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Assessment of Fuzzy Failure Mode and Effect Analysis (FMEA) for Reach Stacker Crane (RST): A Case Study

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A B S T R A C T

FMEA (Failure Mode and Effect Analysis) refers to a proactive quality tool that enables the identification and prevention of the potential failure modes of a product or process. However, in executing traditional FMEA, the difficulties such as vague information, relative importance ratings, decisions on same ratings, and opinion difference among experts arise which reduce the validity of the results. This paper presents a fuzzy logic based FMEA depending on fuzzy IF-THEN rules over traditional FMEA to make it precise and give proper maintenance decision. Here, the Risk Priority Number (RPN) is calculated and compared to the Fuzzy Risk Priority Number (FRPN) to give maintenance decision. Furthermore, the FMEA of Reach Stacker Crane (RST) is presented to demonstrate the proposed Fuzzy FMEA.

Keywords: Failure mode and effect analysis (FMEA), Risk priority number, Fuzzy theory, Fuzzy FMEA, IF-THEN rules.

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1. Introduction

Quality, reliability, and safety come first for the heavy and expensive machineries. Ensuring quality and reliability, the Failure Mode and Effect Analysis (FMEA) is one of the established method in the fields of quality. So, the research are in rampant march in FMEA modification, as the traditional FMEA technique incurs some difficulties and limitations on problem solving.

It may be difficult or even impossible to precisely determine the probabilities of failure events in FMEA. Much information of FMEA is expressed in the linguistic way such as ‘likely’, ‘important’, and ‘very high’, etc. In addition, most components or systems degrade over time and have multiple states. An assessment on these states is also often subjective and qualitatively

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described in the natural language such as ‘degradation of performance’, ‘reliability’, and ‘safety’. It is difficult for conventional FMEA to evaluate these linguistic conventional FMEA [2].

In this paper, the fuzzy logic and inference system is applied on the Reach Stacker Crane (RST) which works consistently in the port. Again, although the traditional FMEA gives somewhat information of failure mode and corrective actions, but it does not necessarily gives the correct answer. Here, the fuzzy risk value is calculated and compared with the Risk Priority Number (RPN), so that the potential failure modes of the main parts of RST can be understood.

Traditional FMEA form does not indicates the maintenance decision and maintenance schedule for the failure prone parts. It would be beneficial for the maintenance industry if the FMEA form indicates the maintenance decision. For this convenient, the FMEA is merged with fuzzy logic and is proposed in this case study.

2. Literature Review

FMEA application dates back to 1949 when the US Army used it in the aeronautic sector in order to solve reliability and safety problems during the design and production phases. The FMEA tool has become standard practice in Japanese, American, and European manufacturing companies from aerospace to the automotive and electronics sectors, from the food industry to the energy sector and the medical and pharmaceutical arenas. A lot of research has been carried out to enhance the performance of FMEA in the past decade.

Xu et al. [4] presented the FMEA of diesel engine's turbocharger system and illustrated the feasibility of such techniques. Bell et al. [5] developed a tool that automated the reasoning portion of a Failure Modes and Effects Analysis (FMEA) and a flexible causal reasoning module that had been adapted to the FMEA procedure. Wang et al. [6] proposed an approach combining FMEA and the Boolean Representation Method (BRM). Bowles and Pelaez [7] showed two fuzzy logic based approaches for assessment. The first was based on the numerical rankings used in a conventional Risk Priority Number (RPN) calculation used in crisp inputs. The second, which could be used early in the design process when the less detailed information was available and allowed fuzzy inputs. On the other hand, the method in Ref [8] is based on the theories of possibility distribution and probability of fuzzy events to treat uncertainties of the data and multiple failure modes. Nevertheless, the probability of fuzzy events must be known when using the method. El-Shal and Morris [9] described an investigation of the use of fuzzy logic to modify SPC rules with the aim of reducing the generation of false alarms to improve detection speed. He and Adamyan [10] presented an impact analysis methodology for design of products and processes for reliability and quality. Capunzo et al. [11] experimented the application of the Failure Mode and Effect Analysis (FMEA) technique in a clinical laboratory to evaluate, decide, and measure the outcomes. Lee [12] used the Bayes probabilistic networks as a new methodology for encoding design failure modes and effects analysis (BN-FMEA) models of mechatronic systems. Dittmann et al. [13] introduced an approach that integrates a technique of knowledge engineering (Ontologies) and a technique of quality engineering (Failure Mode and Effects Analysis). Kandel [14] presented the basic concepts of fuzzy set theory within a context of real-world applications. The self-contained book can be used as a starting point for people interested in this fast growing field as well as by researchers looking for new application techniques. Quin and Widera [15] showed the quantitative approaches applied to in service inspection, failure modes, effects, and criticality analysis (FMECA) methodology.

