Original Article

Integration of fuzzy set theory and TOPSIS into HFMEA to improve outpatient service for elderly patients in Taiwan

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Abstract

Background: Taiwan became a World Health Organization—defined aging country in 1993, and it is estimated to become an aged country by 2017, surpassing Japan as the fastest aging country in the world. However, healthcare services in Taiwan need a wide range of improvements to cope with the challenges of population aging.

Methods: Healthcare failure mode and effects analysis (HFMEA) developed by the Department of Veterans Affairs’ National Center for Patient Safety (NCPS) was used to evaluate the inconvenience of outpatient registration process for elderly patients. Also, fuzzy set theory was used along with technique for order preference by similarity to ideal solution (TOPSIS) method in multiple criteria decision making (MCDM) to rank the failure risks in the HFMEA.

Results: The top three failure modes ranked by the TOPSIS method were “short consultation time,” “possible complications of the checkup or treatment were not told,” and “opinions and feelings of patients and relatives were not respected.” Based on those failure modes, improvements were proposed and results were feedback to hospitals. A random sample of 40 elderly patients was selected for interview at the outpatient department of a tertiary medical center in Taiwan. Thirty-seven out of the 40 elderly patients (92.5%) agreed with the executive expert team. This meant the improvement proposals were effective.

Conclusion: In this study, HFMEA was extended to explore the impacts of geriatric outpatient service process failures on elderly patients. Using fuzzy set theory and the TOPSIS method in multiple criteria decision making to rank the severity of the failure modes, the risk assessment of the geriatric outpatient service process was more objective when analyzed with quantitative data.

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Keywords: fuzzy set theory; healthcare failure mode and effects analysis (HFMEA); technique for order preference by similarity to ideal solution (TOPSIS)

1. Introduction

Population aging is a global issue, and the World Health Organization (WHO) has listed population aging as one of the major health issues in the 21st century (WHO, 1999). Due to economic growth and the success of public health and medical services in Taiwan, the average life expectancy has been prolonged, yet the birth rate was reduced dramatically. Altogether, it results in a significant population aging in Taiwan. The elderly population in Taiwan exceeded 7% of the total population in 1993, and reached 10.8% in 2011. More importantly, by 2020, the elderly population will reach 20% of total population, almost doubling the current number of elderly population within only 14 years. To cope with the escalation of elderly population in Taiwan, developing age-friendly healthcare services is critical, but the rapid demographic transition may result in difficulties of timely development of age-friendly care.

Most of the applications of system safety theories and methods in the medical industry are adopted from the national defense and manufacturing industries in the United States. In terms of the application of medical system in patient safety, the Joint Commission on the Accreditation of Healthcare Organization (JCAHO) cited adverse events in the root cause of care.
analysis (RCA) investigation in 1997. In 1999, Senders and colleagues introduced failure modes and effects analysis (FMEA), strongly recommending that the FMEA should be used in the prevention and detection of medication errors. In 2001, the JCAHO emphasized improvement of patient safety in healthcare organizations and promoted using the FMEA as a tool to reduce medical risks. Meanwhile, the Department of Veterans Affairs’ National Center for Patient Safety (NCPS) developed health care failure mode and effect analysis (HFMEA) in 2002 to analyze patient safety in the veterans health care system in the United States. The results suggested that HFEMA should be used to analyze medical systems with high risks. During the past few years, FMEA has become a risk process management analysis method that is widely used by the medical industry in the United States. In 2003, Hilborne proposed using both RCA and FMEA to improve medical quality and urged that FMEA be the medical risk assessment method. Furthermore, the JCAHO officially listed HFMEA as an official standard in 2003 with the expectation that every medical care unit improve high-risk processes.

