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Original research

The integration of Fuzzy FMEA and AHP methods for optimizing of logistic systems

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ABSTRACT

This study seeks to enhance the logistics system of a logistics company through the integration of Fuzzy FMEA and AHP methodologies. The focus is on optimizing efficiency and quality within the logistics system to meet competitive market demands. The issue at hand is the potential for breakdowns in manufacturing and distribution processes, which may impede overall performance. The aim is to detect possible failures, assess failure risks using the Fuzzy FMEA method, and improve decision-making through the AHP method. The research methodology includes a literature review, data analysis, and the use of Expert Choice software for weight calculations and rankings. Data were collected from the decision-makers involved in the company. The findings show that the integration of Fuzzy FMEA and AHP methodologies can effectively identify potential failures, assess risks with greater accuracy, and prioritize improvement measures within the logistics framework of a traditional bag factory. In summary, the integration of Fuzzy FMEA and AHP methodologies can enhance risk management and decision-making within the logistics system, mitigate failure risks, optimize production and distribution processes, and more effectively meet client requirements. This integration presents an innovative approach to improving logistics systems.

1. Introduction

Logistics systems are essential for maintaining the efficient movement of goods and services, particularly in challenging circumstances like the COVID-19 pandemic. The pandemic exposed weaknesses in the logistics industry, emphasizing the need for the development of robust strategies to improve logistics systems [1]. The combination of Fuzzy Failure Mode and Effects Analysis (FMEA) with the Analytic Hierarchy Process (AHP) offers a promising method for enhancing the dependability and effectiveness of logistics systems [2].

The Fuzzy FMEA-AHP technique provides a systematic approach to examining failure modes in logistics systems, particularly in the context of unexpected events such as the COVID-19 pandemic. The integration of fuzzy logic with AHP allows for a thorough assessment of failure causes and aids in decision-making to improve the resilience of logistics systems [2]. Furthermore, the incorporation of fuzzy logic into the Analytic Hierarchy Process (AHP) has been recognized as a valuable approach in decision-making processes. Fuzzy Analytic Hierarchy Process (AHP) techniques have gained significant popularity for dealing with imprecise data and subjective assessments. These methods offer a more refined and accurate evaluation of complex systems, leading to improved precision [3]. The integration mentioned enables a more thorough examination of failure modes and the ranking of solutions within logistics systems, thereby enhancing decision-making processes [3].

In addition, the application of fuzzy logic approaches, such as Fuzzy TOPSIS and fuzzy VIKOR methodologies, has played a crucial role in assessing and choosing logistics providers to improve sustainability in supply chains [4]. These methods provide a systematic approach to decision-making, considering many variables and uncertainties that are inherent in the selection process. As a result, they

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encourage the adoption of sustainable practices within the logistics business.

To summarize, the combination of Fuzzy FMEA and AHP techniques offers a valuable chance to better logistics systems by offering a structured framework for analyzing failure modes, prioritizing solutions, and improving decision-making processes [5], [6], [7]. By utilizing fuzzy logic to handle uncertainties and AHP to rank criteria, this integrated approach has the potential to greatly enhance the dependability, effectiveness, and sustainability of logistics systems, particularly when confronted with unexpected obstacles like as the COVID-19 pandemic.

This research is conducted in a conventional bag industry that mass-produces bags using established methods. However, the products often suffer from defects, potentially leading to financial losses and decreased customer satisfaction. Product defects can arise from several factors, such as damage to goods, delays in delivery, and errors in packaging. Optimizing the logistics system is a critical need for this company.

The main problem faced is product defects, which can have serious consequences such as financial losses, decreased customer satisfaction, and compromised company reputation. Therefore, it is necessary to optimize the logistics system by using the Fuzzy FMEA and AHP methods to overcome the problem of product defects effectively and efficiently. The Fuzzy FMEA method is an approach used to identify, evaluate, and reduce potential failures in a system or process.

The limited implementation of Fuzzy FMEA-AHP in real-world logistics scenarios is one of the primary gaps in the existing literature. Reference [2] suggest a Fuzzy FMEA-AHP methodology that is specifically designed to analyze the causes of failure in logistics systems during the COVID-19 pandemic. Their method integrates fuzzy logic into the FMEA framework to generate a fuzzy risk priority-weighted number (F-RPWN), and AHP is employed to designate weights to a variety of risk indicators. This innovative incorporation enables a more nuanced comprehension of risks; however, the study underscores the necessity of additional empirical validation in a variety of logistics contexts.

Moreover, despite the fact that numerous studies have investigated the individual applications of FMEA and AHP, there is a dearth of comprehensive frameworks that effectively integrate these methodologies. Reference [8] addresses the creation of an imprecise FMEA model that is facilitated by AHP and is intended to assess the likelihood of logistics system failures. Although this research does not delve thoroughly into the practical implications of this integration in optimizing logistics operations, it suggests the potential for integrating these methodologies. This implies the necessity of conducting more comprehensive case studies that illustrate the applicability of the Fuzzy FMEA-AHP framework in a variety of logistical contexts.

A significant gap exists in the investigation of hybrid models that integrate supplementary decision-making methodologies with Fuzzy FMEA and AHP. Reference [9] introduces a hybrid FMEA model that combines fuzzy AHP with TOPSIS for the evaluation of quality risks. This study demonstrates the versatility of hybrid techniques and underscores the possibility for additional research into their synergistic application within logistics systems. The amalgamation of various decision-making frameworks may yield a more effective instrument for risk assessment and prioritizing in logistics.

AHP offers a systematic approach to decision-making by deconstructing complex issues into more manageable elements. This hierarchical method enables the assessment of multiple criteria, permitting decision-makers to rank risks according to factors like severity, occurrence, and detectability [10]. The integration of AHP and Fuzzy FMEA creates a robust risk assessment framework that identifies potential failures and quantifies their impacts, aligning with decision-makers' preferences and the operational context [11].

