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ORIGINAL ARTICLE

Quality function deployment based failure mode and effect analysis approach for risk evaluation

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Abstract

The traditional failure mode and effect analysis (FMEA) aims to define the risk priority number of each failure mode by multiplying occurrence, severity and detection parameters of each failure mode. Many studies in the literature commented the traditional FMEA due to its limitations such as equal importance degrees, discrete ordinal scales and multiplication of *O*, *S* and *D* criteria. This study suggests coping with these drawbacks a new method, which combines the quality function deployment (QFD) method under interval type-2 fuzzy set, Bayesian network and VIKOR method. The previous studies generally handle to rank the failure modes as only goal. This paper investigates concurrently the failure modes and the reasons of failure modes. QFD method provides us this benefit by employing customer requirements (CRs) and design requirements (DRs). CRs are the reasons of failure modes while DRs are failure modes. This study presents a new perspective to examine the correlations of CRs and DRs as linguistic terms by using Bayesian network. The VIKOR method deals with ranking the failure modes by aggregating the weights of O, S and D criteria. The developed method is utilized for risk evaluation of tile and marble works in building construction. The result shows that the most significant design requirement or failure mode is DR14 (unsuitable plug-socket utilization).

Keywords Quality function deployment · Risk evaluation · VIKOR · Interval type-2 fuzzy number · Bayesian network

1 Introduction

Occupational health and safety concept is the main consideration of the life safety. Human needs are endless. The next need arises as every need is met. The life right must first be secured before all needs are met. Conditions such as occupational accidents, injuries, deaths and occupational diseases have increased with industrialization so that they have led to the occupational health and safety concept. It has been understood that the main way to success is to invest in human life. Occupational accidents are not related to only the employees, but also to the family, the firm and the government. Those who are exposed to occupational accidents and occupational diseases are employees but also have costs for the company and society. The material and moral difficulties experienced by the family of the person who suffered occupational accidents. The companies suffered serious financial losses due to occupational accidents. The state lost both the healthy and producing labor force and the financial losses. These three parties were damaged as a result of these accidents. Occupational Accident and Occupational Diseases Statistics prepared and published by Social Security Institution in 2015 show that 14% of occupational accidents occur in the construction sector [18].

The construction sector affects other sectors and is the locomotive sector in the economic growth of the countries. Therefore, the construction sector presents a significant role in developed and developing countries. The construction sector, which is labor intensive, uses various electrical equipment. Impacts of occupational hazards in construction sector are higher than in other sectors. The housing sector is one of the most important areas of the

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construction sector. One of the important indicators reflecting the developments in the housing sector is the data related to the building license showing the beginning of the construction constructions. Seventy million m^2 and 202 million m^2 areas are granted a license for 2004 and 2016 in Turkey, respectively. This change means that it is carried out in a broader area of new construction. With the increase in the number of employees in the construction sector and the development of the sector, the risk of occupational accidents has increased. The rate of fatal occupational accidents occurred in Turkey rose to 30% in the construction sector and higher rates after 2009 [10].

Failure mode and effects analysis (FMEA) is a widely utilized risk assessment method to identify and eliminate potential defects in manufacturing and service systems. The failure mode is defined as the situations in which a potential failure may occur in the part, subsystem, system or process when performing the design purpose [7].

FMEA is a method prioritizing the failure modes that will provide the greatest contribution to the overall system so that it ensures to prevent the improvements for hundreds of failure modes with little contribution. However, data compilation and analysis for hundreds of failure modes with little contribution also require great time and labor. Data compilation and analysis is important for pre-screening at the start of FMEA since it will increase the effectiveness of FMEA. FMEA may be required for many parts during the design phase; the proposed model will also shorten product planning and planning time. FMEA is an analysis technique, which aims to prevent failure modes by estimating the risks. It is based on the principle of perceiving the problem that will arise with the emergence of the failure mode as a customer. Occurrence, severity and detection parameters are estimated for all failure modes identified in the FMEA study.

In an exemplary FMEA process, the process is first defined in all its stages. Possible failure modes that may occur during the process are identified and the causes of these failure modes are determined. By making use of past events, the occurrence of failure mode is determined. As a result of the failure mode, what the severity of the event will be is determined. The detection score of the failure mode is made by taking into account the failure mode or the methods used to discover the cause of this failure mode. The risk priority number (RPN) value for each failure mode is obtained by multiplying the values of occurrence, severity and detection parameters. This value can also be defined as the relative importance of the failure mode and is used to determine which failure mode is more important.

Equation (1) introduces the formulation of RPN [15].

$$\mathrm{RPN} = O \times S \times D \tag{1}$$

Many papers presented various methods to overcome the limitations of the traditional FMEA. These papers about FMEA are summarized in Table 1. RPN includes O, S and D parameters and its value is achieved by the multiplication of these parameters. The existing papers ignored the relationship between failure modes and the reasons of failure modes. This work suggested the QFD method to cope with this drawback. The QFD method tackles the correlations of design requirements (DRs) and customer requirements (CRs), relationship between CRs and DRs. In this paper, CRs and DRs explain the reasons of failure modes and failure modes, respectively. This paper supplies to tackle the relation between the reasons of failure modes and failure modes for each parameter O, S and D by employing the QFD method unlike other papers. In the result of the QFD method, this study achieves three rankings including the O, S and D rankings of failure modes. This paper uses VIKOR approach to integrate these rankings in order to obtain only one ranking. Interval type-2 fuzzy (IT2F) numbers are employed in the QFD method and the weights of O, S and D parameters to collect the judgments of the experts. IT2F numbers are used to reduce the loss of information in opinions of experts about the relationship and correlations of CRs and DRs. IT2F numbers allow experts to present their opinions more accurately. This work also introduces a new method, which integrates Bayesian network, VIKOR method and IT2F set-based QFD method, for risk evaluation based on FMEA. This paper handles Bayesian network approach to examine the correlations of CRs and DRs. The utilization of Bayesian network for the correlations contributes to the QFD literature. This study investigates the ranking of the failure modes in risk evaluation based on FMEA. Experts offer their judgments about correlations of DRs and CRs, relationship between CRs and DRs for each parameter O, S and D by employing IT2F numbers. The opinions of each expert are aggregated by using IT2F numbers operations. The quality function deployment (QFD) method is used to define the weights of failure modes and this operation is realized for each parameter O, S and D. These weights are utilized to evaluate O, S and D parameters-based failure modes in the VIKOR (VIsekriterijumska optimizacija i KOm-promisno Resenje) method. This work proposes to use the VIKOR method in order to rank the failure modes. This paper proposes to use Bayesian network to investigate the correlations among CRs and the correlations among DRs in the QFD method as main difference from the other studies. The priority value of each DR can be modified in the outcome of effect of the other DRs. The priority value of each CR can be modified in the outcome of effect of the other CRs. Bayesian network is a benefit approach to investigate the effects among criteria. Bayesian network

