MethodsX 11 (2023) 102278

Contents lists available at ScienceDirect

MethodsX

journal homepage: www.elsevier.com/locate/methodsx

Evaluation of the failure effects of a screwing station using a new approached FMEA

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ARTICLE INFO

Method name:
Evaluation of the failure effect in the FMEA method

Keywords:
Risk assessment
Network science
FMEA
Failure tree analysis

ABSTRACT

Recognizing the importance of risk assessment and the large-scale industrial spread of network research, we developed a new approach to risk assessment.

- The risk assessment takes into account the chains of impact between each level and the frequency of effects and their causes.
- In contrast to the traditional FMEA methodology, we evaluate the frequency of occurrence and detectability not only at the level of causes but also at the level of effects.
- All this is complemented by a toolkit of network research methodology. The new methodology is validated through a real industry example, which is a risk assessment of a screwdriver station.

Specifications table

Subject area:	Engineering
More specific subject area:	*Quality Engineering*
Name of your method:	*Evaluation of the failure effect in the FMEA method*
Name and reference of original method:	*N.A*
Resource availability:	*N.A*

Method details

Background

Risk assessment is an important part to ensure process safety. The two most commonly used methods in risk assessment are the Fault Tree Analysis and the Failure Mode and Effect Analysis. Both methods have advantages and limitations too. This study aims to apply network science technics to extend these two methods in risk assessment. Network research is becoming more widespread, even in industrial use. New assessment methods provided by networks can assure an opportunity to identify and estimate risks as accurately as possible. Networks can be used to explore relationships between product or process levels and to evaluate chains of impact. The 21st century is characterized by massive technological changes, and most manufacturing industries face the challenge of developing cost-effective products and innovations that not only meet customer needs but also environmental concerns [1]. For this, the preparation of a risk assessment and the parallel development of existing risk assessment techniques are essential. In manufacturing processes, it

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https://doi.org/10.1016/j.mex.2023.102278
Received 31 January 2023; Accepted 30 June 2023
Available online 1 July 2023

is particularly essential to carry out the widest and most accurate risk assessment possible, as potential defects also affect the product and the environment, such as operators and surrounding equipment. Therefore, we chose as an example a production line screwing station, which can be found in almost every automotive plant. Through this example, a new approach to risk assessment methodology is presented.

We can use several methods to assess risks. However, Failure Mode and Effect Analysis is the most commonly used risk assessment method to understand and systematically measure the risks of a product or process [2]. The FMEA methodology has already been applied in many areas, such as automotive industry, manufacturing industry, nuclear power industry, electronics industry, chemical industry, agriculture, hospital and mechanical engineering [3] due to the common structures and languages of the method [4]. The method assesses risks on three levels: failure cause, failure mode, and effect [5]. Occurrence and detection are used to assess the causes of errors, which means the chance of errors occurring and being detectable. With the severity of the effect of the fault, we assess the extent to which the customer is affected by the occurrence of the fault. This is given by the value of severity [6]. These three factors are evaluated on a predefined scale, the range of which is usually 1-5 or 1-10. According to the old approach, the product of these three values gave the risk priority number, in descending order of which the risks with the highest value were the most severe, requiring further action [7]. In the new edition of the FMEA handbook, this has already been defined differently, with the introduction of the action priority assessment that looks at the combinations of the three values according to the table in the handbook. Based on the combinations, it classifies the risks into three priority categories, which are low, medium, and high [8]. There are several types of FMEA such as System-FMEA which is used to analyze systems and subsystems, Product-FMEA which helps to gather the risks of design, Process-FMEA which assesses the risks during the processes [9] and Machinery-FMEA, which identifies the risk associated with machinery and equipment failure [10]. While perhaps less attention is paid in research to the risk assessment of machines, it is an equally important part of any manufacturing process. The safety of the manufacturing machines affects the personal safety of the employees as well as the safety of the product to be manufactured. The safety of machines and their risk assessment are addressed in ISO 12100 [11] which is a Type-A standard [12]. The standard includes several steps such as the limitations of the machines, the potential risks, their identification, and evaluation [13]. Companies use various documents to ensure compliance with mechanical, electrical, and ergonomic safety requirements. MFMEA, which can be found in the standard, can also be used for this [14]. There are several examples of this (what?) in the literature. FMEA and reliability analysis of critical equipment machinery in the Malaysian Palm Oil Mill was performed, where the basis of the risk assessment was the frequency of equipment failure [15]. An integrated IT2F-MCDM-based FMEA method was also used to analyze failures of CNC machines due to human errors, where the evaluated parameters were extended to the safety, economic impact, occurrence, and detection [16]. Failure tree and FMEA methods were also used together to eliminate failures of a 3D printer and to find the reasons for the failures [17]. The FMEA methodology can not only assess the risks related to the operation of the machines, but it can also help to design the maintenance related to the operating system and quantify the severity of personnel injury and environmental pollution [18].