The combination of these two methodologies has been evidenced in multiple applications, highlighting their efficacy in optimizing logistics systems. The integration of Fuzzy FMEA and AHP has been utilized in agricultural supply chain risk management, aiding in the identification and prioritization of risks related to logistics operations [11]. In the realm of green logistics, the integration of these methods has been employed to assess the sustainability of logistics enterprises, yielding insights into their operational efficiencies and environmental impacts [12].

Moreover, the current literature frequently neglects to address the distinct issues encountered by logistics systems across various sectors. Although several studies examine broad logistical difficulties, there is a necessity for focused study that takes into account sector-specific elements, particularly within the oil and gas supply chain, as articulated by Ahmad [13]. This sector-specific strategy could improve the relevance and efficacy of the Fuzzy FMEA-AHP integration by customizing the methodology to tackle distinct operational risks and decision-making parameters.

The integration of Fuzzy FMEA and AHP enhances risk assessment and optimizes logistics systems by prioritizing activities through a deeper comprehension of risks. This cohesive strategy is especially pertinent in dynamic settings, such as logistics, where uncertainties and interruptions frequently occur. Research indicates that utilizing this methodology can result in superior decision-making and increased operational resilience [2], [14].

2. Material and method

The fuzzy approach [15] is a significant theory used to handle the process of information decomposition. Fuzzy-FMEA [16], [17] employs appropriate fuzzing risk index parameters with membership functions, including severity (S), occurrence (O), and detection (D). This approach utilizes expertise and understanding to construct a knowledge-based system using fuzzy IF-

THEN rules [18]. Expert knowledge and decision-making can be utilized to construct more sophisticated and suitable knowledge-based models. The ambiguous findings are subsequently de-ambiguated to acquire the RPN value [19]. The procedure underlying the proposed Fuzzy FMEA-AHP technique is illustrated in Fig. 1.

Fig. 1 demonstrates that risk assessment is the key stage. The initial stage involves system identification. We need to identify the components comprising the logistics system that will be examined. Subsequently, a comprehensive system analysis is conducted, wherein the logistics system is thoroughly examined and subsequently broken down into three distinct groups. The third phase involves doing a risk evaluation. This evaluation includes calculating the weight and F-RPN (Failure Mode and Effects Analysis Risk Priority Number). The weight W and F-RPN are then merged using the Fuzzy FMEA-AHP approach suggested in this research. Ultimately, the F-RPWN (Final Risk Priority Weight Number) is obtained. Lastly, the fourth section of this study focuses on risk management, specifically utilizing the proposed Fuzzy FMEA-AHP method for case analysis [2], [20]. The ranking of each risk can be visibly perceived by calculation, and thereafter examined and processed accordingly [7].

2.1. Failure Mode Effect Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a systematic method used in various industries to identify, evaluate, and mitigate potential risks associated with failures in a product, process, or system [21]. By focusing on failure modes and their impact on desired goals, FMEA provides a robust framework for identifying preventive and corrective measures to improve overall reliability and quality. In this study, the assessment in FMEA will be the basic reference for further data processing. FMEA is used to evaluate the reliability of a system by classifying failures based on their effect on the success of the system's mission. In the results below, a traditional FMEA calculation will be used first, in order to determine the Risk Priority Number (RPN) [22]. RPN is used to prioritize failures based on the risk they pose. The higher the RPN value, the higher the risk and the main priority is needed on failures that have a high RPN, where to calculate RPN using Eq. (1).

$$RPN = S * O * D \tag{1}$$

2.2. Fuzzy FMEA

Fuzzification in Fuzzy FMEA pertains to the transformation of qualitative evaluations of risk factors—namely severity, incidence, and detection—into fuzzy values. This approach facilitates the portrayal of expert judgments that are frequently subjective and ambiguous. Instead of assigning a precise numerical value to the severity of a failure mode, experts can articulate their evaluations using linguistic variables (e.g., "high," "medium," "low"). The linguistic concepts are subsequently correlated with fuzzy sets, which offer a spectrum of potential values instead of a singular point estimate [2], [23]. The fuzzification process generally adheres to a systematic methodology. Initially, specialists are requested to assess the risk elements utilizing linguistic assessments. These assessments are subsequently converted into fuzzy integers, typically triangular or trapezoidal, which represent the degree of membership of each linguistic phrase. A "high" severity may be depicted by a fuzzy number encompassing a range of values, illustrating the ambiguity in the expert's assessment [3]. This change is essential as it facilitates a more nuanced comprehension of risks, tolerating variety in expert perspectives and mitigating the potential bias inherent in conventional numerical evaluations. Table A1 (see Appedices) shows the operating risks in logistics system.

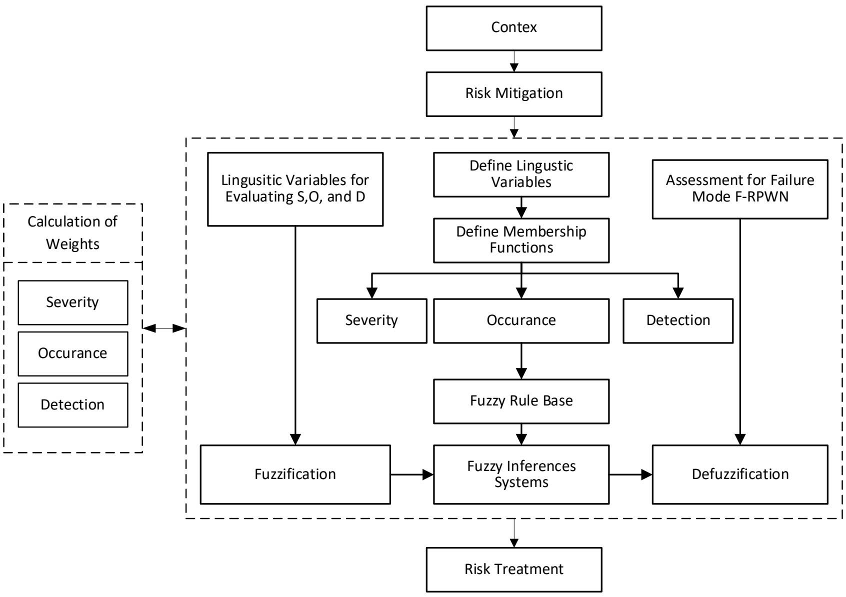

Figure 1. Method implementation technique

Table 1.
Linguistic tables and fuzzy numbers on severity, occurrence and detection