Table 1 Papers about FMEA in the literature

Authors	Methods
Efe et al. [8]	Fuzzy PROMETHEE (Preference ranking organization method for enrichment evaluation)
Zhou and Thai [21]	Fuzzy and grey theories
Jiang et al. [11]	Fuzzy evidential method
Efe et al. [7]	Linear programming, AHP and VIKOR under intuitionistic fuzzy set
Chen and Deng [3]	Dempster–Shafer evidence theory and grey relational projection method
Ghoushchi et al. [9]	Fuzzy best–worst method, multi-objective optimization by ratio analysis based on the Z-number theory
Efe [5]	Quality function deployment and VIKOR based on intuitionistic fuzzy numbers
Li et al. [13]	MULTIMOORA under interval-valued intuitionistic fuzzy numbers
Liu et al. [15]	Grey relational analysis method
Liu et al. [16]	MABAC method under interval-valued intuitionistic fuzzy set
Liu and Deng [14]	D numbers theory
Cao and Deng [2]	Geometric mean method based on information quality
Qin et al. [19]	Interval type-2 fuzzy-based evidential reasoning method
Wang et al. [20]	Extended matter-element model and AHP
Zhu et al. [22]	Regret theory and PROMETHEE under linguistic neutrosophic context

uses conditional probability values for relations among criteria. Bayesian network purposes to determine the correlations of CRs and DRs as the linguistic terms. These linguistic terms are transformed to interval type-2 fuzzy numbers. This study contributes to the current literature as follows:

- Bayesian network is used to examine the correlations of CRs and DRs in QFD approach. This presents a novel approach by integrating Bayesian network and QFD method.
- This study deals with overcoming the limitations of the traditional FMEA by employing a novel method, which is QFD method under IT2F set, Bayesian network and VIKOR method.
- The existing papers generally examine only failure modes. This paper focuses on simultaneously the failure modes and the reasons of failure modes. The QFD method ensures this advantage by using CRs (the reasons of failure modes) and DRs (failure modes).

This study includes five sections. The handled IT2F set operations are introduced in Sect. 2. The handled IT2F number-based QFD method, Bayesian network and VIKOR method are submitted in the third section. Section four focuses on an application of the offered method. The last section offers the achieved conclusions.

2 Preliminaries

$\tilde{\tilde{A}}_1$ and $\tilde{\tilde{A}}_2$ are trapezoidal IT2F numbers [6], where $\tilde{\tilde{A}}_1 = (\tilde{A}_1^U, \tilde{A}_1^L) = ((a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)), (a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)))$ and $\tilde{\tilde{A}}_2 = (\tilde{A}_2^U, \tilde{A}_2^L) = ((a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1(\tilde{A}_2^U), H_2(\tilde{A}_2^U)), (a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1(\tilde{A}_2^L), H_2(\tilde{A}_2^L)))$.

$\tilde{A}_1^U$ and $\tilde{A}_1^L$ present the upper and lower bounds of $\tilde{\tilde{A}}_1$, respectively. $a_{11}^U, a_{12}^U, a_{13}^U$ and a_{14}^U are upper bounds of $\tilde{\tilde{A}}_1$ so that the ranking is $a_{11}^U \le a_{12}^U \le a_{13}^U \le a_{14}^U$. $a_{11}^L, a_{12}^L, a_{13}^L$ and a_{14}^L are lower bounds of $\tilde{\tilde{A}}_1$ so that the ranking is $a_{11}^L \le a_{12}^L \le a_{13}^L \le a_{14}^L$. $H_1(\tilde{A}_1^L)$ and $H_2(\tilde{A}_1^L)$ are the first and the second membership degrees for lower bounds of $\tilde{\tilde{A}}_1$. Some transactions among two IT2F numbers are presented in Eqs. (2–5) [6]:

$$\begin{aligned}\tilde{\tilde{A}}_1 \oplus \tilde{\tilde{A}}_2 &= (\tilde{A}_1^U, \tilde{A}_1^L) \oplus (\tilde{A}_2^U, \tilde{A}_2^L)\\ &= ((a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U;\\ &\min\{H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\}), (a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L,\\ &a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; \min\{H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\})) \end{aligned} \tag{2}$$

$$\begin{aligned}\tilde{\tilde{A}}_1 \otimes \tilde{\tilde{A}}_2 &= (\tilde{A}_1^U, \tilde{A}_1^L) \otimes (\tilde{A}_2^U, \tilde{A}_2^L)\\ &= ((a_{11}^U \times a_{21}^U, a_{12}^U \times a_{22}^U, a_{13}^U \times a_{23}^U, a_{14}^U \times a_{24}^U;\\ &\min\{H_1(\tilde{A}_1^U), H_2(\tilde{A}_1^U)\}), (a_{11}^L \times a_{21}^L, a_{12}^L \times a_{22}^L,\\ &a_{13}^L \times a_{23}^L, a_{14}^L \times a_{24}^L; \min\{H_1(\tilde{A}_1^L), H_2(\tilde{A}_1^L)\})) \end{aligned} \tag{3}$$

$$\begin{aligned}k \times \tilde{\tilde{A}}_1 &= k \times (\tilde{A}_1^U, \tilde{A}_1^L)\\ &= ((k \times a_{11}^U, k \times a_{12}^U, k \times a_{13}^U, k \times a_{14}^U; H_1(\tilde{A}_1^U)), (k\\ &\times a_{11}^L, k \times a_{12}^L, k \times a_{13}^L, k \times a_{14}^L; H_1(\tilde{A}_1^L))) \end{aligned} \tag{4}$$

where $k > 0$.

$$(A_1^{\approx})^k = (\tilde{A}_1^U, \tilde{A}_1^L)^k = (((a_{11}^U)^k, (a_{12}^U)^k, (a_{13}^U)^k, (a_{14}^U)^k; H_1(\tilde{A}_1^U)), ((a_{11}^L)^k, (a_{12}^L)^k, (a_{13}^L)^k, (a_{14}^L)^k; H_1(\tilde{A}_1^L))) \quad (5)$$

Equations (2–5) present the addition, multiplication, multiplication with crisp number k and exponent operations. The rank value of $\tilde{\tilde{A}}_i$ is calculated by using Eq. (6) [12]:

$$\begin{aligned}\text{Rank}\left(\tilde{\tilde{A}}_i\right) = {} & M_1(\tilde{A}_i^U) + M_1(\tilde{A}_i^L) + M_2(\tilde{A}_i^U) + M_2(\tilde{A}_i^L) \\ & + M_3(\tilde{A}_i^U) + M_3(\tilde{A}_i^L) \\ & - \frac{1}{4}\big(S_1(\tilde{A}_i^U) + S_1(\tilde{A}_i^L) + S_2(\tilde{A}_i^U) + S_2(\tilde{A}_i^L) \\ & + S_3(\tilde{A}_i^U) + S_3(\tilde{A}_i^L) + S_4(\tilde{A}_i^U) + S_4(\tilde{A}_i^L)\big) \\ & + H_1(\tilde{A}_i^U) + H_1(\tilde{A}_i^L) + H_2(\tilde{A}_i^U) + H_2(\tilde{A}_i^L)\end{aligned} \quad (6)$$

$M_p\left(\tilde{A}_i^j\right)$ shows the mean value.

$$M_p(\tilde{A}_i^j) = \left(a_{ip}^j + a_{i(p+1)}^j\right)/2, \ 1 \le p \le 3.$$

$S_q\left(\tilde{A}_i^j\right)$ shows the standard deviation value.

$$S_q(\tilde{A}_i^j) = \sqrt{\frac{1}{2}\sum_{k=q}^{q+1}\left(a_{ik}^j - \frac{1}{2}\sum_{k=q}^{q+1} a_{ik}^j\right)^2}, \ 1 \le q \le 3,$$

$$S_4\left(\tilde{A}_i^j\right) = \sqrt{\frac{1}{4}\sum_{k=1}^{4}\left(a_{ik}^j - \frac{1}{4}\sum_{k=1}^{4} a_{ik}^j\right)^2}.$$

$H_p\left(\tilde{A}_i^j\right)$ shows the membership degree of the element $a_{i(q+1)}^j$ in $\tilde{A}_i^j$, $1 \le p \le 2, j \in \{U, L\}$, and $1 \le i \le n$.