The presented paper applies fuzzy FMEA for Reach Stacker Crane in the service industry where it provides the maintenance team a whole lot idea about the risk priority.

3. Proposed Methodology

The proposed methodology has been described steps by steps in the following.

3.1 Traditional FMEA

FMEA is a widely used quality improvement and risk assessment tool in manufacturing industry. This tool combines the human knowledge and experience to (1) identify known or potential failure modes of a product or process, (2) evaluate the failures of a product or process and their effects, (3) assist engineers to initiate corrective actions or preventive measures, and (4) eliminate or reduce the chance of the failures occurring. In a traditional FMEA, three parameters (severity, occurrence, and detection) are utilized to describe each failure mode by rating on a 1-10 scale.

Severity rating is the seriousness of the effect of a failure to the next component, subsystem, system, or customers. Occurrence rating is the likelihood or frequency of the failure occurring with 1 being the least chance of occurrence and 10 being the highest. Detection rating is the inability to detect the failure or the probability of the failure not being detected before the impact of the effect be realized. Traditionally, the criticality assessment of FMEA is performed by developing a Risk Priority Number (RPN). RPN is the product of the severity (S), occurrence (O), and detection (D) ratings. Failure modes having a higher RPN are assumed to be more important and given a higher priority for corrective action than those having a lower RPN.

3.2 Fuzzy Inference Based FMEA Approach

Fuzzy inference by using IF-THEN rule for FMEA has been developed to deal with the drawbacks of traditional FMEA and fuzzy rule based FMEA approaches. Fuzzy IF-THEN approaches based on defuzzification require consequent steps of evaluation [1].

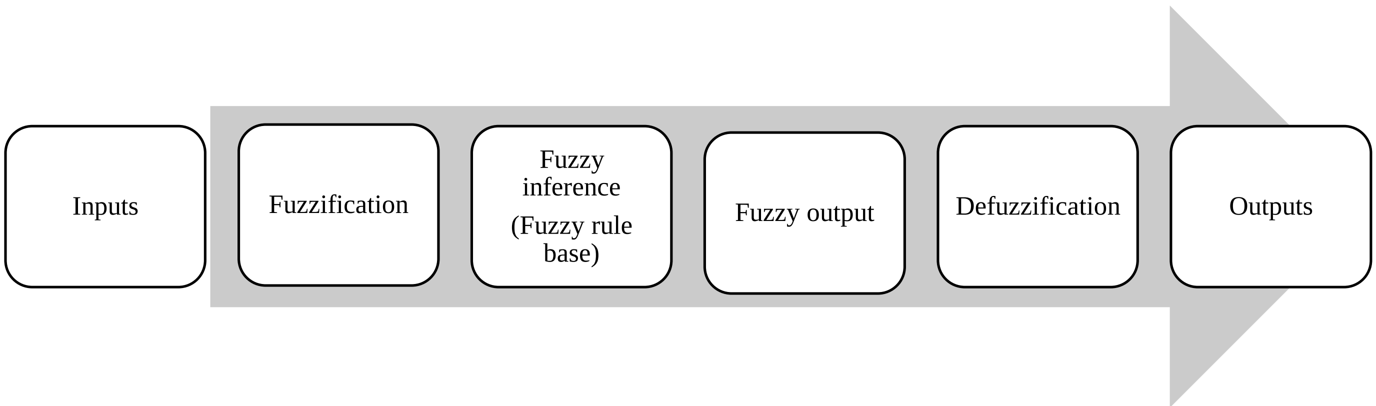

Figure 1. Structure of FMEA Based on Fuzzy Theory.