Fuzzy Value			Category
Severity	Occurrence	Detection	
1,2,3,4	1,2,3	1,2,3,4	Very Low
3,4,5	2,3,4,5	3,4,5	Low
4,5,6	4,5,6,7	4,5,6	Fair
5,6,7	6,7,8,9	5,6,7	High
6,7,10,10	8,9,10,10	6,7,10,10	Very High

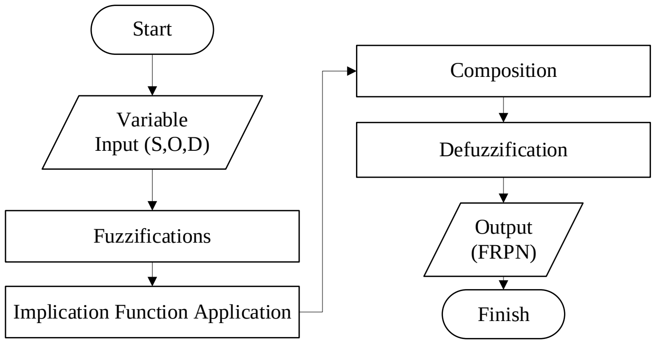

Figure 2. Fuzzy system flowchart

$$\mu[x]=\begin{cases} 0 & ;\ x \le a \\ \frac{(x-a)}{(b-a)} & ;\ a \le x \le b \\ 1 & ;\ x \ge b \end{cases} \quad (2)$$

$$\mu[x]=\begin{cases} 0 & ;\ x \ge a \\ \frac{(b-x)}{(b-a)} & ;\ a \le x \le b \\ 1 & ;\ x \le b \end{cases} \quad (3)$$

$$\mu[x]=\begin{cases} 0 ; & x \le a \text{ or } x \ge c \\ \frac{(x-a)}{(b-a)} ; & a \le x \le c \\ 1; & b \le x \le c \\ \frac{(d-x)}{(d-c)} ; & c < x \le d \end{cases} \quad (4)$$

$$\mu[x]=\begin{cases} 0 ; & x \le a \text{ or } x \ge c \\ \frac{(x-a)}{(b-a)} ; & a \le x \le b \\ \frac{(c-x)}{(c-b)} ; & b \le x \le c \end{cases} \quad (5)$$

Upon completion of fuzzification, the fuzzy risk priority number (F-RPN) can be computed. This entails consolidating the imprecise numbers attributed to severity, occurrence, and detection to construct a thorough risk assessment for each failure scenario. The incorporation of AHP improves this approach by facilitating the prioritization of risk factors according to their relative significance, as established by pairwise comparisons across experts. Traditional AHP approaches often encounter difficulties due to the ambiguity of expert opinions, making the fuzzy AHP (FAHP) approach advantageous. FAHP integrates fuzzy logic within the AHP framework, facilitating enhanced management of subjective evaluations and augmenting the consistency of the decision-making process [8], [9].

Fuzzy FMEA first starts from the Fuzzification process, which is the process of converting risk factors into Severity, Occurrence, and Detection into Fuzzy, where the assessment of the risks that have been identified is evaluated using three parameters in accordance with the Fuzzy FMEA concept approach, namely Fuzzy FMEA input which includes the value of the level of impact/severity (S), the level of occurrence/occurrence (O), and the level of detection/detection (D). The rating scale for S, O, and D uses input variables with a range of 1-10, and is grouped into 5 categories of linguistic levels each, and also includes Fuzzy values in each category as in Table 1 [24].

The linguistic table above shows the categories and Fuzzy values that will be used in the fuzzification process, where the three inputs are converted into a Fuzzy form using a membership function to produce the membership level of each input. To determine the membership value or degree of membership [25], as shown in Eqs. (2)-(5).

After the membership degree of each input is obtained, the next step is to perform Fuzzy computation and defuzzification to get a single value (crisp). In this research, a defuzzification method in the form of a centroid is used, which is a single value of the output variable calculated by finding the center of gravity of the variable in the form of a Fuzzy membership function.

The risk assessment in this method uses the Fuzzy Logic Toolbox available in MATLAB software, which is a collection of tools used in the design of Fuzzy systems [26]. This tool can also be used to create or edit FIS (Fuzzy Inference System) within the MATLAB environment. Fig. 2 shows the flowchart of the Fuzzy system used to determine the priority of risk handling using the Fuzzy Logic Toolbox in MATLAB.

The *fuzzification* process of FMEA involves converting input data into *Fuzzy* form to describe the uncertainty or ambiguity associated with the input values. In this process, values as an instance *severity, occurrence* and *detection* are translated into *Fuzzy* membership functions that reflect the degree of membership of each value on a predefined *Fuzzy* set. This allows the use of *Fuzzy* logic to acknowledge uncertainty in risk assessment and enables adaptive and flexible decision-making based on that level of uncertainty. Next is the Evaluation of *Fuzzy "If - Then"* rules to find out the inference results of the fuzzification process consisting of 125 different rules that serve for *Centroid* calculation in the defuzzification process , which will produce a crisp value, and calculate the *Fuzzy* RPN value [27].