If

$$\tilde{\tilde{A}} = (\tilde{A}^U, \tilde{A}^L) = ((a_1^U, a_2^U, a_3^U, a_4^U; h_U), (a_1^L, a_2^L, a_3^L, a_4^L; h_L))$$

is a trapezoidal IT2F number, the lower $\left(M_*(\tilde{A})\right)$ and upper $\left(M^*(\tilde{A})\right)$ possibility mean values are computed by using Eqs. (7–8). h_U and h_L indicate the upper and lower membership degrees, respectively.

$$M_*(\tilde{A}) = \frac{1}{6}(a_1^U + 2a_2^U)h_U^2 + \frac{1}{6}(a_1^L + 2a_2^L)h_L^2 \quad (7)$$

$$M^*(\tilde{A}) = \frac{1}{6}(a_4^U + 2a_3^U)\, h_U^2 + \frac{1}{6}(a_4^L + 2a_3^L)h_L^2 \quad (8)$$

The possibility degree is calculated by using Eq. (9) [6]:

$$p(\tilde{A}_1 > \tilde{A}_2) = \min\left\{\max\left(\frac{M^*(\tilde{A}_1) - M_*(\tilde{A}_2)}{M^*(\tilde{A}_1) - M_*(\tilde{A}_1) + M^*(\tilde{A}_2) - M_*(\tilde{A}_2)}, 0\right), 1\right\} \quad (9)$$

3 Methodology

3.1 Bayesian network

Bayesian theory, which is presented by Thomas Bayes, is employed to evaluate the conditional probabilities. Bayesian network includes a graph theory, which handles a network structure, and probability theory, which handles conditional probability table. Bayesian networks are networks containing probability built on Bayesian theorem allowing us in order to make the inferences about future events by analyzing the events that occurred before a Bayesian network can also be defined as impact diagrams that include utility or value functions and decision maker selection criteria. The relationships between the variables are understood by examining the reasons on each other [17]. Equation (10) shows the formulation of Bayesian network:

$$P(x) = P(x_1, \ldots, x_m) = \prod_{i=1}^{m} P(x_i|\pi_i) \quad (10)$$

π_i = ith parent node.

x_i = ith child node.

$P(x_i|\pi_i)$ = The occurrence probability of ith child node when ith parent node is realized.

Bayesian networks are oriented cycleless diagrams, that is, cycle-free diagrams. A cycle occurs when the path followed by the arrows between the nodes starts at the same node and ends at the same node. Since there is no such situation in Bayesian networks, there is no cycle.

3.2 Quality function deployment

The QFD method struggles with satisfying the customer needs to solve the design quality problems [1]. QFD approach simultaneously focuses on CRs and DRs. QFD approach is a customer-oriented quality methodology that transforms customer demands into measurable performance changes, helping to achieve an optimized process and a good distribution/sales channel. The relationship matrix is called quality house in the quality function deployment. It introduces the relationship between CRs and DRs, which indicates the effects of DRs on the performance of the relevant CRs. Also, the correlation between each DR and the correlation between each CR is shown in the quality house. Using the information specified in the quality house, the design team should determine the priorities of the DRs to ensure maximum customer satisfaction. The QFD process uses the cumulative matrices system known as the house of quality. This conceptual map, like a home, examines information that relates competitive performance and specifications to CRs to help improve the product/service. The quality house measures the relationships between customer expectations, customer priority rates, technical specifications required for the product or service, and performance data related to competitors. This paper used the approach presented by Chen and Chen [4].

$$R_{ij}^{norm} = \frac{\left(\sum_{k=1}^{n} \gamma_{kj}\right) R_{ij}}{\sum_{j=1}^{n}\left(\sum_{k=1}^{n} \gamma_{kj}\right) R_{ij}} \quad (11)$$

γ_{kj} means the correlation between jth DR and kth DR. R_{ij} means the relationship between the ith CR and kth DR. R_{ij}^{norm} means the normalized degree of relationship between the i^{th} CR and k^{th} DR.

$$\mathrm{IR}_i = \frac{\left(\sum_{l=1}^{m} \beta_{il}\right) d_i}{\sum_{i=1}^{m}\left(\sum_{l=1}^{m} \beta_{il}\right) d_i}, \quad i = 1, 2, \ldots, m \quad (12)$$

β_{il} indicates the correlation between ith and jth CRs. d_i is the weight of ith CR. IR_i shows the weight of ith CR-based correlation. AS_j indicates the weight of jth DR.

$$\mathrm{AS}_j = \sum_{i=1}^{m} R_{ij}^{norm} * \mathrm{IR}_i, \quad j = 1, 2, 3, \ldots, n \quad (13)$$

3.3 VIKOR method

The VIKOR method, which focuses on ranking the alternatives, was developed by Opricovic (1998). It aims to define a compromise solution by taking into account the positive and ideal solution as ratio.

Step 1. Define the positive ideal solution $\left(f_j^*\right)$ and negative ideal solution $\left(f_j^-\right)$ for each criteria by using Eqs. (14 and 15):

$$f_j^* = \begin{cases} \max_i r_{ij} & \text{for benefit criteria} \\ \min_i r_{ij} & \text{for cost criteria} \end{cases} \quad i = 1, 2, \ldots, m \quad (14)$$

$$f_j^- = \begin{cases} \min_i r_{ij} & \text{for benefit criteria} \\ \max_i r_{ij} & \text{for cost criteria} \end{cases} \quad i = 1, 2, \ldots, m \quad (15)$$

Step 2. Calculate the values S_i and R_i and Q_i, i = 1,2,…,m by using Eqs. (16–18):

$$S_i = \sum_{j=1}^{n} \frac{w_j \times \left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \quad (16)$$

$$R_i = \max_j \left(\frac{w_j \times \left(f_j^* - f_{ij}\right)}{\left(f_j^* - f_j^-\right)} \right) \quad (17)$$

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*} \quad (18)$$

where $S^* = \min_i S_i$, $S^- = \max_i S_i$, $R^* = \min_i R_i$, $R^- = \max_i R_i$. S_i is the sum of distances to the best value of all criteria for alternative i. w_j shows the weight of j criterion. R_i is maximum distance of alternative i to the worst value for jth criterion. Q_i is calculated by handling group benefit (S_i) and minimum regret (R_i) together.v is presented as a weight for the strategy of maximum group utility, whereas 1-v is the weight of the minimum individual regret. The value of v in Eq. (18) is handled to 0.5 in this study.

Step 3. Rank the alternatives according to the values S, R and Q.

The flowchart of the proposed method is introduced in Fig. 1. This work focuses on handling the correlations of CRs and DRs. The existing papers in the literature generally use the linguistic terms presented by the experts. Then, these linguistic terms are transformed to the related fuzzy numbers. This causes to handle the correlation effects of the other criteria to one criterion separately. This paper aims to examine these correlation effects simultaneously. It ensures to present only one correlation effect to the related criterion. Bayesian network provides to reduce to one correlation effect from many correlation effects. Two parts of QFD method are CRs and DRs. Bayesian network is applied to the correlations of CRs and DRs. This contributes to the related literature integrating Bayesian network and QFD method. Bayesian network obtains the probabilities of five linguistic terms, which are very low, low, medium, high and very high. The linguistic term with the biggest probability is selected as correlation effect. This linguistic term is transformed to IT2F number. The QFD method based on IT2F number is implemented to define the weights of DRs. This study proposes a new approach to cope with the drawbacks of FMEA. It works on risk evaluation for tile and marble works in building construction. FMEA has three criteria, which are O, S and D. The QFD method mentioned above is separately repeated for O, S and D criteria. The obtained three QFD results are combined in the VIKOR method. This provides to achieve only one ranking for DRs instead of three rankings. This contributes to the FMEA literature combining QFD method and FMEA. The current studies generally examine only failure modes. The QFD method also contributes to improve this situation by examining simultaneously the failure modes and the reasons of failure modes. The QFD method uses CRs and DRs as the reasons of failure modes and failure modes in this paper, respectively.

