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Developing a Method for Risk Analysis in Tile and Ceramic Industry Using Failure Mode and Effects Analysis by Data Envelopment Analysis

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Abstract

The failure mode and effects analysis (FMEA) is a widely used analytical technique that helps to identify and reduce the risks of failure in a system, component, or process. One important issue of FMEA is the determination of the risk priorities of failure modes. Risk ranking is produced in order to prioritize the focus on each of the failure modes that are identified. In this study, we applied FMEA which uses data envelopment analysis (DEA), a well-known performance measurement tool, to determine the risk priorities of 10 failure modes in the Tile and Ceramic Company. The Fuzzy set theory in capturing uncertainty fuzzy logic is used to evaluate S, O, and D. Consequently, the results of the DEA – FMEA ranking show that Decorating Fault and Pinhole are ranked the first and the second, respectively, and in order to improve them some suggestions are recommended to managers of company.

Keywords:

Data envelopment analysis, Failure modes and effect analysis, Risk management, Risk priority ranking.

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Introduction

Failure modes and effect analysis (FMEA) is a structured, bottom-up approach that starts with known potential failure modes at one level and investigates the effect on the next subsystem level (Liu*, et al*., 2011; Yang*, et al*., 2011). It is intended to provide information for making risk management decisions (Liu *et al*., 2011) and was first developed as a formal design methodology, proposed by NASA in 1963 for their obvious reliability requirements (Kutlu and Ekmekcioglu, 2012). It has been extensively used as a powerful tool for safety and reliability analysis of products and processes in a wide range of industries, particularly aerospace, nuclear, and automotive industries. In 1977, it was adopted and promoted by Ford Motor Company (Liu *et al*., 2011; Sharma *et al*., 2005; Chang *et al*., 2001).

FMEA has been used successfully by other industries for more than 40 years as a method for predicting how a work process may fail or how a device may be used incorrectly. The technique of FMEA involves the close examination of a high-risk procedure or error-prone process to identify required improvements that will reduce the chance of unintended adverse events (Paparella and Nurs, 2007). FMEA can facilitate the identification of potential failures in the design or process of products or systems (Teng and Ho, 1996).

Its main objective is to allow the analysts to identify and prevent known and potential problems from the customer (Liu *et al*., 2011; Sharma *et al*., 2005). To this end, the risks of each identified failure mode must be evaluated and prioritized; therefore, appropriate corrective actions can be taken for different failure modes (Liu *et al*., 2011).

A good FMEA can help analysts identify known and potential failure modes and their causes and effects. Furthermore it helps them prioritize the identified failure modes and can also help them work out corrective actions for the failure modes (Liu*, et al*., 2011). Each failure mode can be evaluated by three factors as severity, likelihood of occurrence, and the difficulty of detection of the failure mode.

These factors are defined as follows:

Severity (S): It is the assessment of the seriousness of the effect of potential failure mode to the next system or customers if it occurs. It is important to realize that the severity applies only to the effect of the failure, not the potential failure mode. The only reason of reduction in severity ranking is a direct change in design of the system.

Occurrence (O): It is the chance that one of the specific causes/mechanisms leads to failure. The reduction or removal on occurrence ranking must not come from any reason except for a direct change in the design.

Detection (D): It is the relative measure of the ability assessment of the design control to detect a potential cause/mechanism or the subsequent failure mode during the system operation (Kenchakkanavar and Joshi, 2010).

In a typical FMEA evaluation, a number between 1 and 10 (with 1 being the best and 10 being the worst case) is given for each of the three factors. However, in order to obtain a risk priority number (RPN), Severity (S), Occurrence (O), and detect ability (D) must be multiplied $RPN = S \times O \times D$. Then, the RPN value for each failure mode is ranked to find out the failures with higher risks (Kutlu and Ekmekcioglu, 2012).

FMEA can facilitate the identification of potential failures in the design or process of products or systems. This ability can help designers adjust the existing programs, increase compensating provisions, employ the recommended actions to reduce the likelihood of failures, decrease the probability of failure rates, and avoid hazardous accidents (Teng and Ho, 1996).