Table 2.
Proposed risk mitigation in the logistics system

Factor	
1	Logistics Efficiency
2	Quality of Service
3	Production Process Effectiveness
Alternative	
1	Raw Material Supply Scheduling
2	Risk Management
3	Transportation
4	Warehouse Management
5	Inventory Management

Table 3.
FMEA assessment

Failure Factors	S	O	D
Internal	8	4	4
	6	4	8
	7	6	6
	6	5	6
	9	3	7
External	5	7	5
	7	3	8
	9	6	4
	6	5	7
Human	9	2	6
	6	7	4
	8	4	3

Table 4.
Fuzzy FMEA processing results

Failure Factors	No. Indicator	F-RPN	Ranking
Internal	1	500	2
	2	400	11
	3	500	2
	4	500	2
	5	500	2
External	6	400	11
	7	500	2
	8	777	1
	9	500	2
Human	10	500	2
	11	500	2
	12	500	2

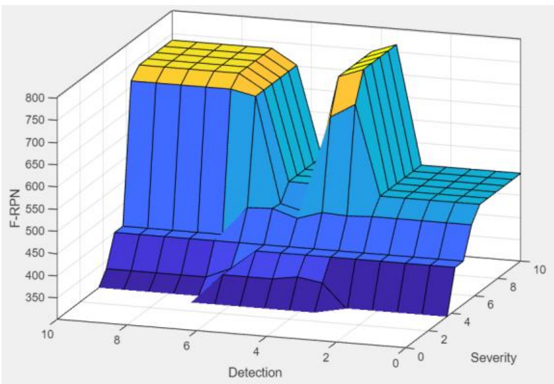

Figure 3. FRPN Surface Control

2.3. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) method has proven to be an effective tool in complex decision making [28]. In this research, the Expert Choice application will be used. The Expert Choice application is also used to determine the weight on each criterion in Severity, Occurrence, Detection contained in the FMEA method, which aims to integrate these two methods. Meanwhile, according to the interview results obtained, suggested alternatives for risk mitigation are shown in Table 2.

3. Results and discussions

3.1. Data collection and processing

The results of data collection on Severity, Occurrence, and Detection Assessment in FMEA are carried out through an interview process with employees, and with the indicators listed in Table 3 and the RPN in Table B2. The severity, occurrence, and detection inputs in the Fuzzy FMEA calculation results have an important role in describing the severity, occurrence, and detection of possible failures that occur in the system. By combining these three factors, we can gain a more complete understanding of the risks and priorities that need to be considered in decision making. The visualization of severity, occurenece, and detection are shown in Figs. B1, B2, and B3 (see Appendices). The membership degree of each indicator is shown in Table A3 (see Appendices).

Inferring fuzzy logic relationships from Mamdani inference involves the use of fuzzy rules consisting of IF-THEN statements. These rules depend on predefined variables and values, which are then used to define the required rules. Furthermore, defuzzification is the process of converting fuzzified inputs, in the form of fuzzy sets resulting from the composition of fuzzy IF-THEN rules, into crisp numbers. The technique used in this research is the Centroid or Center of Gravity (COG) method. The Center of Gravity (CoG) is the most common and aesthetically pleasing of all defuzzification procedures [29]. The fundamental idea of the CoG approach is to identify the point $x*$ at which a vertical line bisects the aggregate into two equal masses.

This method yields an exact value based on the center of gravity of the fuzzy set. The whole area of the membership function distribution representing the combined control action is partitioned into several sub-areas (e.g., triangular, trapezoidal, etc.). The area and centroid of each subregion are computed. The aggregate of all these sub-areas is utilized to ascertain the defuzzified value for a discrete fuzzy collection. Based on the above data, the FRPN results are obtained and ranked from the Based on the above data, the FRPN results are obtained and ranked from the highest to the lowest value on the FRPN is shown in Table 4 and the result of Surface Control to visualize data on F-RPN is shown in Fig. 3.

Table 5.
SOD value weighting results

Ws	Wo	Wd
0.413	0.260	0.327
0.062	0.653	0.285
0.351	0.316	0.333
0.333	0.313	0.354
0.350	0.223	0.427
0.332	0.371	0.297
0.309	0.243	0.448
0.375	0.250	0.375
0.316	0.313	0.372
0.359	0.190	0.452
0.378	0.348	0.274
0.449	0.257	0.294

The Expert Choice application is used to fill out questionnaires on AHP, and weighing on Severity, Occurrence and Detection on each risk indicator, according to their respective S O D values, which are used for integrating FMEA and AHP methods. Table 5 is the result of weighing the S O and D values using the Expert Choice application.

In this integration of Fuzzy FMEA and AHP, an FRWPN value is produced, which represents the weighted results of severity, occurrence, and detection, multiplied by the FRPN value obtained from the previous Fuzzy FMEA processing results. The FRWPN value is also used to clarify the priority ranking, allowing the most important indicators to be prioritized. The table of FRWPN values is presented in Table A4 (see Appendices).

3.2. Analysis and discussions

Fuzzy FMEA and the Analytic Hierarchy Process (AHP) are combined to optimize logistics systems, notably risk management and decision-making. This combination of techniques tackles logistics' inherent uncertainties and complexities, enabling more sophisticated risk assessment and action prioritization.

Fuzzy FMEA improves traditional FMEA by integrating fuzzy logic, thereby addressing uncertainty in risk assessments more effectively. This method facilitates the representation of expert opinions through linguistic variables, which may better reflect real-world scenarios than precise numerical values. Research indicates that fuzzy logic enhances the flexibility and accuracy of risk evaluations across diverse industrial settings, such as production and logistics [30], [31], [32]. Integrating fuzzy logic into the FMEA framework enables organizations to identify and prioritize potential failure modes more effectively, thus enhancing the overall reliability of their operations [33], [34].

