University of Pannonia
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Thesis summary

Supply chain risk analysis

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1 Introduction

In our interconnected globalized world, supply chains play a crucial role, impacting not only businesses but also everyday citizens. Disasters like earthquakes, floods, and fires can disrupt supply chains, affecting products and services worldwide. Risk analysis and management are essential to mitigate these dangers, including external events, like natural disasters, cyber-attacks, and pandemics; or internal ones, like materials handling, storing, incomming process, incomming ispection, labeling, picking, moving to production area etc. Organizations must understand the implications of these risks to maintain stability and resilience in their supply chains (Yacob Khojasteh; Geske; Henke; Huang et al., 2020).

Conducting a risk analysis of supplier networks is a multifaceted undertaking, involving several elements such as the suppliers, their sales- or warehousing centres, the transportation system of goods between them and to customers, the procedures of receiving the goods (identification, warehousing), and the transfer of goods to production. Currently, there is no established risk assessment methodology for effectively managing this intricate system, and the existing literature on this topic is limited in comparison to other fields.

2 Research objectives and research questions

The objective of this dissertation was to create and introduce a system specifically designed for supply chain decision makers to assess risks. This methodology will enable them to straightforwardly identify possible risks. Therefore, the research questions were formulated in the following manner:

R.Q.1. In what ways can a risk management framework tailored to supply chains be constructed to offer a more precise and straightforward estimation than the existing systems?

The methods described in the literature determine the level of risk based on a predetermined set of factors. The authors utilize different individual aggregation functions, however, there is a lack of analysis of the optimal aggregation risk function or framework, as well as the potential for using combinations that have not been previously explored. My objective is to create a comprehensive risk assessment system that is capable of managing uncertain risk elements.

R.Q.2. 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?

Warnings are crucial in the assessment of risks. Numerous endeavors have been made to enhance the risk evaluation warning system. Existing methods in the literature fail to account for warning events that arise from several levels, such as factor, effect, mode, and process. These methods do not provide specific warning criteria for each risk factor individually at each level. The objective was to create a multi-level warning system that can be integrated with the previously indicated comprehensive risk assessment framework.

R.Q.3. Which aggregation method is the most optimal for supply chain?

While there are numerous publications on risk, only a small number specifically analyze risks in the supply chain. The primary cause is a deficiency in comprehending the proper implementation of a risk assessment system, such as Failure Mode and Effects Analysis (FMEA), which is widely employed also in the Supply Chain Management (SCM) system. An easy methodology should be developed for this purpose, utilizing the previously indicated universal risk assessment framework.

3 Literature review and research assumptions

In the following, I highlight the scholarly findings on which I formulated my research assumptions.

In risk analysis or in used methods, authors use a limited to a fixed number of risk factors (Liu et al., 2013a). In addition, during literature investigation can be seen that authors calculate with risk factors, as they are independent (Liu et al., 2013a). One potential reason for disregarding new risk factors is the need to acknowledge their interdependence. These problems require innovative solutions that can effectively tackle the interdependence of risk variables and an unlimited number of risk factors. In literature, predetermined scales with identical factor numbers are commonly utilized.

Risk aggregation plays an important role in various risk assessment process (Bani-Mustafa et al., 2020; Bjørnsen and Aven, 2019). 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). According to Huang et al. (2020) keyword analysis of risk-related literature over the past 20 years confirms that the FMEA remains the most commonly utilized tool for evaluating risks.

The shortcoming of FMEA was presented by several authors Liu et al. (2013a); Lolli et al. (2015); Malekitabar et al. (2018); Wu and Wu (2021). 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 the 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.

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 methods and analyses have been proposed for aggregating risk. It can be observed 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 for prioritizing failure modes. The fuzzy rule-based FMEA approach uses linguistic variables to prioritize failures in a system to describe the 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). The authors 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.

Based on these, I formulated my first assumption

A.1. 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.

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., 2019) for assessing work safety in hot environments, including a warning rating and 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 sub-factor 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.

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. As Kanes et al. (2017) stated, it is important to focus on the area of flexible risk evaluation, as a way forward for improving 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).

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.

A.2. 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.

Supply chain risk factors can significantly impact a company's operations and overall performance (Zhao et al.). Multiple authors (Sime Curkovic, 2013; Wagner, 2016; Vodenicharova, 2017) have examined the reasons behind 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. A pertinent, functional, and adaptable instrument for performing supply network risk assessment is currently non-existent. It is imperative that supply chain managers and risk analysts have easy access to simple instrument or tool, considering the aforementioned activities and global developments that have an impact on the supply chain. 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 risk assessment ranks a mere fourteenth in terms of significance within the publication. 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. 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..

Multiple authors (Sime Curkovic, 2013; Wagner, 2016; Vodenicharova, 2017) have examined the reasons behind 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.

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), FMEA-ANP (Zammori and Gabbrielli, 2012), or Fuzzy Bayesian-based FMEA (Indrasari et al., 2021). Fuzzy FMEA (Petrović et al., 2014) is considered the second most often utilized risk analysis technique, following the FMEA method. 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.

A.3. 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.

4 Research Findings and Theses

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.

For this reason were defined the aggregation function criterias, like validity, monotonicity, sensitivity, symmetricity, linearity, scale fit, and scale endpoint identity (Grabisch et al., 2009; Zahedi Khameneh and Kilicman).

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. $S_5(\mathbf{f}) \in [\sqrt{n}, 10\sqrt{n}] \in \mathbb{R}^+$
- $S_6(\mathbf{f}) =$ 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.

The risk assessment framework, presented in Kosztyán et al. (2020), has undergone an expansion to incorporate a fuzzy module. This addition has been implemented to effectively address the issue at hand.

Typically, Fuzzy FMEA utilizes three to seven linguistic variables (Kozarević and Puška; Cardiel-Ortega and Baeza-Serrato).

At the beginning and end of the interval, the sigmoid function was implemented, and for each range within the interval, the bell/splay function were applied. 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). In accordance with its original score or crisp, each component is converted into the sum of n membership functions.

An analogy can be drawn between the sum of the fuzzy membership functions and the accumulation of factors comprising the fuzzy rule base. An instance of this can be described as follows:

$$W_i(\mathbf{S_i}) = S_1(\mathbf{f_i}) \otimes S_2(\mathbf{f_j}) \otimes \ldots \otimes S_n(\mathbf{f_n}) \tag{1}$$

where $\otimes$ is the aggregation protocol. 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.

