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APPLICATION OF STATISTICAL DATA AND METHODS TO ESTABLISH RPN RATINGS OF FMEA METHOD FOR CONSTRUCTION PROJECTS

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Abstract. The Failure Mode and Effects Analysis (FMEA) is paramount for analytical skills of reliability design in dynamic prevention. The FMEA model is a significant method which can simultaneously reduce the operating errors or delays as well as improve the construction quality. In particular, the Risk Priority Number (RPN) in the FMEA model is a vital tool which helps construction managers prioritize problem-solving. As the Internet of Things and big data analytical skills have become progressively widespread and mature, among the three risk indicators of RPN, the number of operating errors or delays per unit time can be estimated by the data collected from the analysis of statistical methods and regarded as the basis of 10-level classification. In addition, when the loss is larger, then the severity is higher. This paper proposed three evaluation criteria, including Occurrence, Severity, and Detection of RPN in construction engineering, and a 10-level classification model. To assist the construction managers, priority for construction improvement can be identified based on RPN calculations.

Keywords: failure mode and effects analysis, risk priority number, construction engineering, total loss model, failure rate.

Introduction

The model of Failure Mode and Effects Analysis (FMEA) is one of the most important analytical skills for reliability design and in dynamic prevention (Kushwaha et al., 2022; Von Ahsen et al., 2022; Xie et al., 2022). According to the research done by Rakesh et al. (2013), the FMEA method was initiated by America's Grumman Aerospace Corporation in the early 1950s. FMEA was first applied to the failure analysis of the jet aircraft control system and was gradually developed into an analytical technology of system security and reliability design in the hope of effectively solving various problems of failure. Next, the National Aeronautics Space Agency (NASA) also adopted the FMEA model to develop reliability analysis and improvement tools for systems engineering of the Apollo space mission in 1960. Later, the U.S. Armed Forces included the FMEA model as part of military procedures of MIL-STD-1629A (Johnson & Khan, 2003). In the automotive industry, the FMEA model was first introduced into American automotive industry in 1970. Next, in 1993, a handbook about reliability was created with the help of the American Society for Quality (ASQ) and the Automotive Industry Action Group (AIAG). Finally, FMEA has become the certified requirement for QS-9000 (Mattsson, 1995).

The FMEA model has now been widely used in many industries (Wang et al., 2018; Ouyang et al., 2022). For example, some semiconductor manufacturing industries have also introduced FMEA system evaluation operations into the production line management to avoid potential major anomalies and enhance product reliability (Chen et al., 2010). In addition, numerous mass transportation system engineering and construction projects should also use FMEA to prevent and reduce failures in engineering and systems as well as lower the losses caused by system failures (Ng et al., 2022; Chen et al., 2022; Gumasing et al., 2022; Gong et al., 2022). In the process of urbanization, the construction industry plays a very important role in

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quality and reliability of architecture, which are closely related to residents' lives and property safety, especially in Asia where earthquakes frequently happen. In recent years, under the influence of the COVID-19 epidemic, Taiwan's construction industry has faced pressure from labor shortages as well as rising wages and material prices, and builders must face the pressure of operating errors or delays. The so-called operating error here means that the construction does not follow the blueprint or there are some differences from the blueprint after completion. For example, the size of the window does not match, the position is wrong, or the position of the pipeline configuration is wrong, etc. Therefore, how to improve the building quality and diminish losses of costs caused by operating errors or delays is an important issue.