The purpose of MFMEA is to prevent and identify potential design risks, and to help define and control specifications [19]. The FMEA also conducts the assessment in such a way that it always begins to assess risks from the level of causes. It does not define and evaluate the interrelations between each level.

Fault tree analysis starts with a major event and reveals all the events that lead to the main event. Graphically, this is represented by a tree structure. The method also explores particularly critical events and chains. The reliability values must be given along the branches of the fault tree. The evaluation can be used to determine the combinations of events that can be used to eliminate the main event.

The FMEA and FTA methods were used together several times. The failure analysis was improved when the FTA method was used to identify the function, component failure modes, and failure mechanisms, and FMEA was applied to select the critical failures [20]. To eliminate work accidents in Indonesia, FMEA and FTA analyses were also used together. The higher RPN numbers were determined with FMEA and the FTA analysis was selected to determine the process of combination among factors that cause various workplace accidents [21]. An integrated FTA and FMEA method were proposed to analyze safety-critical systems (where, how, when?) [22]. An FTA-FMEA-based validity verification technique was used to verify safety standards (by whom? What for?) [23]. The combination of these two methods can reduce the drawbacks of each method if the FTA is used to determine the root causes and the FMEA is applied to specify the severity, occurrence, and detection numbers [24]. FMEA and FTA, Recursive Operability Analysis were used for quantitative risk assessment to identify the most critical parts of the process and plant [25]. FMEA method was also developed with multiple failure analysis and the weighted priority numbers due to the weights of the three factors (S, O, D) are not equal. S and D have highest priority in the evaluation [26]. The combination of the S&O, S&D and O&D was a new classification method to eliminate the interaction effect [27]. FMEA methodology and deep learning analysis were also used together to enhance maintenance planning, and the results showed 95% accuracy of the risk prediction [28].

However, the disadvantage of both is that they are time-consuming and therefore often not used. As a result, possible failure modes may not be identified. The combination of these two methods may expand the number of failure modes found, due to the different starting points of both methods: bottom-up in FMEA, top-down in FTA. In addition, performing both analyses would be time-consuming and may lead to a loss of focus on the most critical parts of the system, which the failure analysis typically aims to identify [29].

A failure network was developed for better visualization and to understand complicated failure propagation mechanisms among multiple system levels [35]. The IQ-RM software which was developed by APIS also includes the visualization of the failure nets and function nets for a better understanding of the relationships between the components and their failures. The networks help to understand the relationships based on the Bill of material, but it is used just for the visualization and calculation of the RPN number [30]. To reduce the uncertainty a Fuzzy-based Data envelopment was used together with the FMEA method (KA [31]). The Two-