The implementation of this integrated approach enhances decision-making processes in logistics by clarifying risk factors and their interdependencies. The application of fuzzy sets facilitates a more accurate depiction of uncertainties, whereas AHP supports the systematic assessment and prioritization of these risks according to an extensive array of criteria [35]. This synergy enhances the robustness of risk assessments and supports strategic planning and resource allocation in logistics operations.

The integration of Fuzzy FMEA and AHP signifies a notable advancement in optimizing logistics systems. Utilizing the strengths of both methodologies enables organizations to attain a more effective and nuanced comprehension of risks, resulting in enhanced decision-making and improved operational performance.

4. Conclusions

Risk identification in the logistics system is carried out by conducting interviews and direct observation during the research to find out each root cause of potential risks in the logistics system at CV. Metassa Collection which is grouped based on the type of failure in the process, namely Internal Failure, External Failure, and Human Failure.

Risk management strategies based on priorities obtained using the Analytical Hierarchy Process (AHP) method are risk factors related to logistics efficiency with a weight of 0.524 and produce 5 alternative strategies. The selected strategies with the highest priority are Raw Material Supply Scheduling with a weight of 0.293 and Risk Management with a weight of 0.265.

Based on the results of calculations on FRWPN, the priority obtained on risk indicators that must be addressed is the top priority on indicator number 8, namely failure in the production process, then indicator number 3, namely untimely processing, and indicator number 4, namely inaccurate inventory of raw materials.

One significant limitation of the combination of Fuzzy FMEA and AHP is the difficulties in precisely defining and characterizing fuzzy sets. The subjective nature of expert opinions might result in inconsistencies in fuzzy evaluations, thus undermining the dependability of the outcomes. Discrepancies in expert evaluations may stem from differing interpretations of risk levels, resulting in substantial variances in the computed Risk Priority Numbers (RPNs). The problem is exacerbated by the limitation of fuzzy logic, which, although effective in addressing vagueness, may fail to encompass the entirety of uncertainties inherent in intricate logistical systems.

Furthermore, the integration process may bring supplementary levels of complexity. The requirement to synchronize outputs from both FMEA and AHP can create a complex decision-making framework that may be challenging for practitioners to execute efficiently.

This complexity may dissuade stakeholders from fully engaging with the integrated approach, as they could favor simpler, more direct methodologies that produce faster outcomes. The dependence on pairwise comparisons in AHP may result in discrepancies, especially when the number of criteria escalates, hence complicating the decision-making process.

A notable deficiency is the possible over-dependence on quantitative metrics obtained from ambiguous assessments, which may obscure equally vital qualitative insights in risk management. The integration seeks to deliver a thorough evaluation of hazards, although it may unintentionally favor numerical results over the contextual comprehension of the logistics environment. This may result in decisions that are technically valid yet lack practical relevance in real-world contexts, ultimately compromising the efficacy of the risk management strategy.

The amalgamation of Fuzzy FMEA with AHP equips SMEs with an effective instrument for enhancing logistics systems. This hybrid strategy successfully mitigates uncertainty and promotes informed decision-making, hence enhancing risk management and improving operational efficiency and resource allocation. As SMEs negotiate intricate logistical settings, the use of integrated approaches will be crucial for sustaining competitiveness and attaining sustainable growth. Hounsounou et al. illustrate the effectiveness of AHP in evaluating the feasibility of port logistics, emphasizing that the prioritizing of criteria profoundly influences long-term operating strategies. Utilizing AHP alongside Fuzzy FMEA enables SMEs to attain a more thorough comprehension of the risks they encounter and to make informed decisions that correspond with their strategic goals.

Moreover, the use of this comprehensive methodology can transcend logistics optimization in SMEs to encompass other industries with analogous issues. The ideas of Fuzzy FMEA and AHP can be applied across diverse sectors, such as manufacturing and healthcare, where risk management and decision-making are essential for operational success. Ghadge et al. underscore the significance of comprehensive risk assessments in supply chain management, proposing that the established approaches can be applied in many scenarios to improve overall risk management strategies.

Furthermore, the integration of Fuzzy FMEA and AHP enhances the efficiency of resource allocation. By precisely identifying and prioritizing risks, SMEs may concentrate their efforts on minimizing the most significant difficulties, therefore enhancing their logistical operations. Purnama et al. demonstrate that the integration of Six Sigma with Fuzzy AHP and FMEA can substantially enhance quality by methodically tackling flaws and inefficiencies in manufacturing processes. This methodology might also be utilized in logistics to improve service delivery and operational efficiency.

In short, although the integration of Fuzzy FMEA and AHP offers a novel method for enhancing logistics systems, it is crucial to acknowledge its intrinsic limitations. The intricacies of fuzzy assessments, the difficulties in aligning outputs, the risk of excessive dependence on quantitative metrics, and the absence of empirical validation all contribute to the deficiencies of this integrated methodology. Future research should focus on streamlining the integration process, improving empirical validation, and ensuring that qualitative ideas are sufficiently included with quantitative evaluations.

Declaration statement

Andreas Tri Panudju: **Conceptualization, Methodology, Writing-Original Draft.** Isnaini Mahuda, Umi Marfuah, Mutmainah Mutmainah, Wiwik Sudarwati**: Methodology, Data Analyzing.** Andreas Tri Panudju, Isnaini Mahuda **: Collecting data.** Andreas Tri Panudju**: Writing-Review & Editing.**

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The author declares that this manuscript is free from conflict of interest and is processed by applicable journal provisions and policies to avoid deviations from publication ethics in various forms.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] P. Ghasemi, F. Goodarzian, A. Gunasekaran, and A. Abraham, "A bi-level mathematical model for logistic management considering the evolutionary game with environmental feedbacks," *Int. J. Logist. Manag.*, vol. 34, no. 4, pp. 1077–1100, 2023, doi: 10.1108/IJLM-04-2021-0199.