According to the above-stated, the FMEA model should be a critical method which can reduce operating errors or delays and enhance building quality. In the FMEA model, the Risk Priority Number (RPN) can help engineering managers determine the problem-solving priority by multiplying 10 levels of Occurrence, Severity, and Detection each, and then problems can be solved by related improvement techniques and methods (Yuan & Tang, 2022; Liu & Tang, 2022; Chakhrit & Chennoufi, 2021; Jiang et al., 2019). Furthermore, some studies use the belief Jensen–Shannon divergence and entropy measure in the evidence theory to improve the science of FMEA method (Tang et al., 2023; Xie et al., 2020). Based on this concept, this paper will apply statistical data and methods to establish RPN ratings of the FMEA method for construction projects. As the environment of Internet of Things (IoT) and big data analysis technology gradually become prevalent and mature, the number of operating errors or delays per unit time, N, among the three risk indicators is distributed as a Poisson distribution with failure rate λ (Chen & Yang, 2018; Chen & Yu, 2022; Li et al., 2021; Canbolat, 2020). In particular, parameter λ can be estimated by the data collected through the statistical method and analysis and viewed as the basis of 10-level classification. In addition, many studies have pointed out that there is a certain cost or social loss when a mistake occurs, and this loss is a random variable that varies with the type of mistake. Obviously, the greater the loss is, the higher the severity is. Thus, the loss function can be used to represent Severity. Similarly, the expected loss can be estimated by the statistical method according to the collected data, which can be regarded as the basis of 10-level classification. As to Detection, it is usually related to the engineering management system and must be divided into 10 levels by experts or senior construction project managers based on the accumulated statistical data. According to the above, this study proposes a 10-level classification model for three evaluation items, including Occurrence, Severity and Detection of RPN for the construction projects. The model can assist construction project managers to identify the priority of projects that need to improve on the basis of the calculated RPN. In fact, the model proposed in this paper is based on the accumulated data in the past and through the central limit theorem and the quantiles of the normal distribution, the probability is divided into 10 equal parts to form 10 levels. Obviously, the RPN calculated by this method is relatively objective. In addition to the construction projects that can be applied to the above, this model is also applicable to other systems in construction engineering, such as mechanical pipeline engineering, water supply and drainage engineering, weak current engineering, and electrical instrumentation and control engineering.

The remainder of this paper is organized as follows. Section 1 proposes the 10-level classification rules of Occurrence and Severity, respectively. Section 2 establishes 10 evaluation levels of the three evaluation items of RPN for the construction engineering. Section 3 presents an application example. Final section provides conclusions.

1. Level classification rules of occurrence and severity

As mentioned above, this model is also applicable to other systems in construction engineering, such as mechanical pipeline engineering, water supply and drainage engineering, weak current engineering, and electrical instrumentation and control engineering. For construction projects, Detection is usually classified by experts or senior construction project managers into 10 levels according to the accumulated statistical data. Therefore, this study first establishes classification rules of 10 evaluation levels for Occurrence and Severity. In Taiwan, due to factors, such as personal budgets, tastes, preferences, and religious beliefs, everyone tends to make some changes in design to meet his or her own needs when purchasing a pre-sale building, so that operating errors or delays easily occur when the construction industry faces demands for customization. As mentioned above, when operating errors or delays occur, there will be some social losses, such as costs of environmental pollution, to a certain extent (Akadiri et al., 2012). When the number of operating errors or delays, N, for each building with completed inspection is larger, the total loss is also greater. This total loss model (*Tloss*) can be expressed as follows:

$$TLoss = Loss(1) + Loss(2) + \ldots + Loss(N), \tag{1}$$

where N is the number of failures per unit time. Then, the mathematical expectation of the total Tloss can be denoted as follows:

$$E\left[TLoss\right] = \lambda \times \mu_{Loss}, \tag{2}$$

where $\lambda = E\left[N\right]$ is the expected value for the number of operating errors or delays per unit time, and $\mu_{Loss} = E\left[Loss(n)\middle|N=n\right]$ is the mathematical expected value of the loss. Obviously, the higher the value of λ is, the more operating errors or delays per unit time occur. Similarly, the larger the value of μ_{Loss}, the greater the loss caused by each construction error on average. According to Eqn (2), this study defines 10 evaluation levels of Occurrence (*O*) and Severity (*S*) in $RPN = O \times S \times D$ of the construction project, as shown below.

1.1. Occurrence (*O*)

As mentioned earlier, the number of operating errors or delays, *N*, for each building with completed inspection is distributed as a Poisson distribution with failure rate λ. Let $N_1,...,N_h,...,N_k$ be independent random variables identically distributed in a Poisson process with failure rate λ. Then, the sample mean is the unbiased estimator of λ as follows:

$$\lambda^* = \frac{1}{k}\sum_{h=1}^{k} N_h, \tag{3}$$

where $k\lambda^*$ is distributed as Poisson distribution with mean $k\lambda$. Then,

$$E\left[\lambda^*\right] = \frac{1}{k}E\left[\sum_{h=1}^{k} N_h\right] = \lambda \tag{4}$$

and

$$Var\left[\lambda^*\right] = \frac{1}{k^2}Var\left[\sum_{h=1}^{k} N_h\right] = \frac{\lambda}{k}. \tag{5}$$