Stage Optimization Probabilistic Linguistic Preference Relations were applied to develop the FMEA methodology. In the proposed method, a two-stage optimization was used to drive the optimum importance weight of the risk factors [32]. The uncertainty of the risk assessment was also modeled. In the research, the definition of uncertainty and how to model and treat uncertainty are stated [33]. A machine learning methodology was used for risk assessment. The authors stated that modern technology advancement needs the development of new risk assessment methods in the case that a large volume of data becomes available [34]. Risk assessment and social network analysis were also used together in a method called Fuzzy critical risk analysis (FCRA) [36]. A character-based network of the network (NoN) was also applied to identify the critical characteristics of hazards to help guide safety inspectors [37]. A recent study presented an intelligent method that combined fault tree analysis and fuzzy neural networks. The fault tree analysis presented the logical structure of the failures, and the fuzzy neural networks are used to train the relationship mapping between fault symptoms and faults [38]. A mathematical model was created to determine the likelihood of the causes of the failure and to ensure a model to predict fire accidents. The model has been validated, but it also focuses only on the occurrence of the causes of risks [39]. To predict the potential failure of coal and gas outburst events during the underground mining of thick and deep Chinese coal seams, FTA and artificial neural network (ANN) were used together. The result of the model offers a new method to prevent the potential risks [40]. Fuzzy–based Bayesian network, FMEA, and Best worst method were combined to eliminate the limitations of the FMEA, such as subjectivity, absence of weight values of risk parameters, and not considering the conditionality between failure events [41]. A quantitative risk assessment was applied to using ammonia in real industrial refrigeration in Rio de Janeiro and to achieve the assessment model, the PHAST methodology was used. Based on the results, it can be specified, which scenario causes the worst result [42]. Bayesian network for risk assessment was often used in the literate, for example the explicit and implicit one to find the common cause (CC) to a system [43]. Convolutional neural networks were also proposed for detection and classification of fatigue crack damage and risk assessment in polycrystalline alloys, but it is not used the FMEA method for the risk assessment mapped as a network [44]. These studies have addressed several of the shortcomings of the FMEA methodology. FMEA was developed with pairwise comparison methods and network science. A PC-FMEA method was created to eliminate the subjectivity of the method with pairwise comparison and to measure the consistency of the evaluation [45]. In another work, pairwise comparison-based FMEA was assessed and visualized with networks. Two types of networks were created, an individual network and an aggregated network. The evaluation was done by PageRank and the in-degree values of the network. With the networks, the consistency of the evaluation can be also evaluated [46].

From the literature review it was stated that there is a demand to develop the risk assessment methods with network science. However, none of them took the approach of using a risk assessment, based on the FMEA methodology and network research to examine risks not only from the cause of the error but also from the point of view of the effect. The appearance of Quality 4.0 also requires the improvement of the current methods. The currently used quality methods are not capable handling of big data and they are commonly requiring manual work [47]. However, it seems that in the past years, these developments are stopped, and a few innovative methods have been proposed [48]. In addition, understanding and implementing the proposed research need knowledge of using difficult software and methods.

Our study aims to develop a new method that combines some parts of the FMEA, FTA method, and network analysis and to extend the FMEA method with a network-supported effect assessment. The FMEA methodology has not performed this assessment before. Thus, not only would the causes of errors be identified and evaluated, but the effects would also be ranked according to their importance. Network research helps in the visualization and it allows us to evaluate larger data sets. During our research, we also kept in mind to develop an easily usable method. For the visualization and evaluation of the in-degree value, the Gephi program was used. The program is free and easy to use.

Method

FMEA evaluates the severity on the top of the failure net, where the effects are placed. The occurrence and detection values are evaluated in turn by the root causes, on the lowest level. In this case, the effects, the frequency of their occurrence, how much they can be detected, the modes of error are not evaluated at all, and the severity of the causes is also not evaluated. The probability of the effect occurring can be derived from the frequency with which the events that give rise to it occur. One effect could have more than one mode and more than one cause.

Calculation of the new RPN value

The most significant step to ranking the risks is the combination of the SxOxD [49]. The essence of the new approach, importance assessment, is to look not only at the severity of the effect but also at what precedes it from occurring. What matters is not just how severe an effect is when it occurs, but also how likely it is to occur. To determine this, we need to look at how many roots are causing an effect in the network, and what are the chances of them noticing or occurring. The following formulas can be used to calculate this. The formulas were created based on the in-degree of a vertex in a network. Eq. (2) determines the occurrence probability of the effect, Eq. (3) shows the detection probability of the effect in a failure net, which starts from an effect and ends in the roots, sees Fig. 1.

The calculation of the weighted in-degree $w_1 D_j$ can be seen in Eq. (1). [50].

$$w_1 D_j = \sum_{(v_i, v_j) \in E} w_{ij} \tag{1}$$

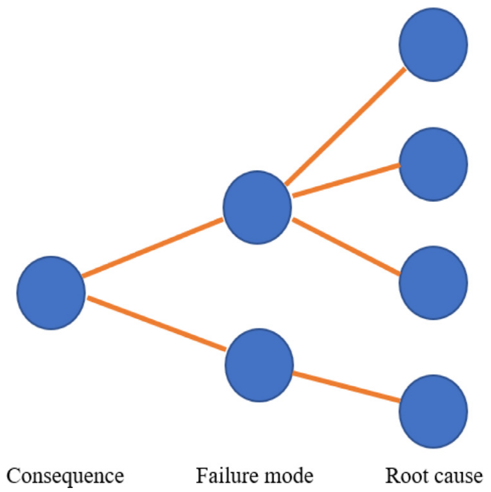

Fig. 1. The failure net includes the levels as Effect, Failure mode which can be more than one level, and the Root Cause.