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

4.1 Evaluating the Results of Used Aggregation Functions

Two approaches appeared viable for comparing the outcomes 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 distinct 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 via TOPSIS method using RSTUDIO's TOPSIS algorithm.

4.2 Evaluation of aggregation functions

Six risk aggregation methods, which consider five factors as input and employ multiplicative, average, median, modified Euclidean distance, geometrical mean, and Fuzzy functions, were investigated. 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.

A comprehensive summary of the simulations conducted using Oracle's Crystal Ball is provided in Table 1.

Table 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 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.

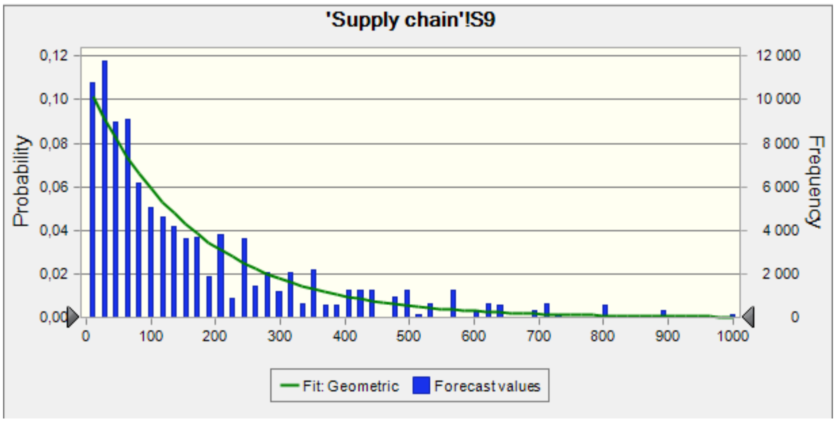


Figure 1: Standard FMEA frequency/values distribution.

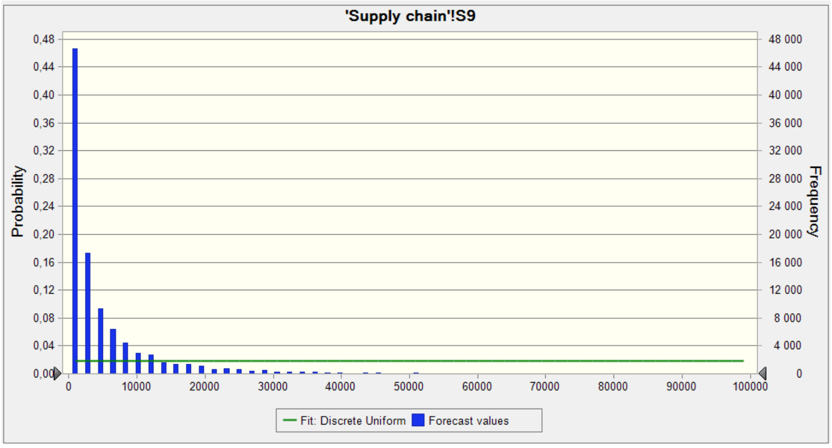


Figure 2: TREF Multiplication frequency/values distribution

The results obtained via the **Multiplication Aggregation Method**, as depicted in Figure 2, exhibit a level of comparability to those obtained from a conventional FMEA. 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.

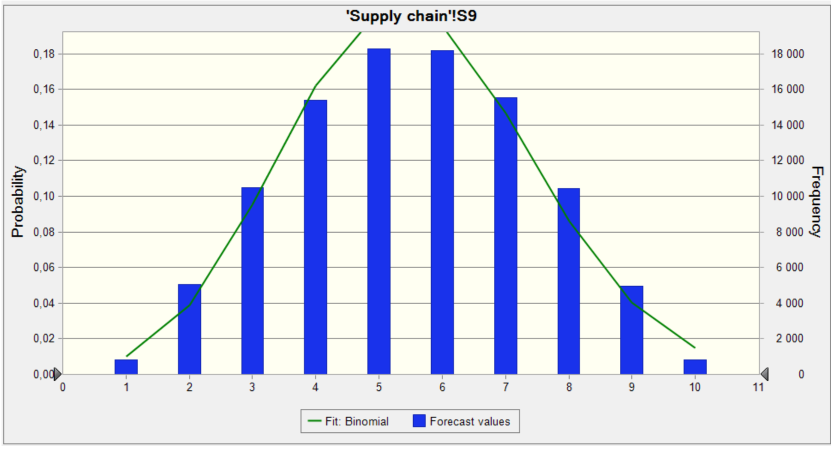


Figure 3: TREF Average frequency/values distribution

The input range and output range for the **Average aggregate** in Figure 3 are identical, spanning from 1 to 10. This method demonstrates strong linearity and is very easy to calculate. 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.

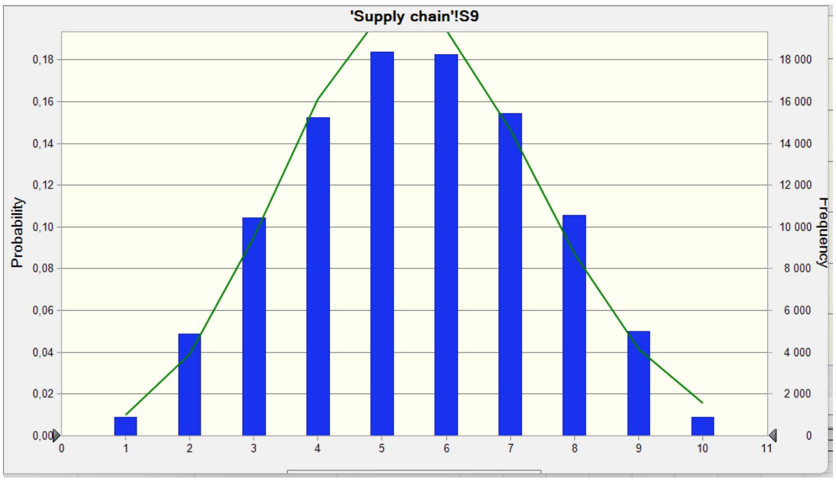


Figure 4: TREF Median frequency/values distribution

The **Median aggregation** yields the lowest Skewness score, as depicted in Figure 4, 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 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.

