited to a fixed number of risk factors. In addition, during the literature investigation, it can be seen that the authors calculate with risk factors, since they are independent (Liu et al., 2013a). One of the possible causes of ignoring additional risk factors is that their dependence should be addressed. These issues call for new solutions that can address the dependence of risk factors on an arbitrary number of risk factors.

2.3.1 Scales

Various scales have been developed for risk assessment in the literature; they can be divided into two categories of predefined or invariant scales according to the state of evaluation.

In the case of **invariant scales**, in the early stages of risk evaluation, the scale was not used; risk evaluation was performed via percentage of occurrence (Etherton and Myers, 1990). Later, linguistic scales were used with 3-5 distinguished levels, and the assessment was made by the evaluation team's top ratings percentage (Gauthier et al., 2018; ISO 12100, 2010). Linguistic scales (Merrick et al., 2005) use pairwise comparison instead of percentage. After the comparison, the ranking order of all the alternatives can be determined and the best ones are selected from among a set of feasible alternatives. The main challenge of this approach is to interpret the resulting risk values. In fact, regardless of whether the results have risky or less risky effects, the results will fluctuate around the same value.

Linguistic scales are also commonly used in Fuzzy FMEA (Betül Aktürk), but this will be discussed in Section 3.3.1.

Another approach is to use **predefined scales** for all factors. Before performing the evaluations, the appropriate numeric scales were defined first in the failure analysis (Liu et al., 2013a). Various scoring guidelines exist; e.g., Goodman as cited by Silva et al. (2014) developed the 10-point scales for evaluating the failure modes with respect to each risk factor. Similarly, Lolli et al. (2015) developed an evaluation scale for assessing the 3 risk factors such as the widely known FMEA. In some cases, mixed scales can be found, as in Fine Kinney (Kinney and Wiruth, 1976), where for likelihood and exposure [0.1,10] is used and for consequence [1,100] is used. Both approaches can be used in risk evaluation; however, predefined scales, in particular the FMEA method using the product formula, were the most common (Liu et al., 2013a).

The Fuzzy implementation offers an advantage in this regard, as it employs linguistic variables in place of scales, which are applicable to each factor and resolve the issue when various scales are employed.

In literature, predetermined scales with identical factor numbers are commonly utilized.

2.4 Risk aggregation

Risk aggregation plays an important role in various risk-assessment processes (Bani-Mustafa et al., 2020; Bjørnsen and Aven, 2019). Risks can be aggregated for several purposes. It can happen at the lowest level of the systems (processes, products) during the calculation of a complex indicator from the factors. The total risk value of certain areas can be formed, but risk can also be aggregated along the organizational hierarchy. Aggregation can be considered a method for combining a list of numerical values into a single representative value (Pedraza and Rodríguez-López, 2020, 2021). Traditionally, the risk value is calculated based on a fixed number of risk components. Failure mode and effect analysis (FMEA), which is a widely used risk-assessment method, includes three risk components: the occurrence (O), detectability (D), and severity (S) (Fattahi and Khalilzadeh, 2018; Liu et al., 2013b; Spreafico et al., 2017). Several methods and analyses have been proposed to aggregate risk. Traditionally, FMEA uses the risk priority number (RPN) to evaluate the risk of failure. The occurrence factor measures the likelihood that a failure mode occurs. The severity is the expected consequence of failure. The ability to recognize an error before it affects customers is measured by the detection factor. Scales based on guidelines for usage (such as Fine Kinney and FMEA) and for evaluation/aggregation require different functions, such as additive, average, product, geometrical mean (Kokangül et al., 2017; Maheswaran and Loganathan, 2013b; Wang et al., 2009), logarithmic (Malekitabar et al., 2018), median (Karasan et al., 2018), radial distance (Malekitabar et al., 2018), but the most common is the FMEA method with product formula (Liu et al., 2013a). The multiplication of these factors generates the RPN, and the aggregation is performed only at the factor level. Detailed procedures for carrying out an FMEA have been documented in Stamatis (2003) and Tay and Lim (2006). Traditional FMEA has proven to be one of the most important early preventive methods (Liu et al., 2013a, 2014; Silva et al., 2014), whereas the traditional RPN method has been criticized in the literature (see the summary in Liu et al. (2013a); Lolli et al. (2015); Malekitabar et al. (2018)).

Numerous alternative approaches have been proposed to overcome the shortcomings of traditional FMEA. It can be seen from one of the most recent reviews of FMEA conducted by Liu et al. (2013a) that the fuzzy rule-based system is the most popular method to prioritize failure modes. The fuzzy rule-based FMEA approach uses linguistic variables to prioritize failures in a system to describe severity, detection, and occurrence as the riskiness of failure (Tay and Lim, 2006; Petrović et al., 2014; Bowles and Peláez, 1995; Cardiel-Ortega and Baeza-Serrato). However, the most commonly used membership functions are triangular and trapezoidal (Riahi et al., 2012). An advantage of using fuzzy rule-based FMEA for risk evaluation is that the resulting evaluation becomes qualitative and has the ability to model uncertain and ambiguous information. A disadvantage of fuzzy rule-based FMEA approaches is that they can produce erroneous results if analysts do not have a sufficiently deep understanding of the system. In addition, similar to traditional FMEA, fuzzy rule-based FMEA aggregates only at the factor level. Other aggregation techniques have also been proposed in the literature, e.g., geometric mean (see e.g. Kokangül et al., 2017; Maheswaran and Loganathan, 2013a; Wang et al., 2009), median Karasan et al. (2018), and radial distance Malekitabar et al. (2018). The weighted geometric mean is also applied in the analytic hierarchy process (AHP) (Braglia and Bevilacqua, 2000) or analytic network process (ANP) (Liu and Tsai, 2012; Torabi et al., 2014; Wang et al., 2018). The AHP/ANP enables the decomposition of elements into a hierarchy and calculates weights for the risk factors. In the AHP, each element in the hierarchy is considered to be independent of all the others (Kutlu and Ekmekçioğlu, 2012). However, ANP does not require independence among elements, so it can be used as an effective tool also in the case of interdependency (Saaty, 2004; Wang et al., 2018).

In addition, the authors emphasize a remarkable shift towards **integrated methods** for ranking failure modes when aiming at accurate risk evaluation. For instance, fuzzy evidential reasoning is integrated with grey theory (Chang et al., 1999; Liu et al., 2011), fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) with fuzzy AHP (Kutlu and Ekmekçioğlu, 2012; Djenadic et al.), and VIKOR (VIsekriterijumska optimizacija i KOmpromisno Resenje) or EDAS (Evaluation Based on Distance from Average Solution) (Panchal et al., 2019c) with fuzzy logic (Liu et al., 2012; Panchal et al., 2019b; Panchal and Srivastava, 2019) and gray techniques (Panchal and Kumar, 2016; Panchal et al., 2018; Panchal and Srivastava, 2019). There is a trend towards the use of more than one method to improve the efficacy and empirical validity of risk evaluation results (Liu et al., 2013a; Chang et al.). Recent research (Lolli et al., 2015; Liu et al., 2014) also shows a shift toward integrated methods (e.g., ANP (dos Santos et al., 2015; Zammori and Gabbrielli, 2012) has been combined with other models), so that synergies can be maximized.

It may be inferred from the literature that there is no universally accepted method for aggregating. The writers employ various singular aggregation functions, but analysis about the best aggregation risk function, or a framework, what whether there is the possibility to use their combinations that have not been previously used.

2.5 Risk warning system

Warnings play a vital role in risk evaluation (Khan et al., 2015; Øien et al., 2011). Conventional risk evaluation has the disadvantage of having rigor (Kalantarnia et al., 2009), repeatedly adopting a single index (Zheng et al., 2012) or a list of warning indicators (Øien et al., 2011) to signal warning events, and failing to capture meaningful failures. There have been many efforts to develop the warning system of risk evaluation. Ilangkumaran et al. (2015) proposed a hybrid technique (Liu et al., 2015; Panchal et al., 2019a) to assess work safety in hot environments including a warning rating and a safety grade at the risk factor level. Øien et al. (2011) have developed a set of risk indicators that can provide warnings about potential major accidents. Zheng et al. (2012) proposed an early warning rating system for hot and humid environments calculating safety indexes at the factor and subfactor levels. In addition, Xu et al. (2002) suggested two levels of warnings. In the scientific literature, the risk hierarchy is occasionally mixed with risk level; e.g., Chen et al. (2012); Manuele (2005) use the action levels as risk hierarchies, and no real hierarchy levels are used.

Liu et al. (2013a); Shaker et al. (2019) conclude that objective and combination weighting methods should be applied in risk evaluation because they evaluate relative importance objectively without decision makers. However, some doubts remain concerning the applicability of integrated methods to real-life circumstances, e.g., the need to add risk factors to the determination of risk priority of failure modes (Liu et al., 2013a) and the need to support the aggregation of risk levels from different domains. Considering risk effects in different domains is important because the same source of hazards often causes risks in multiple management areas with different levels of relevance (Pasman et al., 2014). Therefore, the sources of hazards describing the possible risk effects in different management system areas (e.g., ISO 9001 (2015); ISO 14001 (2015) and ISO 45001 (2017) (previously OHSAS 18000) should be considered and developed holistically and cohesively (Abad et al., 2014; Asif et al., 2013; Bernardo, 2014; de Oliveira, 2013; Rebelo et al., 2016). Domains such as health and safety, quality or environment can be considered in risk evaluation with different weights. To conclude, priorities and demands can be different by domains, which calls for flexible risk aggregation.

Risk evaluation is the process of assessing the impact and likelihood of identified risks based on Chang and Wen (2010) and Hansson and Aven (2014). The main aim of risk evaluation is to determine the importance of risks and to prioritize them according to their effects on systems, processes, designs and/or services for further attention and action (Klinke and Renn, 2002). In other words, this process determines which risk source warrants a response. The need for this process is based on the fact that organizations, processes and projects face a large number of risks, each with different effects; thus, it may be impractical or even impossible to manage them all because of time and resource constraints.

Additionally conventional risk evaluation approaches nevertheless ignore the fact that many contemporary organizational and process components or failure effects across hierarchical levels of a system are inherently complex (O'Keeffe et al., 2015; Pasman et al., 2014), and they are not sufficient to explain all that can go wrong. Such situations call for new approaches, suggesting the need to develop flexible and adaptive risk evaluation methods (Aven, 2016; Reiman et al., 2015) that change to fit the environmental and situational factors of the organization. As Kanes et al. (2017) stated, it is important to focus on the area of flexible risk evaluation, as a way forward to improve current risk evaluation methodologies. O'Keeffe and his team also emphasized that a risk evaluation process should be recursive rather than linear, flexible rather than rigid and pluralist not binary (O'Keeffe et al., 2015). Such a situation calls for different approaches and methods, and it is a challenge for the risk field to develop suitable frameworks and tools for this purpose (Aven and Zio, 2014; SRA, 2015).

As a result of a shift in risk evaluation thinking from traditional and rigid to flexible and adaptive attributes, new risk evaluation methods should be developed where flexibility is one of the most important characteristics.

This summary shows that methods developed in the literature do not address warning events originating from multi-levels such as factor, effect, mode, and process in order to specify unique warning rules for each risk factor separately at each level.

2.6 Risk evaluation in the supply chain

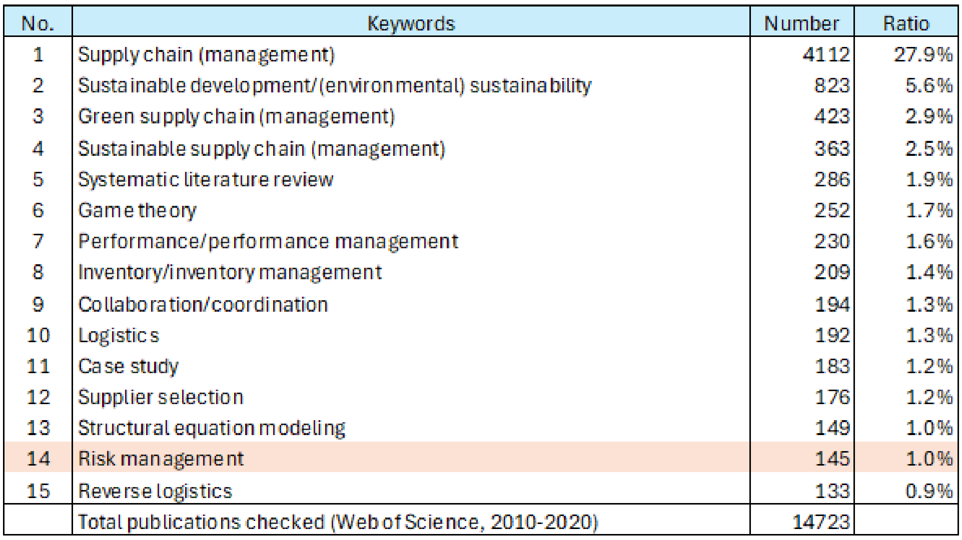
A supply chain risk refers to the potential occurrence of events or circumstances that can negatively impact the flow of goods, services, or information within a supply chain network (Heckmann et al.).

In the past decade, numerous organizations have incurred expenses amounting to hundreds of millions of dollars or euros due to unforeseen disruptions and weaknesses in their supply chains. At the heart of these problems is the absence of dependable mechanisms to identify and effectively mitigate the escalating supply chain risks that result from increased global interconnectedness. As a consequence, the evaluation of supply chain risk is progressively gaining importance.

Supply chain risk factors can significantly impact a company's operations and overall performance (Zhao et al.). Here are some key risk factors that businesses need to consider when managing their supply chains:

There has been an exponential increase in the quantity of risk analysis papers published since the beginning of the century (Huang et al., 2020; Fang et al.). Considering the number of scholarly articles dedicated to the most widely used risk analysis techniques and pragmatic implementations of FMEA in diverse domains, the supply chain would rank last on this list Huang et al. (2020). In regard to supply chain risk analysis, uncharted territories still remain.

Fang et al. literature review is very interesting , because they made a bibliometric keywords analysis on 14723 SCM related publications published between 2010 and 2020, to examine the primary concerns of authors and research trends. The result can be seen on Table 2.2.



No.	Keywords	Number	Ratio
1	Supply chain (management)	4112	27.9%
2	Sustainable development/(environmental) sustainability	823	5.6%
3	Green supply chain (management)	423	2.9%
4	Sustainable supply chain (management)	363	2.5%
5	Systematic literature review	286	1.9%
6	Game theory	252	1.7%
7	Performance/performance management	230	1.6%
8	Inventory/inventory management	209	1.4%
9	Collaboration/coordination	194	1.3%
10	Logistics	192	1.3%
11	Case study	183	1.2%
12	Supplier selection	176	1.2%
13	Structural equation modeling	149	1.0%
14	Risk management	145	1.0%
15	Reverse logistics	133	0.9%
	Total publications checked (Web of Science, 2010-2020)	14723	

TABLE 2.2: Keyword analysis on Web of Science between 2010-2020, based on Fang et al. data

As indicated in Table 2.2, the risk assessment ranks a mere fourteenth in terms of significance within the publication. Remarkably, this analysis by Fang et al. indicates that the number of SCM-related publications remained virtually constant between 2010 and 2014, but begins to increase in 2015.

The Covid-19 pandemic has opened a new era in the field of supply chain management. We can address a sudden increase in the number of articles related to the supply chain. Their number will be augmented to 18,000 in the year 2024. The majority of those articles pertain to resilience, as indicated by Figure 2.1. The Supply Chain and its resilience-related article employs the second scale.

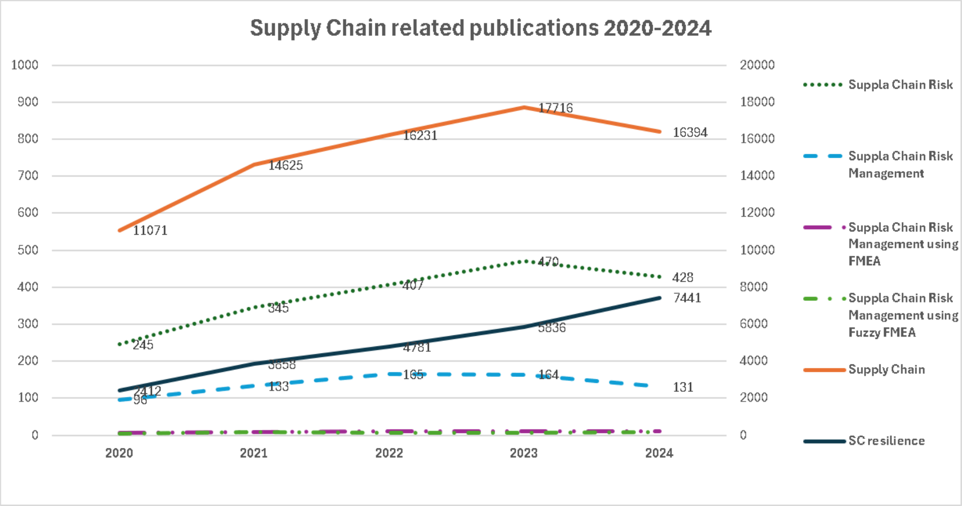


FIGURE 2.1: Keyword analysis on Web of Science between 2020-2024 (data collected at 26.07.3024)

However, the proportion of risk, FMEA, and Fuzzy FMEA remains unchanged from the previous presentation by Fang et al., with only an increase in the number of articles concerning high interest. This data is corroborated by the literature study conducted by Emrouznejad et al.

The supply chain of each company is unique, so risk factors can vary based on industry, location, and specific circumstances. Implementing robust risk evaluation practices and leveraging technology can help mitigate these risks and enhance supply chain resilience.

The **evaluation and selection of suppliers** are critical components of the supply chain. Dickson established the initial classification system in 1966 (Dickson, 1966), and Cheraghi subsequently revised it in 2011 (Cheraghi et al., 2011). Huang et al. (2020) published a systematic review of the literature in 2021 demonstrating the exponential growth of risk analysis publications over the past two decades. Keyword analysis reveals that “FMEA”, “system”, “risk evaluation”, “criticality analysis”, and “failure mode” have reached prominent positions. Similar findings were published by Liu et al. (Liu et al., 2013a) in 2013. It can be concluded that the FMEA continues to be the most widely utilized tool for risk assessment; however, it is presently employed in conjunction with alternative evaluation approaches (Liu et al., 2013a; Huang et al., 2020).

Multiple authors (Sime Curkovic, 2013; Wagner, 2016; Vodenicharova, 2017) have examined the reasons for the limited use of FMEA and other risk analysis methods in the supply chain. The researchers conducted an analysis and successfully identified the main factors: the main difficulty impeding wider deployment appears to arise from a lack of understanding of how to apply FMEA within a supply chain environment.

The utilization of the Severity (S), Occurrence (O), and Detection (D) scales persists, and it is advisable for the team to evaluate them in a manner consistent with a conventional FMEA. The utilization of the Action Priority Level, which is determined based on the values of the S, O, and D components from a designated Action Priority (AP) Table, has replaced the use of RPN. The suggested table for AP levels is derived from the values assigned to the components S, O, and D. However, it is subject to modification based on factors such as the nature of the business, the specific process, or the industry involved. The AP table delineates the instances in which the organization is authorized to initiate action, as opposed to the responsibility of the FMEA team. No action is required for Low AP levels, while any lack of action for Medium AP levels should be adequately justified. In the case of High AP levels, immediate action must be taken to mitigate the risk. This suggests that instead of relying on the RPN value, the actions are selected based on the specific values of the factors. Regrettably, as demonstrated in Table B.1, the current system is incapable of accurately discerning the actual amount of risk.

It may be inferred from the existing body of research that the supply chain industry uses risk analysis methods that closely resemble those employed in various other domains. The authors exclusively employ the FMEA (Ewa Kulinska and Dendera-Gruszka, 2021; Ebadi et al., 2020; Indrasari et al., 2021) assessment technique, or a modified version of FMEA with factors limited to 5 levels instead of 10 (Aleksic et al., 2020). Alternatively, they utilize mixed evaluation techniques such as Fuzzy-FMEA (Mustaniroh et al., 2020; Trenggonowati et al., 2021; Lu Lu and de Souza, 2018; Wu and Wu, 2021; Petrović et al., 2014), Fuzzy-AHP (Trenggonowati et al., 2020; Canbakis et al., 2018; Djenadic et al.), FMEA-ANP (Zammori and Gabbrielli, 2012), or Fuzzy Bayesian-based FMEA (Indrasari et al., 2021). According to Liu et al. (2013a); Djenadic et al., the main classification of MCDM (multi-criteria decision making) is discrete multi-attribute decision-making (MADM) methods and continuous multi-objective decision making (MODM) methods. In general, the MCDM methods that are implemented in the Fuzzy-FMEA model are the AHP and TOPSIS. The application of the AHP method introduces the rank of factor's significance to the comprehensive RPN. The TOPSIS method in the Fuzzy composition reduces the subjectivity of the initial expert assessments (Djenadic et al.).

Fuzzy FMEA (Petrović et al., 2014) is considered the second most often utilized risk analysis technique, following the FMEA method. Fuzzy logic is used in situations characterized by prevalent uncertainty and ambiguity, aiming to mitigate the influence of subjectivity. The use of the fuzzy method enables the application of specific linguistic descriptions in the process of evaluating factors. The three membership functions commonly utilized in Fuzzy FMEA are triangular, trapezoidal, and Gaussian (Ling, 2004; Kubler et al.; Johanyák and Kovács, 2004).

The conventional approach for assessing supply chain risk predominantly involves employing the FMEA framework, which incorporates three key factors: Severity, Occurrence, and Detection. A limited number of authors argue against the adequacy of three factors and instead propose the utilization of models that incorporate either four (expense, time, flexibility, and quality) (Zhu et al., 2020) or five (likelihood, consequence of time/delay, consequence of additional expense, consequence of damage to quality, and visibility) (Wan et al., 2019) factors. In the present case, commonly employed variables were assessed, namely Visibility and Consequence, with the latter being determined by the provider's delay, the cost associated with the supplier, and the quality of the given components.

In the context of supply chain risk analysis, new factors have emerged, such as Quality, Time, Cost (Zhu et al., 2020; Indrasari et al., 2021), Intensity (Ebadi et al., 2020), Consequence (Vodenicharova, 2017), Effect, Cause, Measure (Dendera-Gruszka and Kulińska, 2020), and others.

Salamai et al.; Roscoe et al.; Srivastava and Rogers; Mohammed et al. further contributed to the expansion of our knowledge and were duly incorporated into our knowledge base. Additional sources of input include "Lessons learned" shared internally and externally from other factories within the corporation, education provided by external companies, best practices shared (Cuthbertson et al.) or collected from our expert members' previous workplaces, outputs from audits, feedback from auditors, customer audits, and brainstorming meetings with customers and suppliers.

Internal supply chain interruption can potentially arise due to:

- Instances of internal operational disruptions;
- Instances of significant management, staff, and operational procedure changes;
- Instances of failure to implement contingency plans in response to problems;
- Instances of inadequate implementation of cybersecurity policies and controls leading to cyberattacks and data breaches;
- Instances of non-compliance with labor laws or environmental standards;
- Instances of unavailability of products to meet customer demands (attributable to inventory issues, ERP system malfunctions, human errors, etc.).

The external supply chain risk might arise due to factors such as:

- Unpredictable or misunderstood consumer/customer demand;
- Delays in the transportation and distribution of commodities, encompassing many types such as components, finished products, and raw materials;
- The potential risks posed by terrorism, armed conflict, economic or political penalties, as well as social, governmental, cyber attacks, and economic challenges;
- The management of supplier risk includes concerns regarding the physical infrastructure and regulatory compliance of a supplier;
- Natural disasters, such as tornadoes, hurricanes, floods, droughts, landslides, and earthquakes;

- Human errors occur at all levels and in all locations.

The above list serves as an example of the types of factors that should be taken into account; nevertheless, they should be considered in light of past supply chain issues, trends, and potential challenges. Internal factors can generally be managed, whereas external factors are rarely controllable and can only be predicted based on the factory's experience with the environment and suppliers.