3.3 Fuzzification of Information

Through defining the membership functions of input fuzzy sets which are determined by expertise, the three parameters (S), (O), and (D) ratings, can be transformed into fuzzy input [1]. This approach uses linguistic variables to represent the severity, occurrence, and detection of each failure mode. Each linguistic variable has five linguistic terms to describe it. These linguistic terms are Remote (R), Low (L), Moderate (M), High (H), and Very High (V). In the proposed fuzzy FMEA approach, several experts are required to develop the membership functions of the three variables. Assume that there are experts asked to determine the membership functions. Assign the degrees of competence Wi (i = 1, 2,…n) for each of the experts according to their experience and knowledge about this domain. The sum of the degrees of competence must be one. Furthermore, the triangular fuzzy number (a, b, c) is used to develop the membership functions in this approach where x represents the specified rating and u(x) represents the value of its membership function (the degree of membership). In order to evaluate whether a given rating $x \in X$ may belong to a linguistic term, each of the experts is asked to give the values $a, b, c \in X$ in the interval [0, 10]. The value of membership function is zero such as u (a) when the rating doesn't belong to the linguistic term. And, the value of membership function is one such as u (b) when the rating completely belongs to the linguistic term. For example, three experts are asked to determine the membership function of the linguistic variable severity. Risk, the output linguistic variable, is used to represent the priority for corrective action with five linguistic terms: Low (L), Fairly Low (FL), Moderate (M), Fairly High (FH), and High (H). Experts are also asked to determine this output membership functions.

Table 1. Interpretations of Linguistic Terms for Developing the Fuzzy Rule Based System [3].

Linguistic term	Probability of occurrence	Severity	Detection
Remote	It would be very unlikely for these failures to be observed even once.	A failure that has no effect on the system performance, the operator probably will not notice.	Defect remains undetected until the system performance degrades to the extent that the task will not be completed.
Low	Likely to occur once, but unlikely to occur more frequently.	A failure that would cause slight annoyance to the operator, but that cause no deterioration to the system.	Defect remains undetected until system performance is severely reduced.
Moderate	Likely to occur more than once.	A failure that would cause a high degree of operator dissatisfaction or that causes noticeable but slight deterioration in system performance.	Defect remains undetected until system performance is affected.
High	Near certain to occur at least once.	A failure that causes significant deterioration in system performance and/or leads to minor injuries.	Defect remains undetected until inspection or test is carried out.
Very High	Near certain to occur several times.	A failure that would seriously affect the ability to complete the task or cause damage, serious injury or death.	Failure remains undetected; such a defect would almost certainly be detected during inspection or test.

Table 2. Value of Membership Function.

		b_i				
i	W_i	R	L	M	H	V
1	0.5	1	3	5	7	10
2	0.3	1	3.5	5.5	8	10
3	0.2	1	3.7	6	8.5	10
b		1	3.29	5.35	7.6	10

3.4 Rule Evaluation

By using the IF-THEN rules gathered from experts and engineers and integrating them into fuzzy rule, the fuzzy IF-THEN rules in fuzzy rule base can be combined into a mapping from fuzzy inputs to fuzzy conclusion. Fuzzy rule base is a collection of fuzzy IF-THEN rules which are constructed from experts experience and judgment. In fuzzy IF-THEN rule, the antecedent (the IF-part) is compared to the fuzzy input variables, and the consequent (the THEN-part) is the fuzzy output variable. Each fuzzy IF-THEN rule is expressed as:

IF severity is Remote and occurrence is Remote and detection is High, THEN risk is Low. Because each of the three input linguistic variables has five linguistic terms, the total number of combinations is 125 (5×5×5). All the combinations should be grouped to generate the fuzzy rule base. The example of some rules presented in Table 1.