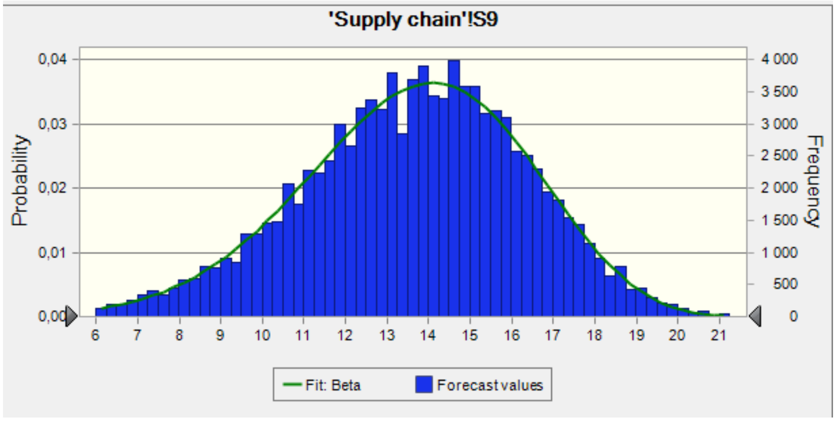
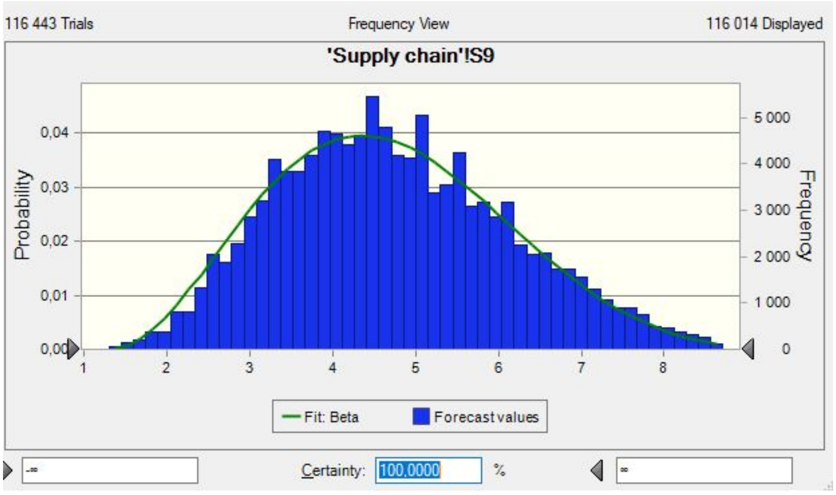


Figure 5: TREF Euclidean Distance frequency/values distribution

Linearity is only average and computation is challenging in the case of the **Euclidean distance (generalized) aggregate** (see Fig. 5). Interpretation is challenging in n-dimensional space where $n > 3, n \in \mathbb{N}$. 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.



-∞ Certainty: 100,0000 % ∞

Figure 6: 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.

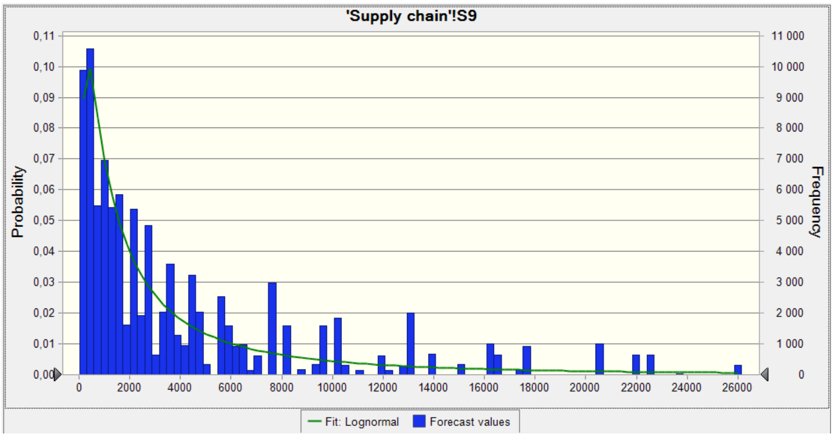


Figure 7: TREF Fuzzy frequency/values distribution

The outcome data for the **Fuzzy aggregation method** (refer to Figure 7), 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

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.

T.1. I have demonstrated that 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. This affirmation is validated via the first case study made at an EMS company

4.3 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. Corrective/preventive actions are scheduled if a risk factor is not lower 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 proposes 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.

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

- W1 at least $n^{(N-1)}$ of risk factors are not lower than the specified threshold;
- W2 at least $n^{(N)}$ aggregated risk values are not lower than the specified threshold;
- W3 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.

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

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. Scale values can be a result of a pairwise comparison (see e.g. Merrick et al., 2005).

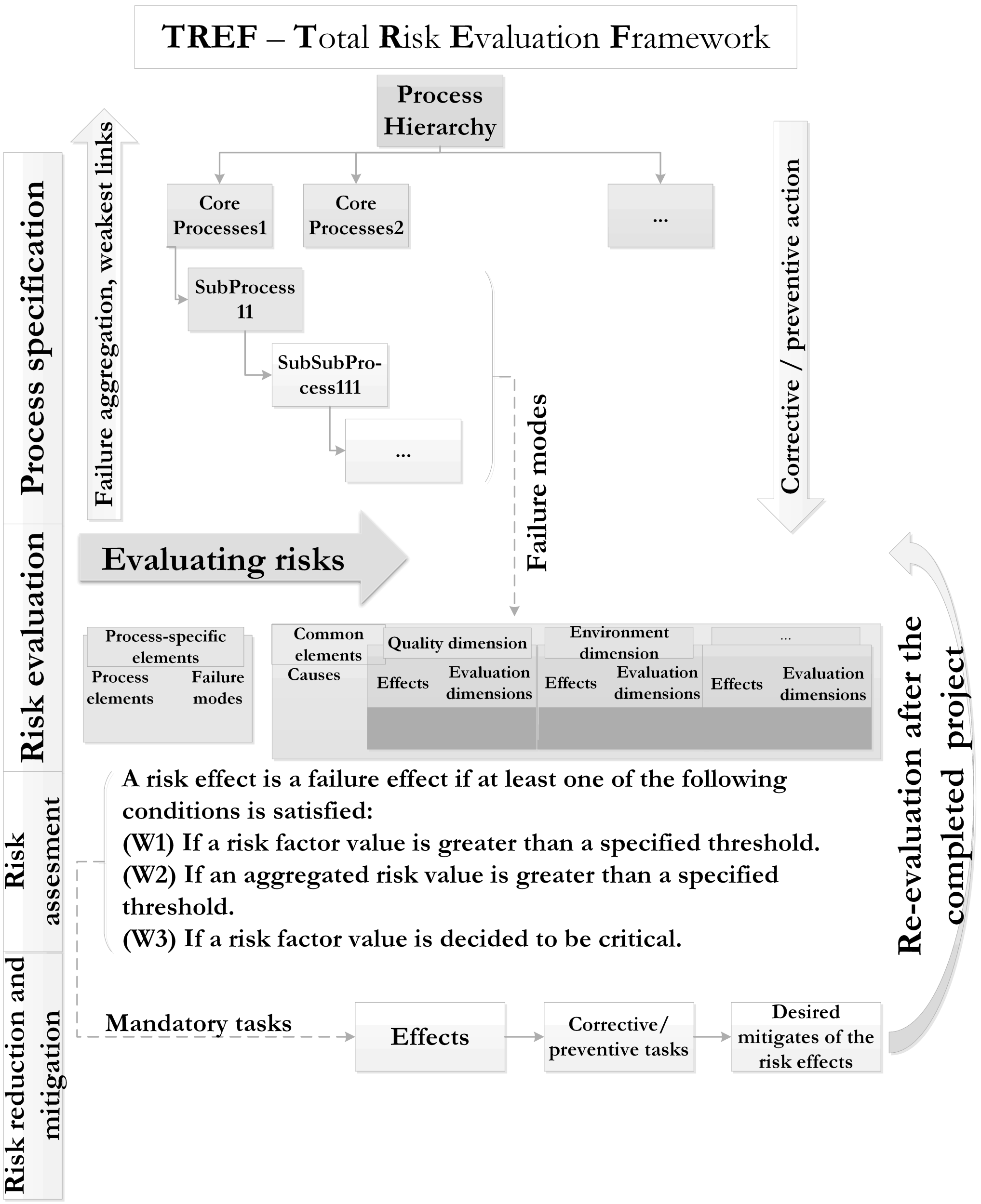
Applying the *risk aggregation protocol* iteratively, the risk values can be specified in a higher hierarchy level.

