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Infectious Disease Risk Assessment using Different Enhanced-FMEA Approaches

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ABSTRACT

Three years before, the global spread of COVID-19, originating in China, rapidly impacted numerous countries, causing a surge in cases and fatalities. Governments worldwide encountered significant challenges not only in healthcare but also across various sectors. As an alternative to reducing the spread of COVID-19, many researchers implemented the Failure Mode and Effect Analysis (FMEA) method to mitigate the associated transmission risks in specific settings. However, this method did not thoroughly examine the process of assigning importance weights and expert judgments to the risk factors, potentially limiting the comprehensive outcome of the risk assessment. This paper discusses the comparison between FMEA, fuzzy-based FMEA, and FMEA-based fuzzy TOPSIS to assess their effectiveness in handling infectious diseases. The longhouse at Pasai Siong, Sarawak, was chosen as a case study due to being one of the most significant clusters during the pandemic in Sarawak. The study's findings suggest that all risk assessment methods unanimously identify the living room (F 3.1) as the most critical area with the highest transmission potential, emphasizing the necessity of prioritizing this area. However, slight variations in rankings across methods were observed due to the distinct approaches taken by each assessment method.

1. Introduction

Infectious diseases are illnesses caused by pathogens that originate from infected persons, animals, or contaminated objects, which then affect the host [1]. There are various pathways facilitating the transfer of infectious agents from their natural reservoirs to susceptible hosts, including direct and indirect transmission. Direct transmission involves the transfer of microorganisms between body surfaces, passing from an infected or colonized individual to another through physical contact [1]. On the other hand, indirect transmission occurs when a person interacts with a contaminated object, often due to unclean hands contaminating surfaces or the environment

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[1]. Microorganisms can persist on these surfaces, potentially transferring to the next individual who touches them.

In the past few years, the outbreak of the coronavirus disease 2019 (COVID-19), caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), has resulted in significant morbidity and mortality on a worldwide scale [2]. This type of infectious disease has impacted over 273 million individuals and caused the deaths of more than 5.3 million people. As COVID-19 evolved, it has sparked inquiries regarding the factors influencing the risk of contracting COVID-19 as well as those management against the disease.

Despite the widespread use of FMEA and its variants in infectious disease risk management, comparative methodological evaluations of these risk assessment approaches in real-world outbreak scenarios, especially in non-healthcare settings remain limited. Most existing studies tend to apply these methods in isolation, without assessing their relative strengths, limitations, and adaptability to complex environments such as communal living spaces. Addressing this gap is crucial to identify the most reliable and context-appropriate method for evaluating infectious transmission risks beyond clinical environments. Therefore, this study aims to analyze and evaluate the most effective risk management technique for controlling the spread of the virus while minimizing disruptions to daily life and the economy. To achieve this, three risk assessment methods are considered: (i) Failure Mode and Effect Analysis (FMEA), (ii) fuzzy-based FMEA, and (iii) FMEA-based fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). FMEA, a conventional method, focuses on identifying and prioritizing failure modes directly from the risk priority number (RPN), which results from the combination of severity, occurrence, and detection rating [3]. Fuzzy-based FMEA utilizes fuzzy logic to address uncertainties associated with the risks [4]. Meanwhile, FMEA-based fuzzy TOPSIS is a hybrid method that offers a comprehensive evaluation by considering expert judgments in weighting [5]. All these methods will be applied in a real case study focusing on the COVID-19 outbreak in a longhouse in Pasai Siong, Sibu, Malaysia.

The paper's structure is as follows: In Section 2, the background and related research on risk management, along with various risk assessment models, is presented. Section 3 offers a comparative analysis of the three risk assessment models. Moving to Section 4, we present the analysis of infectious disease risk assessment models concerning specific risk factors. In Section 5, a summary of the three assessment methods is presented in the form of a table. Finally, in Section 6, we conclude our work and propose avenues for future research.

2. Literature Review

An infectious disease risk assessment is a crucial component in any organization's workplace or non-healthcare settings. The first step in preventing exposure to infectious diseases involves identifying and evaluating disease risks [6]. Typically, the risk assessment process involves three main stages: risk identification, risk analysis, and risk evaluation, as shown in Figure 1. Within this assessment process, several commonly used methods for risk assessment are available, including the FMEA method (conventional semi-quantitative), fuzzy-based FMEA (utilizing artificial intelligence), and FMEA-based fuzzy TOPSIS (employing an integrated approach).