The traditional FMEA has been proven to be one of the most important early preventative actions in system, design, process, or service which will prevent failures and errors from occurring and reaching the customer. However, the FMEA has been extensively criticized for various reasons (Pillay and Wang, 2003; Sharma*, et al*., 2005):

- Different sets of O, S, and D ratings may produce exactly the same value of RPN; however, their hidden risk implications may be totally different. For example, two different failure modes with values of 2, 3, 2 and 4, 1, 3 for O, S, and D, respectively, will have the same RPN value of 12. However, the hidden risk implications of the two failure modes may be very different because of the different severities of the failure consequence. This may cause a waste of resources and time, or in some cases a high-risk failure mode might be left unnoticed.

- The relative importance among O, S, and D is not taken into consideration.
- The three factors are assumed to have the same importance. This may not be the case when considering a practical application of FMEA.
- The mathematical formula for calculating RPN is controversial. There is no rationale as to why O, S, and D should be multiplied to produce the RPN.
- Small variations in one rating may lead to vastly different effects on the RPN, depending on the values of the other factors.
- The three factors are difficult to determine precisely. Much information in FMEA can be expressed in a linguistic way such as very important or high and soon (Liu *et al*., 2011).

In this study, the fuzzy approach allows experts to use linguistic variables to determine S, O, and D for FMEA. Furthermore, a new FMEA was applied, which utilizes DEA, a well-known performance measurement tool, to determine the risk priorities of failure modes. The proposed FMEA takes into account the relative importance weights of risk factors, but it is not necessary to specify or determine them subjectively, which are determined by DEA models. The new FMEA measures the maximum and minimum risks of failure modes, which are geometrically averaged to reflect the overall risks of the failure modes; based on which the failure modes can be prioritized.

Literature Review

As stated above, FMEA is a reliable technology for preventing defects and improving product safety and quality. The main function is to point out the design or system failure mode, explore the impact of failure for the system, give qualitative or quantitative assessment, and then take necessary correction measures and prevention policies. FMEA has been widely used in the definition and elimination of known or latent failure to improve reliability and security (Ho and Liao, 2011).

The procedure for performing an FMEA is to systematically evaluate and document the potential impact of each failure on the product operation and mission success, personnel and product safety, maintainability, and maintenance requirements.

The FMEA is initiated at the lowest indenture level and precedes through increasing indenture levels (bottom-up approach), up to the main unit level until the entire FMEA is complete (Sharma *et al*., 2005).

The failure mode is defined as the manner in which a component, subsystem, system, process, etc. could potentially fail to meet the design intent. A failure cause is defined as a weakness that may result in a failure. For each identified failure mode, their ultimate effects need to be determined, usually by a FMEA team. A failure effect is defined as the result of a failure mode on the function of the product/process as perceived by the customer (Liu *et al*., 2011).

As mentioned before, Risk Priority Number (RPN) is the product of Severity (S), Occurrence (O), and Detection (D) and is calculated by formula1:

$$RPN = S \times O \times D \qquad (1)$$

The parameters with the highest RPN make efforts to take corrective action to reduce RPN. The purpose of the RPN is to rank the various parameters; concern should be given for every method available to reduce the RPN (Kenchakkanavar and Joshi, 2010).

There are two phases in FMEA. The first phase is concerned with identification of the potential failure modes and their effects. It includes defining the potential failures of product's component, subassemblies, final assembly and its manufacturing processes, and the second phase is concerned with performing criticality analysis to determine the severity of failure modes by evaluating and ranking (RPN) the criticality level of each failure (Sharma *et al*., 2005).

Table 1. The definition of FMEA

Definition	Author(s)
FMEA is an analysis technique for defining, identifying, and eliminating known and/or potential failures, problems, errors from systems, design, processes, and/or services before they reach the customers.	Liu *et al*., 2011; Yang *et al*., 2011
FMEA is intended to provide information for making risk management decisions.	Pillay *et al*., 2003
FMEA is a design analysis discipline that considers the effects of any failure in a design and identifies the more serious problems such as areas where the design may need to be improved.	Barendsa *et al*., 2012
FMEA is a powerful tool used by system safety and reliability engineers/analysts to identify critical parts, functions, and components whose failure will lead to undesirable outcomes.	Ho and Liao, 2011
FMEA is "a systematic method of analyzing and ranking the risks associated with various product (or process) failure modes (both existing and potential), prioritizing them for remedial action, acting on the highest ranked items, re-evaluating those items and returning to the prioritization step in a continuous loop until marginal returns set in".	Barendsa *et al*., 2012
The failure mode and effects analysis (FMEA) is a widely used analytical technique that helps with identifying and reducing the risks of failure in a system, component, part, and process.	Boldrin *et al*., 2009
FMEA is known to be a systematic procedure for the analysis of a system to identify the potential failure modes, their causes and effects on system performance.	Cassanellia *et al*., 2006
Failure Modes and Effects Analysis (FMEA) is a general and effective methodology for analyzing potential reliability problems early in the development cycle where it is easier to take actions to overcome these issues.	Hu *et al.*, 2012