Where w_{ij} the weight of the edge between i and j and the w_1D_j is the weighted in-degree of node j.
In a directed graph, in-degree means the number of the in-connected edges of a certain node [51].

$$C_o = \sum_{i=1}^{n} O_i \tag{2}$$

Where C_o is the probability of occurrence of an effect and O_i is the probability of occurrence of the i^{th} failure node.

$$C_D = \sum_{i=1}^{n} D_i \tag{3}$$

Where C_D is the probability of detection of an effect, D_i is the probability of detection of the i^{th} failure node. The C_o and C_D values were calculated based on the weighted number of steps as a network indicator in the Gephi network modelling program. The later we notice a problem in the process, the more severe the effects become, so weighting is necessary.

$$IC = C_S \cdot C_o \cdot C_D \tag{4}$$

Where IC means the Importance of the Effect, C_S means the severity of the effect, C_o means the probability of occurrence of the effect and C_D means the probability of detection of the effect. Severity should be determined based on the basic FMEA method. Indicates how severe the effect is for the customer. (What indicates it?)

Case study

The method has also been applied to the already completed FMEA of a screwing station production line. The networks were constructed from the results of the risk assessment, and the risk factors were calculated for the effects based on the formula presented in the method section. In this chapter, the possible application of the developed method is presented.

The machinery FMEA network

The example relates to one application of a production line on which a car seat frame is manufactured. Here, the risk assessment was concerned with whether the production line met its requirements in terms of accident prevention, product protection, and ergonomics. The results of the risk assessment of the screwing station were selected from the production line. For 40 functions, 46 effects, 41 error modes, and 40 error causes were defined. Of course, there may be overlaps between these, the same errors may be responsible for multiple error modes and effects, and so on. As a result, 16 different effects, 34 different error modes, and 6 different error causes were determined. The 16 different effects are described in Table 1.

After the evaluation, the detection values of the effects are shown in Table 2, the occurrence values of the effects are shown in Table 3, the severity values of the effects are shown in Table 4, and the importance of the effects are shown in Table 5.

The network of the risks, in case of two indicators such as occurrence and detection, were also created. A weighted Machinery FMEA network was created M = {V, E, W}, where V is the set of vertices, E is the set of edges and W is the weight of the edges. In the network α_{ij} means the connection between i and j, and every connection has (i, j) a weight as w_{ij}. For the visualization and the evaluation of the weighted in-degree of the nodes, the *Gephi* program was used. The results of the risk assessment in an Excel table were implemented into the program. The structure of the Excel table was as follows: three columns were created, one for the starting

Table 1
Description of the 16 effects of the failures for the screwing station.

ID	Description of effect
C1	The operator is injured during traffic
C2	The operator will be injured in the long run
C3	The time required to complete the task is long
C4	The design of the equipment makes it difficult for the operator to work
C5	Improper maintenance
C6	The operator does not see the information displayed on the visual unit properly
C7	Wire breaks
C8	Screwing error
C9	Screwing does not start
C10	The conveyor cannot transport the product
C11	Decreased ability to concentrate
C12	Hearing impairment
C13	Electric shock to the operator
C14	The equipment is damaged
C15	The operator suffers from burns
C16	The operator is injured during work

Table 2
Detection of the effects (C_D) based on the number and detection values of previous events.

ID	C_D
C1	17
C2	38
C3	3
C4	38
C5	3
C6	29
C7	4
C8	4
C9	10
C10	8
C11	6
C12	7
C13	4
C14	2
C15	3
C16	26

Table 3
Occurrence of the effects (C_O) based on the number and occurrence values of previous event.

ID	C_O
C2	42
C4	42
C6	41
C16	41
C1	23
C10	9
C9	8
C15	7
C3	6
C13	6
C14	5
C5	4
C7	4
C8	4
C11	4
C12	4

Table 4
Severity of the effects (C_S) based on the number and occurrence values of previous events.