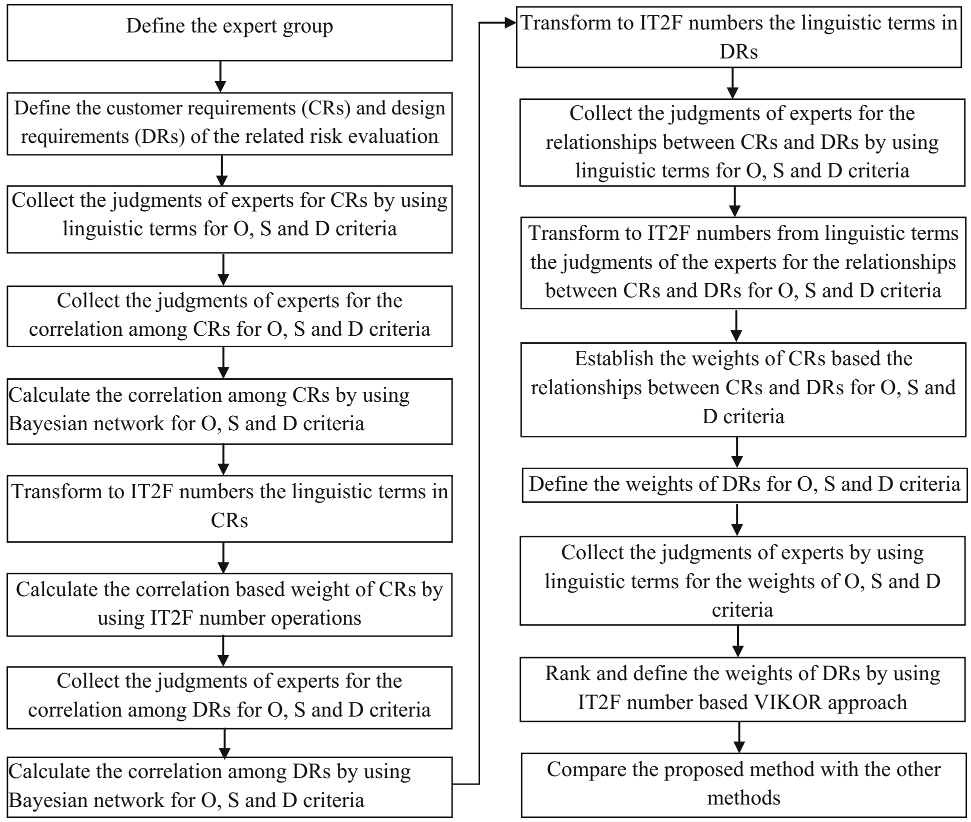

Fig. 1 Flowchart of the proposed approach

4 FMEA for tile and marble works in building construction

There are many potential failure modes in constructions. When these failure modes occur, they bring a high cost to the firm. In order to reduce these costs, it is necessary to create a safe work environment in building construction. Marble is a soft and long-lasting substance. The marble, which has taken its final form with the changes they have shown for centuries, is the product of the chemical reactions that the magma has come to the surface. A system, design, process or service often has many failure modes and effects. In this case, it is necessary to prioritize and evaluate each failure mode and its effect according to the risk values. The type of high risk (or most dangerous) failure mode should be corrected first. The FMEA method is an analysis technique that can detect that failure mode before a failure mode occurs. FMEA is used to eliminate the failure mode or to reduce its effect. In this study, this feature of FMEA is used for risk assessment. This paper focuses on simultaneously the failure modes and reasons of failure modes for tile and marble works in building construction. QFD approach, which includes CRs and DRs, is very useful to handle both parameters, simultaneously. CRs in this study are failure modes for tile and marble works in building construction. These are equipment origin failure modes (CR1), environment origin failure modes (CR2), management origin failure modes (CR3) and worker origin failure modes (CR4). DRs in this study are the failure modes for tile and marble works in building construction. These are falling when carrying material by hand (DR1), falling the material from pallet truck (DR2), tearing of the sack when transporting sharp materials with sacks (DR3), failure of destroyed railings and falling from a height (DR4), dropping of the materials such as tiles, marble when employees are passing through unsafe areas (DR5), gripping on sharp edges of material (DR6), lack of protection of the machines used in cutting works (DR7), broken handles of non-electric hand tools (DR8), contact to skin with the mortar or building chemical (DR9), dust in the environment (DR10), object leakage to the eye (DR11), open electric cable ends (DR12), use of damaged cables (DR13), unsuitable plug-socket utilization (DR14), no grounding (DR15), clutter of electrical cables (DR16), wet floor (DR17), lack of Material Safety Data Sheet forms of chemicals (DR18) and hitting of the exploding stone to the workers when the spiral cutting is realizing (DR19). This study proposes an integrated approach to rank failure modes for tile and marble works in building construction.

4.1 Results

The firm managers want to eliminate the failure modes of tile and marble works in building construction in terms of occupational health and safety. Therefore, they appointed an expert committee of five people who are proficient in occupational safety area. After the first elimination, nineteen failure modes and four reasons of failure modes were analyzed for further evaluation. A team of five experts consists of three occupational health and safety experts (E1, E2 and E3), a site chief (E4) and an academician (E5). Five experts E1, E2, E3, E4 and E5 offered their views about failure modes of tile and marble works in building construction by employing a survey. The importance degrees of the experts are determined by taking into account their information and experimentation so that the importance degrees of the experts E1, E2, E3, E4 and E5 are 0.15, 0.20, 0.25, 0.20 and 0.20, respectively. Experts obtained at least 10 years of experience in risk evaluation.