2.7 Synthesis of challenges from literature

Can be concluded, in the supply chain are used almost the same risk analysis tools, like in other areas. That means the authors use just FMEA (Ewa Kulinska and Dendera-Gruszka, 2021; Ebadi et al., 2020; Indrasari et al., 2021), or mixed evaluation methods, like Fuzzy-FMEA (Mustaniroh et al., 2020; Trenggonowati et al., 2021; Lu Lu and de Souza, 2018), or Fuzzy-AHP (Trenggonowati et al., 2020), or Fuzzy Bayesian-based FMEA Indrasari et al. (2021). Numerous authors attempted to use alternative aggregation methods, such as Euclidean, multiplicative, additive, median, or other functions. Alternatively, they attempted to integrate FMEA with AHP, ANP, TOPSIS, or other methodologies, frequently employing Fuzzy logic. In case of Fuzzy FMEA, most often used membership functions are the triangular, trapezoidal and Gaussian (Ling, 2004).

If we check the number of factors in the case of supply chain risk evaluation, still most often is used the standard FMEA with 3 factors, Severity, Occurrence and Detection. Few authors conclude 3 factors are not enough, and present model with 4 factors (Indrasari et al., 2021; Zhu et al., 2020), or 5 factors (Wan et al., 2019). In this case common factors used were completed with Visibility and Consequence (as value), and the consequence was established as a function of the delay caused by the supplier, the cost regarding the supplier, and the quality of supplied parts.

Based on the keyword analysis of Fang et al., it can be inferred that in the field of SCM, new areas of interest have emerged, such as sustainable development and green supply, as well as the emergence of big data and blockchain. However, the analysis of risks in SCM continues to be largely overlooked (see Table 2.2).

The complexity of supply chain risk analysis lies in the fact that each stand-alone process requires its own risk analysis (see Figure 2.2). However, due to the wide range of factors, scales, and areas of action involved, which also overlap with other management system requirements, the existing risk evaluation frameworks are insufficient to handle these complexities. The risk aggregation models are specific to a given area, for example, insurance, bankruptcy risk, production.

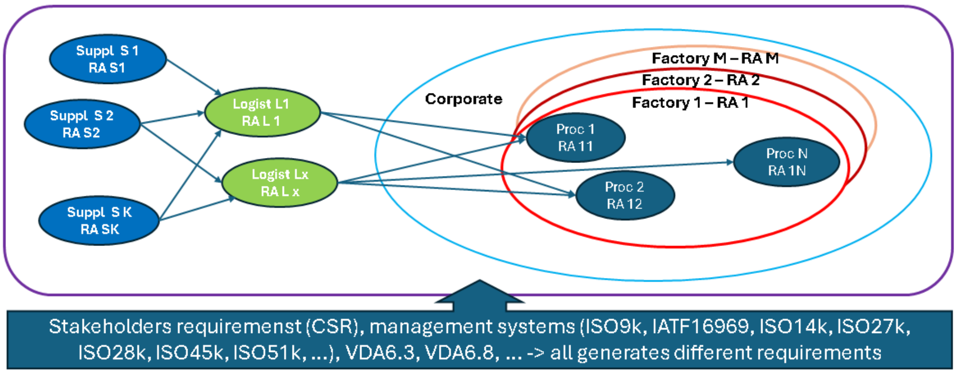


FIGURE 2.2: The complexity of supply chain risk.

The complexity of the supply chain, which encompasses various stages such as manufacturing at suppler, storage (all those noted with RA S1...SK), transportation, delivery, evetually storage in distribution centers) are noted as RA L1...LX, and followed by potencial risk related to logistical activities of customers factories, noted as RA 11...RA1N to RA M1...MN (considering M factories within one corporation), along with the potential risks associated with cyber security, IT failures (like the major IT outage from 19 July 2024, which blocked several financial services, doctors' offices, some TV broadcasters and airports regarding Microsoft-CrowdStrike issue), political decisions (ex. Ukraine's decision to halt the transit of Russian Lukoil oil to Hungary and Slovakia on 17 July 2024), natural disasters, and accidents, necessitates a flexible risk analysis framework.

In summary, a pertinent, functional, and adaptable instrument for performing supply network risk assessment is currently nonexistent. It is imperative that supply chain managers and risk analysts have easy access to simple instrument or tools, considering the aforementioned activities and global developments that have an impact on the supply chain. The forthcoming instrument ought to enhance its efficacy in discerning credible threats, encompass a more extensive spectrum of risk factors surpassing the present three boundaries, and uphold a degree of user-friendliness comparable to that of the conventional FMEA methodology.

This framework should be capable of accommodating an indefinite number of factors, handling factors with varying scales, and providing a unified output in the form of risk levels or priority orders. Flexibility in risk evaluation can be implemented in the following areas: scale, number of factors, aggregation, and warning system. Such a framework would assist decision makers in effectively mitigating or accepting the consequences of these risks.

It is quite beneficial to be able to spot a risk beforehand. Therefore, multiple papers analyze the warning systems that aim to notify us about potential hazardous events. Efforts were made to build a comprehensive warning system for risk assessment in order to address potential alerts (Ilangkumaran et al., 2015; Øien et al., 2011; Zheng et al., 2012), but none of them addressed warning events from factors, effects, modes, and processes in order to specify unique warning rules for each risk factor separately in each level.

Therefore, it is required to have a flexible risk evaluation framework which can be tailored to the specific needs of companies, operate with warning levels on different domains, and help their decision-makers.

2.8 Research assumptions

By revisiting the research questions formulated in Section 1.2, and critically reviewing the findings and relationships within the literature, it becomes possible to formulate the corresponding research assumptions. The tree research assumptions are as follows:

RA1: Conventionally employed three-factor risk analysis systems (e.g., FMEA) yield a less precise risk estimation than multi-factor systems. Increasing the number of factors (higher, than 3), carefully selecting them, can be achieved a more precise risk estimation.

RA2: Alert/warning limits per domain provide management or staff with a more precise depiction of potential risks, as they will blend in with the other values if they only occur once in a set. By emphasizing them and assigning them a limit value, management can be made aware of their significance and impact.

RA3: By carefully choosing the appropriate aggregation function and arranging them in a certain sequence, the evaluation of risks can yield an ideal outcome. This outcome can effectively communicate to top management which risks should be prioritized for mitigation.

Chapter 3

Mathematical background

3.1 Problem formulation

Several authors acknowledged in the preceding chapter that three factors are insufficient for a comprehensive risk assessment. As the number of factors increases, the aggregation function becomes more intriguing. The same limitations that are evident in the FMEA become apparent when employing multiplicative aggregation, which is the same logic as the aggregation function in the FMEA. As a result, the research investigates the criteria that define an aggregation function, the various types of aggregation functions that can be employed, and the benefits and drawbacks of these functions in the context of risk assessment.

The second half of this chapter provides an overview of a hierarchical warning system, which can be implemented at many levels, such as individual factors, processes, departments, or the entire organization.

3.2 Aggregation Functions Criteria

The aggregation function combines the values of elements into a shared output function, where the values represent the level of risk. In the study conducted by the authors in Kovács et al.; Calvo et al. (2002); Grabisch et al. (2011), various aggregating functions were examined. Aggregation functions require several conditions (Grabisch et al., 2009; Zahedi Khameneh and Kilicman), including validity, monotonicity, sensitivity, symmetricity, linearity, scale fit, and scale endpoint identity.

- Validity: Consider the manner in which the risk emanates from the constituents.

$$F : \mathbb{I}^n \to \mathbb{R}; \quad x \in \mathbb{I}^n; \quad a, b \in \mathbb{R}; \quad F(x) = a, \text{ and } \quad F(x) = b \Rightarrow a = b \tag{3.1}$$

- Monotonicity: refers to the property of a function where it exhibits non-decreasing behavior, meaning that it yields a non-negative reaction to any increase in its arguments. In other words, the function does not reduce its output value when any input value is increased.

$$F : \mathbb{I}^n \to \mathbb{R} \quad x, x' \in \mathbb{I}^n, \quad x \geq x' \Rightarrow F(x) \geq F(x') \tag{3.2}$$

The membership functions and the defuzzification function employed in this study exhibit monotonic characteristics.

- Sensitivity refers to the degree of responsiveness or reactivity exhibited in a certain context. In the specific scenario of rigorous monotonicity, sensitivity refers to the extent to which a change in one variable directly and consistently influences a change in another variable.

$$F : \mathbb{I}^n \to \mathbb{R} \quad i \in [n] \quad F(x) \neq F(x+\lambda) \quad x \in \mathbb{I}, \quad \lambda \neq 0 \quad x+\lambda \in \mathbb{I} \tag{3.3}$$

- The property of symmetricity, also known as commutativity, is true when the components or elements of a distribution follow a symmetric distribution. In such cases, the distribution of the aggregated values also exhibits symmetry. This property is also observed in the Fuzzy functions employed.

$$F : \mathbb{I}^n \to \mathbb{R} \quad F(x) = F(|x|) \tag{3.4}$$

- Linearity refers to the property where, in the scenario of components or factors adhering to a uniform distribution, the resulting distribution of the aggregated values will also exhibit uniformity.
- Scale fitting: The aggregate processes should be conducted using the scale values that have been applied. This criterion is also met as the range of each factor is identical.
- Scale endpoint identity: In order to adhere to the boundary criteria, the endpoints of the scales were modified to fall within the interval [1, 10]. This adjustment was important as it ensured that each factor's potential values were defined within the same range.

3.3 Risk Aggregation Functions

Definition 1. *Let* $\mathbf{f} = [f_1, f_2, \ldots, f_n]^T$, $(n \geq 3, n \in \mathbb{N})$ *be the vector representing the set of risk factors. Let* $r = S(\mathbf{f})$ *represent the* ***resulting risk value****, where S is a monotonous aggregation function. The* ***risk aggregation protocol*** *(RAP) is denoted as* $(\mathbf{f}, S)$.

Remark 1. *It is commonly assumed that the risk factors* f_i *and* f_j*, where* $(i \neq j)$ *are independent of one another. Nevertheless, the proposed RAP does not need its independence.*

According to the provided definition, the quantity of factors, including severity, detection, incidence, cost, and others, is denoted by the variable $n \in \{3, 4, 5, \ldots\} \in$

$\mathbb{N}$. The risk ranking numbers, denoted as $f_i \in \{1, 2, \ldots, 10\}$ are related to factor i. This input will be employed by aggregation functions to evaluate each risk case.

Several instances of aggregation functions S are as follows, along with their respective output ranges:

- $S_1(\mathbf{f}) = \prod_{i:=1}^{n} f_i$ is the product of risk factors. If $n = 3$, and the factors can be the severity, occurrence, and detection, resulting the original RPN (risk priority number) from the FMEA. $S_1(\mathbf{f}) \in [1, 10^n] \in \mathbb{N}$
- $S_2(\mathbf{f}) = \sqrt[n]{\prod_{i:=1}^{n} f_i}$ is the geometrical mean. The range $S_2(\mathbf{f}) \in [1, 10] \in \mathbb{R}$
- $S_3(\mathbf{f}) = Median(\{\mathbf{f}\})$ is the median (middle element) in a sorted list of risk factors. $S_3(\mathbf{f}) \in [1, 10] \in \mathbb{N}$
- $S_4(\mathbf{f}) = \frac{1}{n} \sum_{i:=1}^{n} f_i$ is the average of risk factors. $S_4(\mathbf{f}) \in [1, 10] \in \mathbb{R}^+$
- $S_5(\mathbf{f}) = \sqrt{\sum_{i:=1}^{n} f_i^2}$ is the generalized n-dimensional radial distance of risk factors. $S_5(\mathbf{f}) \in \left[\sqrt{n}, 10\sqrt{n}\right] \in \mathbb{R}^+$
- $S_6(\mathbf{f})$ = Aggregation of Fuzzy membership functions based on rule base. In this case, the output function range depends on the defuzzyfication function established by user, and can be in any prespecified range.

Other aggregation functions, such as *Sum*, *Geometrical mean*, and *Logaritmic*, are available in the literature; however, their behavior is comparable to that of the functions previously described. For instance, the *Sum* aggregation function's behavious is equivalent to the *Average*'s multiplied by a constant number n, which represents the number of factors. The behavior of the *Geometrical mean* and *Logarithmic* aggregation functions is identical to that of the *Product* aggregation function. In both instances, the figure at the upper risk values is reduced, which implies that the resulting risk levels are compressed into a lower range.

The utilization of risk analysis inside the supply chain is not as prevalent as it ideally should be, primarily due to a lack of competence among purchasing, procurement, and logistics managers, as stated in the preceding chapter. The risk assessment framework, presented in Kosztyán et al. (2020), has undergone an expansion to incorporate a Fuzzy module, which was one of my contributions to that article. This addition has been implemented to effectively address the issue at hand.

3.3.1 Implementation of Fuzzy Aggregation Function

The methodology employed in the previously disclosed fuzzy aggregation function will not be altered. Fuzzy logic comprises three distinct phases, with the initial one being **Fuzzyfication/Fuzzyfier**. In this phase, the factors (crisps) are converted into fuzzy input variables in the form of membership functions. The subsequent process, **Inference**, produces output fuzzy variables by utilizing the fuzzy rule base to ascertain which control actions ought to be executed in light of the fuzzy input variables. This constituent could potentially be considered an aggregation protocol. In the concluding phase, **Defuzzyfication/Defuzzifier**, the produced output is transformed back into genuine output variables, namely the value and/or risk level.

Fuzzyfication/Fuzzyfier

Initially, it is necessary to define the input fuzzy variables by employing the input membership functions. This implies that fuzzy membership functions should be used to convert each risk factor into an input fuzzy variable. The designation for these values is “crisps”. A multitude of linguistic variables influence the number of membership functions associated with a given variable. Typically, Fuzzy FMEA utilizes three to seven linguistic variables (Kozarević and Puška; Cardiel-Ortega and Baeza-Serrato). It is possible to incorporate additional variables; however, in the given context, the rule base became exceedingly intricate. In the beginning, the input fuzzy variables must be defined through the utilization of input membership functions.

At the beginning and end of the interval, the sigmoid function was implemented:

$$\mu(x,a,b)_{sigu} = \begin{cases} 0, \ x \le a \\ \frac{1}{1+e^{a(x-b)}}, & \text{any other case} \end{cases} \tag{3.5}$$

$$\mu(x,a,b)_{sigd} = \begin{cases} 1 - \frac{1}{1+e^{a(x-b)}}, \ x \le a \\ 0, & \text{any other case} \end{cases} \tag{3.6}$$

where a is the steepness of function, and b is the inflection point.

For each range within the interval, the bell/splay function is applied:

$$\mu(x,a,b,c)_{spl} = \frac{1}{1 + \left|\frac{x-b}{a}\right|^{2c}} \tag{3.7}$$

where b is the center of function, a is the width of curve and c is the steepness of function.

Both the splay and bell are Gaussian membership functions that were selected due to their smoothness, non-zero value at all point intervals, continuous differentiability, and mathematical and computational tractability (Johanyák and Kovács, 2004).

As illustrated in Figure 3.1, for $n = 5$ (5 linguistic levels), in accordance with its original score or crisp, each component is converted into the sum of n membership functions.

$S_i(\mathbf{f_i}) = \sum_{i:=1}^{n} \mu_i(x), x \le 10$ and $x \in \mathbb{R}^+$, other variables of membership functions are constants (a, b, c).

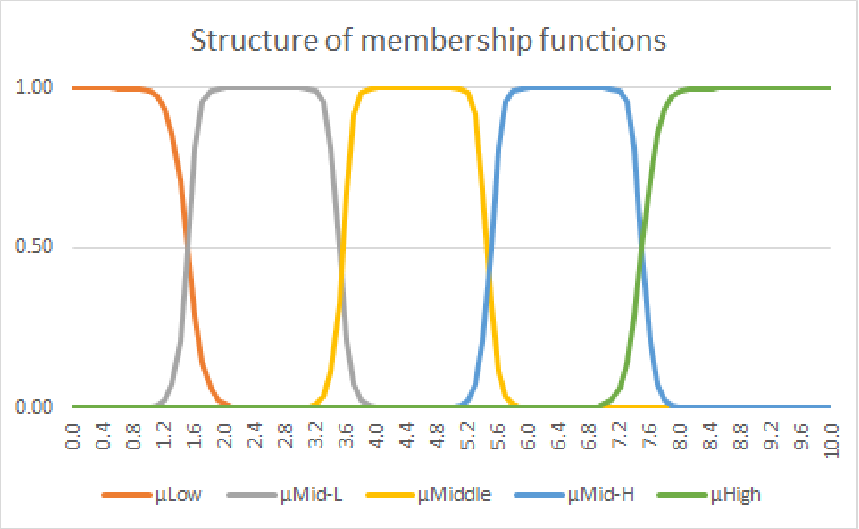


FIGURE 3.1: The structure of Fuzzy membership functions for each factor.

Each factor will have its own sum of membership functions, noted $S_i(\mathbf{f_i})$, $f_i \in \{1, 2, \ldots, 10\} \in \mathbb{N}$, representing the classification of risk converted in a number.

Fuzzy Rule Base

An analogy can be drawn between the sum of fuzzy membership functions and the accumulation of factors comprising the fuzzy rule base. The literature also contains considerable variation regarding the selected aggregation method for fuzzy sets: only sums, products, maximal functions, or the Mamdani Fuzzy Inference (MFI) are employed due to the more comprehensible and intuitive nature of their rule bases. The MFI functions optimally in expert system applications in which the norms are established based on the expertise possessed by human beings. The input of this aggregation consists of fuzzy sets, and the output is also a fuzzy set. The output is determined by the center of mass or gravity, and the rule basis is a simple IF-THEN structure. An instance of this can be described as follows:

$$W_i(\mathbf{S_i}) = S_1(\mathbf{f_i}) \otimes S_2(\mathbf{f_j}) \otimes \ldots \otimes S_n(\mathbf{f_n}) \tag{3.8}$$

where $\otimes$ is the aggregation protocol.

Defuzzyfication

The final phase entails the transformation of the amount of risk from a fuzzy state to a crisp state. In this phase, the determination of risk level will be achieved by converting the membership functions in real numbers. Several viable defuzzification strategies, including:

- Center of gravity of area—see Figure 3.2

- Bisector of area refers to a vertical line that partitions a fuzzy set into two subregions of equivalent area. The phenomenon in question may exhibit alignment with the center of gravity, however this correlation is not universally observed;
- Mean of Max level;
- Largest of Max—the max value of the highest output membership function;
- Max—the max limit value achieved by any output function;
- Smallest of Max—the lowest value of the highest output membership function;
- Low—is the lowest value achieved by any output function.

The calculation of the center of gravity of the membership function is performed, considering the factor's value, and subsequently, the results are aggregated.

$$x_i = \frac{\int \mu_C(x)xdx}{\int \mu_C(x)dx} \tag{3.9}$$

$\int \mu_C(X)dx$ represents the measure of the region enclosed by the membership function C. If the parameter μ_C is established based on multiple discrete membership functions, the center of gravity can be mathematically represented as the sum of these functions.

$$x_i = \frac{\sum_{i=1}^{N} \mu_C(x_i)x_i}{\sum_{i=1}^{N} \mu_C(x_i)} \tag{3.10}$$

In actuality, it is feasible to explicitly determine the center of gravity of the membership functions by clearly describing the functions. The following diagram presents a visual representation of the methodologies employed in the calculation of accurate output (Figure 3.2).

The case study detailed in Section **??** employs the center of gravity methodology.

It can be asserted that the chosen and implemented fuzzy function, which includes the defuzzification process with the exception of sensitivity, satisfies every one of the six criteria previously outlined as prerequisites for an aggregate function. Given that the input values consist of natural numbers ranging from [1, 10], this aspect becomes relatively inconsequential (Section 3.2).

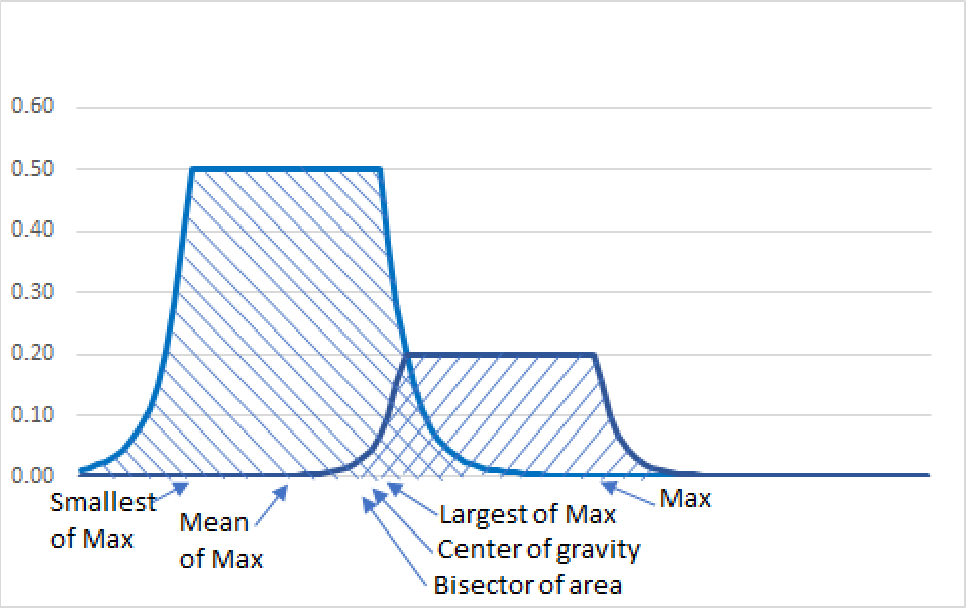


FIGURE 3.2: Used defuzzyfication methods to obtain the final output value.

With regard to supply chain risk analysis, what is the advantage of fuzzy? Their aggregation with fuzzy membership functions is not influenced by linguistic levels and no scales are used. This method provides the risk evaluation framework with the ability to aggregate risk from various risk hierarchies (process, department, or external companies) throughout the entire supply chain.

3.3.2 Weighting the risk aggregation functions

An inherent characteristic of all aggregation functions is their failure to differentiate among factors; instead, they treat them as equivalent. This means that a flexible system should be able to weigh the importance of different aspects.

Definition 2. *Let* $\mathbf{f} = [f_1, f_2, .., f_n]^T$, $(n \geq 2,\ n \in \mathbb{N})$ *be the vector of risk factors and let* $\mathbf{w} = [w_1, w_2, .., w_n]^T$ *be the weight vector of risk factors* $(w_i \in \mathbb{R}^+)$. *Denote* $r = S(\mathbf{f}, \mathbf{w})$ *as a* ***resulting risk value****, where* S *is a monotonous aggregation function. Denote* $(\mathbf{f}, \mathbf{w}, S)$ *as the* ***risk aggregation protocol*** *(RAP).*

Remark 2. *Usually, it can be assumed the risk factors* f_i *and* f_j, $(i \neq j)$ *are independent of each other. However, the proposed RAP does not require their independence.*

The proposed risk aggregation protocol (RAP) can integrate the traditional FMEA, Fuzzy FMEA and the Fine Kinney risk evaluation methods. RAP generalizes these three types of methods; therefore, they can be considered special cases of the proposed RAP.

Example 1. *In the case of traditional FMEA,* $n = 3$, $w_i := 1$, $f_i \in \{1, 2, .., 10\}$, $i := 1, .., n$, $S := \prod_{i:=1}^{n} f_i$.

Example 2. *In the case of Fuzzy FMEA,* $n = 3$, $w_i := 1$, $f_i := \mu_i(x)$, $\mu_i(x) : I \to [0,1]$ *is the so-called membership function,* $i := 1, .., n$, $S(\mathbf{f}, \mathbf{1}) := \prod_{i:=1}^{n} \int_I f_i dx = \prod_{i:=1}^{n} \int_I \mu_i(x) dx$.

Example 3. *In the case of the Fine Kinney approach,* $n = 3$, $w_i := 1$, $f_1 \in \{0.1, 0.2, .., 10.0\}$ *(likelihood of occurrence),* $f_2 \in \{0.5, 1.0, .., 10.0\}$ *(exposure factor),* $f_3 \in \{1.0, 2.0, .., 100.0\}$ *(factors of possible consequences),* $S := \prod_{i:=1}^{n} f_i$.