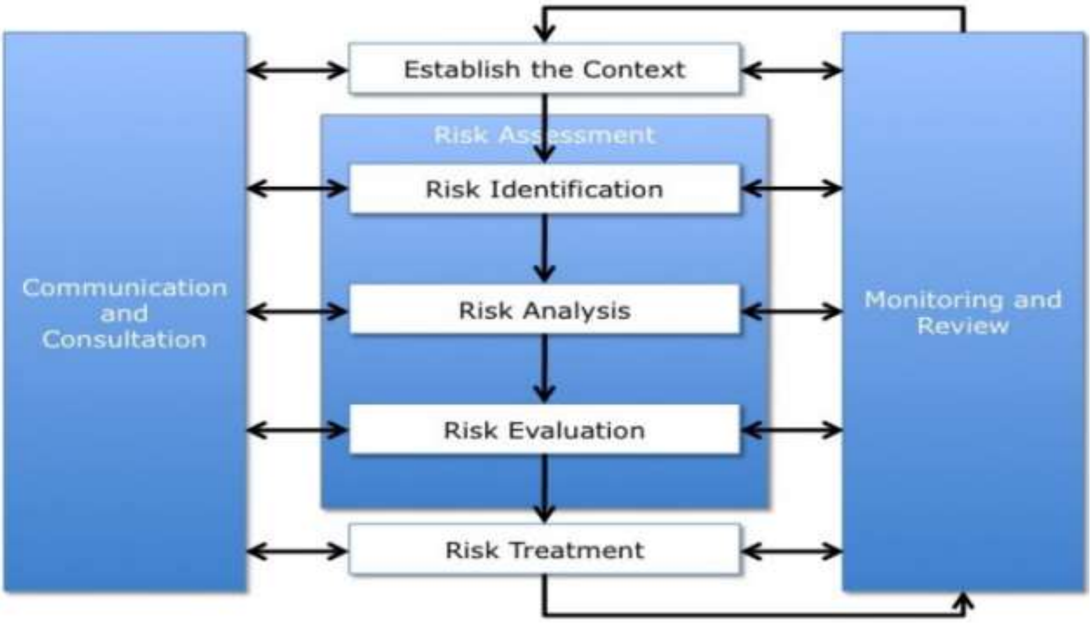

Fig. 1. General overview of risk management process [7]

In recent times, the FMEA method has been integrated into the hospital retrocession dispensing process, focusing on the transmission risk associated with SARS-CoV-2 [8]. This method aims to analyze and map the infectious transmission risk of SARS-CoV-2 during hospital retrocession and has identified 12 failure modes that could result in significant consequences, including the transmission risk of COVID-19.

Another method, called fuzzy-based FMEA, assesses and identifies hazards in a hospital's sterilization unit, thereby reducing the spread of infectious diseases from contaminated medical devices [9]. This method employs triangular fuzzy membership functions and utilizes 125 decision rules for each hazard determination.

Among the various risk assessment models, there is another model-based approach known as fuzzy TOPSIS, which identifies risk based on alternatives and criteria [10]. This technique operates on the principle that the optimal alternative exhibits the highest levels across all considered attributes, while the negative ideal represents the alternative with the poorest attribute values overall.

These risk assessment models differ significantly in their approaches to identifying, mitigating, prioritizing, and avoiding risks. This paper conducts a comparative analysis of these models, specifically focusing on certain risk elements, highlighting their differences in handling various aspects of risk assessment.

3. Methodology: Transmission Potential Assessment Methods

This study focuses on specific methods selected for a detailed comparison. These risk assessment models are explicitly tailored to meet the demands of risk management within the infectious disease domain. These models were selected because of their specialized focus on managing risks or related aspects within this particular domain. Below, detailed descriptions of the selected models are provided for further clarification:

3.1 Failure Mode and Effect Analysis (FMEA)

This method involves a comprehensive questionnaire where a panel of selected experts filled out the FMEA form. The expert panel comprised individuals with relevant knowledge and experience in infectious disease management and public health. The panel included:

i. Dr. Helmy bin Hazmi, a public health physician and medical lecturer at Universiti Malaysia Sarawak (UNIMAS), with a specialization in epidemiology and biostatistics;
ii. Nursyuhada Ariefa binti Yusuf, an ICU staff nurse at Thompson Hospital with hands-on experience in managing COVID-19 patients; and
iii. Ami anak Samjun, a longhouse resident familiar with the daily social interactions and spatial arrangements within the communal environment.