[2] G. Jin, Q. Meng, and W. Feng, "Optimization of Logistics System with Fuzzy FMEA-AHP Methodology," *Processes*, vol. 10, no. 10, 2022, doi: 10.3390/pr10101973.

[3] Y. Liu, C. M. Eckert, and C. Earl, "A review of fuzzy AHP methods for decision-making with subjective judgements," *Expert Syst. Appl.*, vol. 161, p. 113738, 2020, doi: 10.1016/j.eswa.2020.113738.

[4] M. H. Naseem, J. Yang, and Z. Xiang, "Prioritizing the solutions to reverse logistics barriers for the e-commerce industry in pakistan based on a fuzzy ahp-topsis approach," *Sustain.*, vol. 13, no. 22, p. 12743, 2021, doi: 10.3390/su132212743.

[5] R. Septifani, I. Santoso, and B. N. Rodhiyah, "Risk mitigation strategy of rice seed supply chains using fuzzy-FMEA and fuzzy-AHP (Case study: PT. XYZ),"

IOP Conf. Ser. Earth Environ. Sci., vol. 230, no. 1, 2019, doi: 10.1088/1755-1315/230/1/012059.

[6] A. J. Shie, W. F. Wu, M. Yang, X. Wan, and H. Li, "Design and process optimization of combined medical and elderly care services: An integrated service blueprint–TRIZ model," *Front. Public Heal.*, vol. 10, 2022, doi: 10.3389/fpubh.2022.965443.

[7] A. Karasan and M. Erdogan, "Creating proactive behavior for the risk assessment by considering expert evaluation: a case of textile manufacturing plant," *Complex Intell. Syst.*, vol. 7, no. 2, pp. 941–959, 2021, doi: 10.1007/s40747-020-00246-0.

[8] E. Laufer, "Similarity Measure Supported Fuzzy Failure Mode and Effect Analysis," *Acta Polytech. Hungarica*, vol. 21, no. 2, pp. 187–202, 2024, doi: 10.12700/APH.21.2.2024.2.10.

[9] S. Ilyasu *et al.*, "Application of hybrid failure mode effect analysis based on fuzzy AHP and fuzzy TOPSIS in quality risk assessment of fixed-dose artemether-lumefantrine tablets," *medRxiv*, p. 2024.01.26.24301832, 2024, doi: 10.1101/2024.01.26.24301832.

[10] P. Zandi, M. Rahmani, M. Khanian, and A. Mosavi, "Agricultural risk management using fuzzy topsis analytical hierarchy process (Ahp) and failure mode and effects analysis (fmea)," *Agric.*, vol. 10, no. 11, pp. 1–28, 2020, doi: 10.3390/agriculture10110504.

[11] N. N. Sabila, A. Profita, and Y. Sukmono, "The Application of Fuzzy FMEA and TOPSIS Methods in Agricultural Supply Chain Risk Management (Case Study: Kabupaten Paser)," *Tek. J. Sains Dan Teknol.*, vol. 18, no. 1, p. 23, 2022, doi: 10.36055/tjst.v18i1.14260.

[12] A. K. Yazdi, Y. J. Wang, and A. R. Komijan, "Green supply chain management in an emerging economy: Prioritising critical success factors using grey-permutation and genetic algorithm," *Int. J. Logist. Syst. Manag.*, vol. 36, no. 2, pp. 199–223, 2020, doi: 10.1504/IJLSM.2020.107386.

[13] Q. A. Ahmad, S. Ashraf, M. S. Chohan, B. Batool, and M. L. Qiang, "Extended CSF-CoCoSo Method: A Novel Approach for Optimizing Logistics in the Oil and Gas Supply Chain," *IEEE Access*, vol. 12, pp. 75678–75688, 2024, doi: 10.1109/ACCESS.2024.3390938.

[14] A. O. OLUWOLE, B. O. Odedairo, and V. Oladokun, "Managing Supply Chain Risks: A Fuzzy-Failure Mode and Evaluation Approach for Ranking Threats," *J. Eng. Stud. Res.*, vol. 27, no. 4, pp. 60–69, 2021, doi: 10.29081/jesr.v27i4.300.

[15] J. Balaraju, M. Govinda Raj, and C. S. Murthy, "Fuzzy-FMEA risk evaluation approach for LHD machine-A case study," *J. Sustain. Min.*, vol. 18, no. 4, pp. 257–268, 2019, doi: 10.1016/j.jsm.2019.08.002.

[16] H. Yin, C. Liu, W. Wu, K. Song, D. Liu, and Y. Dan, "Safety assessment of natural gas storage tank using similarity aggregation method based fuzzy fault tree analysis (SAM-FFTA) approach," *J. Loss Prev. Process Ind.*, vol. 66, 2020, doi: 10.1016/j.jlp.2020.104159.

[17] S. Hassan, J. Wang, C. Kontovas, and M. Bashir, "Modified FMEA hazard identification for cross-country petroleum pipeline using Fuzzy Rule Base and approximate reasoning," *J. Loss Prev. Process Ind.*, vol. 74, 2022, doi: 10.1016/j.jlp.2021.104616.

[18] C.-H. Chang, J. Xu, and D.-P. Song, "An analysis of safety and security risks in container shipping operations: A case study of Taiwan," *Saf. Sci.*, vol. 63, pp. 168–178, 2014, doi: 10.1016/j.ssci.2013.11.008.