HFMEA combines the advantages of FMEA, hazard analysis and critical control point (HACCP), and RCA, which is a process improvement method covering hazard score matrix, severity assessment criteria, occurrence assessment criteria, decision tree, action, effect feedback and management unit approval. When a medical system is being assessed, experts with different expertise would find the failure modes, causes, severity, incidence and effects together; the team then decides whether actions or measures are needed to improve the failure based on the decision tree; the improvement measures conducted need to be approved by management units, and the effects need to be assessed regularly in order to be used as a reference for the process. The above method is highly appropriate for application in the improvement of medical-related processes.

The risk priority number (RPN) traditionally used in the HFMEA is the number obtained by multiplying the values of two determining factors, the incidence and the severity of the potential problem. However, the value of each factor is determined and obtained by converting linguistic description to numeral score, for which people often question its objectivity. On the other hand, fuzzy theory converts linguistic or colloquial descriptions into a fuzzy set and uses a series of systematic fuzzy operations to transfer linguistic or colloquial description into applicable information. Therefore, fuzzy theory is used in research along with the TOPSIS method in multiple criteria decision making (MCDM) to rank the failure risks in the HFMEA. The purpose of the research is to provide an alternative method to assess the failure risks of the HFMEA while improving the quantitative conversion issue of the decision-making factors in the HFMEA described above. It is hoped that the processes that need urgent improvements can be found.

2. Methods

HFMEA is divided into five steps: defining the HFMEA topic, assembling the executive expert team, graphically describing the process, conducting a hazard analysis and the final step, actions and measures (NCPS, 2001). After integrating fuzzy theory with the TOPSIS method, the steps were modified for this study as shown in Fig. 1. First of all, HFMEA was used to analyze the important factors that caused inconveniences of elderly patients during the registration process in the outpatient department. The data obtained from the observations were then transformed into fuzzy numbers. The fuzzy functions were selected to carry out defuzzification to quantify and define the functions. Next, the TOPSIS method was used to calculate the distance of the assessment attributes from the positive and negative ideal solutions, calculate the relative performance indices and rank the assessment indices to understand the importance level of each assessment index in the experts’ decision-making process (Fig. 1).

2.1. Defining the HFMEA topic

The first step in the HFMEA is to select the medical processes with high risks. Perrows used complexity and tight or loose coupling level to categorize the systems and found that accidents are more prevalent in the systems with higher complexity and tighter or looser coupling level. The topic of the research was based on the results of the improvement of the outpatient service for elderly patients in Taiwan, based on the Perrows’ principle, which was done by Kuo and colleagues. The method of the research was first to extract medical treatment-seeking needs of elderly patients and design the geriatric outpatient service process. Next, the ANP was used to calculate the weights of the elderly patients’ needs. The relation matrix was established by the correlation between the needs matrix and the correlation matrix. The three matrixes were then combined into a super matrix. After

![Fig. 1. Research steps.](image-url)
limiting the super matrix, the crucial geriatric outpatient services were obtained.10

2.2. Assembling the team

After one or more high-risk geriatric outpatient services were selected, the next step was to assemble the executive team. The team consists of seven different experts who were doctors and nurses in the geriatrics field, registered nurses, and medical administration staff in the medical quality field. Only through cross-field brainstorming and continuous exchange of ideas can HFMEA be truly applied in improving the geriatric outpatient service.

2.3. Graphically describing the process

After defining the HFMEA topic and confirming the subject to be drawn was the geriatric outpatient service process, the draft process was constructed according to the steps, and every service process was numbered in order. If the process was highly complicated, then the process may be expanded to several subprocesses. The subprocess that impacts the patients the most or has the highest failure occurrence was set to be the key analysis point. Finally, the team members examined the authenticity and accuracy of the process.

2.4. Conducting a hazard analysis

2.4.1. List failure modes

The possible failure modes of each outpatient service process were listed, and the possible potential failure modes of all sub-processes were found and numbered in order.

2.4.2. Calculate hazard index

The severity, probability, and hazard assessment of each failure mode were determined, and the hazard indices were calculated.