Table 3. Specified fuzzy rules.

Rule	Severity	Occurrence	Detection	Risk
1	R	R	M,H or V	L
2	M	M	R,L or M	M
3	M	M	R or L	FH
4	H	M	R or L	H
5	H	M	M,H or V	FH
6	V	L	L	H

3.5 Fuzzy Inference Process

In this paper, minimum inference engine is used to combine the fuzzy IF-THEN rules in fuzzy rule base and implicate the fuzzy conclusion. The minimum inference engine uses: (1) min operator for “and” in the IF-part of rules and max operator for the “or” in the IF-part of rules, (2) the union combination (max operator) to aggregate the consequence of individual rules. In the following, an example is presented to explain the process of the minimum inference engine.

There are several defuzzification algorithms have been developed. In this paper, the Centroid method (also called center of area, center of gravity) defuzzifier will be adopted due to its advantages of plausibility, computational, simplicity, and continuity. Determining the defuzzifier value is:

$$C = \frac{E(x)xdx}{E(x)dx}. \quad (1)$$

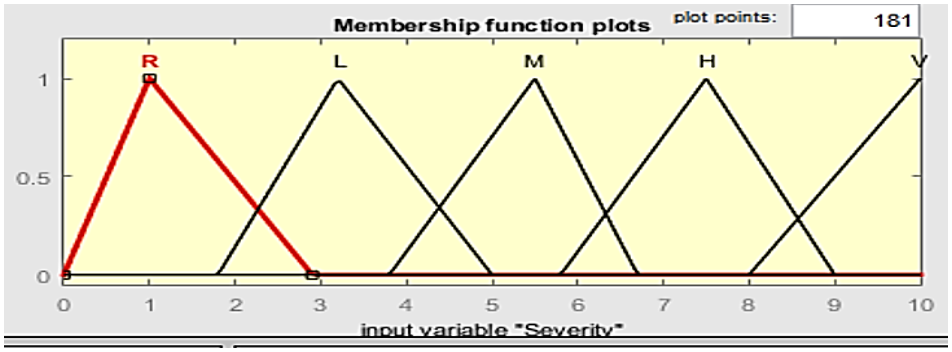

Figure 2. Membership Function for Severity (Matlab).

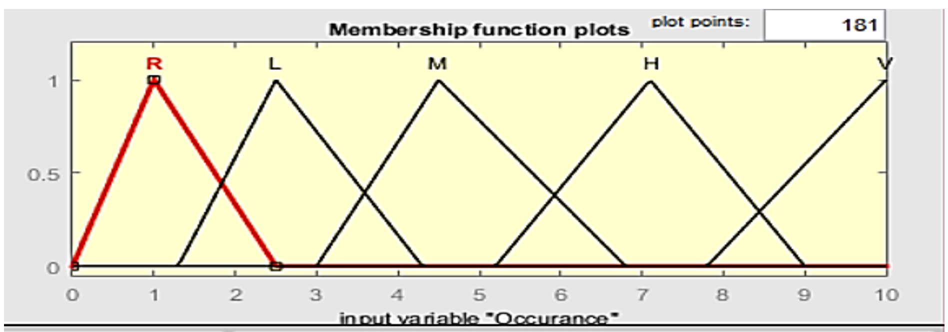

Figure 3. Membership Function for Occurrence (Matlab).