Let

$$Z_O = \frac{\sqrt{k}\left(\lambda^* - \lambda\right)}{\sqrt{\lambda}}, \tag{6}$$

then according to the Central Limits Theorem (CLT), Z_O is an approximate standard normal distribution for large *k*, that is $Z_O \xrightarrow{k\to\infty} N(0,1)$. Based on Eqn (6), the 10 evaluation levels of Occurrence (*O*) are expressed as follows:

$$O = \begin{cases} 1 & \text{if } Z_O < Z_{0.9} \\ h & \text{if } Z_{0.1\times(11-h)} \le Z_O < Z_{0.1\times(10-h)}, h = 2,3,...,9. \\ 10 & \text{if } Z_{0.1} < Z_O \end{cases} \tag{7}$$

Z_a is the upper a quintile of the standard normal distribution. Obviously, $Z_a = -Z_{1-a}$ for $0 \le a \le 1$. Thus, $p\{Z \le Z_{0.9}\} = \Phi(Z_{0.9}) = 0.1$ implies $Z_{0.9} = -1.28$ and $Z_{0.1} = -Z_{0.9} = 1.28$. Similarly, $Z_{0.8} = -0.84$, $Z_{0.2} = 0.84$, $Z_{0.7} = -0.52$, $Z_{0.3} = 0.52$, $Z_{0.6} = -0.25$, $Z_{0.4} = 0.25$, and $Z_{0.5} = 0$.

1.2. Severity (*S*)

As mentioned earlier, the greater the value of mathematical expectation μ_{Loss} each loss, the greater the loss caused by each operating error or delay on average, so that the severity is higher. Let $L_{h,1},...,L_{h,j},...,L_{h,n_h}$, $h = 1, 2, \ldots, k$ be a random sample of loss per unit time with mean μ_S and standard deviation σ_S, then the sample mean is displayed below:

$$\bar{L} = \frac{1}{n}\sum_{h=1}^{k}\sum_{j=1}^{n_h} L_{h,j}, \tag{8}$$

where $n = \sum_{h=1}^{k} n_h$. Let

$$Z_S = \frac{\sqrt{n}\left(\bar{L} - \mu_S\right)}{\sigma_S}, \tag{9}$$

then according to the Central Limits Theorem (CLT), Z_S is an approximate standard normal distribution for large *n*, that is $Z_S \xrightarrow{n\to\infty} N(0,1)$. Based on Eqn (10), the 10 evaluation levels of Severity (*S*) are expressed as:

$$S = \begin{cases} 1 & \text{if } Z_S < Z_{0.9} \\ h & \text{if } Z_{0.1\times(11-h)} \le Z_S < Z_{0.1\times(10-h)}, h = 2,3,...,9. \\ 10 & \text{if } Z_{0.1} \le Z_S \end{cases} \tag{10}$$

2. Evaluation levels of the RPN establishment for construction engineering

According to the 10-level classification rules of Occurrence and Severity, this study first establishes 10-level evaluation comparison tables for these two items. Next, this study establishes a 10-level evaluation comparison table for Detection. Finally, the 10-level evaluation comparison tables for these 3 items are introduced individually as follows.

2.1. The 10-level evaluation comparison table for Occurrence

We assume that the number of architecture with completed inspection in the i^{th} year is k_i, and $i = 1, 2, \ldots, m$; the number of operating errors or delays of the h^{th} building is $n_{i,h}$, and $h = 1, 2, \ldots, k_i$. Then,

$$\lambda_0 = \frac{1}{k}\sum_{i=1}^{m}\sum_{h=1}^{k_i} n_{i,h}, \tag{11}$$

where $k = \sum_{i=1}^{m} k_i$. Based on Eqn (7), when $O = 1$, we have $Z_O < Z_{0.9}$, equivalent to

$$\lambda^* < \lambda_0 - 1.28 \times \sqrt{\lambda_0/k}. \tag{12}$$

Similarly, when $O = 1$, we have $Z_{0.1\times(11-h)} \le Z_O <$ $< Z_{0.1\times(10-h)}$, equivalent to

$$\lambda_0 - Z_{0.1\times(11-h)}\sqrt{k} \le \lambda^* < \lambda_0 - Z_{0.1\times(10-h)}\sqrt{\lambda_0/k}, \tag{13}$$

where $h = 2, 3, \ldots, 9$. Finally, when $O = 10$, we have $Z_{0.1} < Z_O$, equivalent to

$$\lambda_0 + 1.28 \times \sqrt{\lambda_0/k} \le \lambda^*. \tag{14}$$

Based on Eqns (12)–(14), the 10-level evaluation comparison table for Occurrence is shown in Table 1.