Although Fine Kinney involves elements with varying levels and steps, FMEA considers factors with uniform characteristics.

The utilization of the Analytic Hierarchy Process (AHP) technique involves the determination of the relative importance of factors to evaluate the outcome of risk evaluation. The initial phase of the proposed model involves the mutual ranking of factors, which determines their influence on the overall risk. The approach relies on doing a systematic evaluation of each parameter by comparing them in pairs. The method's output values range from 0 to 1, with a total sum of 1. A significant benefit of using this approach is the ability to assess the coherence of the individual risk evaluation members for making the decision.

The first step in this method is the mutual comparison of two alternatives in each interaction. For that purpose, the Saaty scale of relative importance is used with reciprocal values. The numerical value of the priority vector is used to form matrix M(m n) in which n is the number of criteria considered and a_{ij} is the relative comparison measure of w_i/w_j while $i, j = 1, ..., n$. By calculating the matrix, the result of the AHP method was obtained for alternative ranking according to given parameters and subparameters. The output value is defined as a weight coefficient of different factors $(W_{f1}, W_{f2}, ..., W_{fn})$. The final step in the AHP method is the consistency check. This is achieved by calculating the value consistency index (CI) and the random consistency index (CR). To fulfill a consistency condition, the value (CR) must be less than 0.1. In other cases (CR > 0.1), it is necessary to determine the reasons for the inconsistency (usually by repeating pairwise comparisons with the risk assessment team) (Saaty, 2004).

$$CI = \frac{\lambda_{max} - n}{(n-1)} \tag{3.11}$$

where λ_{max} is the weighted mean of coefficient λ_i calculated by Eq 3.12, n is the number of compared elements.

$$\lambda_{max} = \frac{1}{n} \sum_{i:=1}^{n} \lambda_i \tag{3.12}$$

$$\lambda_i = \frac{\sum_{j:=1}^{n} a_{ij} W_i}{W_i} \tag{3.13}$$

$$CR = \frac{CI}{RI} \tag{3.14}$$

where RI is the random index that depends on the number of components n determined by Saaty (Saaty, 2004).

To include weights, AHP/ANP can be integrated into the traditional FMEA, Fuzzy FMEA and Fine Kinney methods. In addition, the proposed RAP allows us to consider arbitrary risk factors (more or less than three).

Example 4. *In the case study, $n \geq 2$, $n \in \mathbb{N}$, $w_i \in \mathbb{R}^+$, $f_i \in \{1, 2, .., 10\}$, $\sum_{i:=1}^{n} w_i = 1$, $i := 1, .., n$, and were used five types of functions:*

- $S_1(\mathbf{f}, \mathbf{w}) = \prod_{i:=1}^{n} f_i^{w_i}$ *is the weighted geometric mean of risk factors.*
- $S_2(\mathbf{f}, \mathbf{w}) = max(\{f_1 w_1, .., f_n w_n\})$ *is the weighted maximum value of risk factors.*
- $S_3(\mathbf{f}, \mathbf{w}) = Median(\{\mathbf{f}, \mathbf{w}\})$ *is the weighted median of risk factors.*
- $S_4(\mathbf{f}, \mathbf{w}) = \sqrt{\sum_{i:=1}^{n} w_i f_i^2}$ *is the weighted radial distance of the risk factors.*
- $S_5(\mathbf{f}, \mathbf{w})$ = *Aggregation of Fuzzy membership functions based on rule base. The weighting can be applied in the last defuzzyfication step.*

In the case of $w_i = 1/n$ for s S_1, S_3 and S_4, and $w_i = 1$ for S_2 produces the unweighted multiplicative, unweighted median and unweighted radial distance and the unweighted maximum of risk factors.

3.3.3 Evaluating the Results of Used Aggregation Functions

Two viable approaches appeared to be viable to compare the results produced by the aggregating functions.

- One is when the **range of output arguments of functions is set to be identical**; this is typically resolved by multiplying the values by a constant. This was promptly abandoned due to the potential complexity that the behavior of the functions would have introduced to the situation.
- An alternative approach entails **comparing the output values** generated by different aggregating functions in the same order in which they assign equivalent risks.

This second methodology will be further implemented, elucidated in the validation methodology, and will be applied in the case study. In order to achieve this, it is necessary to employ ranking techniques.

Rank correlation

The Spearman's rank correlation coefficient is a statistical measure that quantifies the strength and direction of the association between two variables:

$$r_s = 1 - \frac{6 \sum_{i=1}^{N} (R_{Xi} - R_{Yi})^2}{N(N^2 - 1)} \tag{3.15}$$

where R_{Xi} and R_{Yi} represent the ranks of the first and second variables, respectively. The Spearman's rank correlation coefficient is a statistical measure that quantifies the strength and direction of the association between two variables. The sign and magnitude of the value fall within the range of $[-1; +1]$.

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)

The application of a multi-criteria decision analysis technique will be employed to evaluate a set of alternatives and ascertain the ranking of the risk analysis models implemented. The TOPSIS method chooses the alternative that has the shortest geometric distance from a positive ideal solution and the greatest geometric distance from a negative ideal solution (Chakraborty). The model is dependent on a comparison of the supplied data with the best data from the selected aggregation functions. The optimal outcome is the one that closely aligns with the ideal, which holds significance particularly in regards to risk.

Let A represent the pairwise comparison matrix for factors as follows:

$$A = \begin{pmatrix} a_{11} & \dots & a_{1n} \\ \dots & \dots & \dots \\ a_{n1} & \dots & a_{nn} \end{pmatrix} \tag{3.16}$$

where a_{ij} are the judgement scores, considering $a_{ij} = 1/a_{ji}$, and $a_{ii} = 1$. This matrix is normalized with:

$$k_{ij} = \frac{a_{ij}}{\sum_{j=1}^{n} a_{ij}} \tag{3.17}$$

The local weight resulting:

$$w_i = \sum_{j=1}^{n} \frac{k_{ij}}{n} \tag{3.18}$$

The variables h_i are used to represent the risk incidents, where i ranges from 1 to n. Similarly, the variables f_j are employed to designate the TOPSIS evaluation criteria, with j ranging from 1 to m. The numerical results of the alternative h_i with respect to the criteria f_j are represented by the variable x_{ij}.

The formula for the normalized decision matrix can be expressed as follows:

$$d_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \tag{3.19}$$

The weighted normalized decision matrix elements can be generated:

$$V_{ij} = w_i \times d_{ij} \tag{3.20}$$

The ideal best solution V_j+ and the ideal worst solution V_j- are determined by aggregating the highest and lowest values of each criterion.

For beneficial criteria:

$$V_j^+ = max[V_{ij}] \quad V_j^- = min[V_{ij}] \tag{3.21}$$

For non-beneficial criteria:

$$V_j^+ = min[V_{ij}] \quad V_j^- = max[V_{ij}] \tag{3.22}$$

Euclidian distances are measured from the ideal best (S_i^+) and ideal worst (S_i^-) values:

$$S_i^+ = \sqrt{\sum_{j=1}^{m}(V_{ij} - V_j^+)^2} \quad S_i^- = \sqrt{\sum_{j=1}^{m}(V_{ij} - V_j^-)^2} \tag{3.23}$$

The performance score (relative closeness to the ideal solution) can be calculated:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{3.24}$$

The ranked options are subsequently arranged in descending order as the final step.

This methodology is suitable for pairwise correlation analysis, specifically when the number of variables being compared does not exceed seven. Implementing this strategy gets problematic in situations where there are more than ten hazards, which is a frequently seen phenomenon in real-world scenarios. An illustration depicting the initial use of the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) may be observed in the Bognár and Hegedűs context.

When evaluating a case that involves more than seven significant individual hazards, it is recommended to engage a team of experts who possess a broad knowledge of the consequences associated with each risk. The individuals possess the capability to produce a matrix that facilitates the rating of effects, dangers, and impacts, alongside another matrix that enables the evaluation of results. One can utilize RSTUDIO to input both matrices and calculate their ranks using the TOPSIS algorithm (Yazdi). This methodology will be represented in Section 6 Step 6 & 7 and in the case study (Section **??**).

3.4 Evaluation of aggregation functions

Six risk aggregation methods, which consider five factors (as example) as input and employ multiplicative, average, median, modified Euclidean distance, geometrical mean and fuzzy functions, are very interesting and used in literature. The utilization of the frequency perspective in the assessment process can prove to be useful. The Crystal Ball application developed by Oracle, which is an add-in for Microsoft Excel, was employed for this purpose. For the examination of three variables, specifically for the conventional FMEA, the trial number was established at 10,000. In this particular case, the sensitivity for each element was 33.3 %. In the case of evaluating five factors, the trial numbers were set to 100,000 to achieve equal sensitivity for each element, with each factor accounting for 20 % of the total. The figures that were generated to illustrate the distribution of frequencies and values are presented in Figures 3.5 to 3.11.

The related sensitivity for the standard FMEA (with 3 factors, O, S D) can be seen in Figure 3.3

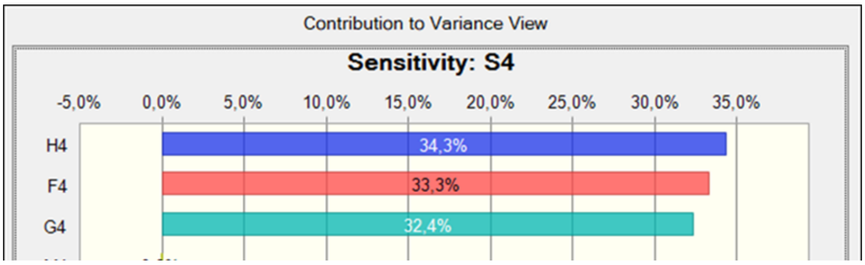


FIGURE 3.3: Standard FMEA sensitivity distribution for its 3 factors (O,S,D).

The sensitivity in the case of the five-factor distribution (Figures 3.6 - 3.11 looks like Figure 3.4. Figure 3.4 represents the sensitivity for the TREF Multiplication case, but for other aggregation functions with 5 factors, the deviations are within 2. 4%. A trial count of 100,000 was chosen for 5 parameters in order to attain almost identical sensitivity values.

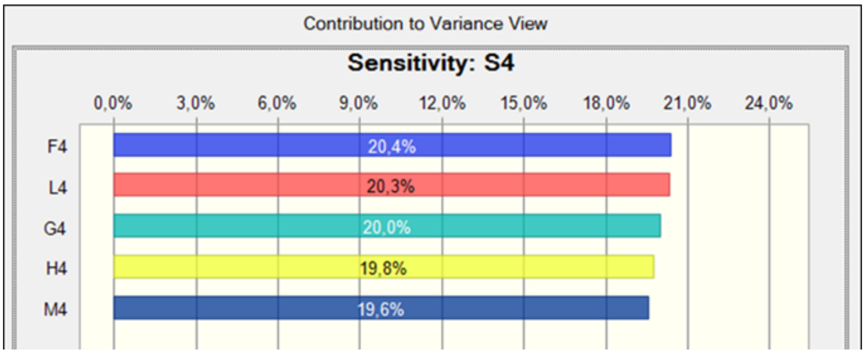


FIGURE 3.4: TREF Multiplicative sensitivity distribution for its 5 factors (O,S,D,Co,Cn).

A comprehensive summary of the simulations conducted using Oracle's Crystal Ball is provided in Table 3.1.

TABLE 3.1: Characteristics of different aggregation methods for 5 factors including the standard FMEA with 3 factors.

Item	**FMEA**	**TREF Multi**	**TREF Aver**	**TREF Median**	**TREF EucDist**	**TREF Fuzzy**
Factors	3	5	5	5	5	5
Skewness	1.66	3.34	-.0025	-.003	-.32	3.28
Kurtosis	5.77	18.84	2.36	2.37	3.02	17.91
Min	1	1	1	1	2	8
Max	1000	100000	10	10	22	77348

Skewness in Table 3.1 refers to the absence of symmetry in the data set, whereas Kurtosis assesses whether the data exhibit heavy (positive) or light (negative) tails relative to a normal distribution.

Upon examination of the simulation Figures 3.5 to 3.11, it is evident that:

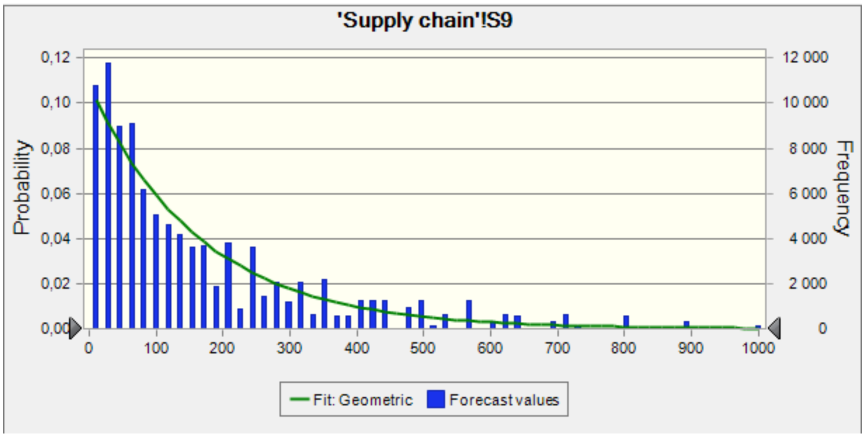


FIGURE 3.5: Standard FMEA frequency/values distribution.

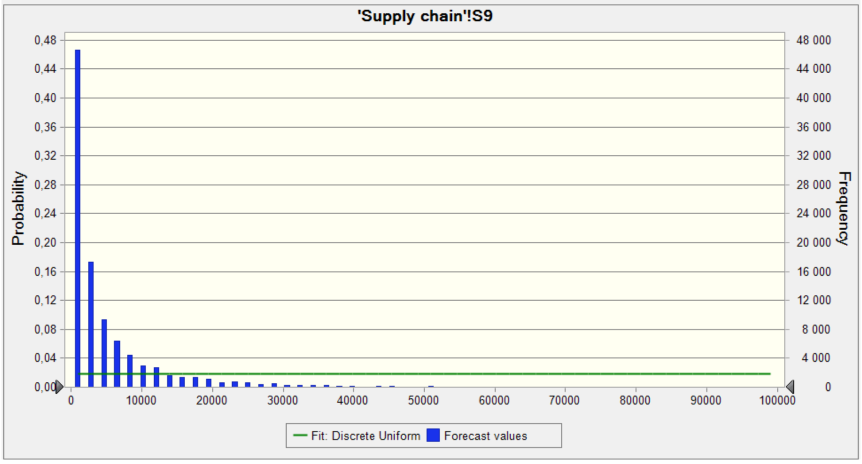


FIGURE 3.6: TREF Multiplication frequency/values distribution

- The results obtained via the **Multiplication Aggregation Method**, as depicted in Figure 3.6, exhibit a level of comparability to those obtained from a conventional FMEA. However, it should be noted that the former method involved the consideration of five components, whereas the latter method typically considers three components. The linearity of the Multiplication technique and the standard FMEA is commendable. Consequently, the outcome for a scenario including n factors will yield a range of $[1, 10^n] \in \mathbb{N}$ for each factor, where the range of each factor is $[1, 10] \in \mathbb{N}$. The concerns of FMEA are equally relevant in this particular case. This is the most commonly used aggregation method. It is crucial to highlight that this aggregation function solely utilizes a small number of values within the range of $[1, 10^n]$. For instance, when considering 3 factors only 120 values are used from a range of $[1, 1000] \in \mathbb{N}$, for 4 factors only 274 values are used from a range of $[1, 10000] \in \mathbb{N}$, and for 5 factors only 546 values are used from a range of $[1, 100000] \in \mathbb{N}$. There are a total of seven unique values in the upper third part for all three cases. In the upper half, there are 7 distinct values for three factors (from 1000), 21 for four factors (from 10,000), and 23 for five factors (from 100,000). There are positive and negative aspects to this issue. Negative: only a few numbers from a substantial range are utilized. To the contrary, the high-risk procedures are notably emphasized.

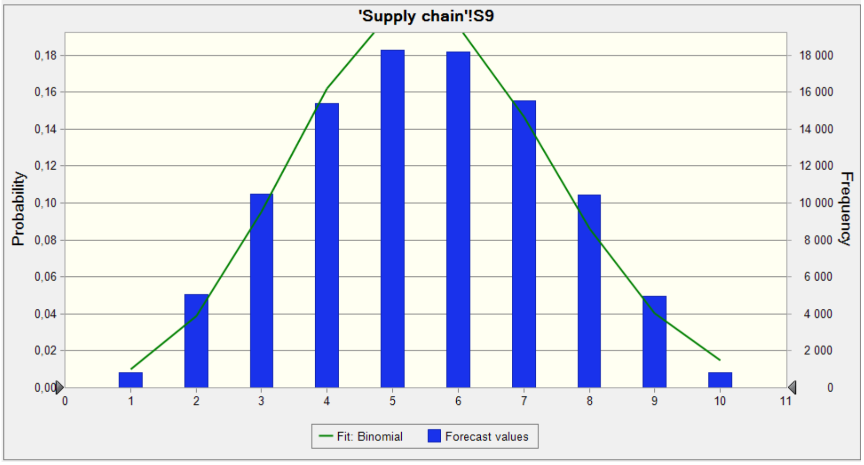


FIGURE 3.7: TREF Average frequency/values distribution

- The input range and output range for the **Average aggregate** in Figure 3.7 are identical, spanning from 1 to 10. This method demonstrates strong linearity and is very easy to calculate. The components/factors range must be measured on the same interval scale. The presence of extreme values can pose challenges in some scenarios. In that case if one factor attains its maximum value and the remaining factors maintain low values, the resulting output will nevertheless fall below the midpoint of the output range. In this particular scenario, the presence of low-value components effectively mitigates the impact of any extreme values, hence impeding the identification and analysis of potential risks.

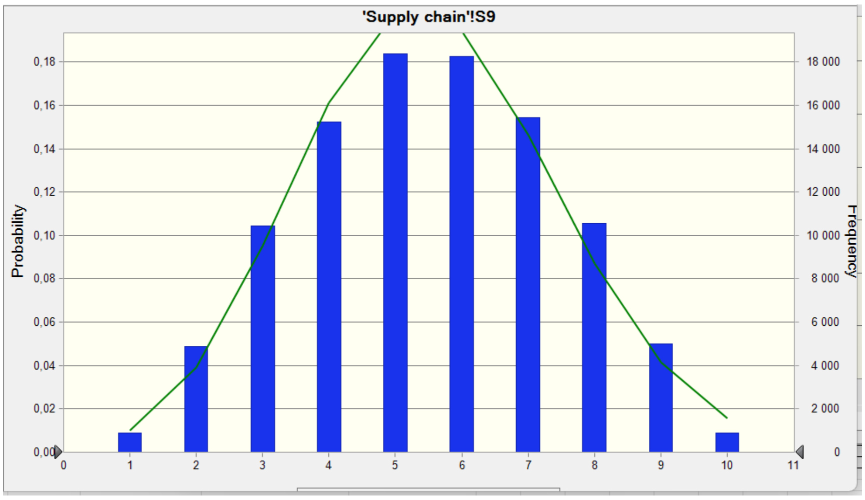


FIGURE 3.8: TREF Median frequency/values distribution

- The **Median aggregation** yields the lowest Skewness score, as depicted in Figure 3.8, suggesting that the data exhibits a high degree of symmetry. The Kurtosis score of our dataset is rather low, suggesting a moderate level of customization in the data. The resulting scale is the same as the components' scale, and this function can also be used on ordinal scales. The calculation is not easy in practice. The scale is relatively rough and can be considered correct only for homogeneous risk components. This situation bears resemblance to the Average aggregation approach.

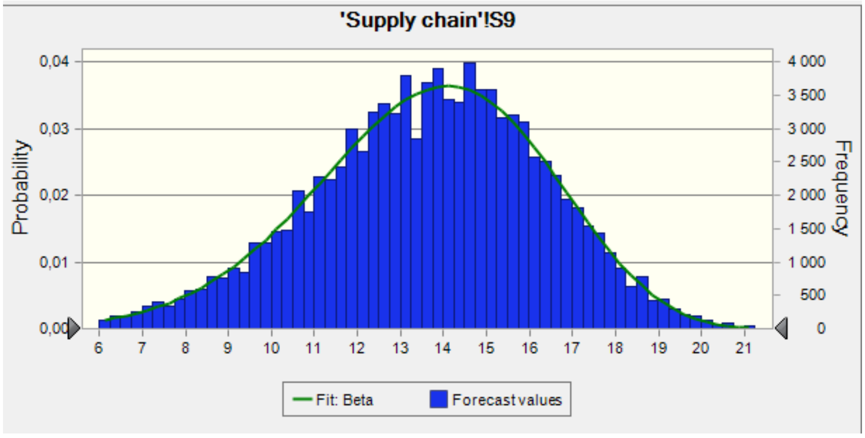


FIGURE 3.9: TREF Euclidean Distance frequency/values distribution

- Linearity is only average and computation is challenging in the case of the **Euclidean distance (generalized) aggregate** (see Fig. 3.9). Interpretation is challenging in n-dimensional space where $n > 3, n \in \mathbb{N}$. In the case of n factors, the output will be $[\sqrt{n}, 10\sqrt{n}] \in \mathbb{R}^+$ for each factor's range of values of $[1, 10] \in \mathbb{N}$. The linearity of the Euclidean distance (generalized) aggregate is only average, and its computation is problematic, as depicted in Figure 3.9.

The Euclidean distance frequency/value distribution closely resembles the geometric mean. Based on the case study, it is evident that this function is ranked third among all the functions that were assessed.

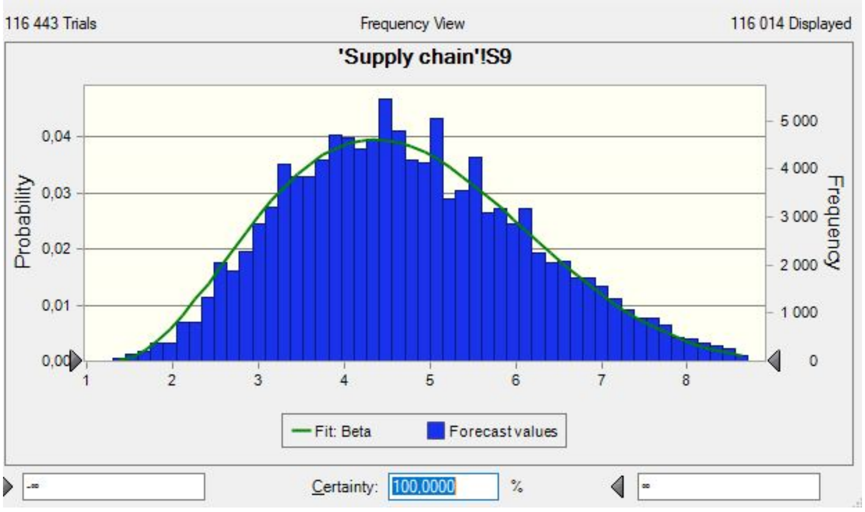


FIGURE 3.10: TREF Geometrical mean frequency/values distribution

- In the case of the geometrical mean, the number of output values is equal to the number of unique numbers, as is the case with multiplicative aggregation functions. However, the root function pushes the tip of the curve towards the center area, resulting in a shorter high values spectrum and a nearly symmetrical appearance.