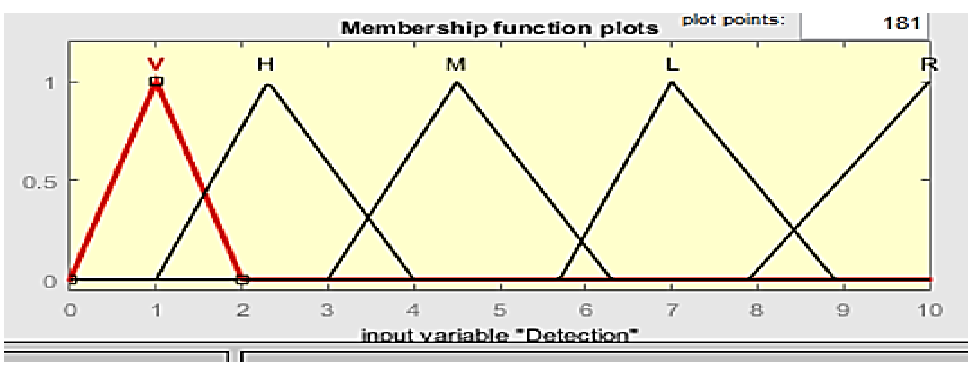

Figure 4. Membership Function for Detection (Matlab).

4. Implementation of the Case Study

The real-world case study has been done for Kalmar DRF 400–450 (RST) in Kamlapur Internal Container Depot, Dhaka, Bangladesh and has been illustrated the steps of the proposed methodology in following.

4.1 Fuzzy FMEA of Reach Stacker's Main Parts

Kalmar DRF 400–450 is a 'Reach Stacker' for container handling. The machine has a lift capacity of 40–45 tons depending on version. The engine is a six cylinder four-stroke direct-injected diesel engine. The transmission is hydro mechanical with gears in constant mesh. It has four forward gears and four reverse gears. The engine power is transmitted with a torque converter. The driveline/axle consists of a drive shaft and a rigid drive axle with hub reduction. Drive takes place on the front wheels. The service brake is of the type disc brake in oil which is built together with the drive wheels' wheel hubs. The parking brake is of the type disc brake and acts on the drive axle's input shaft steering takes place on the rear wheels with a double-acting hydraulic cylinder. The steering axle is oscillation-mounted in the frame. The wheels are mounted on the hubs with clamps. Twin wheels are mounted on the drive axle and the steering axle single wheels. Load handling is the components and functions for handling loads. Loads are lifted with an attachment that is mounted on a lifetable telescopic boom.

Load handling is divided into the functions lift and lower, extension, side shift, spreading, rotation, tilt, levelling, and load carrying. Lift and lower is the function to lift and lower the boom. Extension is the function to push out and retract the boom. Side shift is to move the attachment sideways in relation to the machine. Spreading is to adjust the width between the attachment's lifting points. Rotation is to rotate the load in relation to the machine. Tilt is to angle the load in the machine's longitudinal direction. Levelling is to angle the load in the machine's lateral direction (sideways). Load carrying is to grab the load. The control system are functions for warning the operator of dangerous situations and malfunctions. The control system has diagnostic possibilities that facilitates the troubleshooting.

The frame supports the machine; the engine, transmission, drive axle, and steering axle are mounted in the frame. On the frame's sides there are tanks for fuel, hydraulic oil, and oil for the brake system. The cab is located in the Centre and can be moved fore-aft. As an option, the cab is available in a side-mounted version that can be raised and lowered.

4.2 Reach Stacker Crane Case Study

For the convenient of the case study, the Reach Stacker has been divided into five major parts. According to their importance and severity of the components, the main part has also been subdivided into their parts. The following schematic figure depicts our case study parts of the RST.