This diverse panel provided insights from both clinical and community perspectives. The structured FMEA guide was used to identify and evaluate potential failure modes in the longhouse setting through the RPN. The RPN acts as an overall indicator of risk for system users and guides decisions about optimization measures. A higher RPN indicates a greater need for risk reduction through design enhancements and quality assurance actions. The RPN can be calculated as in Eq. (1):

$$RPN = Severity*occurrence*detection \tag{1}$$

In this study, the scale table was established through discussions with experts. Table 1 incorporates a scale ranging from 1 to 10, encompassing values for severity, occurrence, and detection.

Table 1
Scale table for severity, occurrence and detection

Linguistic term	Severity	Occurrence	Detection
Very low	1	1	1-2
Low	2-3	2-4	3-5
Medium	4-6	5-6	6-8
High	7-8	7-8	9
Very high	9-10	9-10	10

Meanwhile, the FMEA procedure is depicted in Figure 2. The process commences by identifying and listing various areas or activities related to infectious disease transmission in the longhouse. For each identified area, potential failure modes leading to transmission potential are listed. Subsequently, experts are required to rate each failure mode for severity, occurrence and detection using the scaling from Table 1. Following this, the RPN for each failure mode is calculated by multiplying the three respective scales, allowing for the ranking of potential failures based on their criticality level [11]. If no modification is deemed necessary, prevention measures can then be implemented to mitigate the risk of disease transmission.

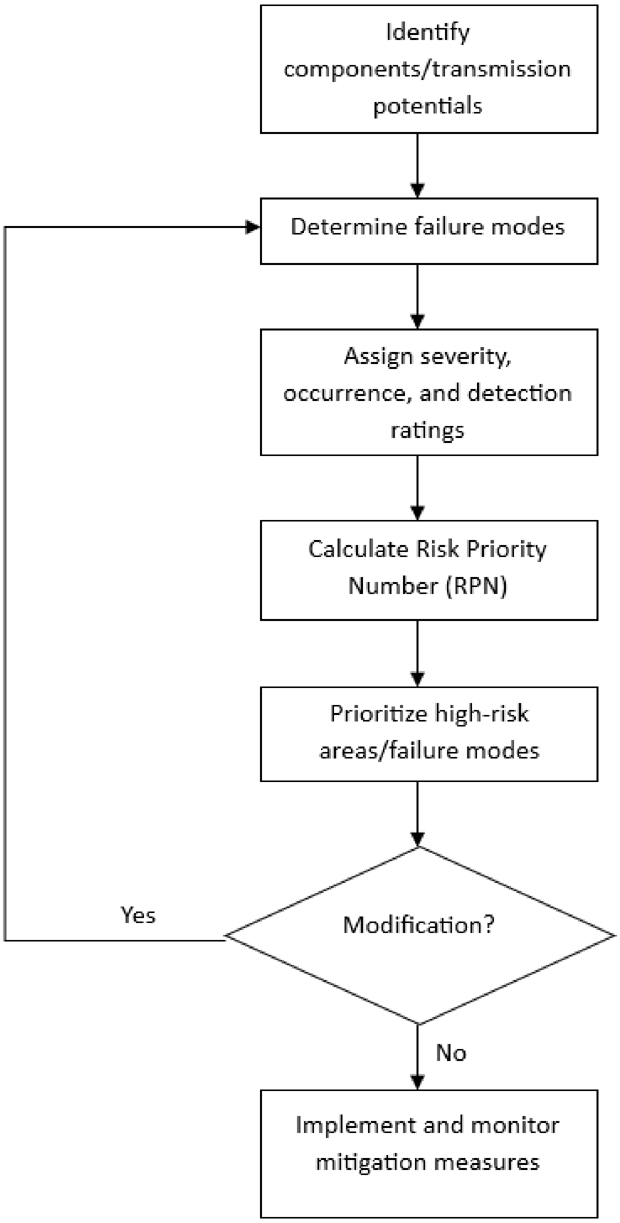

Fig. 2. Conventional FMEA procedure

However, this method considers severity, occurrence, and detection criteria to have equal relative importance. In the context of managing COVID-19 infections, this assumption might not accurately capture the pandemic's complexities. Equal weighting of criteria could potentially be less effective in truly assessing the diverse impact of different failure modes [12].