The judgments of experts are achieved by using the linguistic terms in Table 2. QFD approach aims to find the weights of DRs by using the weights of CRs, correlation among CRs, correlation among DRs, relationships between CRs and DRs. This study also focuses on FMEA approach for failure modes of tile and marble works in building construction. FMEA approach handles three parameters, which are occurrence, severity and detection of failure mode. Table 3 presents the judgments of experts for the weights of CRs without correlation. Table 3 states that the importance degree of CR3 for occurrence criterion according to expert 2 is medium. This paper calculates the correlations and relationships of CRs and DRs for each of these three parameters. This work proposes the Bayesian network method to examine the correlations among CRs and the correlations among DRs. Bayesian network calculations are realized by using Netica programming. Figures 2, 3, 4 and 5 show a graphical structure of Bayesian network for occurrence parameter of CRs according to expert 1. The biggest probability value in each parent node is accepted as the correlation effect value. For example, Fig. 2 means that the biggest probability value of CR1 is %31.6 and very high linguistic term is selected as correlation effect value for occurrence parameter of CR1 according to the judgment of expert 1. Figures 3, 4 and 5 define the biggest probability values of CR2, CR3 and CR4, respectively. These values are handled as correlation effect values for occurrence parameter of CR2, CR3 and CR4 according to the judgment of expert 1. The correlation effects to CRs are calculated by using Bayesian network and are indicated in Table 4. The correlation effect to CR3 from the other CRs for severity criterion according to expert 2 is low. Similar operations are repeated for occurrence, severity and detection parameters according to all experts. The importance degrees of CRs with correlation for *O*, *S* and *D* criteria are presented in Table 5. The correlation effects to CR3 from the other CRs for severity criterion according to experts 1, 2, 3, 4 and 5 are *M*, *L*, *H*, *M* and *M*, respectively. These judgments are aggregated by using IT2F number operations in Eqs. (2–5). The correlation effect to CR3 from the other CRs for severity criterion is 0.190 and is presented in Table 5. Figure 6 presents Bayesian network structure for occurrence parameter of DRs according to expert 1. Figure 6 includes 4 parent nodes, which are DR1, DR9, DR11 and DR12. DR3, DR6 and DR10 affect to DR1. DR18 affects to DR9. DR7 and DR19 affect to DR11. DR13, DR14 and DR16 affect to DR12. Figure 6 is used to define the biggest probability values of DR1, DR9, DR11 and DR12. These values are handled as correlation effect values for occurrence parameter of DR1, DR9, DR11 and DR12 according to the judgment of expert 1. Similar operations are repeated for occurrence, severity and detection parameters according to all experts. The correlation effects to DR1, DR9, DR11 and DR12 for occurrence, severity and detection criteria according to experts are calculated by using Bayesian network and are indicated in Table 6. The correlation effect to DR1 from the DR3, DR6 and DR10 for detection criterion according to expert 3 is high. The correlation effects to DR1 from the other DRs for detection criterion according to experts 1, 2, 3, 4 and 5 are *L*, *M*, *H*, *M* and *H*, respectively. These judgments are aggregated by using IT2F number operations in Eqs. (2–5). The correlation effect to DR1 from the other DRs for detection criterion is 0.232 and is presented in Table 7. Table 7 is obtained after the opinions of decision makers in Table 6 are combined and normalized to 1. Table 7 presents the correlation effect to DRs as a group opinion.

Table 2 Linguistic terms

Linguistic terms	IT2F numbers
Very low (VL)	(0.08, 0.11, 0.15, 0.18;0.8), (0.04, 0.09, 0.17, 0.22; 1)
Low (L)	(0.20, 0.25, 0.33, 0.36; 0.8), (0.17, 0.22, 0.38, 0.43; 1)
Medium (M)	(0.40, 0.45,0.54,0.57;0.8), (0.30, 0.40, 0.60, 0.66; 1)
High (H)	(0.77, 0.80, 0.86, 0.90; 0.8), (0.72, 0.75, 0.90, 0.95; 1)
Very high (VH)	(0.95, 0.97, 0.98, 0.99; 0.8), (0.92, 0.96, 0.99, 1.00; 1)

Table 3 Judgments of experts for the weights of CRs without correlation

	O				S				D			
	CR1	CR2	CR3	CR4	CR1	CR2	CR3	CR4	CR1	CR2	CR3	CR4
DM1	*M*	VH	*L*	*H*	*M*	VH	*L*	*H*	*H*	VH	*M*	*H*
DM2	*H*	*M*	*M*	*H*	*H*	*M*	*M*	*H*	*M*	*H*	*M*	*H*
DM3	*L*	*H*	*M*	*H*	*L*	*H*	*M*	*H*	*L*	VH	*M*	*M*
DM4	*M*	VH	*L*	VH	*M*	VH	*L*	VH	*L*	*H*	*L*	VH
DM5	*L*	*H*	VL	*M*	*L*	*H*	VL	*M*	*M*	*H*	VL	*M*

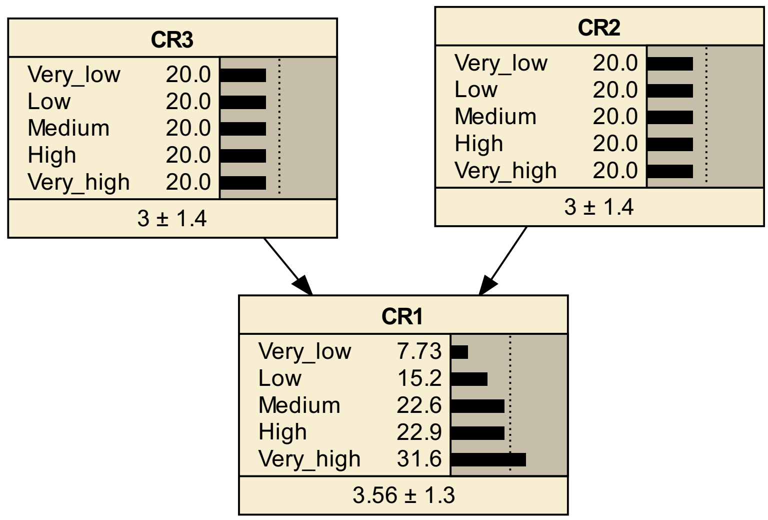

Fig. 2 Bayes network structure for CR1 child node

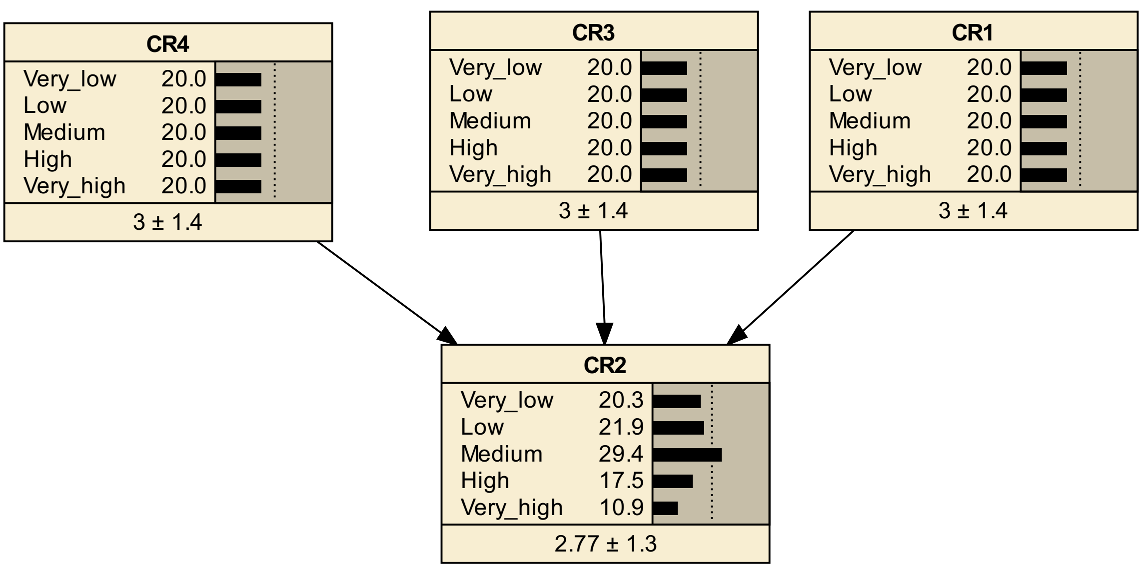

Fig. 3 Bayes network structure for CR2 child node

Tables 8, 9 and 10 introduce the relationships between CRs and DRs for *O*, *S* and *D* criteria, respectively. The relationship between CR1 and DR2 for occurrence criterion according to expert 1 is medium according to Table 8. The relationship between CR1 and DR1 for occurrence criterion according to expert 1 is non-available according to Table 8. Five experts introduce their opinions about the relationships between four CRs and nineteen DRs. The other judgments of five experts for severity and detection criteria are collected in Tables 9 and 10. The relationships between CR1 and DR2 for occurrence criterion according to experts 1, 2, 3, 4 and 5 are medium, low, high, high and