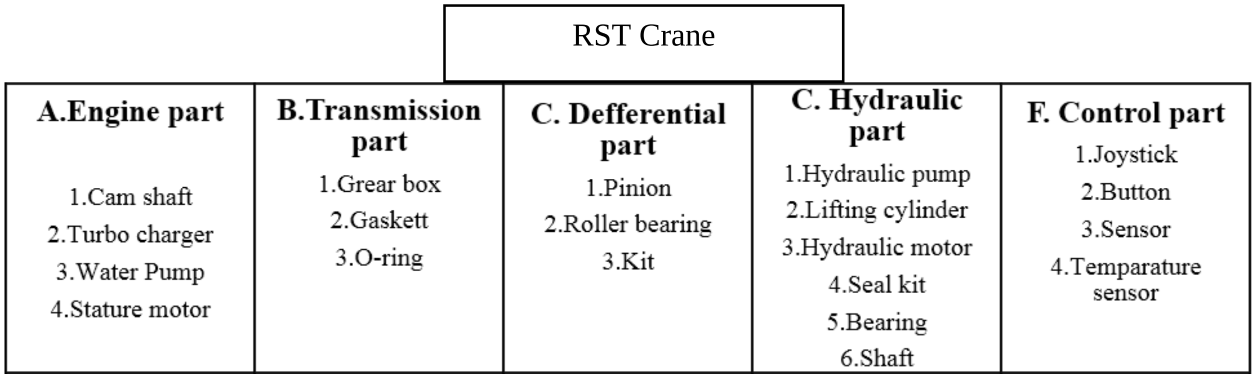

Figure 5. Block Diagram of RST Crane Parts.

The main components are expressed as Engine parts, Transmission parts, Differential parts, Hydraulics parts, and Control parts. In order to mathematically express each failure mode, let F_{ij} represents the jth failure mode in the ith subcomponents (i=A, B, C, D, E, and j=1,2,3….n). After conducting the traditional FMEA and the proposed FMEA, the partial results of them are presented in the Table 4 and compared in the result section.

4.3 Data Analysis and Findings

Matlab software has been used to analysis the data of the parts. Before analysis the data of the parts, all the parts are scored (0-10) in the prospect of the severity, occurrence, and detection. With the help of the maintenance expert and the maintenance team, all the parts are scored and ruled in Matlab. Then the risk priority number and the fuzzy risk priority have been ranked in the table.