Source: research results

The FMEA procedure

As outlined by Pillay and Wang (2003), the process for carrying out an FMEA can be divided into several steps (Pillay and Wang, 2003; Sharma *et al.*, 2005; Tay and Lim, 2006). These steps are briefly explained here:

1. Develop a good understanding of what the system is supposed to do when it is operating properly.
2. Divide the system into sub-systems and/or assemblies in order to localize the search for components.
3. Use blue prints, schematics, and flow charts to identify components and relations among components.

4. Develop a complete component list for each assembly.
5. Identify operational and environmental stresses that can affect the system. Consider how these stresses might affect the performance of individual components.
6. Determine failure modes of each component and the effects of failure modes on assemblies, sub-systems, and the entire system.
7. Categorize the hazard level (severity) of each failure mode (several qualitative systems have been developed for this purpose).
8. Estimate the probability. In the absence of solid quantitative statistical information, this can also be done using qualitative estimates.
9. Calculate the risk priority number (RPN): the RPN is given as the multiplication of the index representing the probability, severity, and detect ability.
10. Determine if action needs to be taken depending on the RPN.
11. Develop recommendations to enhance the system performance.

These fall into two categories:

- Preventive actions: avoiding a failure situation.
- Compensatory actions: minimizing losses in the event that a failure occurs.

Many studies accomplish about FMEA, some of the related work that presented about FMEA are shown below:

To overcome the drawbacks mentioned before, a number of approaches have been suggested in the literature. For example, Yang *et al*. (2008) presented a fuzzy rule-based Bayesian reasoning approach for prioritizing failures in FMEA. The technique is intended to deal with some of the drawbacks concerning the use of conventional fuzzy logic (i.e. rule-based) methods in FMEA (Yang *et al*., 2008).

Wang *et al*. (2009) proposed fuzzy risk priority numbers (FRPNs) for prioritization of failure modes to deal with the problem that is not realistic in real applications to determine the risk priorities of failure modes using the risk priority numbers (RPNs) because they require the risk factors of each failure mode to be precisely evaluated (Wang *et al*., 2009).

Barends *et al*. (2012) propose a probabilistic modification of FMEA, replacing the categorical scoring of occurrence and detection by their estimated relative frequency and maintaining the categorical scoring of severity. Using this probabilistic modification of FMEA, the frequency of occurrence of undetected failure mode(s) can be estimated quantitatively, for each individual failure mode, for a set of failure modes, and the full analytical procedure (Barendsa *et al*., 2012).

Liu *et al*., (2011) presented an FMEA using the fuzzy evidential reasoning (FER) approach and grey theory to solve the two problems and improve the effectiveness of the traditional FMEA. As it is illustrated by the numerical example, the proposed FMEA can well capture FMEA team members' diversity opinions and prioritize failure modes under different types of uncertainties (Liu *et al*., 2011).

Yang *et al*. (2011) used the modified Dempster–Shafer (D–S) theory to aggregate the different evaluation information by considering multiple experts' evaluation opinions, failure modes and three risk factors respectively in the aircraft turbine rotor blade. A simplified discernment frame is proposed according to the practical application. This method is used to deal with the risk priority evaluation of the failure modes of rotor blades of an aircraft turbine under multiple sources of different and uncertain evaluation information (Yang *et al*., 2011).

Bas (2011) used a general framework for child injury prevention and a multi-objective, multi-dimensional mixed 0-1-knapsack model was developed to determine the optimal time to introduce preventive measures against child injuries. The risk factors for each injury, variable, and time period were based on risk priority numbers (RPNs) obtained from failure mode and effects analysis (FMEA) methodology, and these risk factors were incorporated into the model as objective function parameters. A numerical experiment based on several different situations was conducted, revealing that the model provided optimal timing of preventive measures for child injuries based on the variables considered (Bas, 2011).