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. 8), thresholds should be specified for all levels.

Based on the proposed iterative bottom-up calculation method, 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. 8). However, different failure modes and risk effects may have the same causes (common causes) (see Fig. 9). The only restriction is to avoid cycles in the process hierarchy.



A risk effect is a failure effect if at least one of the following conditions is satisfied:

(W1) If a risk factor value is greater than a specified threshold.

(W2) If an aggregated risk value is greater than a specified threshold.

(W3) If a risk factor value is decided to be critical.

Figure 8: The proposed Total Risk Evaluation Framework (TREF)

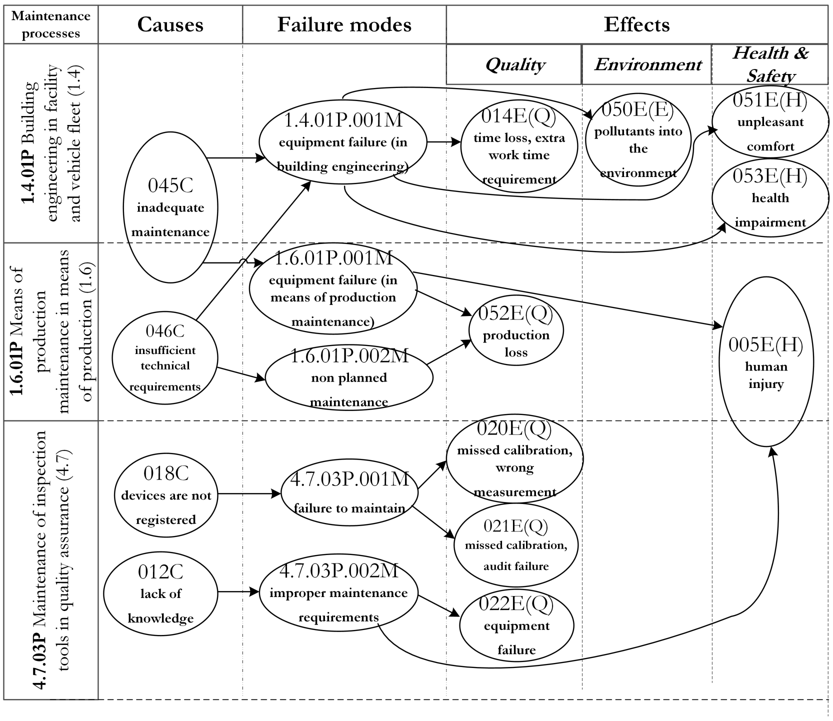
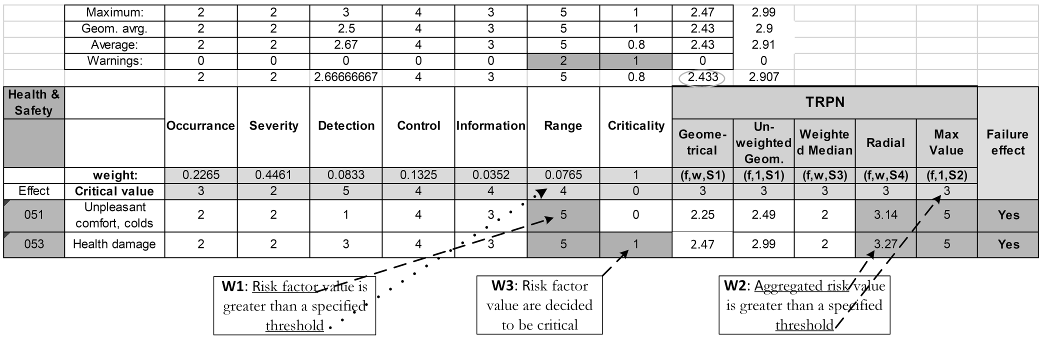


Figure 9: The TREF graph for evaluating the risk maintenance process: the chain of causes, failure modes and effects

Fig. 10 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 **??** in Section 4.3). Fig. 10 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 4.3), 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**

W1: Risk factor value is greater than a specified threshold

W3: Risk factor value are decided to be critical

W2: Aggregated risk value is greater than a specified threshold

Figure 10: The evaluation of TRPN for failure mode (1.4.01P.001M) effects (051E(H) and 053E(H))

T.2. 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.

In summary, the proposed total risk evaluation framework allows for a more accurate estimation of risk. Additionally, this framework can incorporate a warning system that can identify risk levels in various domains or managing systems such as quality, environmental, health and safety, energy saving, and cyber security. This is particularly useful in situations where these domains are not integrated into a unified risk assessment system within a company or corporation.