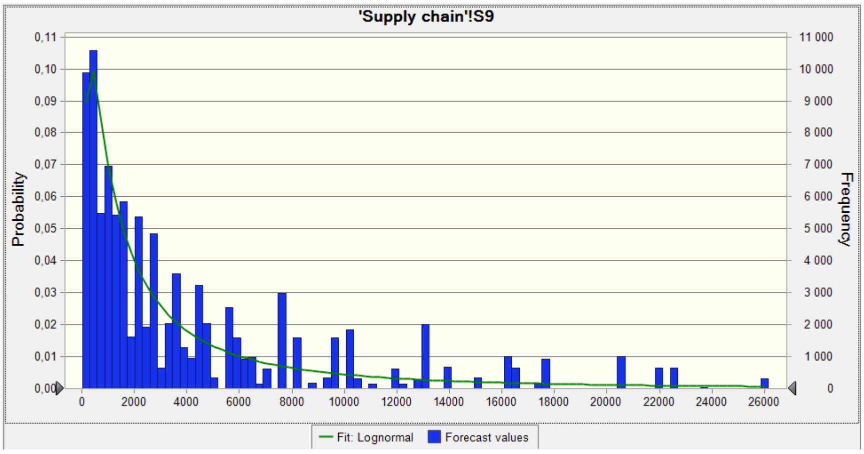


FIGURE 3.11: TREF Fuzzy frequency/values distribution

- The outcome data for the **Fuzzy aggregation method** (refer to Figure 3.11), which is determined by the used membership and defuzzification functions, exhibit similarities to those of the TREF Multiplication. The calculation is very complex, and needs experience. However, it is important to note that the output consists of just five primary groups (see Figure 3.1).

In conclusion, it is important to acknowledge that aggregations utilizing multiplication approaches, such as FMEA, generalized TREF Multiplication, and TREF Fuzzy with respect to defuzzification, yield the most unfavorable distribution. However, their significant contributions become essential in situations where elements exhibit elevated levels of risk, and their simplicity in usage makes them the most commonly used aggregation function.

The least advantageous functions are the average and the sum - both functions essentially disregard the selection of high-risk factors, hence reducing the potential for identifying high-risk situations. The range of output values in their case is very limited.

When comparing the multiplication function to the geometrical mean and generalized Euclidean distance, their outputs have distinct values numbers are same. The shape of the frequency/values distribution charts is crucial for this reason. Considering this, based on the shape of the distribution graphic, the multiplication aggregation function has fewer values in the high range, the geometrical mean aggregation function has more, and the Euclidean distance aggregation function has more than the geometrical mean. Depending on the shape of the figures, we can choose an aggregation function based on the data structure. If we need to extend the output range, the best option is to use the multiplicative aggregation function. If we want to distinguish more values in the upper range, we can use geometrical means. Alternatively, if we require a larger amount of data in the upper range, we can utilize the general Euclidean distance. According to the case study, the Euclidean distance function was ranked third out of all the functions evaluated.

Given the benefits of the flexible aggregation functions mentioned above, the generalized Total Risk Evaluation framework can effectively manage risks at various levels. This includes the whole supply chain, integrating risks from internal logistic processes, risks associated with forwarding and logistics companies, and risks related to supplier assessment.

Due to the fact that the objective of risk analysis is to mitigate risk above a certain threshold and the output ranges of various aggregation functions are incomparable (as emphasized in Section 3.3.3), the most effective approach to comparing them is to rank the outputs of each aggregation separately and then compare the results.

3.5 Proposed Warning Systems

The warning system signals to the risk evaluation team or related decision makers where critical failures are, and this team can see the general conditions of the processes. The warning system evaluates risk values at all hierarchical levels, including factors, process, department, company, and corporation levels. This is essential because decision-makers may lack the expertise to understand the whole risk assessment on any level. However, process owners can identify critical thresholds at different levels or critical risk output levels across various hierarchies. These factors are crucial in predicting and warning about potential risks.

As with the calculation of aggregated risk factors, note that in the Total Risk Priority Numbers (TRPNs), the specification of the warning system follows the bottom-up conception. Corrective/preventive actions are scheduled if a risk factor is not less than a threshold **W1**, but also corrective/preventive actions are scheduled if the aggregated value is not lower than a threshold **W2**. The warning system can propose an extra output factor, for example **criticality**, to allow the risk evaluation team to specify corrective/preventive actions **W3**, even if the aggregated risk value is lower than the specified threshold. If its value is 1, corrective or preventive actions should be specified. However, if its value is 0, corrective or preventive actions can be specified because both the risk factors and/or the aggregated risk value can be higher than the thresholds. The criticality factor produces another flexibility for the team to override the evaluation and specify preventive tasks for the events that are not risky but that may be potentially risky events (e.g., nonquantifiable risks and difficultly quantifiable customer expectations, or even their possible changes) and should be evaluated independently from other risk factors.

Definition 3. *Let* $(\mathbf{R}^{(N)}, \mathbf{W}^{(N)}, S)$ *and* $(\mathbf{R}^{(N-1)}, \mathbf{W}^{(N-1)}, S)$ $(N \geq 1)$ *be risk aggregation protocols. Additionally, denote* $Cr^{(N-1)} \in \{0, 1\}$ *as the criticality value in hierarchy level* $N-1$*. Let* $\mathbf{T}^{(N)}, \mathbf{T}^{(N-1)}$ *be threshold vectors, where* $\forall i, j, T_i^{(N-1)}, T_j^{(N)} \in \mathbb{R}^+$*. Denote the intervention function in level N for factor i*

$$K_i^{(N)} = \begin{cases} 1, & R_i^{(N-1)} \geq T_i^{(N-1)} \\ 0, & \text{otherwise} \end{cases} \tag{3.25}$$

A ***warning event*** *has occurred if*

(W1) $\sum_i K_i^{(N-1)} \geq n^{(N-1)}$ *(at least* $n^{(N-1)}$ *of risk factors are not lower than the specified threshold);*

(W2) $\sum_j K_j^{(N)} \geq n^{(N)}$ *(at least* $n^{(N)}$ *aggregated risk values are not lower than the specified threshold);*

(W3) $Cr^{(N-1)} := 1$ *(a risk factor is decided as critical).*

The thresholds and the rule of thresholds can be specified as arbitrary, based on the company experts. Generally, warning thresholds are specified based on former experiences, but standards can also provide a threshold. (In our case study, because the company had to follow more than one standard requirement, the minimum value of the experts' opinions was the threshold.) In addition, the dependence of risk factors can also be addressed by specifying different thresholds for each single risk factor separately.

Definition 4. *We can say that a risk effect is a* ***failure effect*** *if at least one of the conditions (W1)–(W3) is satisfied.*

3.6 The proposed risk evaluation method

It can be concluded that it is important to replace RPN with another number that can generally indicate the risk level. This will be the TPRN (total risk priority number).

It is important to note that the proposed risk aggregation protocol does not require existing (predefined) scales (see Section 2.3.1). Scale values can be a result of a pairwise comparison (see e.g. Merrick et al., 2005).

Applying the *risk aggregation protocol* iteratively, the risk values can be specified at a higher hierarchy level.

Definition 5. *Let* $(\mathbf{R}^{(N)}, \mathbf{W}^{(N)}, S)$, $(\mathbf{R}^{(N-1)}, \mathbf{W}^{(N-1)}, S)$ *be risk aggregation protocols. Denote* $TRPN_i^{(N)} = R_i^{(N)} = S\left(\mathbf{R}_i^{(N-1)}, \mathbf{W}_i^{(N-1)}\right)$ *as the **total risk priority number** i in the hierarchy level N.*

If TRPNs are calculated for the total process tree (see Fig. 4.5), thresholds should be specified for all levels. A Process Tree is a schematic diagram of the activities that a product encounters during its life cycle.

Based on the proposed iterative bottom-up calculation method (see Definition 5), through the process hierarchy or an acyclic process graph, risk values can be calculated for each hierarchy level.

Contrary to traditional FMEA and Fuzzy FMEA, TREF allows the specification of more than one effect to be assigned to a cause (see Fig. 4.5). However, different failure modes and risk effects may have the same causes (common causes) (see Fig. 4.6). The only restriction is to avoid cycles in the process hierarchy.

On the one hand, weights can be calculated by using the ANP method, which can follow the process hierarchy. The application of weights gives a general view of the risks of the process, which are weighted by their importance. However, using weights is only optional. If there is no information on the importance of risk factors, equal weights can be used. The other relevant example of unweighted aggregation uses the maximal value of risk factors. The maximal value can also produce valuable information about risky processes (see S_2 in Example 4) using it without or with weights. This value presents the weak links, means the worst or most risky processes.

In addition to calculating risk values or before performing the task, the thresholds must be specified for all levels (see Risk assessment in Fig. 4.5).

Chapter 4

Designing Steps for Practical Implementation with case studies

4.1 Suppliers and logistics risk assesment

Theoretically the supply chain risk evaluation seems difficult for two reasons:

- Visibility of the supply chain network in the automobile industry is restricted, meaning that the name of suppliers, their performance, provided volumes, and routes are kept confidential and protected by a non-disclosure agreement (NDA) between the supplier and customer. On occasion, consumers suggest using specific subsuppliers. In this scenario, the supplier lacks the option to independently choose the subsuplier for specific submaterials, components, or subassemblies.
- The subsuppliers do not clearly articulate or emphasize their issues, thus creating the perception that they can conceal all the challenges.

The stark reality is not that sorrowful. The Supply Chain Management (SCM) or Quality Assurance (QA) departments, responsible for overseeing and assessing supplier performance, gather multiple data points that lead the company to make assumptions about the activities taking place at individual suppliers. Such information includes the timely receipt of ordered materials, in the correct quantity and quality, as well as the ability to make changes to the order. Any divergent inquiries and responses between parties, providing sufficient information on the performance of suppliers or their subcontractors. The IATF requests the implementation of the supplier (performance) improvement program, as well as supplier self-assessments and audits. These initiatives can also provide valuable information for evaluating supplier risks. The collected data can provide us with a comprehensive assessment of supplier risk. Furthermore, through supplier audits, data on sub-suppliers (without name or address) can potentially reveal potential dangers.

Regarding transportation companies in the supply chain, we can only observe the transportation of goods from our supplier to us. Regarding the remaining logistical aspects, we can only get indirect information, which is regrettably obtained only after a hazardous incident has taken place. Therefore, regarding the second component, it is advisable to gather all previous events or consult relevant websites with information about events. Subsequently, we should analyze the scenario to determine if such problems can arise in our logistic routes. First, while evaluating the logistical risk between us and our supplier, it is important to determine who is responsible for the transportation.

- When the supplier organised the transportation, any nonconformity such as delay, damage of packing, damage of ordered materials, or mixed parts, they will be responsible for addressing or investigating the issue. However, we can provide them with all relevant documentation. Immediate stoppage of unloading is necessary, and the supplier will determine the course of action: either halt all operations and await the arrival of the insurance company, or initiate the unloading process and have their own personnel arrange for sorting, or arrange for our or a third party to sort the delivered materials.
- If we were to arrange the transportation, each item listed above would be provided by our organization's affiliated personnel. However, the risk and assessment of the forwarder engaged will be reassessed for the next shipment order.

4.2 Risk assessment and evaluation in supply chain

This chapter elucidates the practical application of the aforementioned theory. It is crucial to highlight that risk assessment and evaluation is a qualitative approach that necessitates the involvement of a qualified team or teams. This team should include representatives from all areas of risk and the respective departments responsible for analyzing and evaluating them. Certain industries, like the automotive sector, have a competitive edge due to their reliance on specialized teams who collaborate closely through the entire product life cycle, from design to mass production to end-of-life. They are called FMEA TEAM.

Figure 4.1 illustrates the evaluation steps, which are utilized in both the subsequent analysis of the theoretical framework and the case study.

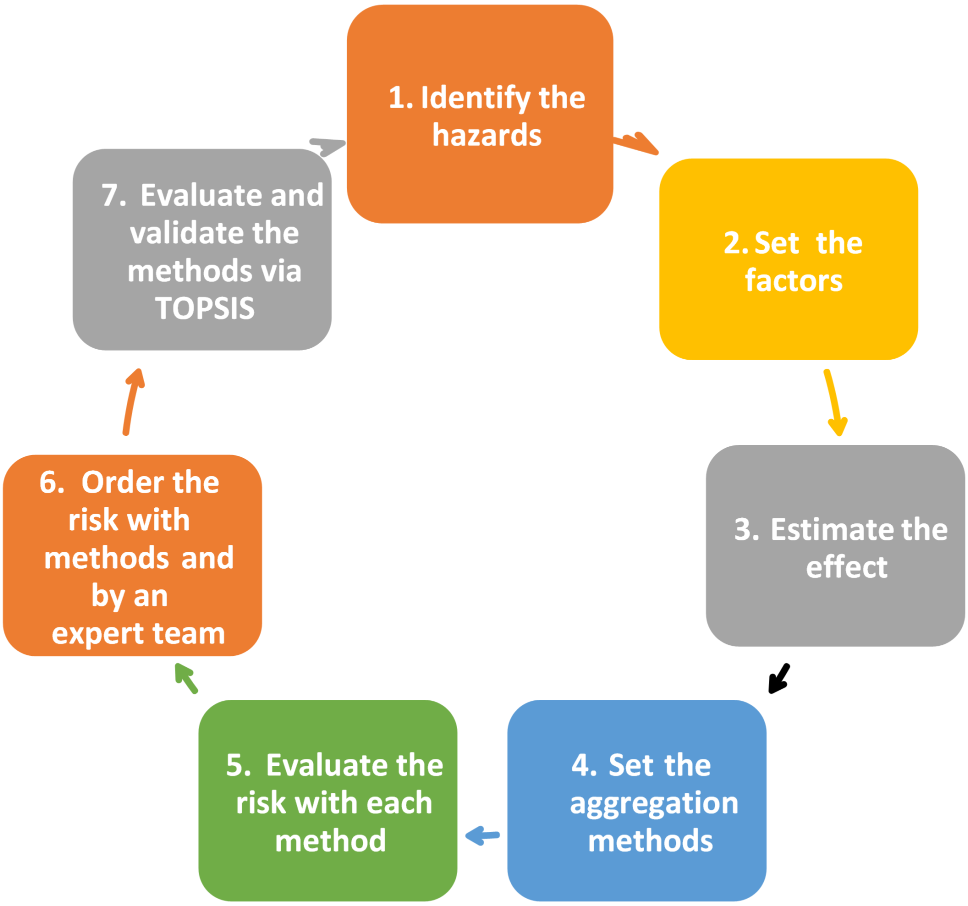


FIGURE 4.1: Determination of the appropriate risk evaluation method.

Step 0—Forming the Team: An assemblage of experts with specialized knowledge in logistics, supply chain, quality management, including all relevant departments such as finance / controlling, warehouse, production, or others, with risk-assessment, -evaluation, and -mitigation experience, should be formed. Many firms already have risk assessment teams, such as the FMEA team in the automotive sector, which is mandated by the IATF16949:2016 (AIAG) QMS standard.

It is crucial that this team demonstrate dedication and possess the appropriate expertise to thoroughly test, assess, evaluate, and validate the risk strategy. The team composition should be adaptable, so that additional experts from different departments may join based on the analysis conducted. Although referred to as Step 0, this essentially serves as the foundation of the evaluation approach. It is advisable for all members of the risk evaluation team to have a thorough understanding of FMEA methodology, and be proficient in the decision-making approach. This will help in effectively identifying all probable failures. It is highly recommended to include an FMEA moderator on this team, as it is also a requirement according to IATF requirements. The moderator's responsibility is to moderate the debates of the FMEA team, ensuring that members' opinions are aligned and ultimately reaching a consensus.

The moderator has specialized training in this field, which has been officially acknowledged with a certificate as an FMEA moderator. When assessing the risk in a supply chain, it is essential to have knowledgeable individuals with expertise in risk evaluation due to the high complexity of the supply chain.

Step 1—Hazards identification: This step is a comprehensive gathering of all supply chain concerns, encompassing claims, losses, and delays. It also involves analyzing news from a related business sector, including potential future events. It is imperative to consider the heightened vulnerability to cyber-attacks, dissemination of misinformation, potential conflicts, and climate fluctuations within the logistical network. If the business has conducted prior risk analyzes, those should also be included in this collection. Each input should be taken into consideration.

Step 2—Factors and scales setting: The list from Step 1 should be used to identify the most accurate factors that describe the risk of organization, department, or process. This phase is exceptionally challenging. The factors included in the FMEA, namely detectability, severity, and occurrence, serve as a solid foundation. However, if there are other elements within these that can enhance our ability to precisely characterize the associated risk, they should be incorporated. In addition to the three factors mentioned above, supply chains also utilize various other elements such as quality, time, cost, intensity, consequence, effect, cause, and measure. The quantity of factors is contingent upon the intricacy of the business or logistic procedures, traffic patterns, business affiliations, and other pertinent considerations (ex. sustainability, energy saving, cyber security, . . .). It is imperative to assess these factors on a case-by-case basis for each company, as the level of risk may vary depending on factors such as geographical location, supply chain network pattern, technological infrastructure, workforce availability and expertise, environmental conditions, core technological capabilities, political/economical/regional stability, etc. If a novel component can enhance the risk analysis from the perspective of the organization's functioning, it is recommended to utilize it.

It is crucial to take into account that the new factors should not exhibit a significant connection with the already chosen or utilized ones. There will be minimal correlation because each new component might be somehow related to the basic factors employed by FMEA. The testing can be conducted using the Correlation or Correlogram functions of MiniTab or by other statistical programs which have those functions in Step 3.

It is important to note that the elements should be linked to specific levels, which are ideally defined by the organization. However, it is recommended that the number of levels should be an even number. Typically, 10 levels are employed, although there is flexibility to differ from this standard.

Step 3—Risk assessment: In this section, is determined the levels of the factors for each risk. The FMEA manual contains specific guidelines for the Severity, Detector, and Occurrence settings in the level settings. For instance, if human detection is involved, the Detectability value must not be lower than 6. Similarly, in manufacturing, if certain areas or parameters are designated as SC (Significant Characteristic) or CC (Critical Characteristic) the Severity value must not be lower than 7. Such regulations can also be implemented for novel factors, particularly once the organization has gained proficiency in their utilization.

This step allows for the testing of the correlation between newly selected factors and existing ones. If a substantial connection is seen, it indicates that the new component does not provide any more value and simply replicates the behavior of an existing factor. In this instance, it is preferable to exclude the utilization of this new factor.

Step 4—Set aggregation methods: This step involves the selection of the aggregating functions that were intended to be utilized for the purpose of analysis.

The standard FMEA will be utilized as a fundamental framework and point of comparison. Due to the inclusion of three levels (L, M, and H) in the revised FMEA, it is important to note that these levels serve solely as indicators for subsequent evaluation and are not intended for the purpose of risk prioritization. Due to this rationale, the analysis will not incorporate the new FMEA.

In the preceding FMEA, the term used to refer to this was Risk Priority Number (RPN). Organizations established a certain RPN level that necessitated action to decrease the risk. In the context of ISO9001:2015 (ISO 9001, 2015), this threshold is typically regarded as the midpoint within the range of factors, resulting in a value of 125 for three factors ($5^3 = 125$). In the automotive industry, companies individually define this limit, which generally falls around 100 or lower, as determined by management. Moreover, when the most severe and imperceptible process flaw is amalgamated with a significantly low occurrence score, the Risk Priority Number (RPN) will amount to 100 ($1 \times 10 \times 10$), a value that falls below the commonly employed action criterion threshold by several firms. The implementation of the updated FMEA methodology will yield a slightly more accurate outcome. However, its effectiveness remains inadequate, as the risk level was merely the result of implementing risk mitigation measures. If individuals are not justified, it is imperative that they become justified.

Every organization has the autonomy to make a decision regarding whether to accept, mitigate, or acknowledge specific hazards. Based on the aforementioned information, the management of the company or the risk assessment team of experts can ascertain the specific aspects that accentuate the level of risk.

Step 5—Evaluate the risk with each method: Section 3.3 provided a detailed presentation of numerous aggregation functions. However, it is possible to introduce additional aggregation functions that adhere to the criteria of aggregation functions. The risk level can be assessed by utilizing each of the selected aggregating functions.

Step 6—Order the results via TOPSIS method and by the experts: This pertains to the arrangement of outputs resulting from aggregating functions. This step comprises two components: the application of the AHP and TOPSIS algorithm for ordering and the ordering process conducted by the expert team members and TOPSIS algorithm.

The determination of the ranking using the TOPSIS method, employing the weight technique. Upon performing a risk analysis using the six risk analysis functions, the resulting risk values are calculated and subsequently arranged in a certain order. This process enables the risk analysis functions to be compared with each other, marking the completion of Step 6.

Step 7—Evaluation and validation: The assessment of outcomes carries considerable significance at this phase, and requires meticulous and strategic preparation. The risk evaluation expert team was asked to form a committee including the most experienced individuals to assign incidents, disregarding the rankings already published or the outcomes of the risk assessment. This indicates that the indicated persons have a deficiency in understanding the output values of TOPSIS ranking and the results of the aggregation functions.

This committee will make a ranking effect matrix (see as example Table C.1) and the impact matrix (see also as example Table C.3) using their respective scores. The precision of these matrices is of utmost importance, as it exerts a substantial influence on the final result. This implies that the perspectives of a specific cohort of specialists with substantial expertise in evaluating the relative effects of each approach should be considered.

The validation of the method involves comparing the results of the committee with the ranking made via TOPSIS. If it coincides, that will be the best aggregation function that can be used by the organization.

The risk assessment is conducted using individuals, thereby yielding qualitative data. Applying any aggregating function to these values yields a qualitative outcome, irrespective of the mathematical functions used to rank the data, such as AHP, TOPSIS, etc. Nevertheless, by conducting the same comparison using the most seasoned experts from the risk analysis team and employing the aforementioned comparative mathematical tools, the outcome should be identical. Attaining unanimity among the team is a challenge. Various strategies, such as averaging all members' opinions, giving greater weight to experts in the linked subject, and using moderation techniques, can be employed to address such circumstances. However, this topic is not within the scope of this dissertation. The occurrence of human error can be mitigated by conducting this study again with the group and comparing the results. If there is a discrepancy in the output, the team should re-assess the corresponding section.

4.3 Application of the proposed method: Supply chain risk evaluation in an EMS company

The experimental study is focused on an electronic manufacturing services (EMS) supplier. Conducting testing within the comprehensive supply chain offers several advantages owing to the central location of this EMS (see Figure 4.2).

In certain instances, manufacturers (S_x) or, in extreme circumstances, direct customers (C_x) are occasionally chosen as the source for larger quantities of raw materials or components, despite the customary practice of EMS firms to purchase them through distributors (D_x). This holds particularly true in cases where the design of the final product is still undergoing development or when it becomes imperative to conduct tests on updated components. To facilitate the installation of these units by original equipment manufacturers (OEMs), the EMS delivers the goods to direct customers (C_x). Subsequently, these customers engage in more processes, such as the development of more intricate modules, testing, and programming.

Under some circumstances, the EMS may also provide the carmaker with goods directly, as indicated by the $EMS - O_x$ connection in Figure 4.2. The instances of S_x and D_x have been simplified in the EMS. They are treated as a single node or "location" because the EMS communicates with them through their Distribution Centers or Offices,although they consist of several factories/locations. Various logistical groups play a crucial role in facilitating the transportation of products between different nodes throughout the process. This case study offers a comprehensive opportunity to analyze a wide range of supply chain issues.

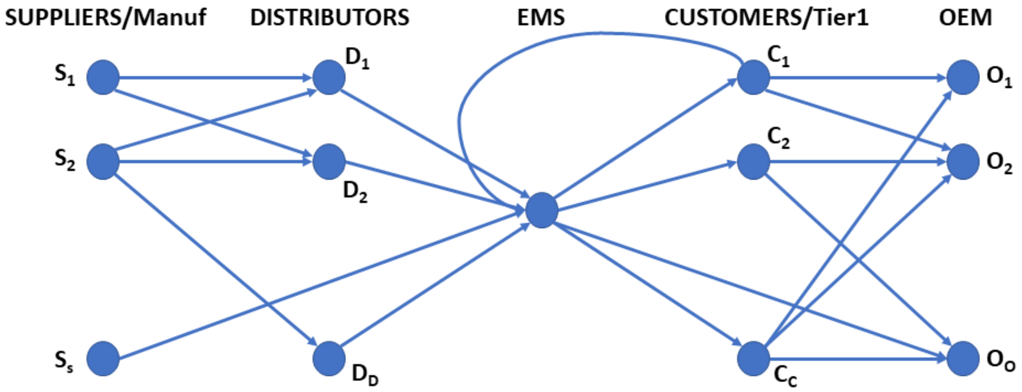


FIGURE 4.2: The supply chain map of the EMS company.