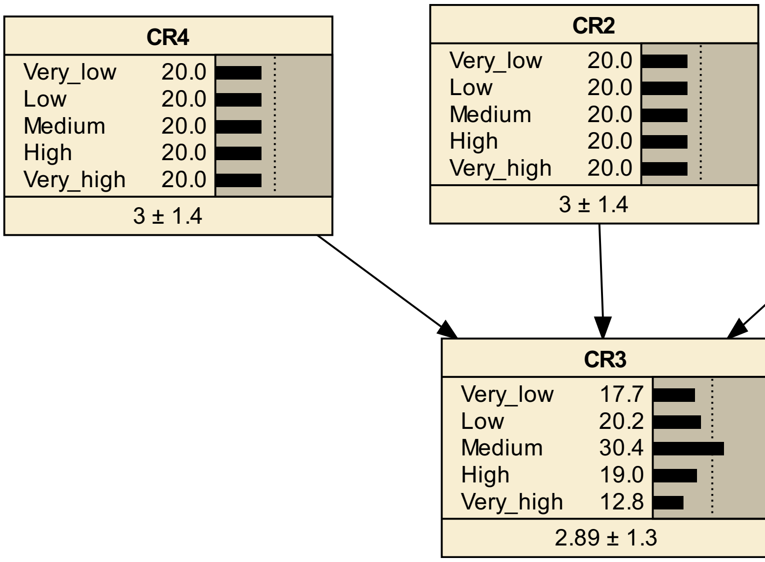

Fig. 4 Bayes network structure for CR3 child node

Fig. 5 Bayes network structure for CR4 child node

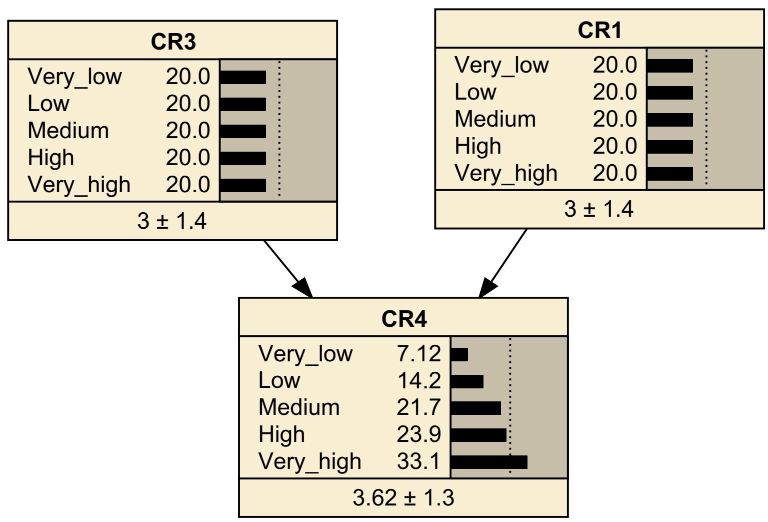

Table 4 Correlation effect to CRs according to experts

	O				S				D			
	CR1	CR2	CR3	CR4	CR1	CR2	CR3	CR4	CR1	CR2	CR3	CR4
E1	VH	*M*	*M*	VH	*H*	*H*	*M*	*M*	*M*	VH	*M*	*M*
E2	*H*	*M*	*H*	*H*	*M*	*H*	*L*	*H*	*M*	*H*	*L*	*H*
E3	*H*	*L*	*M*	*H*	*M*	VH	*H*	VH	*H*	*H*	*H*	*H*
E4	VH	*M*	*M*	*H*	*H*	*H*	*M*	*H*	*H*	*H*	*L*	*M*
E5	VH	*H*	*L*	VH	*H*	*M*	*M*	*H*	*M*	*M*	*L*	*H*

low, respectively. These five linguistic terms are combined by using IT2F number operations in Eqs. (2–5). The relationship between CR1 and DR2 for occurrence criterion is ((0.487, 0.528, 0.600, 0.635; 0.8), (0.437, 0.486, 0.647, 0.699; 1.0)). The rank of this IT2F number is calculated 6.895 by using Eq. (6). The ranks of relationships between CR1 and all DRs are normalized to 1 so that the relationship between CR1 and DR2 for occurrence criterion is calculated 0.135.

$$6.895/(6.895 + 5.310 + 8.164 + 7.570 + 8.086 \\ + 8.267 + 6.614) = 0.135$$

Table 5 Weights of CRs with correlation

	CR1	CR2	CR3	CR4
O	0.228	0.285	0.190	0.297
S	0.220	0.297	0.190	0.293
D	0.216	0.316	0.195	0.273

The similar operations are repeated for severity and detection criteria. Table 11 is obtained after the judgments of experts are aggregated by handling correlation effect and normalized to 1. Table 11 presents the weights of DRs with correlation for occurrence, severity and detection criteria. FMEA approach includes three parameters, which are occurrence, severity and detection. The QFD method ensures to find the importance degrees of DRs for these three parameters. These weights of three parameters are handled in VIKOR approach. In this stage, this paper also determines the weights of *O*, *S* and *D* criteria. The judgments of experts for the importance degrees of *O*, *S* and *D* are indicated in Table 12. The priority values of *O*, *S* and *D* are presented in Table 13. The importance degrees of occurrence criterion according to experts 1, 2, 3, 4 and 5 are high, medium, very high, high and very high, respectively. These five linguistic terms are combined by using IT2F number operations in Eqs. (2–5). The weight of occurrence criterion is ((0.777, 0.807, 0.850, 0.875; 0.8), (0.726, 0.775, 0.881, 0.915; 1.0)). The rank of this IT2F number is calculated 8.493 by using Eq. (6). The ranks of weights of all criteria are normalized to 1 so that the