Table 1. The 10-level evaluation comparison table for Occurrence

Occurrence (O)	Condition
$O = 10$	$\lambda_0 + 1.28\sqrt{\lambda_0/k} \le \lambda^*$
$O = 9$	$\lambda_0 + 0.84\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 + 1.28\sqrt{\lambda_0/k}$
$O = 8$	$\lambda_0 + 0.52\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 + 0.84\sqrt{\lambda_0/k}$
$O = 7$	$\lambda_0 + 0.25\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 + 0.52\sqrt{\lambda_0/k}$
$O = 6$	$\lambda_0 \le \lambda^* < \lambda_0 + 0.25\sqrt{\lambda_0/k}$
$O = 5$	$\lambda_0 - 0.25\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0$
$O = 4$	$\lambda_0 - 0.52\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 - 0.25\sqrt{\lambda_0/k}$
$O = 3$	$\lambda_0 - 0.84\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 - 0.52\sqrt{\lambda_0/k}$
$O = 2$	$\lambda_0 - 1.28\sqrt{\lambda_0/k} \le \lambda^* < \lambda_0 - 0.84\sqrt{\lambda_0/k}$
$O = 1$	$\lambda^* < \lambda_0 - 1.28\sqrt{\lambda_0/k}$

2.2. The 10-level evaluation comparison table for Severity

This study estimates parameter μ_S and variance σ_S^2 based on the m-year projections from the end of last year. As mentioned above, it is assumed that the number of buildings with completed inspection in the i^{th} year is k_i, and $i = 1, 2, \ldots, m$; the number of operating errors or delays of the h^{th} building is $n_{i,h}$, and $h = 1, 2, \ldots, k_i$. Then, the lost data caused by each operating error or delay is $L_{i,h,1}, \ldots, L_{i,h,j}, \ldots, L_{i,h,n_{i,h}}$. The values of parameter μ_S and variance σ_S^2 can then be estimated based on the k sample data. The sample data, sample mean, and sample standard deviation are respectively displayed below:

Sample data	Mean	Standard deviation
$L_{i,1,1}, \ldots, L_{i,1,j}, \ldots, L_{i,1,n_{1,h}}$	$\bar{L}_{i,1}$	$S_{i,1}$
$\vdots$	$\vdots$	$\vdots$
$L_{i,h,1}, \ldots, L_{i,h,j}, \ldots, L_{i,h,n_{i,h}}$	$\bar{L}_{i,h}$	$S_{i,h}$,
$\vdots$	$\vdots$	$\vdots$
$L_{i,k_i,1}, \ldots, L_{i,k_i,j}, \ldots, L_{i,k_i,n_{i,k_i}}$	$\bar{L}_{i,k_i}$	S_{i,k_i}

where

$$\bar{L}_{i,h} = \frac{1}{n_{i,h}} \sum_{j=1}^{n_{i,h}} L_{i,h,j} \tag{15}$$

and

$$S_{i,h} = \sqrt{\frac{1}{n_{i,h} - 1} \sum_{j=1}^{n_{i,h}} \left(L_{i,h,j} - \bar{L}_{i,h}\right)^2}. \tag{16}$$

Since the mean μ_S and standard deviation σ_S are unknown parameters, the estimators of mean μ_S and standard deviation σ_S respectively are expressed as follows:

$$\mu_S^* = \frac{1}{n} \sum_{i=1}^{m} \sum_{h=1}^{k_i} n_{i,h} \times \bar{L}_{i,h} \tag{17}$$

and

$$\sigma_S^* = \sqrt{\frac{1}{n - m} \sum_{i=1}^{m} \sum_{h=1}^{k_i} \left(n_{i,h} - 1\right) S_{i,h}^2}, \tag{18}$$

where $n = \sum_{i=1}^{m} \sum_{h=1}^{k_i} n_{i,h}$. Based on Eqns (9), (10), (15), and (16), when $S = 1$, then $Z_S < Z_{0.9}$, equivalent to

$$\bar{L} < \mu_S^* - 1.28 \times \sigma_S^* / \sqrt{n}. \tag{19}$$

Similarly, when $S = h$, we have $Z_{0.1\times(11-h)} \le Z_S < Z_{0.1\times(10-h)}$ equivalent to

$$\mu_S^* - Z_{0.1\times(11-h)} \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* - Z_{0.1\times(10-h)} \times \sigma_S^* / \sqrt{n}, \tag{20}$$

where $h = 2, 3, \ldots, 9$. Finally, when $S = 10$, we have $Z_{0.1} < Z_S$ equivalent to

$$\mu_S^* + 1.28 \times \sigma_S^* / \sqrt{n} \le \bar{L}. \tag{21}$$

Based on Eqns (19)–(21), the 10-level evaluation comparison table for Severity is illustrated in Table 2.