ID	C_S
C13	10
C1	9
C2	9
C12	9
C15	9
C16	9
C1	9
C5	7
C11	7
C14	7
C6	6
C10	6
C3	5
C4	5
C7	4
C8	4
C9	3

Table 5
Importance of the effects (IC).

ID	IC
C2	14364
C16	9594
C4	7980
C6	7134
C1	3519
C10	432
C12	252
C9	240
C13	240
C15	189
C11	168
C3	90
C5	84
C14	70
C7	64
C8	64

node, one for the destination node, and one for the weights of the connections. Fig 2 shows the example of the detection network. The greater the risk in-degree, the larger the node, and the larger the value given to the indicators O and D the larger the size of the edges.

Based on the importance of the effects, it appears that the C2 effect had the highest value.

What is the importance of an effect in this case?

- Many events can be responsible for their occurrence.
- Preventive events are likely to be hard to detect.
- Preventive events are likely to occur.

Based on the ranking of the results, this is a system where there is a high chance that the operator will be injured in the long run. This in itself is a high risk with a severity value of 9. Supplementing the FMEA with this method thus provides an opportunity not only to examine the causes to be eliminated based on the RPN number or AP but also to examine the risk network to learn about the key implications of the system. After reducing or eliminating the causes of the risk, it is advisable to perform the calculation again and draw the effects. Supplementing the traditional FMEA methodology with this calculation helps to assess which effect is most likely to occur based on the relationships of risks. This allows another aspect of our system to be considered while reducing cost. We see that performing this level of risk assessment provides a complete picture of the future behavior of a system's risks.

The basic FMEA method is focusing on finding the root cause with the highest risk value. The evaluation of the relationship between the risks at different levels is not part of the work. In addition, it does not offer a visualization opportunity. FTA method includes the tree of the failures as a visualization, but not includes the evaluation of the failure effects based on their connections.

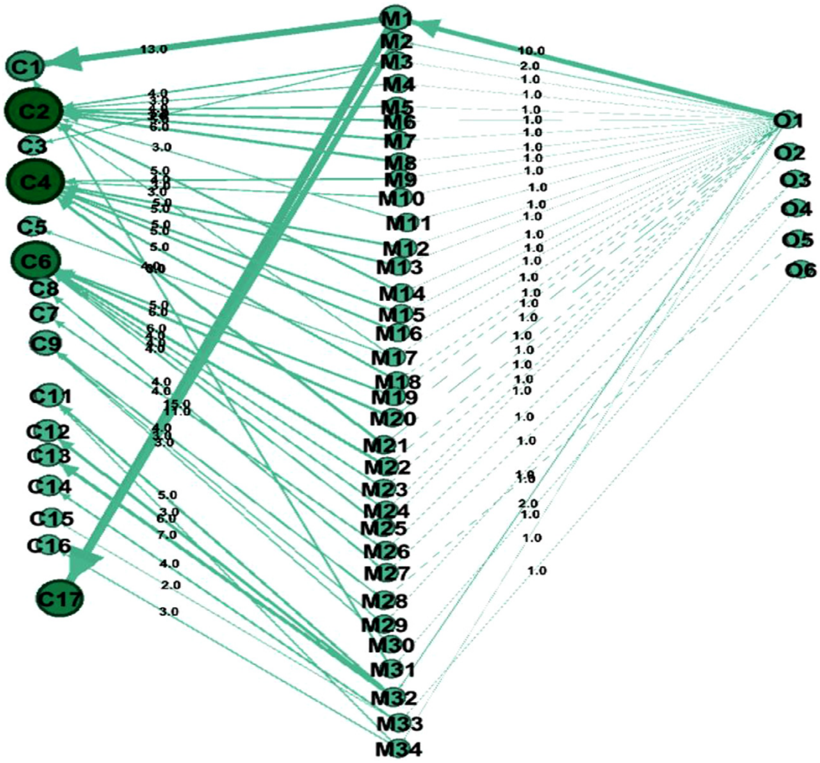

Fig. 2. The detection failure net is where the effects, modes, causes, and their relationships can see.