3.2 Fuzzy-based FMEA

In this method, risk estimation involves using fuzzy numbers or verbal variables. According to Zandi, employing the fuzzy approach is more effective, especially in managing extensive and complex projects where data is insufficient or lacking [13]. In this study, Gaussian fuzzy numbers are utilized due to their distribution shape, which enables the representation of findings within fuzzy environments [14]. The membership function is represented by Eq. (2) and exhibits a shape as depicted in Figure 3 where "*c*" represents the center of the Gaussian membership function, and "σ" denotes the standard deviation determining the width of the curve.

$$Gaussian(x;c,\sigma) = e^{-(1/2)(\,x\text{-}c/\sigma)\text{^}2} \quad (2)$$

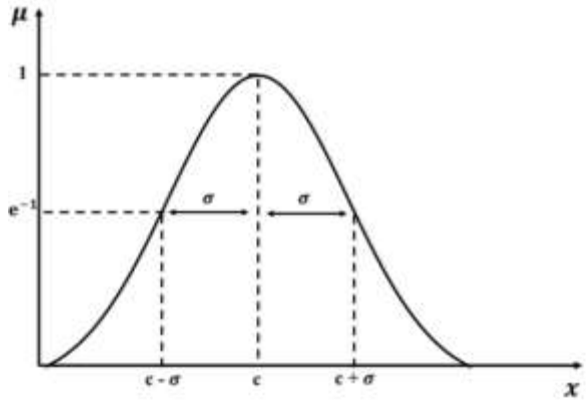

Fig. 3. Gaussian membership function [15]

The process of fuzzy-based FMEA is illustrated in Figure 4. Similar to conventional FMEA, this method initiates by identifying the transmission potential. Subsequently, experts assign ratings for severity, occurrence, and detection using the scale ratings from Table 1, evaluating these risk factors in the form of membership functions. If no correction or modification is necessary, the next step involves gathering fuzzy IF-THEN rules from experts, which will be used in the decision-making process. The final step includes calculating the Fuzzy RPN (FRPN) value, utilized for ranking purposes.