Table 2. The 10-level evaluation comparison table for Severity

Severity (S)	Condition
$S = 10$	$\mu_S^* + 1.28 \times \sigma_S^* / \sqrt{n} \le \bar{L}$
$S = 9$	$\mu_S^* + 0.84 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* + 1.28 \times \sigma_S^* / \sqrt{n}$
$S = 8$	$\mu_S^* + 0.52 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* + 0.84 \times \sigma_S^* / \sqrt{n}$
$S = 7$	$\mu_S^* + 0.25 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* + 0.52 \times \sigma_S^* / \sqrt{n}$
$S = 6$	$\mu_S^* \le \bar{L} < \mu_S^* + 0.25 \times \sigma_S^* / \sqrt{n}$
$S = 5$	$\mu_S^* - 0.25 \frac{\sigma_S^*}{\sqrt{n}} \le \bar{L} < \mu_S^*$
$S = 4$	$\mu_S^* - 0.52 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* - 0.25 \times \sigma_S^* / \sqrt{n}$
$S = 3$	$\mu_S^* - 0.84 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* - 0.52 \times \sigma_S^* / \sqrt{n}$
$S = 2$	$\mu_S^* - 1.28 \times \sigma_S^* / \sqrt{n} \le \bar{L} < \mu_S^* - 0.84 \times \sigma_S^* / \sqrt{n}$
$S = 1$	$\bar{L} < \mu_S^* - 1.28 \times \sigma_S^* / \sqrt{n}$

2.3. The 10-level evaluation comparison table for Detection

As mentioned above, Detection is usually related to the engineering management system, and experts or senior construction project managers must classify it into 10 levels based on their accumulated experience. Based on this principle, this study classifies Detection into 10 levels as shown in Table 3 below.

Table 3. The 10-level evaluation comparison table for Detection

Detection (D)	Likelihood of detection
D = 10	Completely unable to find out the causes of operating errors or delays
D = 9	Very unlikely to find out the causes of operating errors or delays
D = 8	Rarely possible to find out the causes of operating errors or delays
D = 7	Less likely to find out the causes of operating errors or delays
D = 6	Low probability of finding out the causes of operating errors or delays
D = 5	Medium probability of finding out the causes of operating errors or delays
D = 4	High probability of finding out the causes of operating errors or delays
D = 3	Likely to find out the causes of operating errors or delays
D = 2	Extremely likely to know the causes of operating errors or delays
D = 1	Surely able to know the causes of operating errors or delays

3. Application example

In this section, this paper takes four-storey houses built by a construction company in central Taiwan as a case study, and the houses cover an area of 300 ± 10% m^2. This case study illustrates how to establish the 10 evaluation levels of RPN for construction projects. As mentioned earlier, everyone has their own needs when buying a pre-sale home for several reasons, such as personal budgets, tastes, preferences, and religious beliefs. When the construction industry is facing these customized demands, it is easy to cause operating errors or delays listed in the category of civil engineering and architecture. First, according to the construction cases of houses introduced in recent years, the operating errors or delays listed in the category of civil engineering and architecture were counted. The statistical period is 3 years before the end of last year, and the number of houses with completed inspection in the i^{th} year is k_i, i = 1, 2, 3. The number of operating errors or delays in building h is $n_{i,h}$.The statistical results are as follows.

The number of houses with completed inspection in the 1st year is k_1 = 11, and the number of operating errors or delays each building is $n_{1,h}$ as follows:

$n_{1,1} = 11$, $n_{1,2} = 12$, $n_{1,3} = 10$, $n_{1,4} = 11$, $n_{1,5} = 12$, $n_{1,6} = 11$, $n_{1,7} = 11$, $n_{1,8} = 10$, $n_{1,9} = 12$, $n_{1,10} = 11$, $n_{1,11} = 11$.