[19] S. Boral, I. Howard, S. K. Chaturvedi, K. McKee, and V. N. A. Naikan, "An integrated approach for fuzzy failure modes and effects analysis using fuzzy AHP and fuzzy MAIRCA," *Eng. Fail. Anal.*, vol. 108, 2020, doi: 10.1016/j.engfailanal.2019.104195.

[20] B. Karatop, B. Taşkan, E. Adar, and C. Kubat, "Decision analysis related to the renewable energy investments in Turkey based on a Fuzzy AHP-EDAS-Fuzzy FMEA approach," *Comput. Ind. Eng.*, vol. 151, 2021, doi: 10.1016/j.cie.2020.106958.

[21] B. EFE, "An integrated fuzzy approach based failure mode and effects analysis for a risk assessment," *Bitlis Eren Üniversitesi Fen Bilim. Derg.*, vol. 11, no. 2, pp. 678–693, 2022, doi: 10.17798/bitlisfen.1088988.

[22] S. Daneshvar, M. Yazdi, and K. A. Adesina, "Fuzzy smart failure modes and effects analysis to improve safety performance of system: Case study of an aircraft landing system," *Qual. Reliab. Eng. Int.*, vol. 36, no. 3, pp. 890–909, 2020, doi: 10.1002/qre.2607.

[23] J. d. Aguiar, R. K. Scalice, and D. Bond, "Using Fuzzy Logic to Reduce Risk Uncertainty in Failure Modes and Effects Analysis," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 40, no. 11, 2018, doi: 10.1007/s40430-018-1437-5.

[24] L. Liu, "Research on the management system of enterprises using modern Logistics supply chain theory," in *Procedia Engineering*, 2011, pp. 721–725. doi: 10.1016/j.proeng.2011.11.2725.

[25] T. Cherrett, J. Dickinson, F. McLeod, J. Sit, G. Bailey, and G. Whittle, "Logistics impacts of student online shopping – Evaluating delivery consolidation to halls of residence," *Transp. Res. Part C Emerg. Technol.*, vol. 78, pp. 111–128, 2017, doi: 10.1016/j.trc.2017.02.021.

[26] H. Moayedi, M. Raftari, A. Sharifi, W. A. W. Jusoh, and A. S. A. Rashid, "Optimization of ANFIS with GA and PSO estimating α ratio in driven piles," *Eng. Comput.*, vol. 36, no. 1, pp. 227–238, 2020, doi: 10.1007/s00366-018-00694-w.

[27] P. Liu and Y. Li, "An improved failure mode and effect analysis method for multi-criteria group decision-making in green logistics risk assessment," *Reliab. Eng. Syst. Saf.*, vol. 215, 2021, doi: 10.1016/j.ress.2021.107826.

[28] T. L. Saaty, *Decision Making with Dependence and Feedback: The Analytic Network Process*. RWS Publications, 1996. [Online]. Available: http://www.rwspublications.com/books/anp/decision-making-with-dependence-and-feedback/

[29] T. Takagi and M. Sugeno, "Fuzzy Identification of Systems and Its Applications to Modeling and Control," *IEEE Trans. Syst. Man Cybern.*, vol. SMC-15, no. 1, pp. 116–132, 1985, doi: 10.1109/TSMC.1985.6313399.

[30] A. Burduk, "Fuzzy Logic in Risk Assessment of Production Machines Failure in Forming and Assembly Processes," *J. Mach. Eng.*, vol. 24, no. 2, pp. 34–43, 2024, doi: 10.36897/jme/189667.

[31] B. A. de Resende, F. G. Dedini, J. J. Eckert, T. F. A. C. Sigahi, J. de S. Pinto, and R. Anholon, "Proposal of a facilitating methodology for fuzzy FMEA

implementation with application in process risk analysis in the aeronautical sector," *Int. J. Qual. Reliab. Manag.*, vol. 41, no. 4, pp. 1063–1088, 2024, doi: 10.1108/IJQRM-07-2023-0237.

[32] R. Fattahi, R. Tavakkoli-Moghaddam, M. Khalilzadeh, N. Shahsavari-Pour, and R. Soltani, "A novel FMEA model based on fuzzy multiple-criteria decision-making methods for risk assessment," *J. Enterp. Inf. Manag.*, vol. 33, no. 5, pp. 881–904, 2020, doi: 10.1108/JEIM-09-2019-0282.

[33] Ö. M. Testik and E. T. Unlu, "Fuzzy FMEA in Risk Assessment for Test and Calibration Laboratories," *Qual. Reliab. Eng. Int.*, vol. 39, no. 2, pp. 575–589, 2022, doi: 10.1002/qre.3198.

[34] J. J. Cardiel-Ortega, "Probabilistic Fuzzy System for Evaluation and Classification in Failure Mode and Effect Analysis," *Processes*, vol. 12, no. 6, p. 1197, 2024, doi: 10.3390/pr12061197.

[35] S. Zolfaghari and S. M. Mousavi, "A New Risk Evaluation Methodology Based on FMEA, MULTIMOORA, TPOP, and Interval-Valued Hesitant Fuzzy Linguistic Sets With an Application to Healthcare Industry," *Kybernetes*, vol. 50, no. 9, pp. 2521–2547, 2021, doi: 10.1108/k-03-2020-0184.