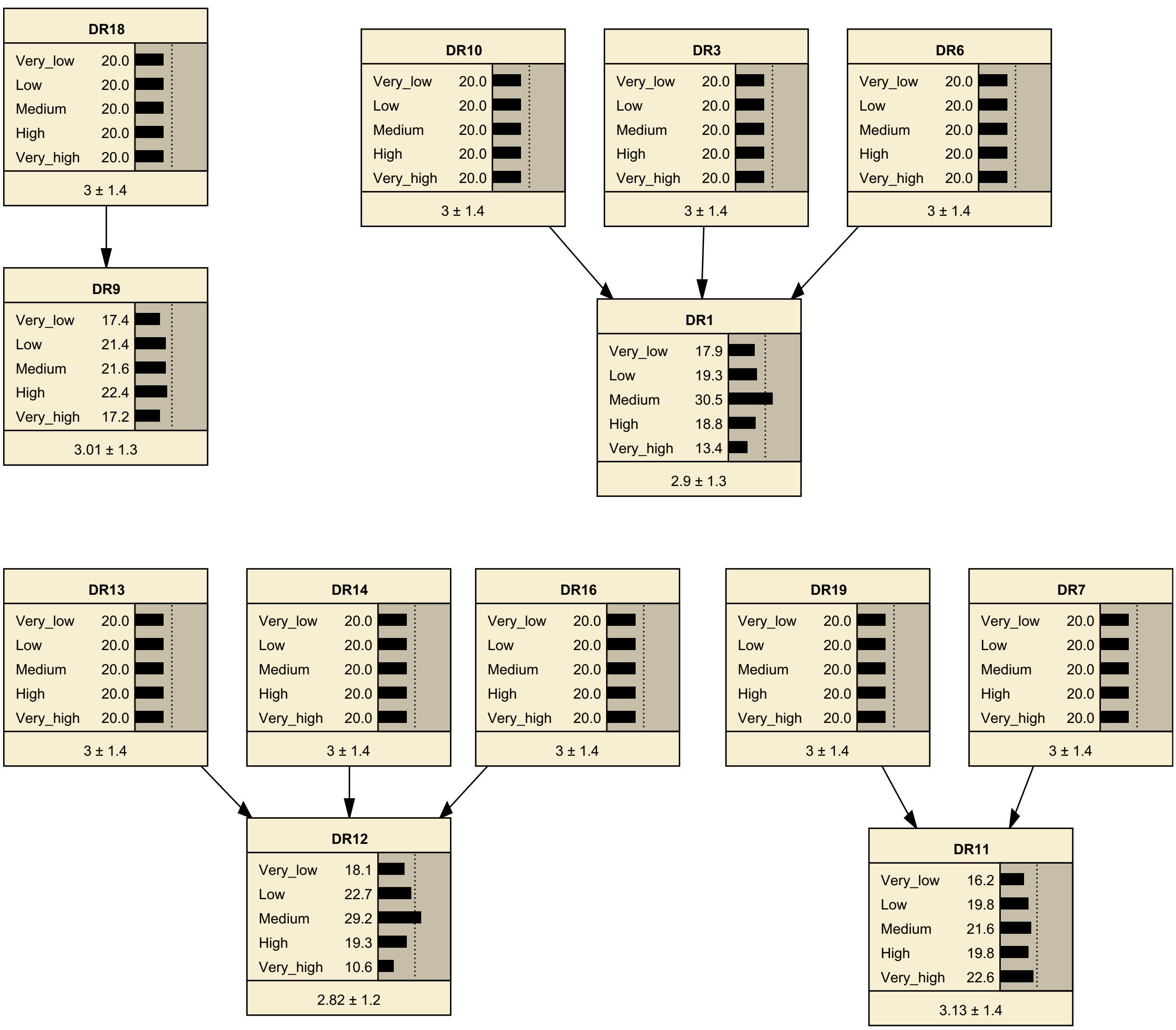

Fig. 6 Bayes network structure for correlation between DRs

Table 6 Correlation effect to DRs according to experts

	O				S				D			
	DR1	DR9	DR11	DR12	DR1	DR9	DR11	DR12	DR1	DR9	DR11	DR12
E1	*M*	*H*	VH	*M*	*L*	VH	VH	*H*	*L*	VH	*H*	*M*
E2	*L*	*M*	*H*	*M*	*L*	*M*	VH	*M*	*M*	*M*	VH	*M*
E3	*M*	*H*	*H*	*H*	*H*	*M*	*H*	*M*	*H*	*H*	*H*	*H*
E4	*M*	*H*	VH	*L*	*L*	*H*	*M*	*H*	*M*	*H*	*H*	*H*
E5	*H*	*M*	VH	*M*	*H*	*H*	*H*	*M*	*H*	*M*	*H*	*M*

Table 7 Correlation effect to DRs

O				*S*				*D*			
DR1	DR9	DR11	DR12	DR1	DR9	DR11	DR12	DR1	DR9	DR11	DR12
0.220	0.256	0.300	0.224	0.224	0.257	0.280	0.239	0.232	0.249	0.281	0.238

weights of *O*, *S* and *D* criteria are defined 0.3691, 0.3716 and 0.2593, respectively.

$$8.493/(8.493 + 8.551 + 5.967) = 0.3691$$

VIKOR approach is employed to order the DRs according to the values of *S*, *R* and *Q*, which are shown in Table 14. The rankings of DRs are introduced in Table 15. The most important design requirement or failure mode is DR14 (unsuitable plug-socket utilization) according to the values of *S*, *R* and *Q*. The second most important failure mode is DR2 (falling the material from pallet truck) according to the values of *S*, *R* and *Q*. This means that the management should start to correct by considering this ranking among failure modes of tile and marble works in building construction.

4.2 Comparison and discussion

This paper compares the results of the proposed approach and the traditional FMEA approach for risk evaluation. Table 16 presents the results of the traditional FMEA approach. The proposed method has three rankings according to the values of *S*, *R* and *Q*. The value of *Q* includes the interaction of the values of *S* and *R* so that the ranking according to the value of *Q* is preferred in VIKOR approach. This study handled the value of *Q* to compare the proposed method and the traditional FMEA method.

Based on the ranking orders results in Table 16, the advantages of the proposed approach according to the traditional FMEA approach can be summarized as follows:

The results of the proposed approach and the traditional FMEA are different except the first thirteen ranks of DRs. The rankings between the first and thirteenth DRs are the same for two methods. The resting six DRs, which are DR3, DR5, DR8, DR9, DR11 and DR19, have different rankings according to the compared two methods. The proposed approach use IT2F number to define the weights of the risk factors, which are *O*, *S*, *D*. The traditional FMEA considers that the weights of the risk factors are equal. VIKOR approach presents more comprehensive results by using the rankings of the values of S, R and Q.

5 Conclusion

Occupational health and safety is a science field, which takes the precautions against all risks and dangers in the work environment and aims to apply all the necessary conditions in this regard in order to protect the employees' right to life. One of the tasks that firms need to do in order to make their employees work efficiently is to ensure a confident job field for workers. Thus, employees can hire themselves more easily. Furthermore, the occurrence of a work accident may result in permanent or temporary job losses. The firms may face losses resulting from payment of compensation and downtime. In order to avoid these situations, firms should make risk assessments in the working environment. Risk assessment is crucial for an organization in a growing competitive environment in terms of occupational health and safety. Although it is not possible to make a completely safe work environment, the goal of a safer work environment can be achieved with the preventions to be taken. Workers, which are an important part of production in all sectors, are the most affected by work accidents and occupational diseases. Workers who work for a certain wage in order to survive are indispensable cornerstones of production. Loss of producing people as a result of possible work geese and occupational diseases does not only cause loss of life or injury.