The possible modes that led to geriatric outpatient service failures and the causes and effects of the potential failures were listed. Next, the severity and probability of the failure modes occurring were assessed, and the table for the hazard score matrix was constructed. The evaluation step was to create risk assessment for the new fuzzy data that were obtained by converting the original data conducted by fuzzy functions. The decision tree analysis supported decision on whether any action was needed. Finally, the TOPSIS method was utilized to obtain risk ranking to understand the failure modes that needed to improve most.

Wang and Mendel (1992) proposed that linguistic variables can be represented in the form of linguistic terms and a linguistic variable can be represented by a fuzzy number. In general, a linguistic variable includes four pieces of data: name, class, range and degree. As the assessment was based on not crisp values, complicated operations and inappropriately expressed linguistic variables were often encountered.11 Therefore, the method proposed by Chen and Huang was applied in the current study.12 Based on the severity and probability of the failure modes, four linguistic term collections were designed to collect the assessment data done by each team member.

As different assessors had different perceptions and opinions towards the same statement and the range defined by each assessor was different, the mean of each assessment data was used to carry out the integration of fuzzy judgment. The equation is shown as follows:

$$E_{ij} = (1/m) \circ \left( E_{ij} \oplus E_{ij} \oplus \ldots \oplus E_{ij} \right) \tag{Equation 1}$$

where $\circ$ represents fuzzy number multiplication, $\oplus$ represents fuzzy number addition, and $E_{ij}$ represents the mean of m assessors’ fuzzy judgments for project $i$ to reach the degree of criteria $j$, which can be represented using the triangular fuzzy numbers shown below:

$$E_{ij} = (LE_{ij}, ME_{ij}, UE_{ij}) \tag{Equation 2}$$

The endpoint values in the above equation, $LE_{ij}$, $ME_{ij}$ and $UE_{ij}$, can be obtained using the equations proposed by Buckley13:

$$LE_{ij} = \left( \frac{\sum_{k=1}^{m} LE_{ij}^k}{m} \right) \tag{Equation 3}$$

$$ME_{ij} = \left( \frac{\sum_{k=1}^{m} ME_{ij}^k}{m} \right) \tag{Equation 4}$$

$$UE_{ij} = \left( \frac{\sum_{k=1}^{m} UE_{ij}^k}{m} \right) \tag{Equation 5}$$

$LE$ represents the lower bound of triangular fuzzy number, $ME$ represents the middle bound of triangular fuzzy number, and $UE$ represents the upper bound of triangular fuzzy number.

After rating the linguistic variables of the decision-making factors in each failure mode and selecting the fuzzy functions, we must conduct defuzzification on these linguistic variables to quantify and define them. In this study, simple center of area defuzzification was used. Based on the research done by Tseng and Klein,14 the membership function of the fuzzy set $A$ was assumed to be $u_A(x)$. When the fuzzy number was a triangular fuzzy number, the triangular fuzzy number was assumed to be $A_i = (L_i, M_i, U_i)$, for which the equation was:

$$F_i = \left( \frac{(U_i - L_i) + (M_i - L_i)}{3} \right) + L_i, \forall i \tag{Equation 6}$$

Before ranking took place, the matrix had to normalized, for which the equation used was:

$$v_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{Equation 7}$$

In the normalized matrix, $Vij$ represents the normalized valued of the $j$-th factor in the $i$-th failure mode and $Xij$ represents the fuzzy value of the $j$-th factor in the $i$-th failure
mode. Next, the ideal solution and the negative-ideal solution must be determined (as in Equations 8 and 9, respectively).

\[
A^* = \{ (\max_{i} v_{ij} | j \in J), (\min_{i} v_{ij} | j \in J') | i = 1, 2, \ldots, m \} = \{ v_{i1}^*, v_{i2}^*, \ldots, v_{in}^* \}
\]

(Equation 8)

\[
A^- = \{ (\min_{i} v_{ij} | j \in J), (\max_{i} v_{ij} | j \in J') | i = 1, 2, \ldots, m \} = \{ v_{i1}^-, v_{i2}^-, \ldots, v_{in}^- \}
\]