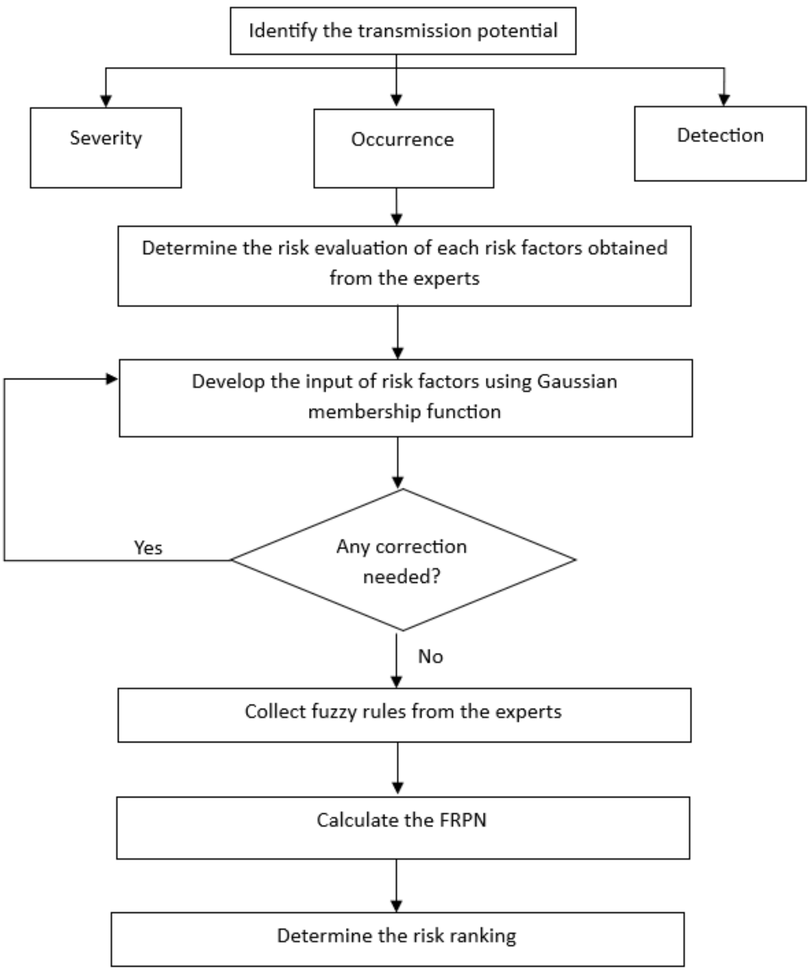

Fig. 4. Fuzzy-based FMEA procedure

The fuzzy system relies on IF-THEN rules for decision-making. This approach usually requires an extensive set of rules, making it a labour-intensive task to obtain a comprehensive rule set [16]. Having more rules provided by users improves the predictive accuracy of the fuzzy RPN model. However, as the number of rules needed increases, the user-friendliness of the model decreases. Users have to provide a significant amount of information or rules for the modelling process, which can make it less accessible or more challenging to use.

3.3 FMEA-based Fuzzy TOPSIS

In the conventional TOPSIS process, both the performance ratings and criteria weights are typically represented as precise, definite values. Fuzzy TOPSIS, an extension of TOPSIS, addresses the handling of ambiguous information by integrating fuzzy membership functions [17]. In this specific study, expert judgments are utilized to quantify the scores of criteria and alternatives. The severity, occurrence, and detection scales are considered as criteria, while the transmission potential is treated as alternatives. Regarding the membership function, this study employs the triangular membership function, as illustrated in Figure 5, where "b" represents a precise central value, "a" corresponds to the lower boundary, and "c" signifies the upper boundary.

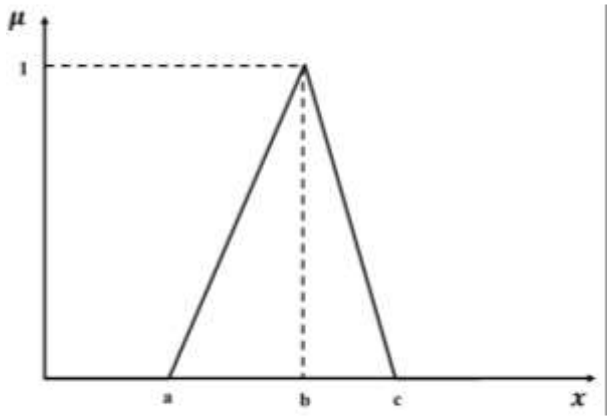

Fig. 5. Triangular membership function [15]

In weighing the criteria, priority is allocated to the severity scale, followed by occurrence and then detection. In contrast to fuzzy-based FMEA, the fuzzy number comprises three values representing the lower limit, mean and upper limit, delineating the shape of the membership function. Table 2 illustrates the triangular fuzzy numbers assigned to each linguistic term, ranging from "Very Low" to "Very High", which are used to quantify the risk factors. These fuzzy values enable the transformation of qualitative expert judgments into numerical values, allowing for more accurate and consistent assessment in the Enhanced-FMEA process.

Table 2
Triangular fuzzy number for severity, occurrences, and detection

Linguistic terms	Fuzzy number
Very low	(1, 1, 3)
Low	(1, 3, 5)
Medium	(3, 5, 7)
High	(5, 7, 9)
Very high	(7, 9, 9)

The process of FMEA-based fuzzy TOPSIS is outlined in Figure 6. Initially, similar to both FMEA and fuzzy-based FMEA, various components contributing to infectious disease transmission must be identified. Next, weights can be assigned to the three risk factors by designating "very high" for severity, "high" for occurrence and "medium" for detection. The fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS) are determined to gauge the alternative's proximity to these ideal solutions. Subsequently, the closeness coefficient is calculated, which will be used in ranking the potential for infectious disease transmission.