Sample data, sample mean, and sample standard deviation are respectively listed as follows:

Sample data	Mean	Standard deviation
$L_{1,1,1},\ldots,L_{1,1,j},\ldots,L_{1,1,11}$	$\bar{L}_{1,1} = 63.14$	$S_{1,1} = 22.23$
$L_{1,2,1},\ldots,L_{1,2,j},\ldots,L_{1,2,12}$	$\bar{L}_{1,2} = 59.83$	$S_{1,2} = 26.57$.
$\vdots$	$\vdots$	$\vdots$
$L_{1,11,1},\ldots,L_{1,11,j},\ldots,L_{1,11,11}$	$\bar{L}_{1,11} = 65.33$	$S_{1,11} = 28.12$

The number of houses with completed inspection in the 2nd year is k_2 = 12, and the number of operating errors or delays each building is $n_{2,h}$ as follows:

$n_{2,1} = 11$, $n_{2,2} = 1$, $n_{2,3} = 12$, $n_{2,4} = 10$, $n_{2,5} = 11$, $n_{2,6} = 10$, $n_{2,7} = 11$, $n_{2,8} = 10$, $n_{2,9} = 10$, $n_{2,10} = 11$, $n_{2,11} = 11$, $n_{2,12} = 10$.

Sample data, sample mean, and sample standard deviation are respectively listed below:

Sample data	Mean	Standard deviation
$L_{2,1,1},\ldots,L_{2,1,j},\ldots,L_{1,1,11}$	$\bar{L}_{2,1} = 52.15$	$S_{2,1} = 21.86$
$L_{2,2,1},\ldots,L_{2,2,j},\ldots,L_{2,2,11}$	$\bar{L}_{2,2} = 49.38$	$S_{2,2} = 25.12$.
$\vdots$	$\vdots$	$\vdots$
$L_{2,12,1},\ldots,L_{2,12,j},\ldots,L_{2,12,10}$	$\bar{L}_{2,12} = 44.37$	$S_{2,12} = 23.75$

The number of houses with completed inspection in the 3rd year is k_3 = 10, and the number of operating errors or delays each building is $n_{3,h}$ as follows:

$n_{3,1} = 11$, $n_{3,2} = 12$, $n_{3,3} = 10$, $n_{3,4} = 11$, $n_{3,5} = 10$, $n_{3,6} = 11$, $n_{3,7} = 10$, $n_{3,8} = 10$, $n_{3,9} = 12$, $n_{3,10} = 11$.

Sample data, sample mean, and sample standard deviation are respectively listed below:

Sample data	Mean	Standard deviation
$L_{3,1,1},\ldots,L_{3,1,j},\ldots,L_{3,1,11}$	$\bar{L}_{3,1} = 47.36$	$S_{3,1} = 21.36$
$L_{3,2,1},\ldots,L_{3,2,j},\ldots,L_{3,2,12}$	$\bar{L}_{3,2} = 53.28$	$S_{3,2} = 25.12$.
$\vdots$	$\vdots$	$\vdots$
$L_{3,10,1},\ldots,L_{3,10,j},\ldots,L_{3,10,11}$	$\bar{L}_{3,10} = 49.13$	$S_{3,10} = 23.21$

Next, according to the above data, the 10-level evaluation comparison tables of Occurrence and Severity were completed respectively. First, we calculate the values of k and λ_0 as follows:

$$k = \sum_{i=1}^{3} k_i = 33$$

and

$$\lambda_0 = \frac{1}{k}\sum_{i=1}^{m}\sum_{h=1}^{k_i} n_{i,h} = \frac{1}{33}\sum_{i=1}^{3}\sum_{h=1}^{k_i} n_{i,h} = 12.1.$$

Based on Eqns (12)–(14), the 10-level evaluation comparison for Occurrence is shown in Table 4 below.

Table 4. The 10-level evaluation comparison table for Occurrence

Occurrence (O)	Condition
O = 10	$11.58 \le \lambda^*$
O = 9	$11.33 \le \lambda^* < 11.58$
O = 8	$11.15 \le \lambda^* < 11.33$
O = 7	$10.99 \le \lambda^* < 11.15$
O = 6	$10.85 \le \lambda^* < 10.99$
O = 5	$10.71 \le \lambda^* < 10.85$

End of Table 4

Occurrence (O)	Condition
O = 4	$10.55 \le \lambda^* < 10.71$
O = 3	$10.37 \le \lambda^* < 10.55$
O = 2	$10.11 \le \lambda^* < 10.37$
O = 1	$\lambda^* < 10.11$