With the present research results, we aimed to expand the toolkit of the already used FMEA methodology. With the new approach, we examined not only the causes of the risks but also the relationships and significance of the consequences. With this method, we evaluated multiple sides of the risky contact network. After the evaluation, we can tell not only what the roots that need to be addressed first are, but also what consequences are expected to occur first. Knowing the risk, it can be seen whether its occurrence causes personal injury or damage to the product or service. It is worth examining the relationships of this consequential risk in the network and addressing those with the highest risk. The final importance number (IC) includes how many preventive events there are, how often they occur, and how easily they can be detected. However, the severity of the consequence also determines its importance. The methodological advantage of the present research is therefore that it adds another factor to the risks in addition to the AP or RPN number. Using networks also helps in the visualization and understanding of the relationships between the risks. The other advantage of the method is that we can quickly process large data sets with it. According to that fact, the results are easily adaptable to the Quality 4.0 environment. The proposed method is applicable to determine the significance of an effect in any network, if the connections have weights and the edges are directed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Edina Ungvári: Conceptualization, Methodology. **István Gábor Gyurika:** Methodology, Visualization. **Tamás Csiszér:** Writing – review & editing.

Data availability

No data was used for the research described in the article.

Acknowledgments

This work has been implemented by the TKP2020-NKA-10 project with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the 2020 Thematic Excellence Programme funding scheme.