(Equation 9)

As the HFMEA uses the degree of influence of the failure as the priority of the improvement order, the closer to the ideal solution means the higher the influence, which means the failure mode needs to be improved first. The equations for calculating the separation degree between each failure mode and the ideal solution \(S_i^+\) and the negative-ideal solution \(S_i^-\) were:

\[
S_i^+ = \sum_{j=1}^{n} (v_{ij} - v_j^*)^2, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n
\]

(Equation 10)

\[
S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n
\]

(Equation 11)

After understanding the separation degree between each failure mode and the ideal solution and the negative-ideal solution, the relative approach degree between each failure mode and the ideal solution was calculated. The equation used was:

\[
C_i = \frac{S_i^-}{S_i^+ + S_i^-}
\]

(Equation 12)

2.4.3. Using a decision tree

To determine whether any action was needed for the failure modes, the decision tree was used to decide whether the final outcome was to take action or to stop (Fig. 2).

2.4.4. Causes for the failure modes that require action

If further improving action was needed, then the causes for the failure modes were found.

2.5. Actions and measures

Finally, the failure factors in this step were investigated and solutions were discussed by all relative staff while the measurement method or index that was used to assess the effect of the solutions was defined.

3. Results

3.1. Geriatric outpatient service process

After confirming the target processes drawn by the team of experts, it appeared the geriatric outpatient registration process had 11 processes (Fig. 3).

3.2. Selecting and rating the failure modes

According to research done by Kuo and colleagues (2011), the key factors to elderly patients’ outpatient needs are “The doctor did not explain the patient’s condition in detail” and “The doctor’s professional ability is insufficient.” Based on the conclusion above, the team of experts discussed and listed the main failure modes of the geriatric outpatient service process: (a) short consultation time, (b) primary diagnosis or differential diagnosis was not told, (c) possible checkup or treatment guideline was not told, (d) unclear explanation of possible complication of the checkups or treatment, (e) opinions and feelings of patients and relatives were not respected, (f) insufficient qualification/experience of doctors, (g) ambiguous or irresponsible answers reply to patients’ questions, (h) patient symptoms were not improved, or complications were formed, and (o) insufficient in-service training of doctors.10

When rating the factors, the hazard analysis matrix was used and the weight of each factor was assumed to be the same. The terms used to rate the severity and probability in the
HFMEA were divided into a four-point scale. The scale of probability was defined as frequent (F), occasional (O), uncommon (U), or remote (R), and the severity as catastrophic (C), major (MA), moderate (MO), or minor (MI). As each expert had different perception and opinion toward the same statement and ranking scales, they were asked to fill in the four scale intervals from 0 to 1. The measurements were put in Equations (1) to (5). After calculation, the numbers were converted to triangular fuzzy numbers. The probability rating of linguistic variables and their fuzzy numbers were F (0.967, 0.82, 0.783), O (0.700, 0.608, 0.517), U (0.433, 0.333, 0.233), and R (0.150, 0.075, 0.000). After defuzzifying, the scales of probability were modified as F (0.881), O (0.608), U (0.333), and R (0.075). Additionally, the severity rating of linguistic variables and their fuzzy numbers were C (1.000, 0.917, 0.833), MA (0.750, 0.658, 0.567), MO (0.483, 0.392, 0.300), and MI (0.217, 0.117, 0.017). After defuzzifying, the scales of severity were C (0.917), MA (0.658), MO (0.392), and MI (0.117). Finally, Equation (6) was used to defuzzify the numbers; after multiplying the numbers together, a new hazard matrix was obtained (Table 1).