To make this process properly, is necessary 2 things:

- a risk assesment or FMEA team, including as member an FMEA moderator
- a regular review of risk assessment process based on PDCA methodology

Fortunately, both items exist (are mandatory!) in an automotive company. In other organizations, those should be established.

In addressing the third research question of my dissertation, I aimed to extend the proposed method developed within the first and second research question to be effectively applicable in supply chain.

4.4 Designing Steps for Practical Implementation

Figure 11 illustrates the steps of evaluation, which are utilized in both the subsequent analysis of the theoretical framework and the case study.

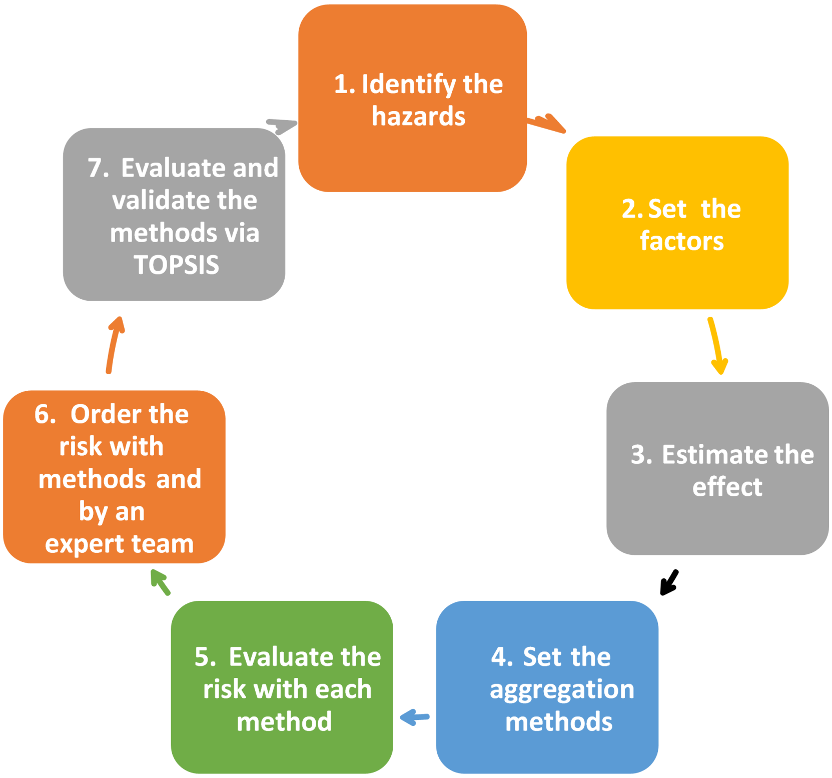


Figure 11: Determination of the appropriate risk evaluation method.

Step 0—Forming the Team: An assemblage of experts with specialized knowledge in logistics, quality management, risk assessment, evaluation, and mitigation, including all relevant departments such as finance/controlling or others, should be formed.

Step 1—Hazards identification: This step is a comprehensive gathering of all supply chain concerns, encompassing claims/history, news, losses, and delays, market feedback, trends in cybers security, etc.

Step 2—Factors and scales setting: The list from Step 1 should be used to identify the most accurate factors that describe the risk and their effects of organization, department, or process. This phase is exceptionally challenging. The factors included in the FMEA, 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 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.

Step 3—Risk assessment: In this section, is determined the levels of the factors for each risk. 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.

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 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 TOPSIS algorithm for ordering and the ordering process conducted by the expert team members.

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 no access to the output values of TOPSIS ranking and the results of the aggregation functions.

This committee will make a ranking effect matrix and the impact matrix 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. If not, the cause of discrepancies can be examined. Minor variations in the range of the same Reference Point Number (RPN) values are considered acceptable.

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. The occurrence of human error can be mitigated by conducting this study again with the group. Using this method, the most appropriate aggregating function for risk analysis within the organization can be selected.

4.5 Setting the warning levels

This is a more difficult assignment because, while several firms utilize the so-called integrated management system with a risk-based approach, they really operate their quality, environmental, energy-saving, and information security management systems separately. In certain cases, integration means that the certification is issued by the same certification authority, typically for budgetary reasons.

In this situation, decision makers receive many reports from various management system's internal 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.

The evaluation methodology is almost same as was presented previously.

While the calculation of risk values and 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, risk factors are evaluated. A warning event has occurred if a risk factor is not lower than the threshold **??** or a criticality value is set to be 1 **??**. 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/preventive actions*** should be prescribed **??** to mitigate the aggregated risk values. General corrective/preventive actions should contain a 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.

T.3. 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.

The estimated outcome was compared to the result obtained by the expert team, and it was determined that they are identical.

T.3.a. [Flexibility] New factors and alternative aggregation functions can be chosen, which effectively emphasize the risk for the associated supply chain.

T.3.b. [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.

T.3.c. [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.

These results offer a new perspective on the implementation of supply chain risk analysis, proposing a simple method to evaluate risks, including the warning system implementation possibility in case, when the risk should be compared for different domains.

In the conclusion of my thesis, I introduced a straightforward approach for evaluating the efficacy of the new risk assessment using Alluvial graphs.

The last one presents an ordering change after implementing the last 2 factors (in total 5 factors) of risk evaluation (see Figure 12):

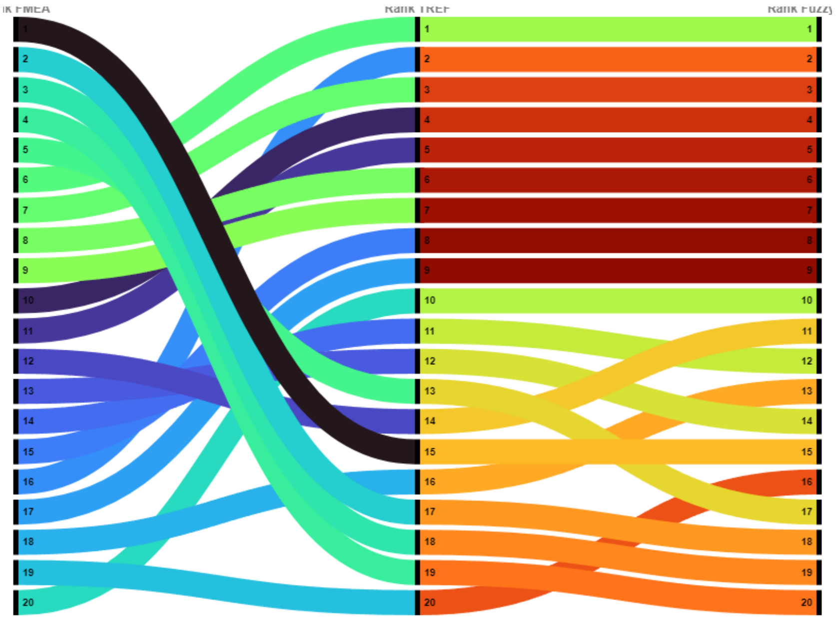


Figure 12: FMEA - TREF Multiplicative - TREF Fuzzy

The primary distinction between Tref Multiplicative and TREF Fuzzy, as shown in Figure 12, is in the levels of factors. The TREF Multiplicative model has 10 levels for each factor, however, the Fuzzy model allows each factor to have 5 membership functions, resulting in a reduction of levels. At deffuzification, the center of gravity approach was employed.