Then, we calculate the values of n, μ_S^* and σ_S^* as follows:

$$n = \sum\nolimits_{i=1}^{m} \sum\nolimits_{h=1}^{k_i} n_{i,h} = 358,$$

$$\mu_S^* = \frac{1}{399} \sum_{i=1}^{3} \sum_{h=1}^{k_i} n_{i,h} \times \bar{L}_{i,h} = 53.82,$$

$$\sigma_S^* = \sqrt{\frac{1}{396} \sum_{i=1}^{3} \sum_{h=1}^{k_i} \left(n_{i,h} - 1\right) S_{i,h}^2} = 30.12.$$

Based on Eqns (17)–(22), the 10-level evaluation comparison for Severity is shown in Table 5 below.

Table 5. The 10-level evaluation comparison table for Severity

Occurrence (O)	Condition
S = 10	$55.86 \le \bar{L}$
S = 9	$55.16 \le \bar{L} < 55.86$
S = 8	$54.65 \le \bar{L} < 55.16$
S = 7	$54.22 \le \bar{L} < 54.65$
S = 6	$53.82 \le \bar{L} < 54.22$
S = 5	$53.42 \le \bar{L} < 53.82$
S = 4	$52.99 \le \bar{L} < 53.42$
S = 3	$52.48 \le \bar{L} < 52.99$
S = 2	$51.78 \le \bar{L} < 52.48$
S = 1	$\bar{L} < 51.78$

Next, we assume that the number of houses completed in the most recent year is k =10, and the average number of operating errors or delays is:

$$\lambda^* = \frac{1}{10} \sum_{h=1}^{10} n_h = 11.2.$$

According to Table 4, O = 8 can be obtained. Then, the average loss is calculated as follows:

$$\bar{L} = \frac{1}{112} \sum_{h=1}^{10} \sum_{j=1}^{n_h} L_{h,j} = 55.45.$$

According to Table 5, S = 9 can be obtained. If a senior construction project manager evaluates the level of Detection as D = 6 according to Table 3, then the RPN of the construction category is equal to $O \times S \times D$ = 8×9×6 = 432.

Apparently, the above-mentioned results are calculated based on the classification done by statistical data and statistical methods. Thus, this classification is more scientific than that based on professional experience. In terms of management, as long as the data collected is complete, the classification will be more consistent since it is calculated based on the quantile of the probability distribution. Accordingly, different classifications will not take place for different experts or managers. Of course, its disadvantage is that data must be accumulated for a period of time so that a complete database can be established. If the data is incomplete, the probability of occurrence for each classification will vary, and overestimation or underestimation will occur.

Conclusions and future research directions

This study proposed a 10-level classification model for three evaluation items, including Occurrence, Severity, and Detection of the RPN for the construction projects. In order to assist construction project managers, this study calculated the RPN for each type of construction project, which is convenient for construction project managers to identify the priority of construction improvement. Since the number of operating errors or delays, N, is a Poisson distribution, this study estimated Occurrence (O) based on the size of the mean. Besides, through the Central Limit Theorem, standardized statistic Z_O was used to approximate the properties of the standard normal distribution to establish the 10-level classification model of Occurrence. By the same token, standardized statistic Z_S was adopted to approximate the properties of a standard normal distribution, in order to create a 10-level classification model of Severity. Next, according to the accumulated data of operating errors or delays, parameter λ in the 10-level classification model of Occurrence was estimated, and the 10-level evaluation comparison table of Occurrence was completed (see Table 4). At the same time, the accumulated lost data were used to estimate parameters μ_S and σ_S in the 10-level classification model of Severity, and the 10-level evaluation comparison table of Severity was completed (see Table 5). Finally, an application example of the RPN for construction was used to explain the application of the above model. In addition to the calculation of the RPN for construction, this model is also applicable to other systems in construction engineering, such as mechanical pipeline engineering, water supply and drainage engineering, weak current engineering, and electrical instrumentation and control engineering. Therefore, the focus of future research can be to apply the model proposed in this paper to the failure mode and effects analysis of the above-mentioned various fields.

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Author contributions

People who contributed to the work are listed in this section along with their contributions: Conceptualization and supervision, YKJ and KSC; data collection, UYS; statistical analysis, KSC; writing original draft of the article, YKJ, UYS and KSC; review and editing of manuscript, YKJ and KSC.

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