Next, decision tree analysis was applied to determine whether any improving action was needed. Can the occurrence and severity of the hazard be controlled in the beginning of the decision tree? The fuzzy hazard index established in this study was larger or equal to 0.219, and the standard score selected in the research was the medium. Based on the results in the decision tree analysis, it can be seen from Table 2 that further action suggestions were needed for three failure modes: V1 “short consultation time,” V4 “unclear explanation of possible complication of the checkups or treatment,” and V5 “opinions and feelings of the patients and relatives were not respected” (Table 2).

3.3. Risk ranking of the failure modes

Before ranking the three failure modes by the TOPSIS method, the matrix had to be normalized. After calculating with Equation (7), the normalized rates of severity and probability for the three-failure mode were V1 (0.652, 0.786), V4 (0.388, 0.542), and V5 (0.652, 0.297).

Next, the TOPSIS method was used to rank the three failure modes. The ideal solution and the negative-ideal solution were, respectively:

Ideal Solution : \( A^+ = \{0.652, 0.786\} \)

Negative – ideal Solution : \( A^- = \{0.388, 0.297\} \).

The values of the three failure modes were put in Equation (10) and Equation (11) to obtain the separation degree between each failure mode and the ideal solution and the negative ideal solution. The ideal solution and the negative-ideal solution with respect to the separation degree of each failure mode were V1 (0, 0.623), V4 (0.359, 0.245), and V5 (0.489, 0.264).

After obtaining the ideal solution and the negative-ideal solution with respect to the separation degree of each failure mode, Equation (12) was used to calculate the relative approach degree between each failure mode and the ideal solution.

Based on the relative approach degrees between the three failure modes and the ideal solution, the improvement priority ranking obtained was: V1 “short consultation time” (1) > V4

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### Table 1

| Fuzzification of hazard scoring matrix. |
|--------------------------|-----------------|-----------------|-----------------|-----------------|
| **Severity of effect**   | **Catastrophic** | **Major**       | **Moderate**    | **Minor**       |
| Probability              | Frequency       | Occasional      | Uncommon        | Remote          |
| Frequent                 | 0.808           | 0.588           | 0.305           | 0.069           |
| Occasional               | 0.558           | 0.400           | 0.219           | 0.049           |
| Uncommon                 | 0.305           | 0.219           | 0.131           | 0.029           |
| Remote                   | 0.069           | 0.049           | 0.029           | 0.009           |

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“unclear explanation of possible complication of the checkups or treatment” (0.406) > V5 “opinions and feelings of the patients and relatives were not respected” (0.351).

### 3.4. Developing improving action and measurement

The top three failure modes ranked by the TOPSIS method were “short consultation time,” “unclear explanation of possible complication of the checkups or treatment,” and “opinions and feelings of the patients and relatives were not respected.” After the team discussion, suggestions/improvement (Table 3) were proposed to the hospital in which this study was conducted. Suggestions/improvement were also expected to feedback more widely toward any type of hospital.

To determine whether the suggested/proposed improvements would be effective, a random sample of 40 elderly patients was selected for interviews at the outpatient department of the hospital in which this study was conducted. For the duration of 1 month (4 weeks), an outpatient service was selected every week and 10 elderly patients (older than 65) were randomly selected from each outpatient service to conduct the interview. The selected patients were asked if they agreed with the causes of the outpatient service failures proposed by the research and whether the improvements would help in modifying the outpatient service. The result, from the answers of 40 aged patients, showed that 37 of the patients (92.5%) agreed with the research, which meant the suggested/proposed improvements would be effective (Table 3).

In conclusion, HFMEA is a structured programming system. The aims of its use are to find the potential failure modes that may put patient safety at risk in advance, discuss the failure causes and the influence on the branch system, the subsystem, and the system above if the failure occurs, and adopt appropriate preventive measures and improvements to increase patient safety. In this study, the application of HFMEA was extended to discover the impacts of geriatric outpatient service process failures on elderly patients as assessment factors. Fuzzy theory and the TOPSIS method were introduced to rank the severity of the failure modes so that the risk assessment of the geriatric outpatient service process was analyzed more objectively by quantitative data. Moreover, the decision-making factors could be adjusted according to the characteristics of the analysis target without
limitation of the three determining factors of the risk priority number or the five key factors in the criticality score evaluation. Also, it ensured different natures of decision-making factors coexisting, while qualitative and quantitative factors could be dealt with simultaneously.