5 Summary

In this dissertation, a study of the factors, scales, and aggregation functions utilized in the risk analysis of supply chains was conducted. The behavior of the aggregating functions was analyzed in order to evaluate them. All aggregating functions were assessed, including the Fuzzy FMEA, which is one of the most widely used ones after the standard FMEA. The proposed approaches were tested through two case studies conducted in diverse environments: supply chain and maintenance. The latter was utilized in several domains to emphasize the significance of a warning system. Also via the case study were the implementation method and validation of models, using the expert teams and PDCA methodology.

5.1 Contribution to the 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 risk evaluation framework that provides a guideline for selecting additional components. It also includes examples that demonstrate the necessary aggregation function when more than three risk factors are utilized.

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 a comprehensive one that may effectively address the deficiencies mentioned earlier. In the case studies, the methodology presented is tested in practice and yields positive results.

5.2 Practical applicability

The practical use and utilization of this proposed technique were a primary emphasis of this thesis and were implemented in practice at 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, and also one the most complex system from risk evaluation point of view.

The implementation was successful in both cases.

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 (financial, image, delays). The methodology that was demonstrated, as well as explained in the Case Study, is readily 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 comprehensive exposition of the method's implementation steps in the case study renders them universal and applicable to sectors and industries beyond supply chain management.

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

6 Publications

My MTMT (Library and Information Centre of the Hungarian Academy of Sciences) profile: Mihálcz István

Publications in Hungarian and international refereed journals:

- Zsolt Tibor Kosztyán, Tibor Csizmadia, Zoltán Kovács, Mihálcz István: Total risk evaluation framework, International Journal of Quality and Reliability Management, Emerald, Vol. 37, No.4, 2020, pp.575-608, ISSN: 0265-671X, doi:10.1108/IJQRM-05-2019-0167
- Zoltán Kovács, Tibor Csizmadia, István Mihálcz, Zsolt Tibor Kosztyán: Multipurpose Aggregation in Risk Assesment, Special Issue Mathematical Methods and Operation Research in Logistics, Project Planning, and Scheduling, Mathematics 2021, 10, 3166, MDPI, pp.1-20, ISSN: 2227-7390, doi: 10.3390/math10173166
- Kovács Zoltán, Csizmadia Tibor, Mihálcz István, Kosztyán Zsolt Tibor: A vállalati kockázatkezelésben használt aggregálófüggvények jellemzése (The characterization of aggregation functions in enterprise risk management˙), STATISZTIKAI SZEMLE 100 (9), 821-853 ISSN: 0039-0690, doi: 10.20311/stat2022.9.hu0821
- István Mihálcz, Zsolt Tibor Kosztyán: REF - A Risk Evaluation Framework on Supply Chain, Special Issue Mathematical Methods and Operation Research in Logistics, Project Planning, and Scheduling, 2nd Edition, Mathematics 2024, 12, 841, MDPI, pp.1-23, ISSN: 2227-7390, doi: 10.3390/math12060841

Conferences:

- Istvan Mihalcz, Dr. Zsolt Tibor Kosztyán: Total Risk Evaluation networks, as a flexible risk analysis tool, 19th ANNUAL ENBIS CONFERENCE, Budapest, Hungary, 02-04.09.2019. pp. 100, ISBN/ISSN: 978-963-489-146-8

- Istvan Mihalcz, Dr. Zsolt Tibor Kosztyán: Risk assessment of corporate processes, Industry Days Conference ”Challenges and Lessons in Management. Focus on Process Management - Industry 4.0 Challenges Conference, Debrecen, Hungary, 07-08.11.2019. pp. 62,
- Istvan Mihalcz: Risk Analysis in Supply Chain Using Fuzzy Functions, New Trends and Challenges in Management - Special Focus on Industry 4.0, Conference, Debrecen, Hungary, 31.03-01.04.2022.

References

(AIAG), A.I.A.G., 2019. Failure Mode and Effects Analysis - FMEA Handbook. volume 1. 1. ausgabe, korrigierter nachdruck ed., AIAG-VDA. URL: https://www.aiag.org/store/publications/details?ProductCode=FMEAAV-1.

Aleksic, B., Djekic, I., Miocinovic, J., Memisi, N., Smigic, N., 2020. Application of FMEA analysis in the short cheese supply chain. Meat Technology 61, 161–173. doi:10.18485/meattech.2020.61.2.6.

Bani-Mustafa, T., Zeng, Z., Zio, E., Vasseur, D., 2020. A new framework for multi-hazards risk aggregation. Safety science 121, 283–302.

Bjørnsen, K., Aven, T., 2019. Risk aggregation: What does it really mean? Reliability Engineering & System Safety 191, 106524.

Bowles, J.B., Peláez, C., 1995. Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. Reliability Engineering & System Safety 50, 203 – 213. URL: http://www.sciencedirect.com/science/article/pii/095183209500068D, doi:http://dx.doi.org/10.1016/0951-8320(95)00068-D.

Canbakis, S.K., Karabas, M., Kilic, H.S., Koseoglu, S., Unal, E., 2018. A risk assessment model for supply chains. Pressacademia 7, 122–125. doi:10.17261/Pressacademia.2018.866.

Cardiel-Ortega, J.J., Baeza-Serrato, R., . Failure mode and effect analysis with a fuzzy logic approach 11, 348. doi:10.3390/systems11070348.

Chen, Y., Song, G., Yang, F., Zhang, S., Zhang, Y., Liu, Z., 2012. Risk assessment and hierarchical risk management of enterprises in chemical industrial parks based on catastrophe theory. International Journal of Environmental Research and Public Health 9, 4386–4402. doi:10.3390/ijerph9124386.