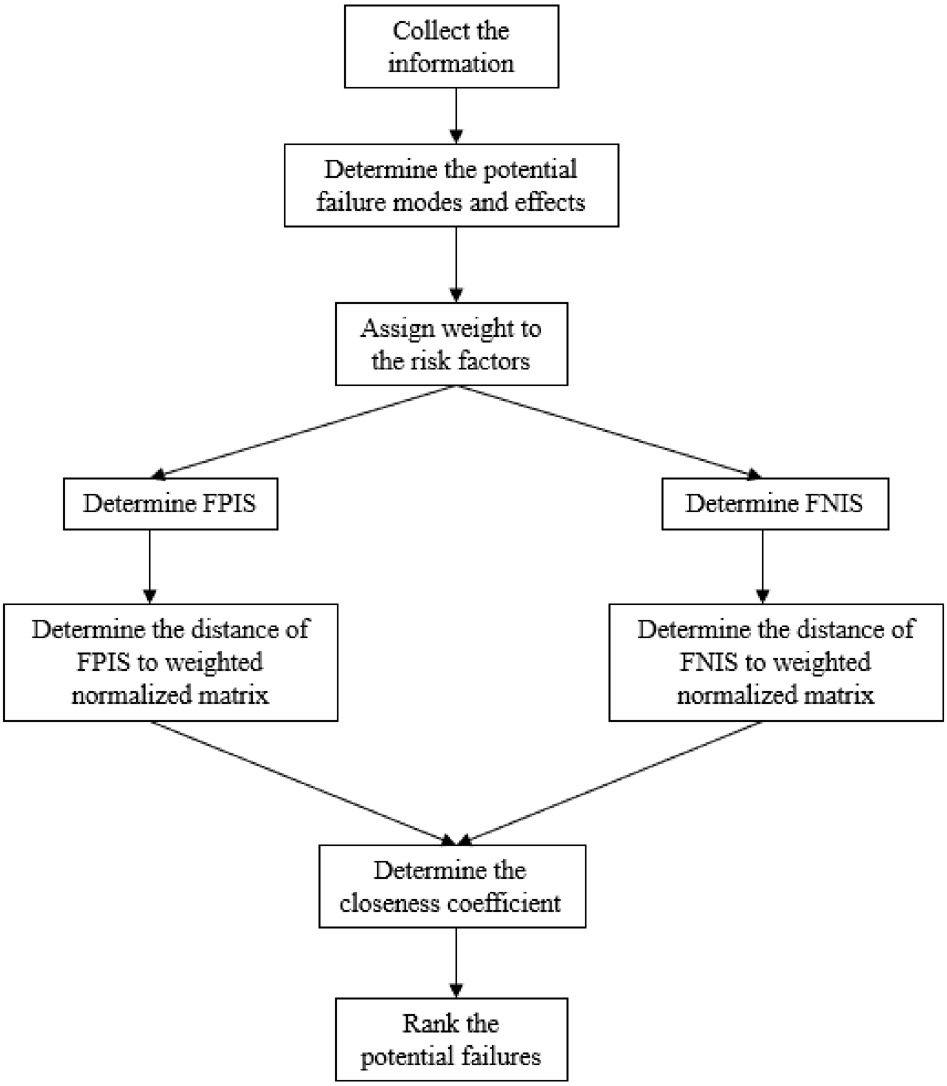

Fig. 6. FMEA-based fuzzy TOPSIS procedure

4. Results and Discussion

In this section, the FMEA methodology using RPN (from FMEA), FRPN (from fuzzy-based FMEA), and FTRPN (from FMEA-based fuzzy TOPSIS) are applied to analyze COVID-19 infections in a longhouse in Sarawak. Table 3 presents various areas within the longhouse setting and their corresponding transmission potentials for infectious agents. Each area, categorized by its location (e.g., *Ruai (a communal hallway or shared gathering area typical in Sarawak longhouses)*, Veranda, Living Room, Bedroom, Family Room, Kitchen, and Washroom), is associated with specifically identified transmission potentials, contributing to the understanding of potential infection spread in domestic environments. Figure 7 shows an on-site image of Raymond Longhouse, located in Pasai

Siong, Sibu, Sarawak. The photo provides visual context to the spatial layout and communal living environment that underpin the risk assessment discussed in this section.