Existing papers in the literature handled the traditional FMEA due to its limitations such as equal importance degrees, discrete ordinal scales and multiplication of occurrence, severity and detection criteria. They suggested many methods for these limitations. This paper

Table 8 Relationships between CRs and DRs for occurrence criterion

		DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19
E1	CR1		*M*	*L*								*H*		*H*	*H*		*H*			*M*
	CR2		*H*			*M*	*H*			*M*				*M*	*M*		*M*			
	CR3	M									*H*		*M*					*H*		
	CR4				*H*			H	M							VH			*M*	
E2	CR1		L	VL								*H*		*H*	*H*		*M*			*L*
	CR2		VH			*L*	*H*			*H*				*L*	*M*		*M*			
	CR3	L									*M*		H					*H*		
	CR4				VH			*H*	*L*							*H*			L	
E3	CR1		*H*	L								*M*		*M*	*H*		*H*			*M*
	CR2		*H*			*H*	*M*			*M*				*M*	*H*		*L*			
	CR3	M									*H*		L					*M*		
	CR4				*M*			*M*	*H*							VH			H	
E4	CR1		*H*	*M*								VH		*H*	*M*		*H*			*H*
	CR2		*M*			*L*	*H*			*L*				*H*	*M*		*H*			
	CR3	H									*H*		*M*					VH		
	CR4				H			*H*	*L*							VH			*M*	
E5	CR1		*L*	*L*								*H*		*M*	*H*		VH			*M*
	CR2		*M*			*M*	VH			*M*				*M*	*L*		*L*			
	CR3	M									*M*		*M*					*H*		
	CR4				VH			*M*	*M*							VH			*M*	

Table 9 Relationships between CRs and DRs for severity criterion

		DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19
E1	CR1		H	L								VH		H	H		H			H
	CR2		M			M	H			M				H	M		M			
	CR3	L									H		H					H		
	CR4				H			VH	M							VH			H	
E2	CR1		M	VL								H		VH	H		H			L
	CR2		VH			L	VH			H				L	H		H			
	CR3	M									M		L					H		
	CR4				H			H	L							VH			L	
E3	CR1		M	L								M		H	VH		H			L
	CR2		VH			H	H			H				M	H		L			
	CR3	L									H		L					H		
	CR4				H			H	H							H			L	
E4	CR1		H	L								H		H	M		VH			H
	CR2		H			L	H			L				H	H		H			
	CR3	L									VH		M					VH		
	CR4				H			H	L							VH			M	
E5	CR1		M	L								H		M	H		VH			M
	CR2		M			L	VH			M				L	L		L			
	CR3	M									H		H					VH		
	CR4				VH			M	L							VH			M	

Table 10 Relationships between CRs and DRs for detection criterion

		DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19
E1	CR1		M	*L*								VH		*M*	*H*		*H*			*H*
	CR2		M			*H*	*M*			*H*				*H*	*M*		*H*			
	CR3	M									*H*		*M*					*M*		
	CR4				*M*			*H*	*H*							VH			*M*	
E2	CR1		M	VL								*M*		VH	*H*		*H*			*M*
	CR2		VH			*M*	*H*			*H*				*L*	*M*		*M*			
	CR3	M									*M*		*M*					*H*		
	CR4				*H*			*M*	*M*							VH			*L*	
E3	CR1		M	M								*H*		*M*	*H*		*M*			*M*
	CR2		VH			*H*	*H*			H				*M*	*H*		*L*			
	CR3	M									*M*		*M*					*M*		
	CR4				*H*			*H*	*H*							*H*			*M*	
E4	CR1		*M*	*L*								*H*		*H*	*M*		VH			*H*
	CR2		*H*			*L*	*H*			*M*				*H*	*M*		H			
	CR3	L									*H*		*M*					VH		
	CR4				*H*			*H*	*M*							VH			*M*	
E5	CR1		*H*	*H*								*H*		*M*	*H*		VH			*M*
	CR2		*M*			L	VH			*M*				*M*	*M*		*M*			
	CR3	H									*H*		*H*					VH		
	CR4				VH			*M*	*L*							*H*			*M*	

Table 11 Weights of DRs with correlation for criteria

O	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
	0.0509	0.0738	0.0229	0.0622	0.0364	0.0458	0.0564	0.0483	0.0466	0.0484
	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
	0.0457	0.0506	0.0697	0.0726	0.0687	0.0711	0.0515	0.0500	0.0285	
S	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
	0.0436	0.0744	0.0205	0.0636	0.0348	0.0493	0.0602	0.0458	0.0499	0.0513
	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
	0.0419	0.0510	0.0706	0.0755	0.0672	0.0732	0.0550	0.0455	0.0267	
D	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
	0.0525	0.0752	0.0240	0.0572	0.0397	0.0490	0.0525	0.0481	0.0561	0.0487
	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
	0.0419	0.0546	0.0701	0.0729	0.0615	0.0734	0.0517	0.0424	0.0285	

Table 12 Importance degrees of criteria according to the experts

	E1	E2	E3	E4	E5
O	*H*	*M*	VH	*H*	VH
S	*M*	*H*	*H*	VH	VH
D	*M*	*L*	*M*	*M*	*L*

Table 13 Weights of criteria

O	S	D
0.3691	0.3716	0.2593

recommends coping with these limitations a new method, which integrates QFD method under interval type-2 fuzzy set, Bayesian network and VIKOR method. This study is implemented for the risk evaluation of tile and marble works in building construction. The first stage of the handled algorithm focuses on the correlations in QFD approach. This work handles the Bayesian network to investigate the correlations of CRs and DRs. Bayesian network ensures to find the correlation effect to each CR and DR so that this contributes to QFD literature. Bayesian

Table 14 Values of *S*, *R* and *Q* for DRs

	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
S	0.4738	0.7334	0.2593	0.6665	0.3743	0.4941	0.6261	0.4923	0.4677	0.5269
R	0.2029	0.3691	0.2593	0.2911	0.1794	0.1951	0.2684	0.1842	0.1989	0.2084
Q	0.3069	0.9838	0.2239	0.7228	0.1464	0.3087	0.6254	0.2800	0.2907	0.3752
	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
S	0.4785	0.5110	0.7034	0.7431	0.7168	0.7145	0.5590	0.5320	0.3193	
R	0.1682	0.2061	0.3397	0.3716	0.3321	0.3561	0.2332	0.1968	0.2362	
Q	0.2265	0.3533	0.8804	1.0000	0.8756	0.9324	0.4696	0.3521	0.2292	

Table 15 Ranking of DRs

	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
S	15	2	19	6	17	12	7	13	16	10
R	13	2	8	6	18	16	7	17	14	11
Q	13	2	18	6	19	12	7	15	14	9
	DR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
S	14	11	5	1	3	4	8	9	18	
R	19	12	4	1	5	3	10	15	9	
Q	17	10	4	1	5	3	8	11	16	

Table 16 Ranking of DRs according to the traditional FMEA

	DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10
Rank	13	2	19	6	18	12	7	14	16	9
	DsR11	DR12	DR13	DR14	DR15	DR16	DR17	DR18	DR19	
Rank	15	10	4	1	5	3	8	11	17	

network aims to define the correlations of CRs and DRs as the linguistic terms. The linguistic term with the biggest probability in the result of Bayesian network is selected as correlation effect. These terms are converted to interval type-2 fuzzy numbers as correlation effect to each CR and DR. The judgments of experts for CRs and DRs are collect by using interval type-2 fuzzy numbers. The use of IT2F numbers in QFD approach provides to handle more vagueness than crisp and type-1 fuzzy numbers. The traditional FMEA uses the RPN, which multiples occurrence, severity and detection parameters. The QFD method determines the weight of each failure mode or design requirement for occurrence, severity and detection parameters. The second stage of the presented algorithm focuses on VIKOR approach. The result of QFD approach presents three rankings of failure modes due to occurrence, severity and detection parameters. These rankings are aggregated in VIKOR approach and the final ranking is defined by using the VIKOR method. The results of the proposed method and the traditional FMEA method are compared to test the efficiency of the obtained rankings. The most significant design requirement or failure mode is DR14 (unsuitable plug-socket utilization) according to the proposed method and the traditional FMEA method. DR2 (falling the material from pallet truck) follows as the second most important failure mode. The obtained results of the proposed method help to make a decision about failure modes of tile and marble works to the managers in the building construction. The future papers can integrate the other fuzzy numbers to QFD approach.

Compliance with ethical standards

Conflicts of interest The authors do not have any conflicts.

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