Ebadi, A., Keyghobadi, A.R., Motadel, M.R., Yeganegi, M.R., 2020. The analysis of sustainable supply chain risks based on the fmea method in the oil and gas industry and factors affecting risk management. Petroleum Business Review 4. doi:10.22050/pbr.2020.115177.

Emrouznejad, A., Abbasi, S., Sıcakyüz, , . Supply chain risk management: A content analysis-based review of existing and emerging topics 3, 100031. doi:10.1016/j.sca.2023.100031.

Ewa Kulinska, D.M., Dendera-Gruszka, M., 2021. New pplication of FMEA nalysis in the eavy ndustry Supply Chain. techreport vol. XXIV, issue 2B, 600-616. European Research Studies Journal. URL: https://www.ersj.eu/journal/2312/download.

Fang, H., Fang, F., Hu, Q., Wan, Y., . Supply chain management: A review and bibliometric analysis 10, 1681. doi:10.3390/pr10091681.

Fattahi, R., Khalilzadeh, M., 2018. Risk evaluation using a novel hybrid method based on fmea, extended multimoora, and ahp methods under fuzzy environment. Safety Science 102, 290–300. doi:https://doi.org/10.1016/j.ssci.2017.10.018.

Geske, S.K..W...M., . Supply Chain Resilience: Insights from Theory and Practice. Springer International Publishing. doi:10.1007/978-3-030-95401-7.

Grabisch, M., Marichal, J.L., Mesiar, R., Pap, E., 2009. Aggregation functions. volume 127 of *Encyclopedia of mathematics and its applications*. Cambridge University Press. URL: http://www.cambridge.org/9780521519267. includes bibliographical references (p. 428-453) and index.

Henke, O.K..H..Z.., . Supply Chain Resilience: Reconceptualizing Risk Management in a Post-Pandemic World. Springer International Publishing. doi:10.1007/978-3-031-16489-7.

Huang, J., You, J.X., Liu, H.C., Song, M.S., 2020. Failure mode and effect analysis improvement: A systematic literature review and future research agenda. Reliability Engineering & System Safety 199, 106885. doi:10.1016/j.ress.2020.106885.

Ilangkumaran, M., Karthikeyan, M., Ramachandran, T., Boopathiraja, M., Kirubakaran, B., 2015. Risk analysis and warning rate of hot environment for foundry industry using hybrid MCDM technique. Safety Science 72, 133–143. doi:10.1016/j.ssci.2014.08.011.

Indrasari, L.D., Vitasmoro, P., Pariyanto, A.Y.T., 2021. FMEA approach to risk factors as a factor in implementing green supply chain management (study in PT. gresik cipta sejahtera). Journal of Physics: Conference Series 1858, 012069. doi:10.1088/1742-6596/1858/1/012069.

Johanyák, Z., Kovács, S., 2004. On the right selection of the fuzzy membership function. GAMF Journal XIX, 73–84. URL: http://johanyak.hu/files/u1/publi/J_K_A_Fuzzy_Tagsagi_Fuggveny_GAMFK_2004.pdf.

Kalantarnia, M., Khan, F., Hawboldt, K., 2009. Dynamic risk assessment using failure assessment and bayesian theory. Journal of Loss Prevention in the Process Industries 22, 600–606. doi:10.1016/j.jlp.2009.04.006.

Kanes, R., Marengo, M.C.R., Abdel-Moati, H., Cranefield, J., Véchot, L., 2017. Developing a framework for dynamic risk assessment using bayesian networks and reliability data. Journal of Loss Prevention in the Process Industries 50, 142–153. doi:10.1016/j.jlp.2017.09.011.

Khan, F., Rathnayaka, S., Ahmed, S., 2015. Methods and models in process safety and risk management: Past, present and future. Process Safety and Environmental Protection 98, 116–147. doi:10.1016/j.psep.2015.07.005.

Kosztyán, Z.T., Csizmadia, T., Kovács, Z., Mihálcz, I., 2020. Total risk evaluation framework. International Journal of Quality & Reliability Management , 575–608doi:https://doi.org/10.1108/IJQRM-05-2019-0167.

Kozarević, S., Puška, A., . Use of fuzzy logic for measuring practices and performances of supply chain 5, 150–160. doi:10.1016/j.orp.2018.07.001.

Kubler, S., Robert, J., Derigent, W., Voisin, A., Traon, Y.L., . A state-of the-art survey &amp testbed of fuzzy AHP (FAHP) applications 65, 398–422. doi:10.1016/j.eswa.2016.08.064.

Ling, W.K., 2004. Nonlinear Digital Filters. Elsevier Ltd, Amsterdam Boston London.

Liu, H.C., Liu, L., Liu, N., 2013a. Risk evaluation approaches in failure mode and effects analysis: A literature review. Expert Systems with Applications 40, 828 – 838. URL: http://www.sciencedirect.com/science/article/pii/S0957417412009712, doi:http://dx.doi.org/10.1016/j.eswa.2012.08.010.

Liu, H.C., Liu, L., Liu, N., 2013b. Risk evaluation approaches in failure mode and effects analysis: A literature review. Expert systems with applications 40, 828–838.

Liu, H.C., You, J.X., Ding, X.F., Su, Q., 2015. Improving risk evaluation in fmea with a hybrid multiple criteria decision making method. International Journal of Quality & Reliability Management 32, 763–782.

Lolli, F., Ishizaka, A., Gamberini, R., Rimini, B., Messori, M., 2015. FlowSort-GDSS – a novel group multi-criteria decision support system for sorting problems with application to FMEA. Expert Systems with Applications 42, 6342 – 6349. URL: http://www.sciencedirect.com/science/article/pii/S0957417415002584, doi:http://dx.doi.org/10.1016/j.eswa.2015.04.028.

Lu Lu, R.Z., de Souza, R., 2018. Enhanced fmea for supply chain risk identification, in: Hamburg University of Technology (TUHH), I.o.B.L., Management, G. (Eds.), The Road to a Digitalized Supply Chain Management: Smart and Digital Solutions for Supply Chain Management,, epubli. pp. 311–330. URL: https://econpapers.repec.org/bookchap/zbwhiclch/209355.htm, doi:10.15480/882.1783.

Malekitabar, H., Ardeshir, A., Sebt, M.H., Stouffs, R., Teo, E.A.L., 2018. On the calculus of risk in construction projects: Contradictory theories and a rationalized approach. Safety Science 101, 72–85. doi:10.1016/j.ssci.2017.08.014.