References

[1] I. Daniyan, K. Mpofu, B. Ramatsetse, M. Gupta, Review of life cycle models for enhancing machine tools sustainability: lessons, trends and future directions, Heliyon 7 (4) (2021) e06790.
[2] S. Hassan, J. Wang, C. Kontovas, M. Bashir, Modified FMEA hazard identification for cross-country petroleum pipeline using Fuzzy Rule Base and approximate reasoning, J. Loss Prev. Process Ind. 74 (2022) 104616.
[3] M.M. Shahri, A.E. Jahromi, M. Houshmand, Failure Mode and Effect Analysis using an integrated approach of clustering and MCDM under pythagorean fuzzy environment, J. Loss Prev. Process Ind. 72 (2021) 104591.
[4] A.P. Subriadi, N.F. Najwa, The consistency analysis of failure mode and effect analysis (FMEA) in information technology risk assessment, Heliyon 6 (1) (2020) e03161.
[5] C. Spreafico, D. Russo, C. Rizzi, A state-of-the-art review of FMEA/FMECA including patents, Comput. Sci. Rev. 25 (2017) 19–28.
[6] S. Rana, R.M. Belokar, Quality improvement using FMEA: a short review, Int. Res. J. Eng. Technol. (IRJET) 4 (6) (2017) 263–267.
[7] E. Ullah, M.M. Baig, H. GholamHosseini, J. Lu, Failure mode and effect analysis (FMEA) to identify and mitigate failures in a hospital rapid response system (RRS), Heliyon 8 (2) (2022) e08944.
[8] Anackovski, F., Kuzmanov, I., & Pasic, R. (2021). Action priority in new FMEA as factor for resources management in risk reduction.
[9] K.D. Sharma, S. Srivastava, Failure mode and effect analysis (FMEA) implementation: a literature review, J. Adv. Res. Aeronaut. Space Sci. 5 (2018) 1–17.
[10] K.K.M. Rosita, M.V. Rada, Equipment reliability optimization using predictive reliability centered maintenance, in: Proceedings of the IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA), IEEE, 2021, pp. 348–354.
[11] F. Gauthier, Y. Chinniah, D. Burlet-Vienney, B. Aucourt, S. Larouche, Risk assessment in safety of machinery: impact of construction flaws in risk estimation parameters, Saf. Sci. 109 (2018) 421–433.
[12] M. Compare, E. Zio, E.L.I.S.A. Moroni, G. Portinari, T. Zanini, Development of a methodology for systematic analysis of risk reduction by protective measures in tyre production machinery, Saf. Sci. 110 (2018) 13–28.
[13] T.P. Huck, N. Münch, L. Hornung, C. Ledermann, C. Wurll, Risk assessment tools for industrial human-robot collaboration: Novel approaches and practical needs, Saf. Sci. 141 (2021) 105288.
[14] F. Gauthier, Y. Chinniah, G. Abdul-Nour, S. Jocelyn, B. Aucourt, G. Bordeleau, A.B. Mosbah, Practices and needs of machinery designers and manufacturers in safety of machinery: An exploratory study in the province of Quebec, Canada, Saf. Sci. 133 (2021) 105011.
[15] Abdullah, I., Mahmood, W.H.W., Fauadi, M.H.F.M., & Ab Rahman, M. N.. (2018) FMEA and reliability analysis of critical equipment machinery in the Malaysian palm oil mill.
[16] S. Boral, S. Chakraborty, Failure analysis of CNC machines due to human errors: an integrated IT2F-MCDM-based FMEA approach, Eng. Fail. Anal. 130 (2021) 105768.
[17] R. Zagidullin, D. Antipov, A. Dmitriev, N. Zezin, Development of a methodology for eliminating failures of an FDM 3D printer using a “failure tree” and FMEA analysis, J. Phys. Conf. Ser. 1925 (2021) 012085 No. 1IOP Publishing.
[18] Y. Wang, G. Cheng, H. Hu, W. Wu, Development of a risk-based maintenance strategy using FMEA for a continuous catalytic reforming plant, J. Loss Prev. Process Ind. 25 (6) (2012) 958–965.
[19] R. Harpster, S. Rama, Risk based PLM for tooling and machinery design and manufacturing, in: Proceedings of the Annual Reliability and Maintainability Symposium (RAMS), IEEE, 2018, pp. 1–6.
[20] J.F.W. Peeters, R.J. Basten, T. Tinga, Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner, Reliab. Eng. Syst. Saf. 172 (2018) 36–44.
[21] M.F.N. Aulady, F. Nuciferani, S. Wicaksono, Application of failure mode effects analysis (FMEA) method and fault tree analysis (FTA) towards health and occupational safety on jetty project, Gresik, Indonesia, JACEE (J. Adv. Civ. Environ. Eng.) 1 (2) (2018) 100–108.
[22] M. Shafiee, E. Enjema, A. Kolios, An integrated FTA-FMEA model for risk analysis of engineering systems: a case study of subsea blowout preventers, Appl. Sci. 9 (6) (2019) 1192.
[23] C.K. Chae, J.W. Ko, FTA-FMEA-based validity verification techniques for safety standards, Korean J. Chem. Eng. 34 (3) (2017) 619–627.
[24] N.A. Wessiani, F. Yoshio, Failure mode effect analysis and fault tree analysis as a combined methodology in risk management, in: Proceedings of the IOP Conference Series: Materials Science and Engineering, 337, IOP Publishing, 2018 No. 1.
[25] M. Barozzi, S. Contini, M. Raboni, V. Torretta, V.C. Moreno, S. Copelli, Integration of recursive operability analysis, FMECA and FTA for the quantitative risk assessment in biogas plants: role of procedural errors and components failures, J. Loss Prev. Process Ind. 71 (2021) 104468.
[26] N. Xiao, H.Z. Huang, Y. Li, L. He, T. Jin, Multiple failure modes analysis and weighted risk priority number evaluation in FMEA, Eng. Fail. Anal. 18 (4) (2011) 1162–1170.
[27] L. Ouyang, Y. Che, L. Yan, C. Park, Multiple perspectives on analyzing risk factors in FMEA, Comput. Ind. 141 (2022) 103712.
[28] M.A. Filz, J.E.B. Langner, C. Herrmann, S. Thiede, Data-driven failure mode and effect analysis (FMEA) to enhance maintenance planning, Comput. Ind. 129 (2021) 103451.
[29] G. Cristea, D.M. Constantinescu, A comparative critical study between FMEA and FTA risk analysis methods, in: Proceedings of the IOP Conference Series: Materials Science and Engineering, 252, IOP Publishing, 2017 No. 1.
[30] J. Worlitz, D. Haschke, M. Peplowsky, I.S. Peplowsky, I.R. Woll, FMEA Software comparison, in: Proceedings of the 20th QMOD Conference on Quality and Service Sciences, Helsingør (Denmark), 2017, p. 2017.
[31] K.A. Adesina, M. Yazdi, E. Zarei, M. Pouyakian, Smart decision fuzzy-based data envelopment model for failure modes and effects analysis, in: Linguistic Methods Under Fuzzy Information in System Safety and Reliability Analysis, Springer International Publishing, Cham, 2022, pp. 151–170.
[32] H. Li, M. Yazdi, Developing failure modes and effect analysis on offshore wind turbines using two-stage optimization probabilistic linguistic preference relations, in: Advanced Decision-Making Methods and Applications in System Safety and Reliability Problems: Approaches, Case Studies, Multi-criteria Decision-Making, Multi-objective Decision-Making, Fuzzy Risk-Based Models, Springer International Publishing, Cham, 2022, pp. 47–68.
[33] M. Yazdi, E. Zarei, S. Adumene, R. Abbassi, P. Rahnamayiezekavat, Uncertainty modeling in risk assessment of digitalized process systems, Methods in chemical process safety, Elsevier, 2022.
[34] X. Li, J. Wang, G. Chen, A machine learning methodology for probabilistic risk assessment of process operations: a case of subsea gas pipeline leak accidents, Process Saf. Environ. Prot. 165 (2022) 959–968.
[35] K. Fujimoto, A. Oyama, K. Fujii, N. Iizuka, K. Okita, Visualization and verification method for failure network analysis of space launch vehicles, Int. Des. Eng. Tech.Conf. Comput. Inf. Eng. Conf. 43277 (2008) 977–982.
[36] C. Ongkowijoyo, H. Doloi, Determining critical infrastructure risks using social network analysis, Int. J. Disaster Resil. Built Environ. (2017).
[37] M. Liu, L. Xu, P.C. Liao, Character-based hazard warning mechanics: a network of networks approach, Adv. Eng. Inf. 47 (2021) 101240.
[38] Y. Chen, Z. Zhen, H. Yu, J. Xu, Application of fault tree analysis and fuzzy neural networks to fault diagnosis in the internet of things (IoT) for aquaculture, Sensors 17 (1) (2017) 153.