The automotive industry places significant importance on the availability of raw materials for manufacture, ensuring that they are provided at the appropriate time, quantity, and quality. Additionally, the industry recognizes the need for problem-free production, which is not the focus of this study, and the timely and accurate delivery of products to customers. Any deviation from this stipulation leads to supplementary costs or a decrease in revenue.

4.3.1 Evaluation team

A team of professionals specializing in logistics, quality management, risk assessment, finance/controlling, and FMEA was assembled within the EMS firm. The primary objective of this team was to conduct comprehensive testing, analysis, and validation of the entire approach. It is advisable for them to be led by an FMEA moderator, a mandatory role in automotive businesses.

4.3.2 Evaluation steps

Following will be a sequential presentation of each step shown in Figure 4.1.

Step 1—Hazards identification: The present study conducted an exhaustive analysis of various supply chain concerns, including claims, losses, and delays, spanning a period of four years. Subsequently, a comprehensive inventory of risks was compiled. Data originates from supplier issues over the past 4 years, such as delivery delays, misordering related to typographical errors, mixed materials during splitting and relabeling at distribution centers, incorrect identification in the incoming warehouse (part numbers identification), materials shortages related to Covod19, market shortages and non-compliant materials ordering, customer procurement assistance, internal registration system security breaches, and so on. Furthermore, the study took into account the experiences of members on errors made at other companies/factories, advice provided or sought by external auditors (such as customers or certification bodies), and recommendations provided by trainers as part of specialized training. In this particular case, a total of 20 unique concerns were identified. A part of the concerns can be seen on Table B.1.

Step 2—Factors setting: The criteria for evaluating each factor, specifically Occurrence, Severity, and Detection, are presented in Tables A.1, A.2, and A.3, respectively. These tables may be found in the Appendix A. Specifically, the Team examined the existing variables (S, O, D) and the impact of risk on this EMS organization and its customers. Importantly, in the automotive industry, the customer holds a unique position: any faulty product received, delay in the agreed shipment (which cannot occur earlier or later), damage to packaging can result in significant expenses and a decline in the supplier evaluation score, which can impact the future business of this EMS company. Regarding this, the Team considers, the estimated cost of nonconformity can be an important factor, which embodies all above mentioned risks effect. Taking into account the control of such risks, the Team advances one step further. Managerial prevention refers to the proactive measures taken to avert potential risks by being aware of them. If it is feasible to exert control, whether full or partial, or if complete control is unattainable. In this latter scenario, we can agree to it, by prearranging provisions or obtaining insurance for the associated future occurrence. For this reason the second newly implemented factors is the controllability. For all 5 factors were selected scales with 10 levels (like in case of standard FMEA).

Step 3—Risk assessment: The findings of the FMEA analysis, considering the aforementioned criteria, are presented in Table B.1. The result was generated by employing both the previous FMEA standard, which solely considered the initial three factors (Occurrence, Severity, and Detectability), and the present FMEA standard which includes the AP (Action Priority) levels.

Table B.1 illustrates three factors that are insufficient in appropriately highlighting the true level of threat. This is the reason why certain authors and researchers have started incorporating additional variables (such as performing analysis with four or five components).

The upper echelons of management within this EMS company were engaged in consultation, which resulted in the selection of two more factors, namely control and cost.

Cost refers to the estimated financial impact incurred due to errors or inefficiencies in handling or logistics. Within the realm of literature, this particular element is commonly referred to as "Value".

The second factor is the Control factor, which assesses the feasibility and effectiveness of controlling, preventing, or mitigating a process, and determines the extent to which it can be achieved. Please refer to Tables A.4 and A.5 for a comprehensive overview of the established evaluation criteria pertaining to the supplementary components.

This stage involves assessing the correlation between the newly selected factors and the existing ones. The Correlation analysis from MiniTab was utilized for this purpose. The Pearson correlation coefficient was utilized to assess both the strength and the direction of a linear relationship between two continuous variables. The outcome is visible in Figures 4.3 and 4.4.

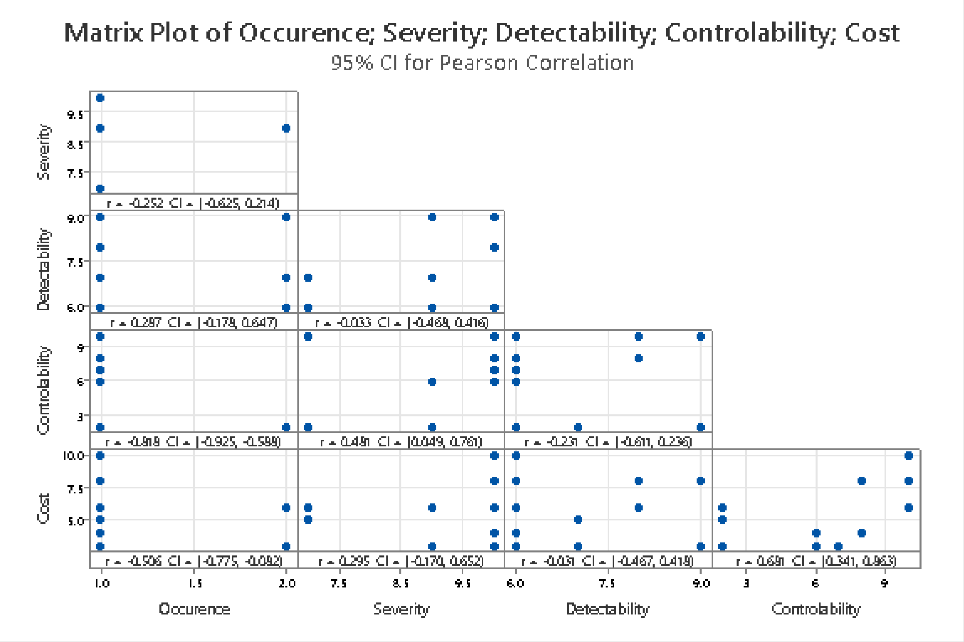


FIGURE 4.3: The factors correlation with Pearson method

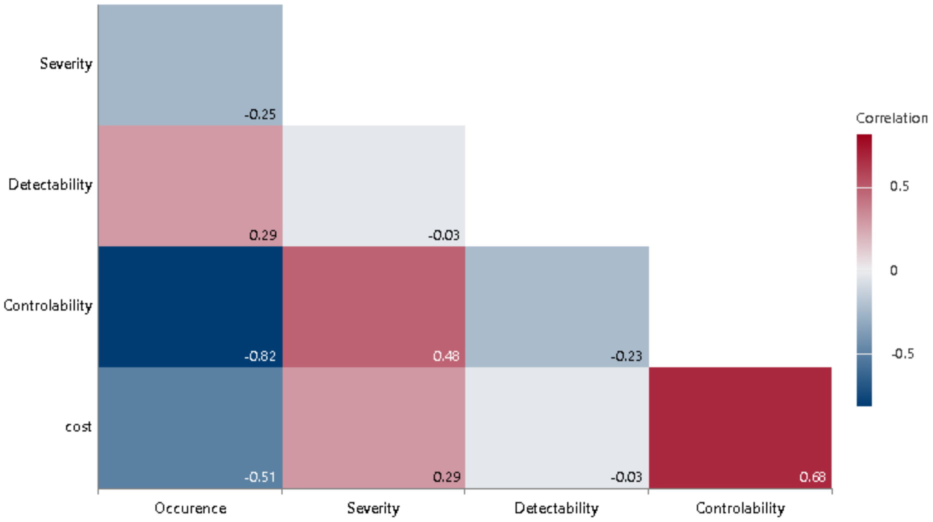


FIGURE 4.4: The factors correlation with color intensity, Pearson method

Figure 4.4 presents the identical information as Figure 4.3, but it represents the level of connection through the use of colors, enhancing its visual appeal (with deeper hues indicating a stronger correlation).

Can be observed a substantial correlations in two cases: Occurrence-Controlability has a correlation coefficient of -0.818, while Cost-Controlability has a correlation coefficient of +0.681. In the first scenario, the association between the Occurrence and Controlability of the processes appears to be connected based on the limited data available (only 20 datasets). The Occurrence values are at a low level, with factor levels of 1 and 2, suggesting a low frequency of events. Additionally, the Controlability of the processes is also very low, which means the risk is high. This results in multiple cases reaching the maximum level (10) in terms of high risk, which can lead to the interruption of the customer's process. Although it may appear that these two levels are connected, they are actually not. After a lengthy discussion, the risk evaluation team concluded that the correlation is indeed a mere coincidence. The connection between Cost and Controlability is positively signed, indicating that the cost of risk increases when the related process cannot be managed. However, the correlation is not very strong, is just 0.68.

The risk assessment team decided to retain both newly adopted variables.

Step 4—Set aggregation methods: The present set of factors include Severity, Occurrence, Detectability, Cost, and Control(ability). The next step involves the selection of the aggregating functions that were intended to be utilized for analysis purposes. The standard FMEA will be used as a fundamental framework and point of comparison. Additional aggregating functions that will be employed encompass Multiplication, Average, Sum, and Euclidean Distance, augmented with Fuzzy. These functions consist of five elements and are all encompassed within the TREF technique. All of these topics are addressed in Section 3.3.

The fuzzyfication function, depicted in Figure 3.1, is consistent across all five failure factors, namely severity, occurrence, detectability, cost, and controllability. With the exception of the initial and final functions, each function possesses a range in which its value is non-zero, and the midpoint is denoted. The variable $Midk$ represents the midpoint, while k denotes the number of linguistic variables utilized to describe each failure. In all instances, the membership function takes on values inside the range of 0 to 1. Here, A_k represents the count of non-zero elements in kS, kO, and kD. The variables S, O, D, Cs, and Cn are used to denote the severity, occurrence, detection, cost, and controllability, respectively.

Step 5—Evaluate the risk with each method: The risk level can be determined by employing each of the six aggregating functions.

Step 6—Order the results via TOPSIS method and by the experts: The outcomes of the aggregation functions are presented in this order, employing two distinct methods: TOPSIS and the expert group.

The determination of the ranking by the TOPSIS method, employing the weight technique. The symbol k_i represents the average value of the membership function, with i denoting the factors S, O, D, Cs, and Cn. Upon doing risk analysis using the aforementioned six risk analysis functions, the resulting risk values are calculated and subsequently arranged in a certain order. This process enables the risk analysis functions to be compared with one another, marking the completion of Step 6. The ranking outcomes are displayed in Table 4.1 below:

TABLE 4.1: A detail from the ranking matrix composed from the standard FMEA, TREF Multiplicative, TREF Average, TREF Median, TREF Distance, and TREF Fuzzy functions - the last 5 evaluations were made using 5 factors.

No	R. FMEA	R. TREF Multi	R. TREF Aver	R. TREF Medi	R. TREF Dist	R. TREF Fuzzy
1	1	15	15	17	14	17
2	2	17	17	18	17	8
3	3	18	18	19	18	9
4	5	13	14	14	16	7
5	4	19	19	20	19	16
6	19	20	20	16	20	20
7	18	16	16	15	15	13
8	9	7	7	7	7	15
9	10	5	5	5	4	2
10	6	1	1	2	1	3
11	11	6	6	6	5	11
12	7	3	3	3	6	14
13	12	14	13	13	12	12

The subsequent results are presented here after entering all the data into R's TOPSIS analysis program (Yazdi) with uniform weights, while considering the assessment of impacts (see Table 4.2):

TABLE 4.2: Ranking of methods using TOPSIS without considering the weights

Alt. row	**Name**	**Score**	**Rank**
1	FMEA	0.6308374	1
2	TREF Multi	0.4312619	4
3	TREF Aver	0.4338759	3
4	TREF Medi	0.4414542	2
5	TREF Dist	0.4132224	5
6	TREF FMEA	0.2516496	6

To illustrate the potential outcome in the absence of an expert-established importance matrix, a random impact matrix was used, yielding the following result (see Table C.2). The highest rank (6) gives the best result.

Step 7—Evaluation and validation: The ranking effect matrix (Table C.1) and the impact matrix (Table C.3) were generated by expert members using their respective scores.

Table 4.3 shows the results obtained by using the matrices indicated earlier as weight and impact in the TOPSIS analysis program implemented in R (Yazdi).

TABLE 4.3: Ranking of methods using TOPSIS with weights

Alt. row	**Name**	**Score**	**Rank**
1	FMEA	0.5959322	1
2	TREF Multi	0.5529383	5
3	TREF Aver	0.5538219	2
4	TREF Medi	0.5418204	3
5	TREF Dist	0.5364203	4
6	TREF FMEA	0.1567300	6

In this scenario, the highest rank also yields the optimal outcome.

This ordering is the same as the ordering made by experts.

The observation reveals that both the order obtained with the random impact matrix (see Table 4.2) and the ordering generated with the weighted impact matrix (see Table 4.3) indicate the optimal aggregation function no. 6, namely the TREF FMEA.

4.4 Setting the warning levels for risk evaluation

This is a more difficult assignment because, in supply chain we have a minimum of three separate systems (suppliers risk assessment, logistic risk assessment, and related factory's incoming materials risk assessment). Additionally, several firms utilize the so-called integrated management system with a risk-based approach, they really operate their quality (QMS), environmental (EMS), energy-saving (EnMS), and data protection management systems (often called information security management system/ISMS or TISAX) separately. In certain cases, integration means that the certification is issued by the same certification authority, typically for budgetary reasons - this means that, in reality, those systems are not really integrated. Additional obstacles that hinder proper integration include: specialists prioritizing their own areas, lack of genuine support and ownership from involved individuals, and significant heterogeneity in system requirements across the covered themes, lengthy document reviews and team meetings.

In this situation, decision makers receive many reports from various management system's auditing groups but lack a consistent basis for risk comparison. It appears practical to examine the occurrence and the consequent harm in value, but this is not a clear basis for decision making because it does not address the total impacts of damages, only those connected to the related management system.

It is beneficial to have specialized warning systems in place for specific areas, developed by experts from those areas. These systems can trigger warnings in various specific scenarios, such as when a certain factor surpasses a crucial threshold or when the output of risk evaluation reaches a certain level.The warning serves to anticipate potential crucial events that may occur, prompting the relevant team to exercise heightened vigilance.

Steps are very similar to previously presented aggregation function selection method.

Step 0—Forming the Team: An assemblage of experts. The expert team must be made up of people with deep cross-functional understanding in at least two fields or processes. Their thorough analysis, evaluation, and Gemba walk (in-place check) is the best methodology for evaluating warning levels, particularly in highly polluted or high-risk polution environments, the proximity of reactive chemicals to each other, or special areas with highlighted risk for cyber attacks, conflict zones, etc. Although the FMEA course is not mandatory for them, it is crucial to have a deep understanding of process errors.

Step 1—Collecting the factors/processes which need warning limits and if is the case, new hazards identification: In this case, the team should establish the critical limit values for related factors and risk levels in several hierarchies. Additional overall risk contexts are included in the assessment that were not apparent in the risk assessment of the different management systems or evaluations, and also for them, it is a case, should be established warning levels.

Step 2—Warning limits setting: Using the process hierarchy, including the core processes, sub-processes and their sub-processes, etc. (see Fig. 4.5), the process-specific elements and failure modes and the chain of causes and risk effects based on their domains should be specified before the proposed TREF is used. This process hierarchy helps us to recognize where can be seen risk interactions, or cross-risks in our system. .

Step 3—Risk assessment: Simulations with preset values. This is a theoretical procedure, but it provides us with real-world input on whether the warning limits/values are correctly defined. At this point, any warning possibilities must be reviewed and each one must be analyzed to see whether the warning signal is legitimate and was released as planned. In this instance, it is best to recreate events from the past or from other similar factories where the failure occurred and then test the warning system with the current settings.

Step 4—Set the warning levels on the real system:

Step 5—Evaluate the risk with each method: This is a continuous monitoring and analysis of the setup based on actual happenings.

Step 6—Correction of warning setting: If the warning system reaction does not meet expectations, the warning levels need to be adjusted. First, in this scenario, the fundamental cause of the deviation must be identified. Simply set the level and proceed to Step 4. It could also be an unreported risk event, necessitating a whole new simulation of the entire system from Step 3.

Step 7—Validation: If the system works correctly during a predefined period (0.5-2 years), with all warning alarms set and works as expected including regular inspections, this validates the system.

This procedure, which begins in Step 3 or Step 4, is an auto learning system that repeats its analysis in a controlled time frame, is a PDCA learning circle. Decision makers, management system or process owners (QMS, EMS,...) determine the frequency of inspections based on nonconformances or adjustments to previous settings.

While the calculation of risk values and the thresholds should be calculated by the bottom-up iterative formula, the operating of the monitoring system can follow both the bottom-up but also the top-down approach.

Bottom-up approach: At the 0-th hierarchy level (see Figure 4.5 the SubSubSub...Processes), risk factors are evaluated. A warning event has occurred if a risk factor is not lower than the threshold (W1) or a criticality value is set to be 1 (W3). For maintenance, this monitoring system shows which risk effect (in which domain) of process mode caused a failure mode and which factor(s) are not lower than a threshold; therefore, a ***specific corrective/preventive action*** must be prescribed to mitigate the value of the risk factor. If a specific corrective/preventive action is not prescribed but the aggregated risk value is not lower than a threshold, a ***general corrective or preventive actions*** should be prescribed (W2) to mitigate the aggregated risk values. General corrective/preventive actions should contain the set of specific tasks, which mitigates the values of risk factors. This bottom-up approach can be extended to the higher hierarchy levels, where general activities in a hierarchy level N should contain specific tasks to mitigate risk factors or risk values in the lower hierarchy.

Top-down approach: The top-down or *managerial approach* can be specified if in addition to the aggregating risk values the number of failure effects are calculated for all hierarchy levels. If there is a warning event on hierarchy level N, a general corrective/preventive action is specified, which, similarly to the bottom-up, may (but in this case not necessarily) contain a (detailed) corrective/preventive action to mitigate risk factors. The number of failure effects in every level helps management to drill down and specify the set of corrective/preventive actions.

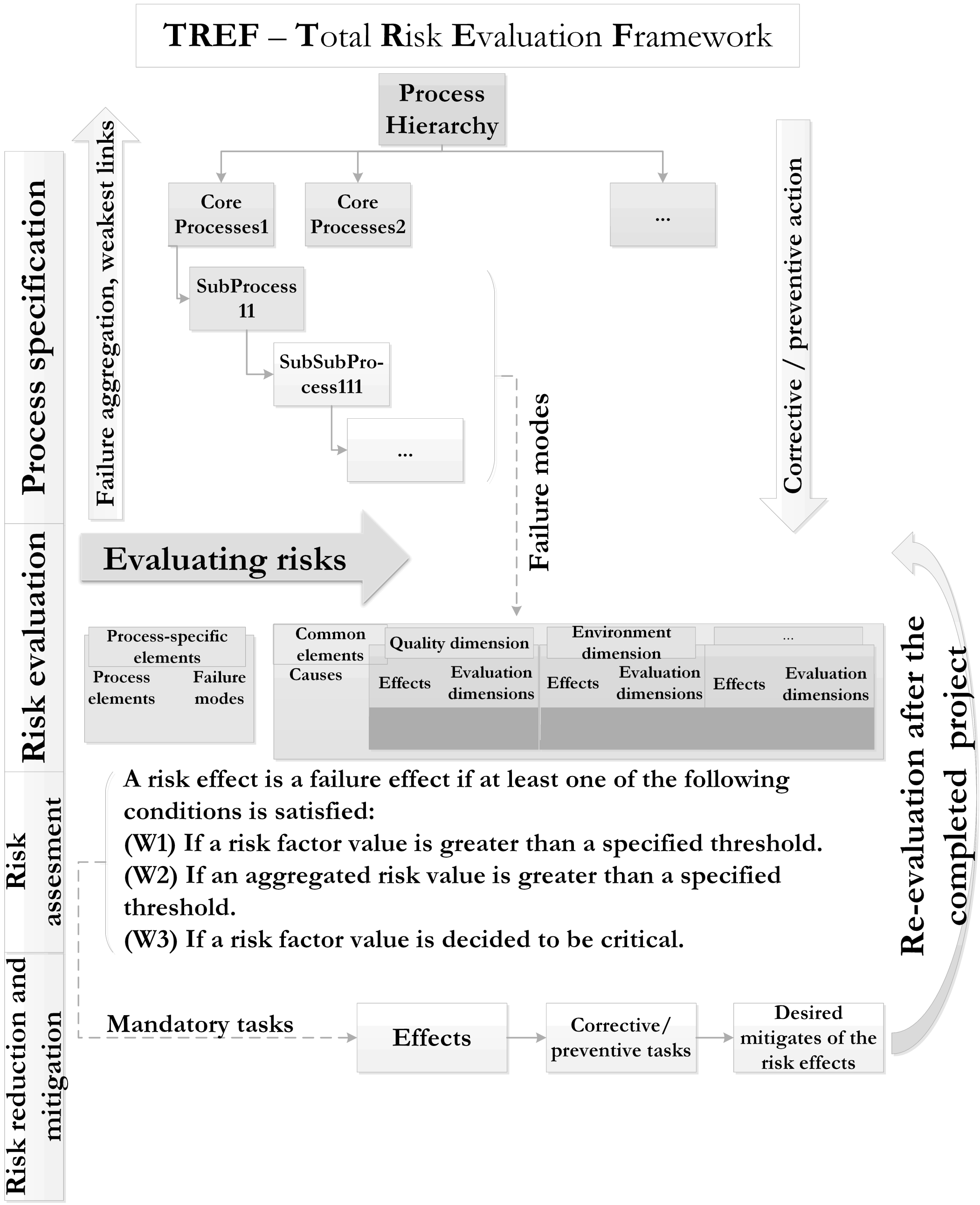


FIGURE 4.5: The proposed Total Risk Evaluation Framework (TREF)

Although the bottom-up approach goes from the lower hierarchy level; specific corrective/preventive actions are specified to mitigate the risk factors, and general corrective/preventive actions are usually specified as a set of specific corrective/preventive actions. The top-down or managerial level starts at the top level of a hierarchy. Aggregated risk values give a general view of risks; however, to reduce the number of failure effects, general corrective/preventive actions should be specified. Nevertheless, these general corrective/preventive actions may (but not necessarily) contain specific corrective/preventive actions. For example, purchasing a new piece of equipment can be a general activity, which can solve several specific problems.

After specifying the set of corrective/preventive actions:

1. The forecasted effect of corrective/preventive actions should be specified (see e.g. Bowles, 2003; Carmignani, 2009).
2. Corrective/preventive actions should be organized as a maintenance project to minimize system shutdowns (see e.g. Kosztyán, 2018).

The proposed TREF includes the schedule of corrective/preventive actions, which is a kind of flexible, discrete time/cost/quality trade-off problem; a future paper will focus on this scheduling problem. After completing risk mitigation projects, the improved risk effects will be re-evaluated (see the Re-evaluation arrow in Fig. 4.5), and if necessary, a new maintenance project will be organized.

4.5 Application of warning levels in the maintenance risk assessment of a motor manufacturing company

The preceding study provides an illustration of the supply chain, which is considered the most intricate system in terms of risk assessment and evaluation. This upcoming case study will illustrate a situation in a plant that involves the integration of three separate management systems: quality (ISO9001), worksafety (ISO45001) and environmental (ISO14001), and presents the applicability of presented risk evaluation method. This case study or example demonstrates the usability of TREF at a lower level when three entirely separate management systems interact with one another, and how the warning system can be set in such an environment. It is not directly related to the supply chain.

This case study was conducted at an electric motor manufacturing company. A single-case design approach was used, where the case is selected because it is critical; i.e., its conditions allow our method to be tested (Dubé and Paré, 2003; Yin, 2013). This Hungarian subsidiary of a multinational corporation operates in the high-technology automotive industry. In the last decade, the market for high-precision drive systems has grown substantially. Manufactured electric motors are installed in critical applications such as surgical power tools, race cars, and high-precision industrial applications. In so-called high-added-value manufacturing, the reliability of products plays a crucial role in their long lifespans. To improve the reliability of processes, a risk assessment was performed. The company has integrated quality management (ISO 9001), environmental management (ISO 14001) and health and safety management (ISO 45001) systems.