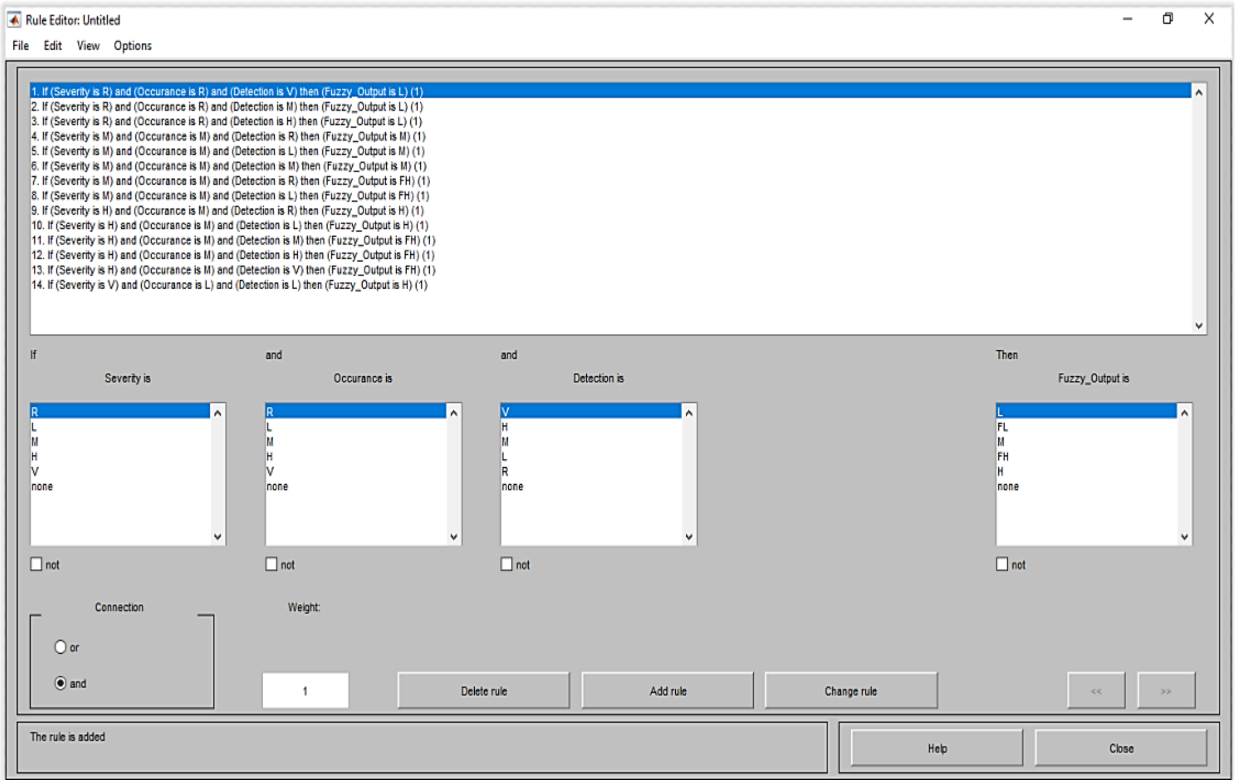

Figure 6. Setting Fuzzy Rules in Matlab.

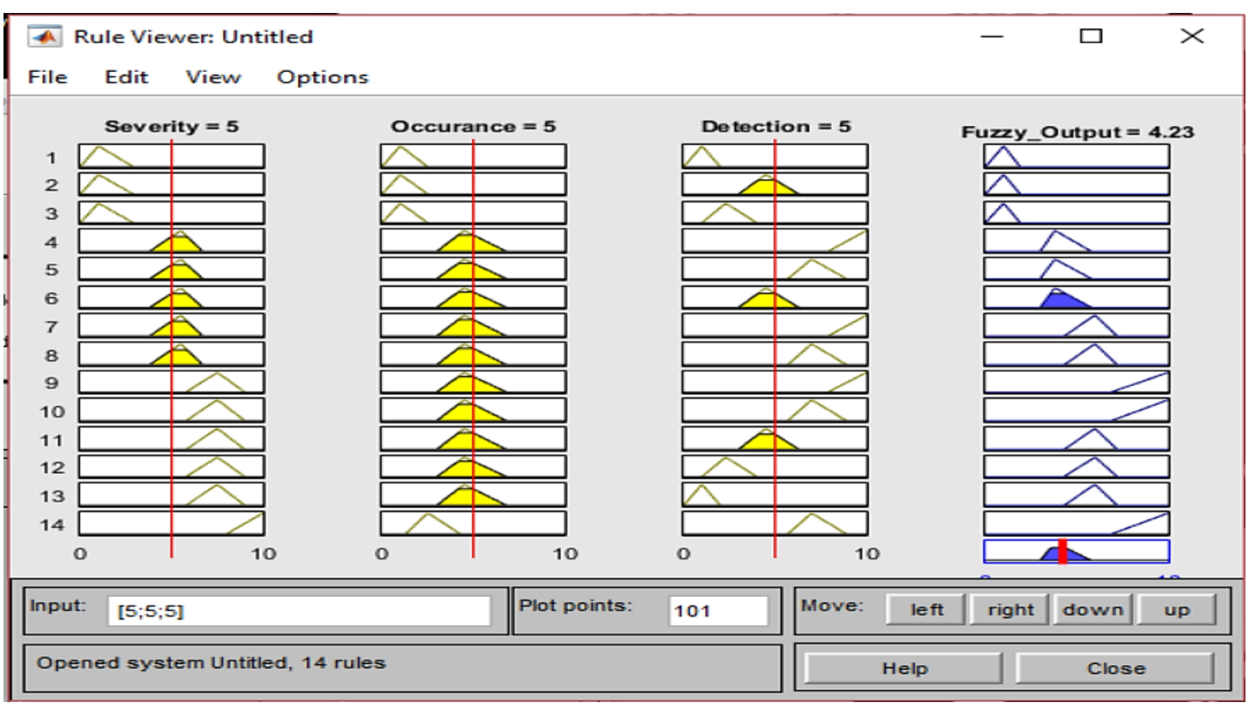

Figure 7. Inputs and Output Views of Risk Priority in Matlab.