Sankar and Prabhu (2001) presented a modified approach for prioritization of failures in a system FMEA, which uses the ranks 1–1000 called risk priority ranks (RPNs), to represent the increasing risk of the 1000 possible severity–occurrence–detection combinations (Sankar and Prabhu, 2001).

Chang *et al.* (2001) also utilized the gray system theory for FMEA, but the gray relational degrees were computed using the traditional scores 1–10 for the three factors rather than fuzzy linguistic assessment information (Chang *et al.*, 2001).

Seyed-Hosseini *et al.* (2006) proposed a method called decision making trial and evaluation laboratory (DEMATEL) for reprioritization of failure modes in FMEA, which prioritizes alternatives based on severity of effect or influence and direct and indirect relationships between them (Seyed-Hosseini *et al.*, 2006).

Tay and Lim (2006) argued that not all the rules were actually required in fuzzy RPN models, and thus proposed different rules reduction systems to simplify the fuzzy logic-based FMEA methodology (Tay and Lim, 2006). Wang *et al*. (2009) also argued that using fuzzy if–then rules for FMEA will result in the problem that the fuzzy if–then rules with the same consequence but different antecedents are unable to be distinguished from one another. As a result, the failure modes characterized by these fuzzy if–then rules will be impossible to be prioritized or ranked. In addition, the use of fuzzy if–then rules has no way to incorporate the relative importance of risk factors into the fuzzy inference system (Wang, 2009).

Material and Methods

DEA

Data envelopment analysis (DEA) is a non-parametric technique for measuring the relative efficiency of the decision-making units (DMUs) that have homogenous inputs and outputs. DEA applies linear programming techniques to the observed inputs/outputs of

DMUs by constructing an efficient production frontier based on the best practices. Each DMU's efficiency is then measured relative to its distance to this frontier (Zerafat *et al*., 2012).

The mathematical form of the basic DEA model is as follows:

$$\begin{aligned} &\max \quad \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \\ &s.t. \quad \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \le 1 \quad j = 1, \ldots, n \\ &\qquad u_r, v_i \ge 0 \qquad r = 1, \ldots, s; i = 1, \ldots, m \end{aligned} \tag{2}$$

Here, x_{ij} is the amount of ith input, y_{rj} is the amount of rth output, v_i Is the weight given to the ith input, u_r is the weight given to the rth output, and k is the DMU being measured. (Seol *et al.*, 2011)

The efficiency ratio ranges from zero to one, with DMU k being considered relatively efficient if it receives a score of one. Thus, each unit will choose weights so as to maximize self-efficiency, given the constraints (Adler *et al.*, 2002).

Consider a set of n DMUs, in which x_{ij} (i= 1, 2, ..., m) and y_{rj} (r= 1, 2, …, s) are inputs and outputs of DMU_j (j= 1, 2, …, n); the standard form of CCR model for assessing DMU_0 is written as (Zerafat *et al*., 2012):

$$\begin{aligned} &\max \sum_{r=1}^{s} u_r \, y_{rj} \\ &s.t. \quad \sum_{i=1}^{m} v_i \, x_{i0} = 1 \\ &\qquad \sum_{r=1}^{s} u_r \, y_{rj} - \sum_{i=1}^{m} v_i \, x_{ij} \le 0 \quad j = 1, 2, \ldots, n \\ &\qquad v_i \ge 0 = 1, 2, \ldots, m \\ &\qquad u_r \ge 0 = 1, 2, \ldots, s \end{aligned} \tag{3}$$

DEA Model for FMEA

Suppose there is n failure modes denoted by $FM_i(i=1,...,n)$ to be prioritized, each being evaluated against m risk factors denoted by $RF_j(j=1,...,m)$. Let $r_{ij}(i=1,...,n; j=1,...,m)$ be the ratings of FM_i on RF_j and w_j be the weight of risk factor $RF_j(j=1,...,m)$. Since the RPN defined as the product of three risk factors O, S, and D has been largely criticized for its mathematical formula and the equal treatment of the risk factors, in this paper the risks of failures with a different mathematical form are shown as follows:

$$R_i = \sum_{j=1}^{m} w_j r_{ij}, i = 1,\ldots,n \qquad (4)$$

Eq. (4) defines the risk of each failure mode as the weighted sum of m risk factors. The risk determined by Eq. (4) as additive risk. It is worthwhile to point out that the definition for additive risks was first proposed by Braglia *et al*. (2003), who defined the RPN as the weighted sum of O, S, and D. This paper require the weights of the risk factors to be specified or determined subjectively; however, in this paper the risk factor weights will be determined automatically by DEA models.