Manuele, F.A., 2005. Risk assesment & hierarchies of control. Safety Management , 33–39URL: https://aeasseincludes.assp.org/professionalsafety/pastissues/050/05/030505as.pdf.

Merrick, J.R.W., van Dorp, J.R., Singh, A., 2005. Analysis of correlated expert judgments from extended pairwise comparisons. Decision Analysis 2, 17–29. doi:10.1287/deca.1050.0031.

Mustaniroh, S.A., Murod, F.A.I.K., Silalahi, R.L.R., 2020. The risk assessment analysis of corn chips supply chain using fuzzy FMEA. IOP Conference Series: Earth and Environmental Science 475, 012052. doi:10.1088/1755-1315/475/1/012052.

Øien, K., Utne, I., Herrera, I., 2011. Building safety indicators: Part 1 – theoretical foundation. Safety Science 49, 148–161. doi:10.1016/j.ssci.2010.05.012.

O'Keeffe, V.J., Tuckey, M.R., Naweed, A., 2015. Whose safety? flexible risk assessment boundaries balance nurse safety with patient care. Safety Science 76, 111–120. doi:http://dx.doi.org/10.1016/j.ssci.2015.02.024.

Panchal, D., Chatterjee, P., Yazdani, M., Chakraborty, S., 2019. A hybrid mcdm approach-based framework for operational sustainability of process industry, in: Advanced Multi-Criteria Decision Making for Addressing Complex Sustainability Issues. IGI Global, pp. 1–13.

Pedraza, T., Rodríguez-López, J., 2020. Aggregation of l-probabilistic quasi-uniformities. Mathematics 8, 1980.

Pedraza, T., Rodríguez-López, J., 2021. New results on the aggregation of norms. Mathematics 9, 2291.

Petrović, D.V., Tanasijević, M., Milić, V., Lilić, N., Stojadinović, S., Svrkota, I., 2014. Risk assessment model of mining equipment failure based on fuzzy logic. Expert Systems with Applications 41, 8157 – 8164. URL: http://www.sciencedirect.com/science/article/pii/S0957417414003832, doi:http://dx.doi.org/10.1016/j.eswa.2014.06.042.

Shaker, F., Shahin, A., Jahanyan, S., 2019. Developing a two-phase qfd for improving fmea: an integrative approach. International Journal of Quality & Reliability Management .

Sime Curkovic, Thomas Scannell, B.W., 2013. Using fmea for supply chain risk management. Modern Management Science Engineering 1, 251–256. URL: https://www.researchgate.net/publication/263733916_Using_FMEA_for_Supply_Chain_Risk_Management.

Spreafico, C., Russo, D., Rizzi, C., 2017. A state-of-the-art review of fmea/fmeca including patents. computer science review 25, 19–28.

Tay, K.M., Lim, C.P., 2006. Fuzzy fmea with a guided rules reduction system for prioritization of failures. International Journal of Quality & Reliability Management 23, 1047–1066. doi:10.1108/02656710610688202.

Trenggonowati, D.L., Bahauddin, A., Ridwan, A., Wulandari, Y., 2021. Proposed action of supply chain risk mitigation air compressor type l unloading

$\frac{1}{4}$ HP using the fuzzy – FMEA and fuzzy – AHP method in PT. XYZ. Journal of Innovation and Technology 2, 10–17. doi:10.31629/jit.v2i1.3204.

Trenggonowati, D.L., Ulfah, M., Arina, F., Lutfiah, C., 2020. Analysis and strategy of supply chain risk mitigation using fuzzy failure mode and effect analysis (fuzzy fmea) and fuzzy analytical hierarchy process (fuzzy ahp). IOP Conference Series: Materials Science and Engineering 909, 012085. doi:10.1088/1757-899x/909/1/012085.

Vodenicharova, M., 2017. Opportunities for the applications of FMEA model in logistics processes in bulgarian enterprises. Logistics & Sustainable Transport 8, 31–41. doi:10.1515/jlst-2017-0003.

Wagner, S.C.T.S.B., 2016. ManagingSupply Chain Risk, Integrating with Risk Management. CRC Press, Taylor Francis Group, LLC. URL: https://www.ebook.de/de/product/24417566/sime_curkovic_thomas_scannell_bret_wagner_managing_supply_chain_risk.html.

Wan, C., Yan, X., Zhang, D., Qu, Z., Yang, Z., 2019. An advanced fuzzy bayesian-based FMEA approach for assessing maritime supply chain risks. Transportation Research Part E: Logistics and Transportation Review 125, 222–240. doi:10.1016/j.tre.2019.03.011.

Wu, X., Wu, J., 2021. The risk priority number evaluation of FMEA analysis based on random uncertainty and fuzzy uncertainty. Complexity 2021, 1–15. doi:10.1155/2021/8817667.

Xu, K., Tang, L., Xie, M., Ho, S., Zhu, M., 2002. Fuzzy assessment of fmea for engine systems. Reliability Engineering & System Safety 75, 17 – 29. URL: http://www.sciencedirect.com/science/article/pii/S0951832001001016, doi:10.1016/S0951-8320(01)00101-6.

Yacob Khojasteh, Henry Xu, S.Z., . Supply Chain Risk Mitigation: Strategies, Methods and Applications. Springer International Publishing. doi:10.1007/978-3-031-09183-4.

Zahedi Khameneh, A., Kilicman, A., . Some construction methods of aggregation operators in decision-making problems: An overview 12, 694. URL: https://www.mdpi.com/2073-8994/12/5/694#:~:text=Therearethreemainconstruction,handledbyeachofthem., doi:10.3390/sym12050694.

Zammori, F., Gabbrielli, R., 2012. Anp/rpn: a multi criteria evaluation of the risk priority number. Quality and Reliability Engineering International 28, 85–104. URL: http://onlinelibrary.wiley.com/doi/10.1002/qre.1217/abstract, doi:10.1002/qre.1217.

Zhao, L., Huo, B., Sun, L., Zhao, X., . The impact of supply chain risk on supply chain integration and company performance: a global investigation 18, 115–131. doi:10.1108/13598541311318773.

Zheng, G., Zhu, N., Tian, Z., Chen, Y., Sun, B., 2012. Application of a trapezoidal fuzzy AHP method for work safety evaluation and early warning rating of hot and humid environments. Safety Science 50, 228–239. doi:10.1016/j.ssci.2011.08.042.

Zhu, Q., Golrizgashti, S., Sarkis, J., 2020. Product deletion and supply chain repercussions: risk management using FMEA. Benchmarking: An International Journal 28, 409–437. doi:10.1108/bij-01-2020-0007.