In this study, maintenance activities were selected as illustrative examples of the model proposed in Fig. 4.5. They allow us to present the evaluation of each domain (separate management systems) and all risk factors. Maintenance activities do not occur in separated functional units but are integrated with the core functions of the company

Maintenance includes a series of actions taken to maintain or restore the functionality of facilities/equipment. *Maintenance activities* occur in three processes: building engineering in facilities and the vehicle fleet (1.4.01P); means of production maintenance (1.6.01P), and maintenance of inspection tools in quality assurance (4.7.03P). In each case, potential failure modes, their causes and effects (on all three domains, i.e.: quality, environmental, health and safety), and the evaluation of risk factors were first identified by the risk evaluation team.

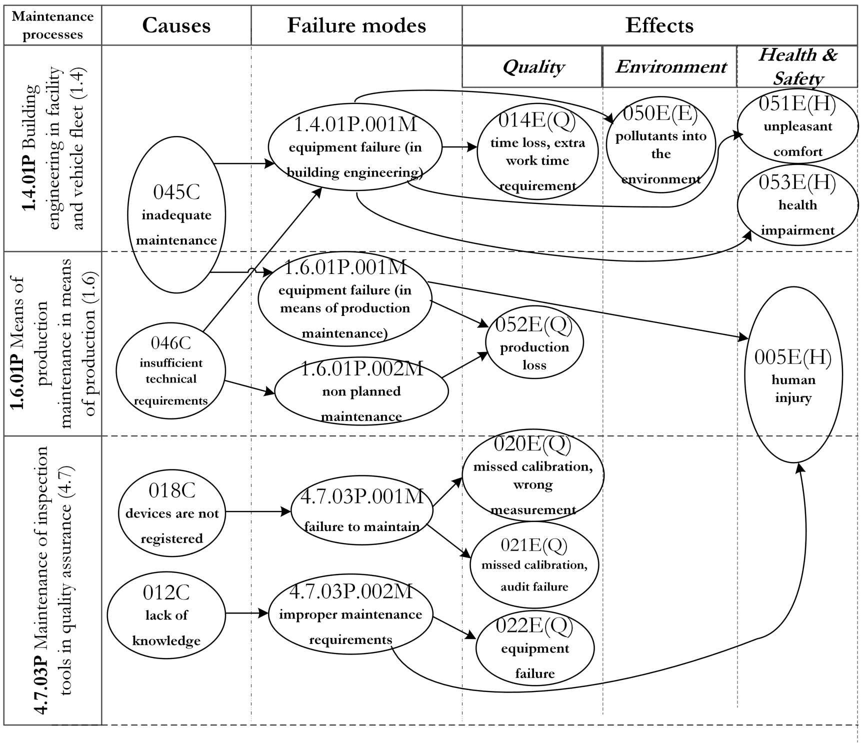


FIGURE 4.6: The TREF graph for evaluating the risk maintenance process: the chain of causes, failure modes and effects

Fig. 4.6 shows the logical connections among 5 failure modes, 4 identified causes, and 9 possible effects. The risk assessment team, including the *system manager*, the *process manager* and an *academic expert*, first identified five potential failure modes. The column marked “Processes”indicates the three maintenance processes: building engineering, means of production maintenance and inspection tool maintenance. The column marked “Causes”indicates the four causes: 045C for inadequate maintenance and 046C for insufficient technical requirements are common causes of two failure modes, and the remaining two causes are 018C for devices not registered and 012C for lack of knowledge. The column marked “Failure modes ”indicates the type, i.e., 1.4.01P.001M: *equipment failure* in building engineering; 1.6.01P.001M: *equipment failure* in means of production maintenance; 1.6.01P.002M: *non-planned maintenance* ; 4.7.03P.001M: *failure to maintain* inspection tools; 4.7.03P.002M: *improper maintenance requirements* for inspection tools. The “Effects by domains ”column indicates the three domains based on the company’s integrated management system: quality, environment and health & safety. The nine effects are 014E(Q): time loss, extra work time requirement; 005E(H): human injury; 020E(Q): missed calibration, incorrect measurement; 021E(Q): missed calibration, audit failure; 022E(Q): equipment failure; 050E(E): pollutants into the environment; 051E(H): discomfort; 052E(Q): production loss; and 053E(H): health impairment.

For example, failure mode *equipment failure* (1.4.01P.001M) is caused by *insufficient technical requirements* (046C) and *inadequate maintenance* (045C), and it affects *quality* (time loss (014E(Q)), *environment* (*pollutants released into the environment* (050E(E))) and *health & safety* (*discomfort* (051E(H)) and *health impairment* (053E(H))). As can be seen from the identifiers, causes and effects are not assigned to processes or failure modes; there is a common database for the whole company. For example "operator failure", "mistyping" might occur in many processes, domains. This allows a smaller data set with codes that are easier to memorize.

To verify the applicability of TREF, it was necessary to compare it with the most frequently used risk evaluation methods, traditional FMEA and Fuzzy FMEA (Liu et al., 2013a). Fuzzy FMEA was developed to help those who were not experts in FMEA with linguistic terms. Developed a fuzzy FMEA method by working backward for this test as an example to test the usability of the TREF. Sigmoid and bell/splay functions were used as membership functions (Johanyák and Kovács, 2004), and calculations were carried out using a weight method. Defuzzyfication relied on the multiplication of membership functions.

For the TREF, were used three additional risk factors in this case study, namely, control (C), information (I), and range (R), for a total of 6 factors. The first 3 are the same as those used in traditional FMEA and Fuzzy FMEA: severity (S), occurrence (O) and detectability (D). This shows that the TREF is flexible and can include any number of risk factors ($n \geq 2$). The risk assessment team agreed on the severity, occurrence, detection, control, information and range values using Tables D.1–D.3.

The next step is to evaluate the importance of each risk factor in all domains to generate their weights. According to ANP, the reciprocal matrix determined by pairwise comparison for the three domains is shown in Table 4.4.

Head	**CI**	**RI**	**W$^{(1)}$**
Objectives	0	0.58	1
Quality	0.0986	1.24	0.4545
Environment	0.1175	1.24	0.4545
Health & Safety	0.1170	1.24	0.0909

TABLE 4.4: Result of the pairwise comparison for the domains (Quality, Environment, Health & Safety). CR=0.0598, Critical Value:=0.1, I:={Q,E,H}

The values in the table were generated according to Saaty (1987, 2004). The CI comes from the matrix of comparisons, RI is the random consistency index and w=weight. The CR is the consistency ratio, which can be calculated as follows: $CR = \sum wCI / \sum wRI$. The weights were calculated using geometric means. The consistency ratio (CR) was calculated using the information in Table 4.4. Based on the risk evaluation team's pairwise comparisons, the importance of the quality and environment domains are judged to be the same, while health & safety is considered less important. Table 4.5 shows the (0-th level) weights ($W^{(0)}_{i,j}$) of the six risk ($i = 1, .., 6$) factors in three domains ($j = 1, 2, 3$).

Factors ($\mathbf{f}$), Weights ($\mathbf{W}^{(0)}$)	**Quality**	**Environment**	**Health & Safety**
$f_{1,\cdot}$=Occurrence	0.1612	0.1364	0.2265
$f_{2,\cdot}$=Severity	0.2459	0.4462	0.4461
$f_{3,\cdot}$=Detection	0.4259	0.0435	0.0833
$f_{4,\cdot}$=Control	0.0943	0.0798	0.1325
$f_{5,\cdot}$=Information	0.0361	0.0400	0.0352
$f_{6,\cdot}$=Range	0.0366	0.2540	0.0765
CR	**0.0796**	**0.0948**	**0.0943**

TABLE 4.5: Results of the pairwise comparisons of the risk factors. Critical Value:=0.1.

In the case of the quality domain, detection has the greatest weight, while in the case of the environment and health & safety domains, severity has the greatest weight. Table 4.5 also shows that the "Range" is the second-most important risk factor in the environment domain.

The effects are evaluated using the method proposed in Section 3. Each effect's TRPN value was obtained by calculating the $S_1 - S_4$ risk aggregating functions. Fig. 4.7 shows the TRPN calculations and two kinds of warnings, i.e., (W1) and (W3). For example, according to $S_1 - S_4$ risk aggregation functions, TRPN for the failure mode's (1.4.01P.001M) 051E(H) effect can be calculated as follows:

$$(\mathbf{f}_{\cdot,3}, \mathbf{W}^{(0)}_{\cdot,3}, S_1) : \ \mathrm{TRPN}^{(1)}_{S_1}(\mathbf{f}_{\cdot,3}, \mathbf{W}^{(0)}_{\cdot,3}) = \prod_{i:=1}^{6} f_{i,3}^{W^{(0)}_{i,3}} = 2.25$$

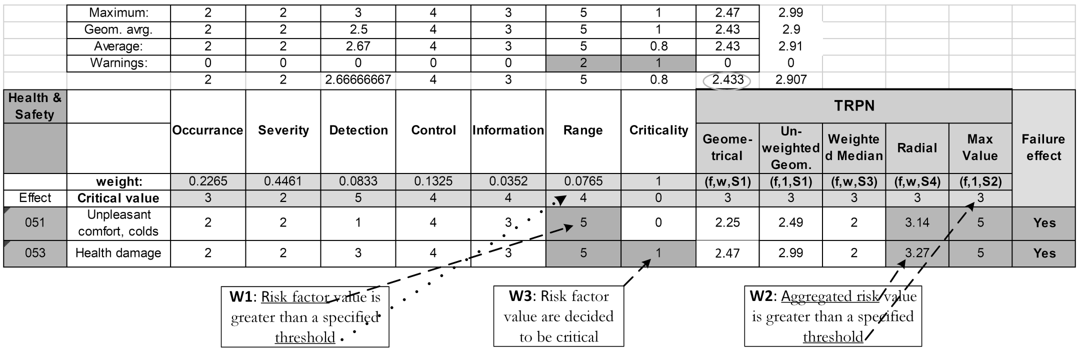
$$(\mathbf{f}_{\cdot,3}, 1/6, S_1) : \ \mathrm{TRPN}^{(1)}_{S_1}(\mathbf{f}_{\cdot,3}, 1/6) = \prod_{i:=1}^{6} f_{i,3}^{1/6} = \sqrt[6]{\prod_{i:=1}^{6} f_{i,3}} = 2.49$$

$$(\mathbf{f}_{\cdot,3}, \mathbf{1}, S_2) : \ \mathrm{TRPN}^{(1)}_{S_2}(\mathbf{f}_3, \mathbf{1}) = \max_i f_{i,3} = 5.00$$

$$(\mathbf{f}_{\cdot,3}, \mathbf{W}^{(0)}_{\cdot,3}, S_3) : \ \mathrm{TRPN}^{(1)}_{S_3}(\mathbf{f}_3, \mathbf{W}^{(0)}_{\cdot,3}) = Median(\{w_1 f_1, .., w_n f_6\}) = 2.00$$

$$(\mathbf{f}_{\cdot,3}, \mathbf{W}^{(0)}_{\cdot,3}, S_4) : \ \mathrm{TRPN}^{(1)}_{S_4}(\mathbf{f}_3, \mathbf{W}^{(0)}_{\cdot,3}) = \sqrt{\sum_{i:=1}^{6} w_i f_i^2} = 3.14$$

Fig. 4.7 shows the TRPN of each effect. The value of range is not lower than the critical value (threshold); therefore, corrective/preventive actions have to be specified to mitigate both (051E(H), 053E(H)) range effects (see (W1) in Section 3.5). Fig. 4.7 also shows that despite average TRPNs ($\mathrm{TRPN}_{051E,H}$ and $\mathrm{TRPN}_{053E,H}$) that are lower than the specified threshold, 053E(H) is critical (see (W3) in Section 3.5), and the risk evaluation team specified corrective/preventive actions to avoid this risk effect.



	Maximum:	2	2	3	4	3	5	1	2.47	2.99				
	Geom. avrg.	2	2	2.5	4	3	5	1	2.43	2.9				
	Average:	2	2	2.67	4	3	5	0.8	2.43	2.91				
	Warnings:	0	0	0	0	0	2	1	0	0				
		2	2	2.66666667	4	3	5	0.8	2.433	2.907				
Health & Safety		Occurrance	Severity	Detection	Control	Information	Range	Criticality	TRPN					Failure effect
									Geome-trical	Un-weighted Geom.	Weighted Median	Radial	Max Value	
	weight:	0.2265	0.4461	0.0833	0.1325	0.0352	0.0765	1	(f,w,S1)	(f,1,S1)	(f,w,S3)	(f,w,S4)	(f,1,S2)	
Effect	Critical value	3	2	5	4	4	4	0	3	3	3	3	3	
051	Unpleasant comfort, colds	2	2	1	4	3	5	0	2.25	2.49	2	3.14	5	Yes
053	Health damage	2	2	3	4	3	5	1	2.47	2.99	2	3.27	5	Yes

FIGURE 4.7: The evaluation of TRPN for failure mode (1.4.01P.001M) effects (051E(H) and 053E(H))

To use the proposed TREF as a module in an expert system, different levels of aggregation should be performed. According to the risk aggregation function (S_1), the weighted geometric mean of the total number of risk priority numbers was calculated for the levels of the processes, the failure modes, the common causes, and the common effects. Since the effect (discomfort 051E(H)) was judged to be four times less important than health damage (O53E(H)) by the risk assessment team, the geometric mean value was weighted (the value input into the oval in Figure 4.7), which is used to calculate $TRPN^{(2)}$ = 2.426. Failure mode 1.4.01P.001M has two other effects, 014E(Q) ($j = 1$) and 050E(E) ($j = 2$), which were evaluated from the quality (Q) and environmental (E) points of view (see Table E.1 in the Appendix E). These values are $TRPN_1^{(1)}$=2.66, $TRPN_2^{(1)}$=2.48 (see Table E.1) and $TRPN_3^{(1)}$=2.36 (see Fig. 4.7). This value (the average TRPN for the quality/environment/health & safety effects of failure mode 014P.001M) represents a general view of failure modes. The weighted average TRPN for failure mode 1.4.01P.001M is:

$$\begin{aligned} TRPN_1^{(2)} &= \left(TRPN_1^{(1)}\right)^{W_1^{(1)}} \cdot \left(TRPN_2^{(1)}\right)_2^{W_2^{(1)}} \cdot \left(TRPN_3^{(1)}\right)^{W_3^{(1)}} \\ &= 2.66^{0.4545} \cdot 2.48^{0.4545} \cdot 2.36^{0.0909} \\ &= 2.55 \end{aligned} \tag{4.1}$$

These values are lower than a critical value (threshold); however, to detect the number of failure effects, had to be calculated both the maximum values of TRPNs and the number of failure effects (see the results in Fig. 4.7 and Table E.1). It is important to note the proposed multi-level approach detected more (in this case, three) failure effects, which would not have been possible when calculating RPNs for only one aspect. Moreover, Fig. 4.7 and Table E.1 show that the traditional RPN, which is based only on the occurrence (O), severity (S) and detection (D) factors, cannot detect the critical range (R) within these effects (014E(Q), 051E(H) and 053E(H)).

Since there was no information on the importance of the processes, unweighted versions of $S_1 - S_4$ formulas are used. E.g., $TRPN^{(3)}_{S_1,1.4.01\text{P}} = 2.55, TRPN^{(3)}_{S_1,1.6.01\text{P}} =$

2.78, $TRPN^{(3)}_{S_1,4.7.03\mathrm{P}} = 2.44$), processes (e.g., $TRPN^{(4)}_{S_1,1.4\mathrm{P}} = 2.64$) and process areas (e.g., $TRPN^{(5)}_{S_1,1\mathrm{P}} = 2.56$). However, another method of aggregation can be used: to calculate the TRPNs of all maintenance processes by using unweighted S_1 formula (geometric mean) ($TRPN^{(3)}_{S_1,\mathrm{MAINTENANCE}} = \sqrt[3]{2.55 \cdot 2.78 \cdot 2.44} = 2.59$), common causes (e.g., $TRPN^{(3)}_{\mathrm{O45C}} = \sqrt[2]{2.55 \cdot 2.78} = 2.66$) and common effects (e.g. $TRPN^{(3)}_{S_1,005\mathrm{E(H)}} = 2.67$).

In addition to the general view, the maximum values of TRPNs and risk factors were calculated for failure modes, processes, process areas and main processes. Were found 6 (W1), 8 (W2), 1 (W3) warnings; thus, should be implemented at least $6 + 8 + 1 = 15$ corrective/preventive actions.

4.6 Conclusion

Both case study shows that the TREF is a flexible risk evaluation framework.

The initial case (Chapter 4.3) demonstrated that the TREF can effectively manage the assessment of risks in the supply chain network. This assessment requires the integration of at least three distinct areas of risk: supplier risk analysis (concerns pertaining to suppliers' activities), logistic risk analysis (concerns pertaining to transportation, materials handling, registration, repackaging, and deliveries), and internal logistics and storage risk analysis (concerns pertaining to material receipt, identification errors, storage, picking, and deliveries to production lines). In all three cases, the quality, environmental, cyber security, and product safety aspects were taken into consideration.

In the second case (Chapter 4.5), the same source of hazards caused risks in multiple management areas, such as automotive customer, special environmental concerns, and data handling of risky processes, and each effect was evaluated using various criteria for the three domains. In addition, TREF can address an arbitrary number of risk factors; were used $6 + 1$ risk factors, namely, severity (S), occurrence (O), detection (D), control (C), information (I), and range (R), with criticality as +1. Finally, different risk factors had different weights in the case of the three domains; e.g. "range" was the second-most important risk factor in the environment domain.

This second example demonstrated the successful application of the proposed risk evaluation model and its associated warning system. This system is capable of managing risks and warnings across various levels and domains. It is not limited to complex systems such as the supply chain, but can also be utilized in a company's processes where risks are assessed in three different domains.

Chapter 5

Evaluation of results

The reason for arranging each output in decreasing order was to ensure that this pattern was accurately represented. The comparative analysis of rank modifications for various aggregation functions is illustrated in Figures 5.1 to 5.6. The ranking orders are presented on Table C.4.

The present graphic depiction of Alluvian representation serves to emphasize the discrepancies in ordering through the comparison of an initial state and a subsequent state. However, the depiction begins with the conventional outcomes of the FMEA as a refference, considering the sequential Risk Priority Number (RPN) or output values. Subsequently, it demonstrates the alteration in the prioritization of the aforementioned risk after the implementation of the novel aggregate function. The final diagram includes a triple figure that visually represents the transition from conventional FMEA to enhanced FMEA that incorporates risk levels. This diagram enables us to discern the differences between the two approaches.

A general observation is a movement towards higher areas in comparison to the original FMEA in terms of controllability, which exceeds level 8 in 16 cases, and also in terms of cost, which also exceeds level 6 in 16 cases. A cross-section of both components with values above level 8 and level 6 yields 15 risk cases when the above criteria is met. Hence, several hazards associated with the use of RPN are elevated to a higher risk level due to the presence of two new factors - and this is valid for all figures below.

Regarding the orange and light green lines in Figure 5.1, they were identified as the highest risks according to original FMEA (with RPN 126 and 162). However, when considering a 5-factor ranking, these risks were moved to the lowest level of risk due to their low cost effect and low-moderate controllability (refer to Table B.1 for individual risk details).

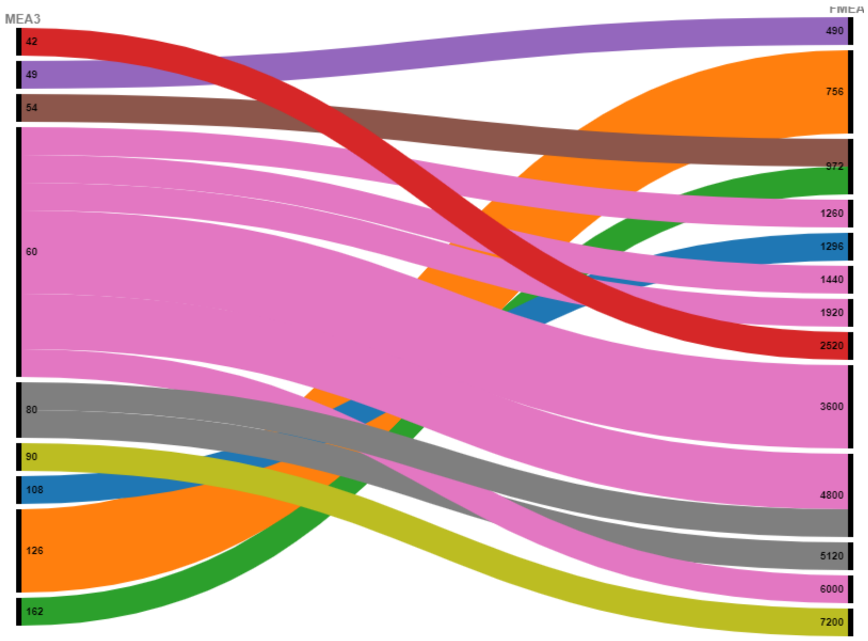


FIGURE 5.1: FMEA with TREF Multiplication

As mentioned in Section 3.4, Figure 5.1 illustrates the typical FMEA, which utilizes only 3 factories, and the 5 factors aggregated with multiplicative method, based on the outcome of the case study conducted at EMS company (SIIX Hungary Kft). The risk evaluation is reorganized by incorporating two additional components, namely Cost and Controllability above the regular FMEA's Severity, Detectability and Occurrence. These two new factors have an impact on the original three factors, which are unchanged, and are also aggregated using multiplication, highlighting a completely new result of risk evaluation. The diagram illustrates a shift in risk levels from low to high in the TREF Multiplicative model due to the introduction of two new factors with high related risks associated to that process. An example is the process of ordering raw materials, which may be impacted by a problem in the distributor's warehouse resulting in a lower quantity of packed materials. In the standard Failure Mode and Effects Analysis (FMEA), this problem was evaluated and scored using the criteria of Occurrence (O), Severity (S), and Detection (D), resulting in a score of 1x7x6=42. Scoring rationale: The event is seldom, so the occurrence score is 1. However, the severity value is 7 due to the potential impact on manpower. The detection score is 6 as the event is likely to be identified during unloading. The two new criteria were evaluated on the basis of their controllability and cost. Controllability was given a score of 10, as it is not within our control to monitor the actions of the supplier. The cost factor was scored 6, as any increase in cost might potentially lead to a halt in production if it impacts the needed quantity by the client. As a result, the last element in the FMEA rank moves to the 10th position in the TREF Multiplicative ranking (see the red line in Figure 5.1.

In general, can be seen a shift to upper area regarding controllability, which in 16 cases are over 8, and also regarding cost, which alsi on 16 cases are over 6. If we make a cross-section of both factors, which hace values above 8 and 6, resulting 15 risk cases, when we meet above condition. This is the reason, why some risks from midrange of RPN are shifted to higher risk level regarding thwo new factor.

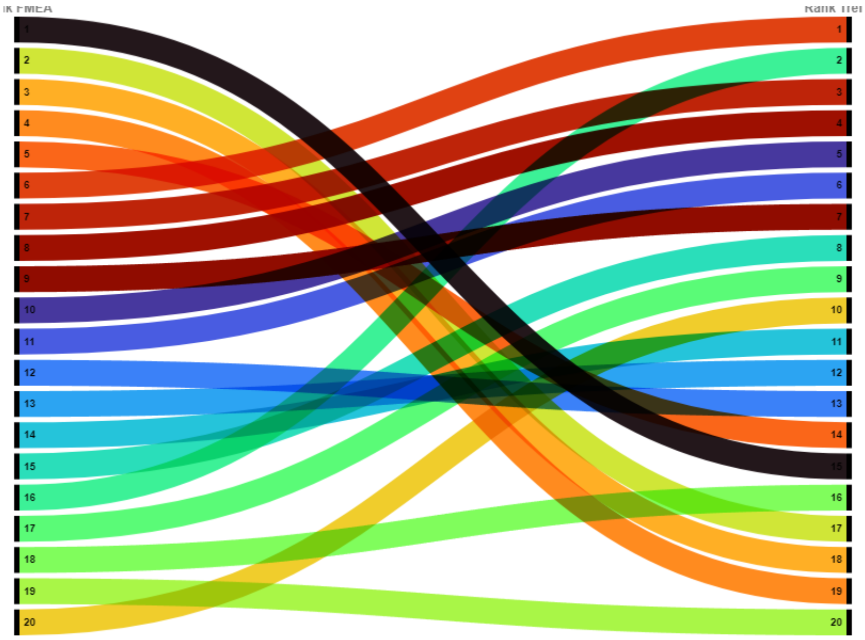


FIGURE 5.2: FMEA - TREF Average, rankings

FIGURE 5.3: FMEA - TREF Median

Figures 5.2 and 5.3 depict the comparison results between standard FMEA and the average and median aggregation functions for 5 factors. In the case of average aggregation, the output is always smaller than the maximum value of the 5 variables since it generates an average output. This method has the potential to mask the risk.