From the research result, it was found that the failure modes that needed improvement were “short consultation time,” “unclear explanation of possible complications of the checkups or treatment,” and “opinions and feelings of the patients and relatives were not respected.” The suggestions for improvement proposed for the above failure modes by the expert team were to “reduce quantity of outpatient services or make changes to outpatient appointment form,” “special assistant for patient instruction, to accompany family members, or learning skills to communicate with elderly,” and “general training in geriatrics for doctors and deeply understanding concepts about sickness and living standards of the elderly.” After verification, 92.5% of the elderly patients surveyed agreed with the above suggestions, showing the improvements meet the needs of elderly patients. Furthermore, the analysis models used in this study can be expanded to other medical processes, and the results may be provided to hospitals as reference. For example, the models can be used to reduce medication error probability, improve standard operation procedures, and maintain patient transport safety.

4. Discussion

4.1. Fuzzy set theory and HFMEA

Fuzzy set theory was proposed by Zadeh in 1965. Different from the crisp set and crisp value in traditional mathematics, Zadeh proposed the fuzzy set and the membership degree to represent the quantification of meaning and used them to deal with the uncertainty and fuzziness in real circumstances. Zadeh believed subjective opinion, speculation, or perception had certain degrees of fuzziness and many traditional accurate quantitative methods and probability calculations were no longer capable of solving human logic and other complicated problems. Therefore, the traditional quantitative methods had to be replaced by the analytical methods in fuzzy mathematics to solve this type of problem. The RPN in traditional HFMEA is obtained by multiplying the three decision-making factors, severity, incidence, and detection. Although it transforms quality to quantity, it is often difficult for members in a team to give correct score. To improve the qualitative issues of the factors in the RPN, fuzzy operations were conducted to transform each factor from non-crisp linguistic degree to a score or the fuzzy association memory (FAM) neural network was utilized to calculate the risk.

4.2. TOPSIS and HFMEA

The TOPSIS method is a multiple criteria assessment method developed by Hwang and Yoon in 1981. It was developed to improve Zenley’s concept which of the compromise solution should be closest to the ideal solution. The TOPSIS method is suitable for use in circumstances where the assessment values can be quantified. It uses “the distance closest to the ideal solution yet the farthest away from the negative-ideal solution” as the basis for choosing between the alternative proposals. This assessment method assumes every criterion is monotone increasing or monotone decreasing. If the criterion is a benefit criterion, then the performance value would be larger and the preference value would also be larger. On the contrary, if the criterion is a cost criterion, the performance value would be smaller. An “ideal solution” is composed of the optimum values of all criteria, whereas a “negative-ideal solution” is composed of the worst values of all criteria. The selection of alternative proposals is based on Euclidean distance. The relative approach degree of each proposal in relation to the ideal solution was calculated and used as the standard for the selection. As the TOPSIS method is not very difficult to utilize, it has been widely applied in the selection of different types of decision-making problems. Thus, the TOPSIS method was adopted in this study as the ranking method for the failure risks found by the HFEMA.

4.3. Limitations

Although process had tried to remain objective, there are still some limitations of the current study. The target of this research included elderly patients over 65 years of age. Many of them refused to be interviewed. Also, a portion of interviewees needed to increase their ability to understand the questionnaire. Getting effective samples was more difficult than usual. Gay’s definition (1992) of sampling indicates that 30 samples are enough to represent the group. Thus, the number of samples was chosen to be 40 for this study. On the other hand, it took more time to explain the failure model and improvement proposals to elderly patients. When asking questions about degree of agreement improvement proposals, the questions were simplified to yes/no questions. Therefore, the results can only be reported as percentages in the statistics.

References