Appendices

Table A1.
Operating risk on the logistics system

No	Failure Factor		
	Internal	External	Human
1	Loss of raw materials or components in the production process	Delayed product delivery	The operator's inaccuracies in following the working procedure
2	Incoherence of production quantities with targets	Product damage during shipment	Lack of understanding of the expected product quality
3	Delayed processing	Product non-compliance with customer specifications	Failure in the production process
4	Inaccuracies in the inventory of raw materials	Return product from customer	-
5	The quality of the product does not meet the company's standards	-	-

Table A2.
RPN ranking results

Indicator	RPN	Ranking
Untimely processing of products	252	1
Failure in the production process	216	2
Delay in product delivery	210	3
Mismatch of production quantity with target	192	4
Product quality that does not meet company standards	189	5
Inaccuracy of raw material inventory	180	6
Employee inaccuracy in following work procedures	175	7
Lack of understanding of expected product quality	168	8
Product non-conformance to customer specifications	168	8
Loss of raw materials or components in the production process	128	10
Product damage during shipping	108	11
Product returns from customers	96	12

Table A3.
Membership degree values of fuzzification results

No	Indicator	μ S	μ O	μ D
1	Loss of raw materials or components in the production process	0.5	1.0	0.5
2	Mismatch of production quantity with target	1.0	1.0	0.5
3	Untimely processing	0.3	1.0	1.0
4	Inaccuracy of raw material inventory	1.0	1.0	1.0
5	Product quality that does not meet company standards	0.8	1.0	0.3
6	Delay in product delivery	1.0	1.0	1.0
7	Product damage during shipping	0.3	1.0	0.5
8	Product non-conformance to customer specifications	0.8	1.0	1.0
9	Product returns from customers	1.0	1.0	0.3
10	Operator inaccuracy in following work procedures	0.8	1.0	1.0
11	Lack of understanding of expected product quality	1,0	1,0	1,0
12	Failure in the production process	0,5	1,0	0,7

Table A4.
FRWPN Calculation Results

Failure Factors	No Indicator	FRPN	Ws	Wo	Wd	FRWPN	Ranking
Internal	1	500	0.413	0.26	0.327	17.5566	6
	2	400	0.062	0.653	0.285	4.6154	12
	3	500	0.351	0.316	0.333	18.4675	2
	4	500	0.333	0.313	0.354	18.4485	3
	5	500	0.35	0.223	0.427	16.6637	9
External	6	400	0.332	0.371	0.297	14.6328	11
	7	500	0.309	0.243	0.448	16.8195	8
	8	777	0.375	0.25	0.375	27.3164	1
	9	500	0.316	0.313	0.372	18.3969	4
Human	10	500	0.359	0.19	0.452	15.4155	10
	11	500	0.378	0.348	0.274	18.0215	5
	12	500	0.449	0.257	0.294	16.9628	7

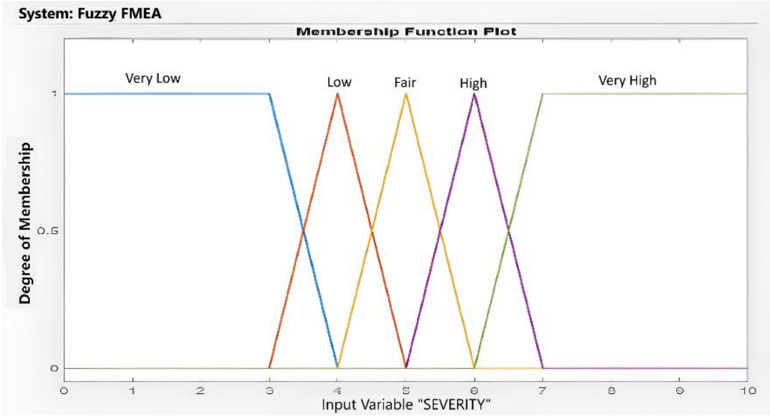

Figure B1. Severity fuzzy input variable

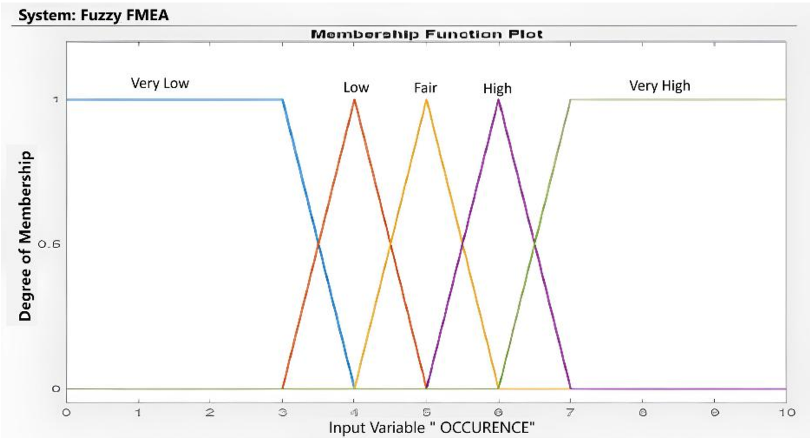

Figure. B2 Fuzzy detection input variable

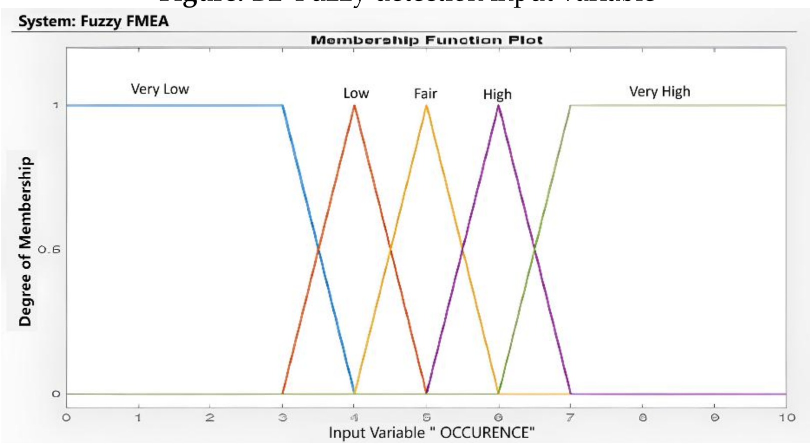

Fig. B3 Fuzzy occurrence input variable