Similarly, in the case of the median aggregation function, the function will choose the middle value from the 5 components, which is always smaller than the maximum value of the 5 factors. This is the reason, why some high ranking risk in FMEA, after aggregation process, will have a subordinate risk level, compared to others. Example: in case of median, one process factor levels are 2, 9, 9 - means in the FMEA this was top rated. This process was ranked with the implemented 2 new factors on levels 2 and 3. The median of this list is 3, and the average is 5 (see the black line in Figure 5.2), and the median is 3 (see the green line in Figure 5.3).

Considering the properties of additive and median aggregation functions, it is advisable to avoid using these functions when the objective is to emphasize potential dangers.

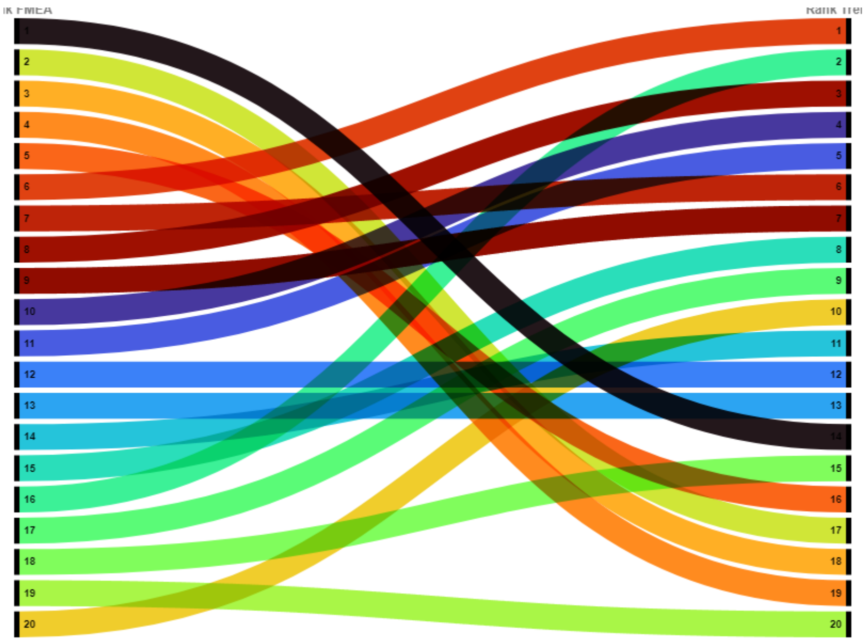


FIGURE 5.4: FMEA with TREF Radial Distance, rankings

On Figure 5.4 can be seen a tranzition from the standard FMEA and the Radial distance aggregation with 5 factors. There seems to be a similarity with Figure 5.2 generated in the first case by the sum, in the second by the sum of squares of squares.

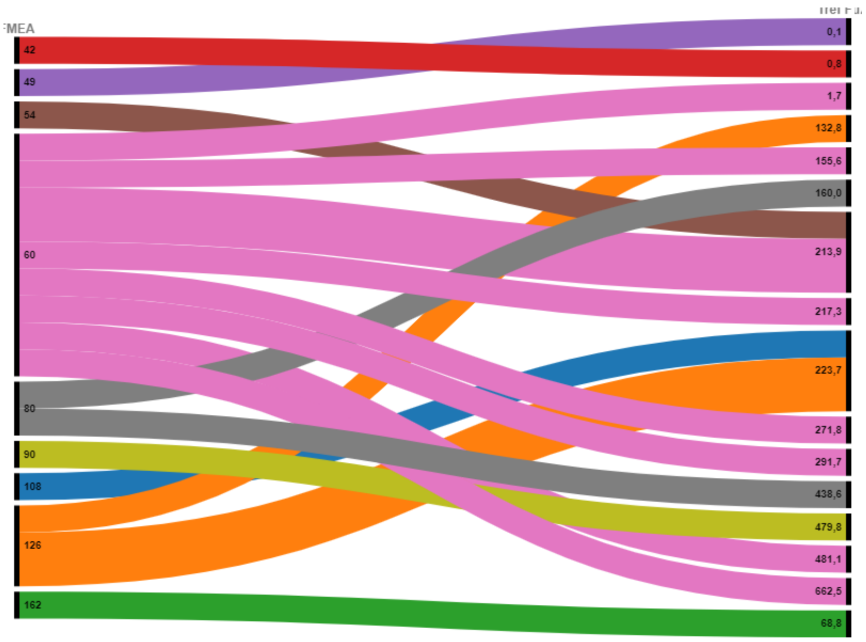


FIGURE 5.5: FMEA with TREF Fuzzy

Although it is challenging to comprehend, based on the TOPSIS result, it is advisable to interpret it using Figure 5.7.

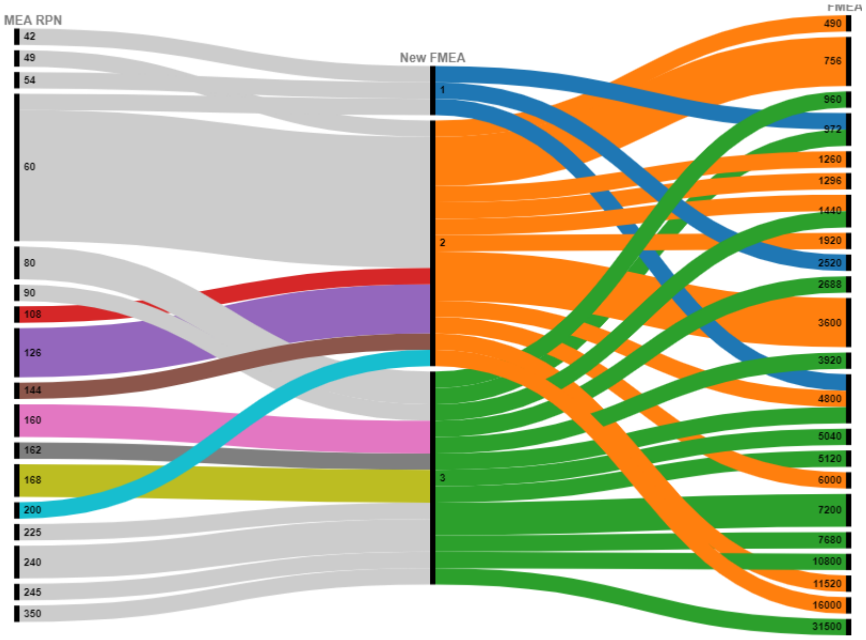


FIGURE 5.6: FMEA - New FMEA - TREF Multiplicative

The Figure 5.6 illustrates the challenge presented by the new FMEA through the implementation of Action Priority levels. These levels, namely Low, Medium, and High, limit the potential for making comparisons. Alternatively, the representation can be extended using the TREF multiplicative approach, taking into account only two extra components while maintaining the same aggregation mechanism.

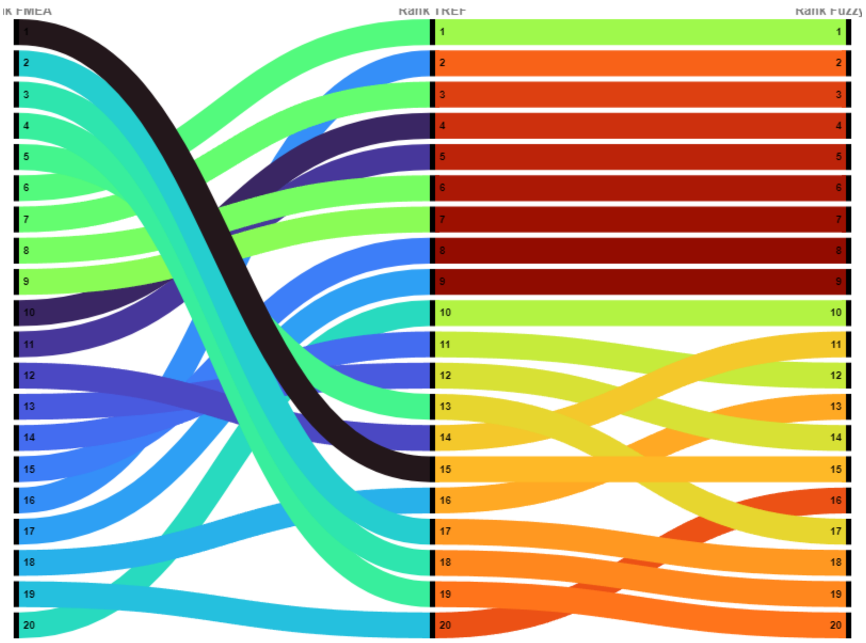


FIGURE 5.7: FMEA - TREF Multiplicative - TREF Fuzzy, rankings

According to Table 4.3, the TREF Fuzzy was determined to be the best outcome based on TOPSIS rating and also by the expert FMEA team. The second best result was the TREF Multiplicative. Figure 5.7 illustrates a transition using two multiplicative aggregations. The first aggregation involves three elements, while the second aggregation involves five factors. These two aggregations are then contrasted with the Fuzzy aggregation of five factors. The top 10 riskiest processes are same for both TREF Multiplicative and TREF Fuzzy. However, there are only differences in the last 10 processes. Fuzzy and enhanced multiplicative aggregation methods effectively identified the top 10 riskiest processes.

Ranking provides a hierarchy of dangers, while TREF provides a computed risk level or value. However, how may these values be interpreted?

The interpretation remains unchanged, as it was provided in earlier chapters. In the context of new FMEA, the Low level does not necessitate any activities, the Middle level, if no measures are necessary, requires an explanation for the requirement, and the High level always requires action to reduce the risk. For RPN, companies specified a limit value, and any value above it automatically triggered actions. The typical limit numbers were either 100 or 125, taken as the multiplication of 5x5x5 at the mid level.

The suggested values for TREF Multiplication are specified as 5^n, where n is the number of factors, if each factor consists of 10 levels. The determination of these limit values is contingent on the risk experts of the companies. The optimal value of limit should be chosen by them, as there is no universally accepted value or rule for this purpose. Within the EMS company, the limit values were established for five elements as 5x5x5x5x5=3215, resulting in 9 high-risk instances compared to the previous FMEA's 4 or the new FMEA's 4 (based just on the number of Highlevels).

Chapter 6

Validation and verification

6.1 Companies overview

This section will provide an overview of the companies/companies from which the data originate.

6.1.1 SIIX Hungary Kft

SIIX Hungary is a subsidiary of SIIX Corporation, which is a worldwide conglomerate specializing in global business organization. Their operations are focused on 4 areas:

- Electronic Manufacturing Service (EMS) is the main core business of the corporation, and set SIIX as the 17th EMS in Worldwide ranking. As Japan's top EMS company, they respond to a wide range of outsourcing needs by leveraging their high-quality, high-precision mounting capabilities at their global bases, from mounting electronic boards used in electrical components in all fields to assembling modules and partially finished products.
- Trading. They provide global procurement services for electronic components, procuring all the necessary parts on behalf of their customers' purchasing departments, and support customers inventory management by providing a logistics menu that includes kitting, VMI (Vendor Managed Inventory) and JIT (Just In Time) for delivery.
- Plasic Molding. They have a plastic injection molding plant within the group, and have a system in place that allows them to handle not only plastic injection molding, but also the subsequent assembly process for finished products.
- Joint Design and Manufacturing company. This new part supports their customers' commercialization needs by proposing new plans and technologies in collaboration with technology partners equipped with the most advanced development and design capabilities from around the world. They collaborate with technology partners in the fields of optics and sensors, communications and IoT, robotics, raw materials, and energy management.

The company was founded in 1957 as an electronic components trading company. In 1969, a sales office was opened in Europe, in Düsseldorf, Germany. In 1992 the incorporation took place, and the name was changed to SIIX (Sakata Inx International Corporation). The business sharing between units: 70% EMS, 27% Trading, 2% PM, and 1% JDM.

The Hungarian factory was established in 2017 as an EMS provider, and the business started in 2018. Automotive products account for 72% of the total, while the remaining portion includes livestock management, household items, industrial automation and tool-drivers, among others.

On average, the company collaborates with more than 260 suppliers, processes more than 1 billion parts monthly from incoming through warehouse to manufacturing area, and manufactures more than 50 distinct products for more than 10 customers.

The usability of the TREF approach on the supply chain was tested using the data of this company. The rationale is that this company is positioned midway in the supply chain, between direct customers, OEMs, forwarders, and printed circuit manufacturers, component manufacturers and their forwarders.

6.1.2 Maxon Motors Hungary Kft

Maxon is a global leading provider of electric drive systems. Their brushed DC motors feature robust permanent magnets and a globally patented ironless rotor design. The coils are self-supporting, resulting in low inertia and a lightweight rotor. These motors offer high output power and rapid acceleration to reach the desired speed or rotation. In addition, they can handle short-term overloads effectively. The DCX and DC-max modular programs can be individually configured according to customer specifications.

Their renumé comes from long service life, low energy consumption, unsurpassed reliability, and excellent control properties of their motors. Those products are made in the Hungarian factory. This location was selected to present the warning system of the presented risk evaluation framework.

The risk associated with this company's maintenance activities was assessed, taking into account three management system requirements. Here the warning system was tested and successfully deployed.

6.1.3 UniTurn Kft

UniTurn Kft is a family business started 28 years ago. Their primary focus now is the production of precise shafts for the automotive industry (15%), as well as domestic electromechanical equipment (85%). Precise refers to the narrow tolerance range of 5-30um within a diameter range of 5-24 mm.

On average, there are 10 suppliers of raw materials, 39 distinct materials stored in the warehouse, with an annual usage of over 2k tons. Production includes more than 50 types of completed goods, with a yearly output of over 12 million shafts.

At this organization, the TREF approach was adopted. It is noteworthy that this company was impacted by the sanctions implemented by the European Union against Russia, namely in relation to the use of steel and other metals. Every customer have requested documentation of compliance with these standards, which are duly maintained.

Sharing of any additional data from the aforementioned three companies is strictly prohibited.

6.2 Context of analysis

The risk in the supply chain network was analyzed in accordance with IATF requirements. This meant that risk should not impede the activity of our customers, which entails ensuring that they receive the ordered products in the correct quantity, quality, and time. Additionally, the risk should have an optimal logistic cost, which is achieved by avoiding extra logistics or handling costs. This is achieved by comparing the basis to an ideal solution, which is a cost-saving solution. Finally, the risk should not impede the production and deliveries of related companies.

In the event that the warning system was deemed an interdisciplinary process, the maintenance operation was considered, which impacts the activities of multiple departments, as well as several management systems, such as the energy saving management system (ESMS), environmental management system (EMS), safety management system (SMS), or quality management system (QMS). Typically, above mentioned management systems' risk are analyzed separately, and the company lacks the necessary tools to consolidate the risk analysis of each management system.

6.3 Threats to validity

Risk analysis involves a combination of quantitative (statistical) and qualitative methodologies. Once we have gathered sufficient data, measurement results and experience, we can effectively manage the risk by employing quantitative methods. In many cases, we rely on expert estimates to determine the outcome, taking into account their knowledge. However, it is important to verify the frequency of the events in question.

The risk analysis, as the FMEA, is a team work, that requires experts/proffesionals of that process or related processes to be part of assessmnet or evaluation team, and it is preferable to be guided this teamwork by an FMEA moderator. The result of this collaboration was to assign a Risk Priority Number (RPN) to each issue. In the case of a new Failure Mode Analysis (FMA) at an Action Priority (AP) level, any issues beyond a specific threshold must be addressed. The entire procedure fails to take into account anything beyond the major issues that have been addressed, hence neglecting all other risk factors. Their re-evaluation is only considered in the event of a new risk concern that may be connected in some way. This is a common procedure in industrial organizations. If risks are reduced / mitigated, the FMEA requires a new assessment. Upon this reassessment, if the level of risk has diminished to a satisfactory degree, the collaboration/teamwork is deemed successful and the mitigation measures are approved.

Risk assessment and evaluation is a quantitative procedure that relies on the understanding and expertise of the team. This is substantiated by gathered data and statistical techniques. This thesis presents proposed methods for enhancing risk assessment, as an alternative to the commonly utilized FMEA. To identify the most suitable factor, checking their correlation, testing the generalized risk priority number using various aggregation functions, the TOPSIS method is employed. Simultaneously, the risk assessment team evaluates the best strategy. The congruence of both theoretical findings and the evaluation conducted by the risk assessment team validates the validity.

In summary, the presented risk evaluation framework is an ongoing/continuous learning process, like the FMEA, in which the status of mitigated failures is deemed temporarily validated until a new failure occurs. In this instance, the mitigating measures will be reassessed, verified, analyzed, approved, and implemented - and the updated status will be validated. This is a continuous PDCA (Plan-Do-Check-Act) process, and the risk assessment will continue to improve over time. If there are any alterations in the circumstances, a complete examination should be repeated.

The proposed method aims to reduce the duration of this process by using novel and more pertinent risk factors that can effectively emphasize the level of risk involved. By selecting the suitable risk factors and employing the appropriate aggregation function, the resultant generalized risk priority number will exhibit a more accurate ordering of risk issues, like in the presented case study.

In order to maintain the effectiveness of this PDCA-like approach, like in the FMEA standard (Chrysler LLC; , AIAG) mandates a periodic re-evaluation, such as on a yearly basis. This reevaluation provides a valuable opportunity to thoroughly assess any changes that have occurred in the investigated area, management system, or process.

For the warning system, the technique remains the same. If warning settings are not configured correctly, the frequency of alert occurrences increases or decreases. Each situation should be individually studied, taking into account the parameters for triggering the alarm, and carefully adjusted. The PDCA methodology is also applicable.

Each instance should be evaluated on the basis of many standards, such as the proper storage of chemicals in warehouses or workplaces. Ensuring adequate segregation between acids and bases is crucial when storing them in the workplace. When acids and bases combine, it can lead to vigorous neutralization reactions that generate excessive heat and hazardous fumes. Therefore, it is necessary to segregate these chemicals according to their incompatibility, limit their quantity, and carefully assess the possibility of mixing them.

Chapter 7

Summary and Conclusion

In the current dissertation, a quantitative approach supplemented with a case study was provided to evaluate the effects of flexibility on different indicators and project databases.

7.1 Research theses

According to the research questions formed in Section 1.2, four research theses were formulated, considering the results of Chapters **??**, 5, and 6.

RT1: [Model] The suggested method for total risk evaluation offers a more comprehensive assessment of risk levels compared to existing methods. It provides the option to select more than three elements and utilize various aggregation algorithms.

RT2: [Model] The proposed warning system can be integrated in the above mentioned total risk evaluation model, and can define thresholds on different levels (factors, risk evaluation levels), or different relations between factors and risk evaluations.

RT3: [Usability] The proposed model's usability was effectively evaluated for supply chain networks. It is important to note that the study of SCM risks is often overlooked in comparison to other risk assessment methods.

> **RT3.1:** [Flexibility] New factors and alternative aggregation functions can be chosen, which effectively emphasize the risk for the associated supply chain.
>
> **RT3.2:** [Simplicity] The multiplicative aggregation method is nearly as straightforward as the FMEA (Failure Mode and Effects Analysis), yielding highly satisfactory outcomes and being easily implementable.
>
> **RT3.3:** [Process steps] Using the presented process steps, easily can be implemented the whole methodology in case of risk evaluation and also in case of warning systems.

The previously formulated research assumptions could be verified with the results that are validated in Chapter **??**, with a case study from 2 important automotive companies.

7.2 Contribution to literature

Currently, there is no commonly approved method for aggregating, as indicated by the literature analysis. The authors utilize different unique aggregation functions; nevertheless, an examination of the optimal aggregation risk function or framework is necessary to establish the feasibility of employing previously unused combinations. Furthermore, the literature includes studies on risk including more than 3 risk factors (namely 4 and 5). However, there is currently no universally applicable approach for aggregating an indefinite number of elements.

This thesis presents a novel risk evaluation framework that provides a guideline for selecting additional factors. It also includes examples that demonstrate the necessary aggregation function when using more than three risk factors.

The existing literature on warning systems fails to address warning events that arise at several levels, such as factor, effect, mode, and process. This means that there is no provision to create distinct warning rules for each risk factor independently at each level.

The proposed risk warning system is comprehensive and can effectively address the deficiencies mentioned earlier. In two case studies, the methodology presented is tested in practice and yields positive results.

7.3 Practical implications

The practical use and utilization of this proposed technique was a primary emphasis of this thesis and was implemented in practice in two companies.

The primary objective was to provide a straightforward approach for SCM decision makers, as the literature review revealed that SCM is the most overlooked domain in risk analysis. The case study conducted at EMS company demonstrates the need of using two more factors and their integration. The tested result, together with the most commonly used aggregation functions, indicates the advantage of the new risk analysis tool, known as TREF. The two recently introduced factors shed light on the risk from a fresh standpoint, revealing that the actual hazardous items vary from those generated using the conventional FMEA approaches.

Based on the data in Table 3.1, Table 4.3, and Figure 5.1 to Figure 5.7, it is possible to conclude that the introduction of the two new factors substantially prolonged the identification of actual risks, i.e., risks that cause substantial damage emerged. The methodology that was demonstrated, as well as explained in the Case Study, is easily implementable by SCM decision-makers. This aids them in identifying the fundamental risks that require preparation and consequently facilitates the identification of such risks. The implementation procedures shown in the case study are extensive and relevant to sectors and industries beyond supply chain management. However, due to the complexity of the supply chain network, such a risk assessment framework is necessary to analyze their risk, and this is the advantage of the thesis presented. The proposed risk analysis framework offers the advantage of consolidating the risk evaluations of many management systems into a unified risk value or ranking, while considering their individual warning systems on different levels.

Examples were shown in the case of a warning system, demonstrating how multiple management systems (such as quality and health and safety) could interact (see Figure 4.5, Figure 4.6 and Figure 4.7. These interactions can effectively identify and bring attention to high-risk concerns in maintenance activities, providing valuable information for decision makers.

Chapter 8

Limitations

The risk analysis is a process that combines both qualitative and quantitative approaches. There is no explicit formula that can be universally used in all circumstances. Individual risk analyses are distinct and applicable to the specific process, department, firm, or network being evaluated. Their validity is heavily influenced by the experience, knowledge, and education of the assessment and evaluation team. The proposed methodology was tested at three companies, and works well. The aggregation functions offered provide a selection of those that are often used in the literature. However, it is possible to identify additional functions that may be more suitable for the intended risk assessment. The environment, inputs, and outputs can be assessed, along with financial, political, geographical, environmental, health, energy saving, cyber security, and supplier-related aspects. This analysis should also consider the interactions between processes, departments within the organization or with interested parties/stakeholders, or with suppliers, members of supply chain. By thoroughly understanding the risk factors being analyzed, a comprehensive evaluation of the risk can be obtained, providing a realistic assessment of the environment.