FMEA models for measuring the maximum and minimum risks of each failure mode are as shown below:

$$\boldsymbol{R}_0^{\max} = Maximize R_0$$
$$Subjectto \begin{cases} R_i \le 1, i = 1,..,n, \\ w_j - 9w_k \le 0,\ j,k = 1,\ldots,m; k \ne j, \end{cases} \qquad (5)$$

$$\boldsymbol{R}_0^{\min} = Minimize R_0$$
$$Subjectto \begin{cases} R_i \ge 1, i = 1,..,n, \\ w_j - 9w_k \le 0,\ j,k = 1,\ldots,m; k \ne j, \end{cases} \qquad (6)$$

where R_0 is the risk of the failure mode under evaluation. The overall risk of each failure mode is defined by Eq. (7) as the geometric average of the maximum and minimum risks of the failure mode. That is:

$$\overline{R}_i = \sqrt{\boldsymbol{R}_i^{\max} \cdot \boldsymbol{R}_i^{\min}}, i = 1, \dots, n \qquad (7)$$

The bigger the geometric average risk, the higher the risk priority. The n failure modes $FM_i (i = 1, ..., n)$ can be easily prioritized by their geometric average risks $\overline{R}_i (i = 1, ..., n)$ (Chin *et al*., 2009).

Defuzzification

Chen and Klien (1997) have proposed an easy defuzzification method for obtaining the crisp number of a fuzzy set, which is shown here in Eq. (8) (Chen and Klien, 1997).

$$K(x) = \sum_{i=0}^{n} (b_i - c) / \sum_{i=0}^{n} (b_i - c) - \sum_{i=0}^{n} (a_i - d) \qquad (8)$$

where Constant values of c and d are lower and upper bound of the membership function, respectively, i. e 1 and 10 and a_i and b_i length of the lower and upper triangular diagram is to describe each of the 10 linguistic variables which the amount of membership function for them is zero. a_1 and b_1 are the average of the triangle membership function which is 1. h_{ij} is the defuzzified crisp number of H_{ij} (Liu *et al*., 2011). Defuzzified values calculated with Klien and Chen's method for each linguistic variable are shown in the following table:

Table 2. Defuzzified values for each linguistic variable

Fuzzy numbers	(1,1,2)	(1,2,3)	(2,3,4)	(3,4,5)	(4,5,6)	(5,6,7)	(6,7,8)	(7,8,9)	(8,9,10)	(9,10,10)
Crisp number	0.0526	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.94

Source: research results

Results

For the purpose of data collection in this study, a number of people who had experience and education related to the tile and ceramic industry were selected and the FMEA form was given to them. These people were production manager, quality control specialists, supervisors, and experts in the glazing.

The risk factors occurrence, severity, and detection have been assessed by the industrial expert's knowledge and experience in the field of evaporator passive systems, by using linguistics terms and ratings. The O, S, and D ratings and meanings resulting from the experience in the passive systems and using the values scaled are shown in Tables 3 to 5 (Ilangkumaran and Thamizhselvan, 2010).

Table 3. Fuzzy numbers of occurrence Probability of occurrence Rating Description

Effect of severity	Fuzzy Rating	Rating	Description
Almost never	(1,1,2)	1	Failure unlikely
Remote	(1,2,3)	2	Rare number of failures
Slight	(2,3,4)	3	Very few failures
Low	(3,4,5)	4	Few failures
Moderately low	(4,5,6)	5	Occasional number of failures
Moderate	(5,6,7)	6	Moderate number of failures
Moderately high	(6,7,8)	7	Moderately high number of failures
High	(7,8,9)	8	High number of failures
Very high	(8,9,10)	9	Very high number of failures
Almost certain	(9,9,10)	10	Failure almost certain