Fig. 7. Raymond longhouse view from the entrance

Table 3
Transmission potentials of infectious agents across longhouse areas

Area	ID	Transmission potentials
Ruai	F 1.1	Social interaction at a close distance. Special events. i.e. Gawai, Christmas, Wedding and Engagement Reception, Funeral, etc.
	F 1.2	Sharing of traditional instruments
	F 1.3	Passing drinks and food during events
	F 1.4	Area contamination with infectious agents (e.g. *ruai* floor, *ruai* wall etc.
	F 1.5	Common access entry to the *ruai* area (shared side entrances also known as *tempuan*)
Veranda	F 2.1	Social interaction at close distance, which involves 2 or more peoples
	F 2.2	Contamination of the area with infectious agents (staircase handle, door handle of the entrances, etc.
	F 2.3	Infected non-residents/outsiders using the same entrances
Living Room	F 3.1	Social interaction at a close distance. Special events. i.e. Gawai, Christmas, Wedding, and Engagement Reception.
	F 3.2	Contamination of the area with infectious agents (furniture, etc.)
Bedroom	F 4.1	Contamination of the area with infectious agents (i.e. door handles, bedroom furniture)
	F 4.2	Poor ventilation
	F 4.3	Sharing of bedroom/ No personal bedroom
Family Room	F 5.1	Contamination of the area with infectious agents (furniture, remote TV, etc.)

	F 5.2	Social interactions at a close distance
Kitchen	F 6.1	Sharing of cooking equipment
	F 6.2	Potential contamination of the tableware and kitchenware with infectious agents
Washroom	F 7.1	Contamination of the area with infectious agents (door handle and faucet handle)

The comparison of rankings obtained by the three methods is illustrated in Table 4. FMEA is utilized to prioritize the 18 transmission potentials across 7 different areas. The analysis reveals that the ranking values for F 3.1 are consistent across all three methods, signifying that social interaction at close distances in a living room poses the highest risk for potential COVID-19 infection. The architectural design of the longhouse appears to impact COVID-19 transmission within the living room. Given the proximity of each section in the longhouse, inadequate air ventilation in that area might facilitate favourable conditions for the transmission of infectious diseases.

The second-highest transmission potential, identified as F 4.2 based on RPN and FRPN values, differs in the FTRPN analysis, where it is considered the highest potential failure. This discrepancy might stem from the shape of the membership functions utilized in the analyses. FMEA uses direct multiplication, while fuzzy-FMEA employs Gaussian membership functions. Meanwhile, FMEA-based fuzzy TOPSIS utilizes triangular membership functions. Dutta highlights that the choice of membership functions can significantly influence the analysis outcomes [18]. For example, the Gaussian function represents its membership in a bell-shaped manner, resulting in a smoother and more gradual transition between membership degrees. In contrast, the triangular function displays its membership in a linear shape, leading to a more abrupt transition from full membership to non-membership. This distinction in membership function shapes could contribute to the variation in rankings observed for F 4.2 across the different analysis methods.

A noticeable large gap exists between the RPN, FRPN and FTRPN rankings for F 1.4, signifying significant differences in how potential failures are assessed across different methodologies. This discrepancy stems from the intricate integration between FMEA and fuzzy TOPSIS. Fuzzy TOPSIS incorporates the weighting factor for the three criteria and also considers experts' opinions, leading to a more nuanced evaluation and larger variations in rankings [19]. The weight assigned by decision-makers to the criteria is very high for severity, high for occurrence, and average for detection. Consequently, the evaluation is more sensitive to the severity scale compared to the others, as even small differences could significantly impact the final output.

In conclusion, this comparative analysis underscores the multidimensional nature of risk assessment methodologies, emphasizing the significance of membership functions, expert opinions, and weighted criteria in determining the priority of each transmission potential. Recognizing this variability is crucial for devising strategies to mitigate COVID-19 transmission or future novel infectious diseases, particularly in rural areas such as the longhouse. These insights offer valuable guidance for decision-makers in crafting effective preventive measures.