Appendix A

Criteria for evaluations for used factors

TABLE A.1: Criteria for evaluating the frequency of Occurrence of logistic defects at incoming

Probability of occurrence	**Occurrence definition**	**Score**
Never	Never	1
Unlikely	Once a year	2
Very low	Once a month	3
Low	Once a week	4
Medium	Once a day	5
Medium high	Daily 2-4 time	6
Important	Daily 5-10 time	7
Very important	Once in an hour	8
Very very important	Hourly 2-4 time	9
Extremely important	Hourly more than 6 time	10

TABLE A.2: Criteria for evaluating the severity of the logistic failure defects

Severity of failure	**Severity ranking**	**Score**
No discernible effect	No discernible effect	1
Slight inconvenience in logistic process	Alarm at SCM	2
Can cause short stops	Red alarm at SCM	3
Can cause considerable stops in process	Can cause written remark	4
Small stops at Tier1	Warning from Tier1	5
Several small stops at Tier1	Escalation by Tier1	6
Serious stops at Tier1	Red alarm at Tier1	7
Delay at final customer	Escalation start from final customer	8
Small stops at final customer	Emergency at final customer	9
Serious stop at final customer	Stop final customer	10

TABLE A.3: Criteria for assessing the detection of defects

Probability of detection	**Detection effect**	**Score**
Automatic detection	No effect	1
Extremely Easy detection	Easy to detect	2
Very high probability	Small delays	3
High probability	Detected delays	4
Medium	Late deliveries	5
Little	Several late deliveries	6
Very little	Line stops	7
Hard to detect	Several line stops	8
Extremely high	Customer stop	9
Undetectable	End customer stop	10

TABLE A.4: Criteria for evaluating the cost of logistic defects

Probability of Cost	Cost definition	Score
Never	No cost	1
Very small	Non significant	2
Small	Tens of	3
Low	Hundreds of	4
Medium low	1-2k	5
Medium	2-5k	6
Significant	5-10k	7
High	10-25k	8
Very High	25-100k	9
Extremely high	Over 100k	10

TABLE A.5: Criteria for evaluating the controllability of logistic defects

Probability of Control	Control definition	Score
Fully controlled	No attention required	1
Exceedingly simple to control	Needs small attention	2
Simple to control	Attention	3
Gap in control	Easy re-planning	4
Several gaps in control	Re-planning	5
Serious gaps in control	Fast reaction	6
Difficult to control	Several fast reactions	7
Very difficult to control	Difficult	8
Partially out of control	Very difficult	9
Completely out of control	Impossible	10

Appendix B

Comparison of standard FMEA risk priority number (RPN) and the new FMEA Action Priority (AP) level

TABLE B.1: A detail from the standard and new FMEA analysis results - for 3 factors

No	Process	Sub-Process	Failure mode	Effect	O	S	D	RPN	AP
1	handling	at supplier	damaged	stop prod/cust	2	9	9	162	H
2	handling	during transp	damaged	stop prod/cust	2	9	7	126	M
3	handling	during uploading	damaged	stop prod/cust	2	9	7	126	M
4	handling	during downloading	damaged	stop prod/cust	2	9	7	126	M
5	handling	delay(nat.hol)	delay in production	stop cust or delay	1	7	7	49	M
6	transport	delay traffic	delay in production	stop cust or delay	1	9	6	54	M
7	transport	delay disaster	delay in production	stop cust or delay	1	10	6	60	M
8	transport	accident	delay in production	stop cust or delay	1	10	6	60	M
9	mat.ordering	order mistake	stop production	stop customer	1	10	6	60	M
10	IT system	IT failure	system error	stop customer	1	10	6	60	M
11	WH	mat.ordering	mat shortage at reseller or supply	stop customer	1	10	6	60	M
12	WH	mat.ordering	mat. shortage market situ	stop customer	1	10	6	60	M
13	WH	mat.ordering	distrib WH issue	stop customer	1	10	6	60	M

Appendix C

Ranking results

TABLE C.1: Ranking of effect by experts from EMS company

No	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
C1	1	4.5	4	5	1	0.33	2	1	7.5	7	3	1.5	2.5	0.83	6	3.5	8.5	5.5	6.5	0.5
C2	0.22	1	0.83	1.2	0.25	0.17	0.33	0.25	3	2.5	0.5	0.33	0.5	0.2	1.5	0.67	4	2	2.5	0.25
C3	0.25	1.2	1	1.5	0.29	0.18	0.4	0.29	3.5	3	0.67	0.33	0.5	0.2	2	0.83	4.5	1.5	2.5	0.2
C4	0.2	0.83	0.67	1	0.22	0.15	0.4	0.29	3.5	3	0.67	0.33	0.5	0.2	2	0.83	4.5	1.5	2.5	0.2
5C	1	4	3.5	4.5	1	0.5	15	1.2	7	6.5	2.5	1	2	0.5	5.5	3	7.5	5	6	0.67
C6	3	6	5.5	6.5	2	1	3.5	2.5	9	8.5	4.5	3	4	1	7.5	5	9.5	7	8	1
C7	0.5	3	2.5	3	0.67	0.29	1	0.83	6.5	5	1.3	0.9	1.2	0.4	4	1.5	6.5	3.5	4.5	0.33
C8	1	4	3.5	4	0.83	0.4	1.2	1	6.5	6	2	1.2	1.5	0.67	5	2.5	7.5	4.5	5.5	0.5
C9	0.13	0.33	0.29	0.4	0.14	0.11	0.15	0.15	1	0.8	0.22	0.17	0.2	0.13	0.15	0.25	2	0.5	0.83	0.12
C10	0.14	0.4	0.33	0.5	0.15	0.12	0.2	0.17	1.25	1	0.25	0.18	0.22	0.13	0.83	0.29	3	0.67	0.91	0.13
C11	0.33	2	1.5	2	0.4	0.22	0.77	0.5	4.5	4	1	0.67	0.91	0.29	3	1.2	5	2.5	3.5	0.25
C12	0.67	3	3	3.5	1	0.33	1.11	0.83	6	5.5	1.5	1	1.2	0.5	0.22	2	6.5	4	5	0.4
C13	0.4	2	2	2.5	0.5	0.25	0.83	0.67	5	4.5	1.1	0.83	1	0.33	3.5	1.2	5.5	3	4	0.29
C14	1.2	5	5	5.5	2	1	2.5	1.5	8	7.5	3.5	2	3	1	6.5	4	8.5	6	7	0.83
C15	0.17	0.67	0.5	0.67	0.18	0.13	0.25	0.2	6.5	1.2	0.33	4.5	0.29	0.15	1	0.4	2	0.83	1.2	0.14
C16	0.29	1.5	1.2	1.5	0.33	0.2	0.67	0.4	4	3.5	0.83	0.5	0.83	0.25	2.5	1	5	2	3	0.22
C17	0.12	0.25	0.22	0.29	0.13	0.11	0.15	0.13	0.5	0.33	0.2	0.15	0.18	0.12	0.5	0.2	1	0.4	0.67	0.11
C18	0.18	0.5	0.67	0.77	0.2	0.14	0.29	0.22	2	1.5	0.4	0.25	0.33	0.17	1.2	0.5	2.5	1	1.2	0.15
C19	0.15	0.4	0.4	0.56	0.17	0.13	0.22	0.18	1.2	1.1	0.29	0.2	0.25	0.14	0.83	0.33	1.5	0.83	1	0.13
C20	2	4	5	6	1.57	1	3	2	8.5	8	4	2.5	3.5	1.2	7	4.5	9	6.5	7.5	1

C.2:

TABLE C.2: Random evaluation of impacts in all risk cases

No	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Eval	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-

C.3:

TABLE C.3: Evaluation of impacts in all risk cases based on ranking matrix

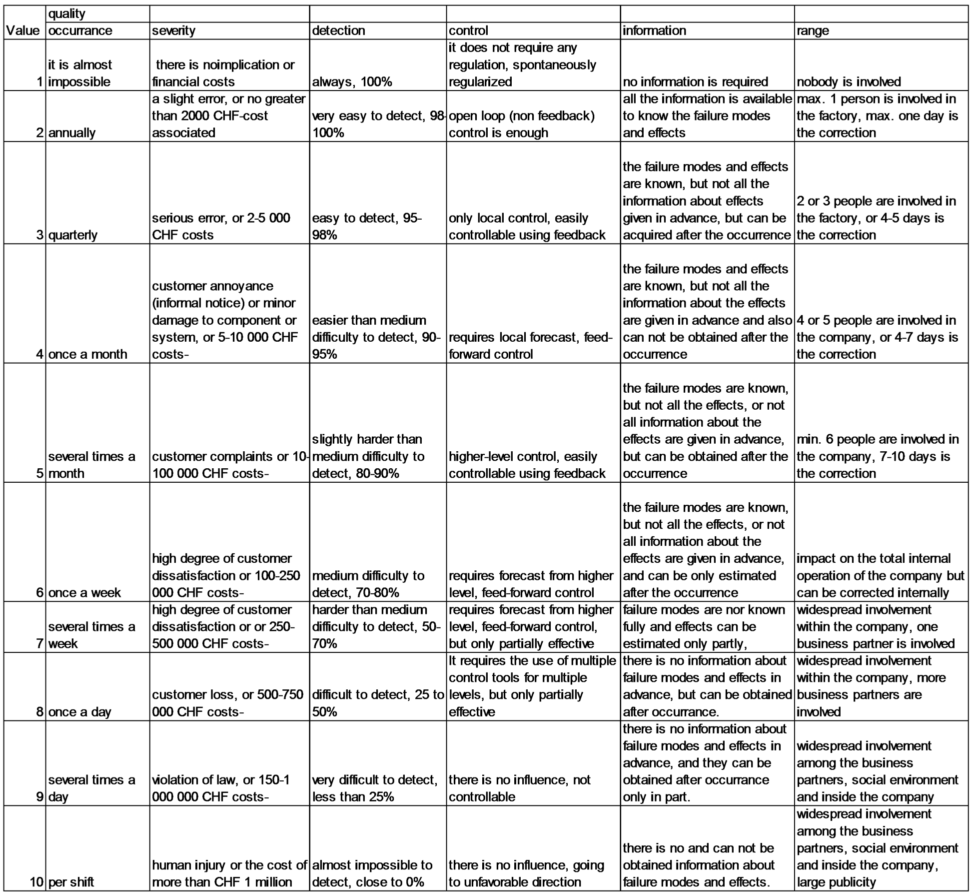
No	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
Eval	-	+	+	+	-	-	-	-	+	+	-	-	-	+	-	+	+	+	+	-

TABLE C.4: Ranking of risk calculated with different aggregation functions from EMS company

Risk no	**Old FMEA**	**New FMEA**	**TREF Multiplicative**	**Fuzzy 3**	**TREF Median**	**TREF Average**	**TREF Fuzzy**
1	20	17	6	19	4	5	4
2	17	5	2	14	1	2	2
3	18	6	3	15	2	3	3
4	16	9	8	2	7	6	6
5	19	7	4	16	3	4	5
6	2	4	1	13	5	1	1
7	3	1	5	3	8	7	7
8	4	12	12	4	9	12	18
9	5	3	15	5	15	15	10
10	15	20	20	20	19	20	11
11	6	15	16	6	16	16	13
12	13	19	18	17	17	17	19
13	7	8	7	7	10	8	12
14	8	10	9	8	11	9	15
15	9	11	10	9	12	10	20
16	10	13	13	10	13	13	9
17	11	16	19	11	20	19	17
18	12	14	14	12	14	14	8
19	14	18	17	18	18	18	14
20	1	2	11	1	6	11	16

Appendix D

Risk factors at electric motors manufacturer - Evaluation scales



	quality					
Value	occurrance	severity	detection	control	information	range
1	it is almost impossible	there is noimplication or financial costs	always, 100%	it does not require any regulation, spontaneously regularized	no information is required	nobody is involved
2	annually	a slight error, or no greater than 2000 CHF-cost associated	very easy to detect, 98-100%	open loop (non feedback) control is enough	all the information is available to know the failure modes and effects	max. 1 person is involved in the factory, max. one day is the correction
3	quarterly	serious error, or 2-5 000 CHF costs	easy to detect, 95-98%	only local control, easily controllable using feedback	the failure modes and effects are known, but not all the information about effects given in advance, but can be acquired after the occurrence	2 or 3 people are involved in the factory, or 4-5 days is the correction
4	once a month	customer annoyance (informal notice) or minor damage to component or system, or 5-10 000 CHF costs-	easier than medium difficulty to detect, 90-95%	requires local forecast, feed-forward control	the failure modes and effects are known, but not all the information about the effects are given in advance and also can not be obtained after the occurrence	4 or 5 people are involved in the company, or 4-7 days is the correction
5	several times a month	customer complaints or 10-100 000 CHF costs-	slightly harder than medium difficulty to detect, 80-90%	higher-level control, easily controllable using feedback	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, but can be obtained after the occurrence	min. 6 people are involved in the company, 7-10 days is the correction
6	once a week	high degree of customer dissatisfaction or 100-250 000 CHF costs-	medium difficulty to detect, 70-80%	requires forecast from higher level, feed-forward control	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, and can be only estimated after the occurrence	impact on the total internal operation of the company but can be corrected internally
7	several times a week	high degree of customer dissatisfaction or or 250-500 000 CHF costs-	harder than medium difficulty to detect, 50-70%	requires forecast from higher level, feed-forward control, but only partially effective	failure modes are nor known fully and effects can be estimated only partly,	widespread involvement within the company, one business partner is involved
8	once a day	customer loss, or 500-750 000 CHF costs-	difficult to detect, 25 to 50%	It requires the use of multiple control tools for multiple levels, but only partially effective	there is no information about failure modes and effects in advance, but can be obtained after occurrance.	widespread involvement within the company, more business partners are involved
9	several times a day	violation of law, or 150-1 000 000 CHF costs-	very difficult to detect, less than 25%	there is no influence, not controllable	there is no information about failure modes and effects in advance, and they can be obtained after occurrance only in part.	widespread involvement among the business partners, social environment and inside the company
10	per shift	human injury or the cost of more than CHF 1 million	almost impossible to detect, close to 0%	there is no influence, going to unfavorable direction	there is no and can not be obtained information about failure modes and effects.	widespread involvement among the business partners, social environment and inside the company, large publicity

TABLE D.1: Risk factors in quality aspect

	environment					
Value	occurrance	severity	detection	control	information	range
1	it is almost impossible	no effect: the effect is unverifiable, change is not sensible	sense perception is directly and immediately possible by anyone, at any time of the day	it does not require any regulation, spontaneously regularized	no information is required	nobody is involved
2	annually	neutral: the effect is verifiable, but the caused change is not sensible	sense perception is directly and immediately possible by anyone, but only in smooth atmospheric / optical / noise conditions (eg. only in daytime)	open loop (non feedback) control is enough	all the information is available to know the failure modes and effects	max. 1 person is involved in the factory, max. one day is the correction
3	quarterly	tolerable: unwanted changes can be detected, but they do not affect any essential features of the given unit	especially difficult to detect sensory, even in daytime, under optimal conditions	only local control, easily controllable using feedback	the failure modes and effects are known, but not all the information about effects given in advance, but can be acquired after the occurrence	2 or 3 people are involved in the factory, or 4-5 days is the correction
4	once a month	acceptable as tolerated status: unwanted changes can be detected, they do affect more essential features of the given unit	sense perception is possible only using tool (eg. light, the use of contrast agents, the use of indicators, etc.)	requires local forecast, feed-forward control	the failure modes and effects are known, but not all the information about the effects are given in advance and also can not be obtained after the occurrence	4 or 5 people are involved in the company, or 4-7 days is the correction
5	several times a month	annoying: functions are sustainable, but conditions are deteriorating.	sense perception is not possible however the change is demonstrable mathematically (calculation, inventory, mass balance, etc.).	higher-level control, easily controllable using feedback	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, but can be obtained after the occurrence	min. 6 people are involved in the company, 7-10 days is the correction
6	once a week	little problem: the irreversibility described above exists, however the change is not over limit or qualification barrier, or the change is over limit, but the effect is reversible without any corrective action	immediately can be detected by instruments in own ownership and use	requires forecast from higher level, feed-forward control	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, and can be only estimated after the occurrence	impact on the total internal operation of the company but can be corrected internally
7	several times a week	problem: irreversibility exists, the change is over one limit or qualification barrier, the effect is reversible without any corrective action	immediately can be detected by instruments from external source	requires forecast from higher level, feed-forward control, but only partially effective	failure modes are nor known fully and effects can be estimated only partly,	widespread involvement within the company, one business partner is involved
8	once a day	restrictive: the change is over each limit, regulation etc., as a consequence the unit gets into lower quality class, but the change is reversible	not all parameters can be detected using „in-situ"procedure	It requires the use of multiple control tools for multiple levels, but only partially effective	there is no information about failure modes and effects in advance, but can be obtained after occurrance.	widespread involvement within the company, more business partners are involved, environmental damage in max. 50 m radius
9	several times a day	Harmful: the change is over each limit, regulation etc., as a consequence the unit gets into lower quality class, the change is irreversible	can be detected only based on sampling, in laboratory conditions	there is no influence, not controllable	there is no information about failure modes and effects in advance, and they can be obtained after occurrance only in part.	widespread involvement among the business partners, social environment and inside the company, environmental damage in 50-200 m radius
10	per shift	terminating: the unit or the whole system ceases to exist or loses determinating features	instrumental analytical tests can not detect (or close to error limit), at most generation changes can be detected	there is no influence, going to unfavorable direction	there is no and can not be obtained information about failure modes and effects.	widespread involvement among the business partners, social environment and inside the company, large publicity, environmental damage is in over 200 m radius

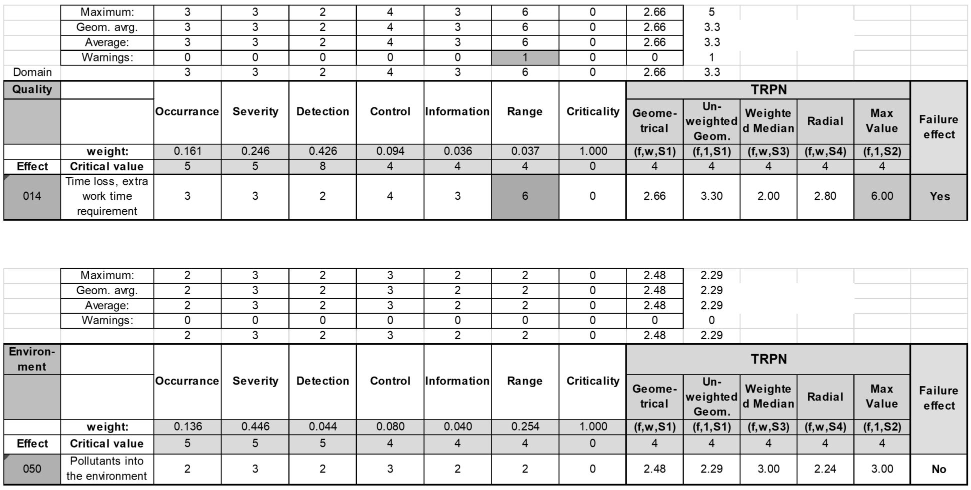
TABLE D.2: Risk factors in environment aspect

	health & safety					
Value	occurrance	severity	detection	control	information	range
1	it is almost impossible	there is no harm	always, 100%	it does not require any regulation, spontaneously regularized	no information is required	nobody is involved
2	annually	not serious work accident, the duration of incapacity to work is not more than 3 days	very easy to detect, 98-100%	open loop (non feedback) control is enough	all the information is available to know the failure modes and effects	max. 1 person is involved in the factory, max. one day is the correction
3	quarterly	not serious work accident, the period of incapacity more than 3 days	easy to detect, 95-98%	only local control, easily controllable using feedback	the failure modes and effects are known, but not all the information about effects given in advance, but can be acquired after the occurrence	2 or 3 people are involved in the factory, or 4-5 days is the correction
4	once a month	work accident causing not serious truncation	easier than medium difficulty to detect, 90-95%	requires local forecast, feed-forward control	the failure modes and effects are known, but not all the information about the effects are given in advance and also can not be obtained after the occurrence	4 or 5 people are involved in the company, or 4-7 days is the correction
5	several times a month	serious work accident with truncation	slightly harder than medium difficulty to detect, 80-90%	higher-level control, easily controllable using feedback	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, but can be obtained after the occurrence	min. 6 people are involved in the company, 7-10 days is the correction
6	once a week	permanent damage, causing the loss independent living ability	medium difficulty to detect, 70-80%	requires forecast from higher level, feed-forward control	the failure modes are known, but not all the effects, or not all information about the effects are given in advance, and can be only estimated after the occurrence	impact on the total internal operation of the company but can be corrected internally
7	several times a week	the loss or significant damage of sensory organ (or sense), reproductive capacity	harder than medium difficulty to detect, 50-70%	requires forecast from higher level, feed-forward control, but only partially effective	failure modes are nor known fully and effects can be estimated only partly,	widespread involvement within the company, one business partner is involved
8	once a day	work accident causing the loss of speaking skill, striking distorsion, paralysis, mental disorder	difficult to detect, 25 to 50%	It requires the use of multiple control tools for multiple levels, but only partially effective	there is no information about failure modes and effects in advance, but can be obtained after occurrance.	widespread involvement within the company, more business partners are involved
9	several times a day	life-threatening injury, damage based on medical opinion	very difficult to detect, less than 25%	there is no influence, not controllable	there is no information about failure modes and effects in advance, and they can be obtained after occurrance only in part.	widespread involvement among the business partners, social environment and inside the company
10	per shift	fatal work accidents (injury, fetus, newborn)	almost impossible to detect, close to 0%	there is no influence, going to unfavorable direction	there is no and can not be obtained information about failure modes and effects.	widespread involvement among the business partners, social environment and inside the company, large publicity

TABLE D.3: Risk factors in health & safety aspect

Appendix E

Risk analysis at electric motors manufacturer - Calculation of TRPN



	Maximum:	3	3	2	4	3	6	0	2.66	5				
	Geom. avrg.	3	3	2	4	3	6	0	2.66	3.3				
	Average:	3	3	2	4	3	6	0	2.66	3.3				
	Warnings:	0	0	0	0	0	1	0	0	1				
Domain		3	3	2	4	3	6	0	2.66	3.3				
Quality		**Occurrance**	**Severity**	**Detection**	**Control**	**Information**	**Range**	**Criticality**	**TRPN**					**Failure effect**
									Geometrical	**Un-weighted Geom.**	**Weighted Median**	**Radial**	**Max Value**	
	weight:	0.161	0.246	0.426	0.094	0.036	0.037	1.000	**(f,w,S1)**	**(f,1,S1)**	**(f,w,S3)**	**(f,w,S4)**	**(f,1,S2)**	
Effect	**Critical value**	5	5	8	4	4	4	0	4	4	4	4	4	
014	Time loss, extra work time requirement	3	3	2	4	3	6	0	2.66	3.30	2.00	2.80	6.00	**Yes**

	Maximum:	2	3	2	3	2	2	0	2.48	2.29				
	Geom. avrg.	2	3	2	3	2	2	0	2.48	2.29				
	Average:	2	3	2	3	2	2	0	2.48	2.29				
	Warnings:	0	0	0	0	0	0	0	0	0				
		2	3	2	3	2	2	0	2.48	2.29				
Environment		**Occurrance**	**Severity**	**Detection**	**Control**	**Information**	**Range**	**Criticality**	**TRPN**					**Failure effect**
									Geometrical	**Un-weighted Geom.**	**Weighted Median**	**Radial**	**Max Value**	
	weight:	0.136	0.446	0.044	0.080	0.040	0.254	1.000	**(f,w,S1)**	**(f,1,S1)**	**(f,w,S3)**	**(f,w,S4)**	**(f,1,S2)**	
Effect	**Critical value**	5	5	5	4	4	4	0	4	4	4	4	4	
050	Pollutants into the environment	2	3	2	3	2	2	0	2.48	2.29	3.00	2.24	3.00	**No**

TABLE E.1: Calculation of TRPNs for effects 014E(Q) and 050E(E)

Appendix F

Electronic supplementary materials

All supplementary materials and resources related to the dissertation can be found online on GitHub.

1. Case study data github repository:
   https://github.com/mihalczi/case$_{s}tudy.git$
2. Theory database github repository:
   https://github.com/mihalczi/theory-parcels.git
3. Excel calculations and data
4. Excel simulation framework

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