Source: Yazdi and Haddadi, 2011

Table4. Fuzzy numbers of Severity

Effect of severity	Fuzzy Rating	Rating	Description
None	(1,1,2)	1	No effect
Very slight	(1,2,3)	2	Very slight effect on product performance
Slight	(2,3,4)	3	Slight effect on product performance
Very Low	(3,4,5)	4	Very low effect on product performance
low	(4,5,6)	5	Low effect on product performance
Moderate	(5,6,7)	6	Moderate effect on product performance with minor damage
high	(6,7,8)	7	High effect on product performance with equipment damage
Very High	(7,8,9)	8	Very high effect and product inoperable
Serious	(8,9,10)	9	Serious effect and product must stop when a potential failure mode affects safe system operation with warning
Hazardous	(9,9,10)	10	Hazardous effect and safety related when a potential failure mode effects safe system operation without warning

Source: Yazdi and Haddadi, 2011

Table 5. Triangular Fuzzy number of detection

Detection	Fuzzy Rating	Rating	Description
Almost certain	(1,1,2)	1	Design control will detect potential cause/mechanism and subsequent failure mode
Very High	(1,2,3)	2	Very high chance the design control will detect potential cause/mechanism and subsequent failure mode
high	(2,3,4)	3	High chance the design control will detect potential cause/mechanism and subsequent failure mode
Moderately high	(3,4,5)	4	Moderately high chance the design control will detect potential cause/mechanism and subsequent failure mode
Moderate	(4,5,6)	5	Moderate chance the design control will detect potential cause/mechanism and subsequent failure mode
low	(5,6,7)	6	Low chance the design control will detect potential cause/mechanism and subsequent failure mode
Very Low	(6,7,8)	7	Very low chance the design control will detect potential cause/mechanism and subsequent failure mode
Remote	(7,8,9)	8	Remote chance the design control will detect potential cause/mechanism and subsequent failure mode
Very Remote	(8,9,10)	9	Very remote chance the design control will detect potential cause/mechanism and subsequent failure mode
Almost impossible	(9,9,10)	10	Design control cannot detect potential cause/mechanism and subsequent failure mode

Source: Yazdi and Haddadi, 2011

In this study, in order to evaluate the proposed method, the failure modes were identified in the process of glazing Tile and Ceramic Company. Then, risks were ranked by the use of DEA-FMEA method and their geometric average.

Tables 6 and 7 show the 10 identified failure modes and their Fuzzy ratings on the three risk factors O, S, and D, respectively.

Table 6. Fuzzy rating for each failure mode

Failure mode	S	O	D
Tonality	(1,2,3)	(8,9,10)	(8,9,10)
Dust	(2,3,4)	(4,5,6)	(4,5,6)
Decorating Fault	(2,3,4)	(7,8,9)	(7,8,9)
Dry Spots	(2,3,4)	(6,7,8)	(6,7,8)
Wrinkles	(2,3,4)	(3,4,5)	(3,4,5)
Crack	(3,4,5)	(3,4,5)	(3,4,5)
Pinhole	(1,2,3)	(4,5,6)	(4,5,6)
Print Sticking	(1,2,3)	(9,10,10)	(9,10,10)
Print Movement	(2,3,4)	(4,5,6)	(4,5,6)
Fracture	(1,2,3)	(8,9,10)	(8,9,10)

Source: research results

Using Chen and Klien's (1997) method, defuzzified values of each failure mode is calculated and shown in the Table 7.

Table 7. DeFuzzifed values for each failure mode

Failure mode	S	O	D
Tonality	0.15	0.85	0.85
Dust	0.25	0.45	0.45
Decorating Fault	0.25	0.75	0.75
Dry Spots	0.25	0.65	0.65
Wrinkles	0.25	0.35	0.35
Crack	0.35	0.35	0.35
Pinhole	0.15	0.45	0.45
Print Sticking	0.15	0.94	0.94
Print Movement	0.25	0.45	0.45
Fracture	0.15	0.85	0.85

Source: research results

The Results of ranking failure modes by the traditional RPN is shown in Table 8.

Table8. FMEA for the Glazing process by RPN

Failure mode	S	O	D	RPN	Priority ranking
Tonality	0.15	0.85	0.85	0.1083	3
Dust	0.25	0.45	0.45	0.0506	6
Decorating Fault	0.25	0.75	0.75	0.1406	1
Dry Spots	0.25	0.65	0.65	0.1056	5
Wrinkles	0.25	0.35	0.35	0.0306	9
Crack	0.35	0.35	0.35	0.0428	8
Pinhole	0.15	0.45	0.45	0.0303	10
Print Sticking	0.15	0.94	0.94	0.1325	2
Print Movement	0.25	0.45	0.45	0.0506	6
Fracture	0.15	0.85	0.85	0.1083	3

Source: research results

By solving DEA models (2) and (3) for each failure mode, respectively, we get the maximum and minimum risks of all the 10 failure modes, which are shown in Table 8 together with their geometric average risks computed by Eq. (7), respectively, and the risk priority rankings of the 10 failure modes. The results are shown in the following table.