Table 4
Comparative analysis of transmission potential rankings: Conventional FMEA, fuzzy-based FMEA, and FMEA-based Fuzzy TOPSIS

ID	RPN ranking	FRPN ranking	FTRPN ranking
F 3.1	1	1	1
F 4.2	2	2	1
F 4.3	3	4	2
F 5.2	4	5	3
F 1.1	5	3	5
F 2.1	6	8	2
F 1.3	7	6	7
F 2.2	8	7	3
F 5.1	9	8	3
F 6.1	9	9	4
F 7.1	9	9	4
F 3.2	10	7	7
F 1.2	11	6	7
F 2.3	12	7	7
F 1.4	13	8	3
F 4.1	13	8	3
F 6.2	14	10	6
F 1.5	15	11	8

5. Comparison between Risk Assessment Methods for Infectious Disease

Table 5 presents a comparative analysis of three risk analysis methodologies: FMEA, fuzzy-based FMEA, and FMEA-based fuzzy TOPSIS, highlighting their key characteristics, findings and challenges in the context of infectious disease cases. It's evident that all methods are semi-quantitative, incorporating both qualitative and quantitative analyses. Qualitative aspects define linguistic terms in membership functions, while quantitative elements scale hazard levels, potential failure frequency, and determination ability [20].

Table 5
Comparative analysis risk methodologies in infectious disease

Parameters	FMEA	Fuzzy-based FMEA	FMEA-based fuzzy TOPSIS
Risk analysis method	Semi-quantitative	Semi-quantitative	Semi-quantitative
Membership function	No such technique is used	Gaussian membership function	Triangular membership function
Weight	Does not involve weighting and is solely dependent on severity, occurrence, and detection scores.	Does not involve weighting, influenced by fuzzy logic and linguistic variables	Normalized and weighted based on fuzzy logic and expert judgment

Findings	User-friendly and straightforward, demanding minimal time and training. This ease of use enables its practical application in real-world settings	This approach can handle incomplete and ambiguous information, such as the mode of transmission, environmental factors, and duration of exposures The membership functions that act as inputs for the decision-making process can be adjusted based on real-time outbreaks	Each failure mode can be influenced based on its respective significance levels through a weighting process in the hierarchical analysis and paired comparison matrix Employing linguistic terms within the fuzzy TOPSIS approach allowed experts to convey their judgments in a more realistic manner
Challenges	Relying only on multiplication to quantify RPN in FMEA has drawbacks. Even small changes in assessing a single risk factor could greatly impact the resulting RPN Potentially generating an RPN that appears similar to others but fails to emphasize specific hazards related to infectious disease transmission	Require 125 IF-THEN rules, which can be troublesome The method presented does not address the interconnections among transmission potentials or verify how the risk factors are interrelated	The integration of fuzzy and TOPSIS methodologies into FMEA for FMEA-based fuzzy TOPSIS introduces complexity, making it challenging for users to effectively comprehend and implement

Notably, only FMEA does not involve membership functions, remaining a straightforward and adaptable method for various risk assessment processes. Contrarily, both fuzzy and fuzzy-TOPSIS employ membership functions, aiding in representing uncertainty, which enhances adaptability to real-time outbreaks and diverse situations.

These observations highlight the strengths of each methodology: FMEA excels in user-friendliness, while fuzzy adaptations (Fuzzy-based FMEA and FMEA-based fuzzy TOPSIS) thrive in handling ambiguity, adapting to real-time outbreaks and leveraging weighted significance and expert judgments for more realistic assessments. However, all methodologies fall short of addressing interconnections and integrating methodologies seamlessly. This limitation might impact their usability and effectiveness in tackling the intricate aspects of infectious disease analysis.

6. Conclusion

In this paper, a comparative study of three risk assessment methods concerning transmission potentials in managing infectious diseases has been conducted. It can be concluded that FMEA is the simplest method commonly implemented in the healthcare sector. However, this method lacks consideration for individual elements within each criterion, rendering it less reliable compared to other risk assessment models.

On the other hand, fuzzy methods do consider various factors through their membership functions, enabling the distinction between desirable and undesirable inputs and resulting in a more nuanced final evaluation. Additionally, fuzzy TOPSIS proves useful in handling complex and uncertain judgments.

However, all the aforementioned risk assessment methods are static in nature, meaning they provide a one-time evaluation of risk based on fixed inputs without adapting to changes over time. They do not account for real-time variations in infection dynamics or incorporate responsive control measures such as vaccination campaigns, quarantine protocols, or policy interventions during an outbreak [21]. Therefore, for future studies, exploring dynamic risk assessment methodologies that consider emergency interventions would be beneficial. These approaches could provide a more comprehensive understanding of managing infectious diseases in real-time situations.

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