[39] F. Ishola, V. Oladokun, O. Petinrin, O. Olatunji, S. Akinlabi, A mathematical model and application for fire risk management in commercial complexes in South Africa, Results Eng. 7 (2020) 100145.
[40] Z. Ruilin, I.S. Lowndes, The application of a coupled artificial neural network and fault tree analysis model to predict coal and gas outbursts, Int. J. Coal Geol. 84 (2) (2010) 141–152.
[41] M. Yucesan, M. Gul, E. Celik, A holistic FMEA approach by fuzzy-based Bayesian network and best–worst method, Complex Intell. Syst. 7 (3) (2021) 1547–1564.
[42] A.C. Rosa, I.T. de Souza, A. Terra, A.W. Hammad, L.T. Di Gregório, E. Vazquez, A. Haddad, Quantitative risk analysis applied to refrigeration's industry using computational modeling, Results Eng. 9 (2021) 100202.
[43] S. Qiu, X. Ming, Explicit and implicit Bayesian Network-based methods for the risk assessment of systems subject to probabilistic common-cause failures, Comput. Ind. 123 (2020) 103319.
[44] H. Alqahtani, S. Bharadwaj, A. Ray, Classification of fatigue crack damage in polycrystalline alloy structures using convolutional neural networks, Eng. Fail. Anal. 119 (2021) 104908.
[45] E. Kulcsár, T. Csiszér, J. Abonyi, Pairwise comparison based failure mode and effects analysis (FMEA), MethodsX 7 (2020) 101007.
[46] E. Ungvári, I.G. Gyurika, Evaluation of PC-FMEA using network analysis, Hung. J. Ind. Chem. 50 (2) (2022) 61–64.
[47] M. Barsalou, Root cause analysis in quality 4.0: a scoping review of current state and perspectives, TEM J. 12 (1) (2023) 73–79.
[48] A. Zonnenshain, R.S. Kenett, Quality 4.0—the challenging future of quality engineering, Qual. Eng. 32 (4) (2020) 614–626.
[49] S. Ahmed, X.C. Gu, Accident-based FMECA study of Marine boiler for risk prioritization using fuzzy expert system, Results Eng. 6 (2020) 100123.
[50] B. Ren, H. Li, J. Shi, Y. Liu, Y. Qi, Identifying the key sectors and paths of the embodied energy in BRICS nations: a weighted multilayer network approach, Energy 239 (2022) 122091.
[51] A.L. Barabási, Network Science, Cambridge university press, 2016.