Table9. FMEA for the Glazing process by DEA

Failures mode	Maximum risk	Minimum risk	Geometric average risk	Priority ranking
Tonality	0.9265	1.3555	1.1206	4
Dust	0.8285	1.1666	0.9831	7
Decorating Fault	1	1.6666	1.2909	1
Dry Spots	0.9428	1.5	1.1892	3
Wrinkles	0.7714	1	0.8783	9
Crack	1	1	1	6
Pinhole	0.6	1	0.7745	10
Print Sticking	1	1.4355	1.1981	2
Print Movement	0.8285	1.1666	0.9831	7
Fracture	0.9265	1.3555	1.1206	4

Source: research results

Based on the results in Tables 8 and 9, the researchers reach the following observations:

Except for failure modes 3, 5, 7, and 8 the risk priority rankings of the other 6 failure modes obtained by their geometric average risks are different from those by their RPNs. This shows the fact that the combination of DEA and FMEA is totally different from the traditional FMEA.

The highest difference among the three sets of risk priority rankings in Tables 8 and 9 happens at failure modes 4 and 6, which have a up to two ranking places difference by the two different FMEA priority methods.

Failure mode 6 is ranked noticeably below failure modes 9 and 2 because it has a small occurrence rating in comparison with failure modes 9 and 2. Failure mode 4 is ranked noticeably below failure modes 9 and 2 because it has a high detection rating in comparison with them.

Discussion and Conclusion

FMEA is a very important safety and reliability analysis tool that has been widely used in a wide range of industries. FMEA, designed to provide information for decision- making in risk management decision-making, is a widely used engineering technique in industries.

Failure Modes and Effect Analysis (FMEA) is known to be a systematic procedure for the analysis of a system to identify the potential failure modes, their causes and effects on system performance. The analysis is successfully performed preferably early in the development cycle so that removal or mitigation of the failure mode is the most cost effective (Cassanellia *et al.*, 2006).

In FMEA, potential failure modes are determined and can be evaluated by risk factors known as severity, occurrence, and detection. In a typical FMEA, the risk priority number of each failure mode is obtained by multiplying the crisp values of the risk factors. However, the crisp values of RPNs have been considerably criticized for many reasons in the literature such as ignoring relative importance among the risk factors, imprecise evaluation, questionable multiplication procedure, and obtaining RPN values not high enough with two factors with very low risk value but a highly risky factor.

Due to the criticisms for RPN calculation in literature, a fuzzy approach is considered for FMEA analysis by its superiority over the traditional approach (Kutlu and Ekmekcioglu, 2012).

For the purpose of improving traditional RPN, this paper proposed an FMEA by data envelopment analysis. To define the risks of failure modes as the weighted sum or weighted product of risk factors, the researchers developed DEA models for measuring the maximum and minimum risks of failure modes. Their geometric averages measure the overall risk of each failure mode and are therefore used to prioritize failure modes.

Assessments of risk factors are not easy, so the evaluators can assess by using the concepts of fuzzy theory and the failure modes can be analyzed more appropriately and accurately. In this study, using fuzzy FMEA with linguistic terms such as, low, moderate, and high to evaluate the risk factors of S, O and D, increases the capability of implementing and feasibility of FMEA.

This study used fuzzy logic to evaluate S, O, and D, and DEA-FMEA was applied to rank failure modes. A real example was used in industry and this method was employed in the process of glazing Tile and Ceramic Company. The results of the DEA–FMEA ranking show that Decorating Fault and Pinhole are ranked the first and the second, respectively. In order to improve them, some suggestions are recommended such as implementing timely replacement templates and using appropriate printing processes to reduce probability of failure modes.

This study has tried to provide the appropriate methodology for ranking and determining efficiency of Failure modes in Tile and Ceramic Company. The proposed model leads to a significant ranking of failure modes and the company will have the opportunity to improve their importance. Using fuzzy theory makes decisions better and closer to reality and actual conditions and the natural environment of the company is considered. It seems that the proposed model determines failure modes efficiency more effectively and efficiently than the classic models.

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