Table 4. The Results of Comparing Traditional FMEA with Fuzzy FMEA.

Failure Mode	(S, O, D)	RPN	Risk (fuzzy)	Ranking (RPN)	Ranking (fuzzy)
F_{A1}	(9, 2, 8)	144	8.81	13	4
F_{A2}	(8, 4, 7)	224	8.91	9	1
F_{A3}	(7, 3, 6)	126	5	16	5
F_{A4}	(9, 5, 9)	405	5	1	5
F_{B1}	(9, 3, 8)	206	8.81	10	4
F_{B2}	(5, 8, 7)	280	5	7	5
F_{B3}	(4, 9, 8)	288	5	6	5
F_{C1}	(8, 5, 9)	360	8.83	2	3
F_{C2}	(7, 4, 9)	252	8.91	8	1
F_{C3}	(6, 8, 7)	336	5	3	5
F_{D1}	(6, 4, 7)	168	5.55	11	9
F_{D2}	(7, 2, 8)	112	4	18	20
F_{D3}	(5, 3, 9)	135	6	15	8
F_{D4}	(2, 4, 3)	24	5	20	5
F_{D5}	(6, 8, 7)	336	4.33	3	18
F_{D6}	(6, 2, 7)	84	5	19	5
F_{E1}	(6, 4, 6)	144	6.03	13	7
F_{E2}	(2, 8, 8)	125	5	17	5
F_{E3}	(7, 6, 8)	336	8.73	3	6
F_{E4}	(6, 5, 5)	150	4.53	12	18

5. Result and Discussion

Comparing the results of the traditional FMEA with the proposed FMEA, the difference between these two methods can be clearly observed in Table 4. The failure modes F_{C3} F_{D5} and F_{E3} have the same RPN of 336 and among them F_{C3} and F_{D5} have the same priority. But the fuzzy risk differs in those and it would be helpful for setting priority on those components.

Consider that the failure modes F_{A1} and F_{E1} where the RPN is 144. The value of (S), (O), and (D) ratings are 9, 2, 8 and 6, 4, 6 for F_{A1} and F_{E1}. Although the RPN for both failure modes are the same and the risk level may be different. The ranks of F_{A1} and F_{E1} are 4 and 7 and the failure mode F_{A1} has a higher priority than F_{A2}. Thus, the traditional FMEA may result in a different action. In addition, the ranking produced by the proposed method doesn't differentiate the failure modes which has the adjacent ratings. If the both failure modes incur the same value and have the adjacent ratings, it will give the same priority to the both components. However, the traditional FMEA method produces the resulting RPN different.

The analysis of the results produced by the traditional FMEA and the fuzzy FMEA methods show that a more accurate, reasonable ranking can be achieved by applying fuzzy FMEA. Other investigations can be carried out in the same manner. In addition, the fuzzy rule based can also be revised or updated when more information of a product or process is available. As a result, the proposed assessment method can be continuously improved.

6. Conclusion

In this paper, a FMEA based on fuzzy theory approach was proposed and a prototype of the risk assessment expert's system was developed. The analysis of a Reach Stacker (RST) Crane was presented to demonstrate the proposed fuzzy FMEA method. In practice, subjective judgment was described in natural language which was sometimes inaccurate, vague, and uncertain. In conducting FMEA, assigning the (S), (O), and (D) ratings in natural language produced an unrealistic and misleading impression. As a result, the RPN produced by these three ratings overlooked the relative importance among these parameters and resulted in misunderstanding. The application of linguistic terms allows experts to provide a more reasonable and meaningful information for these three parameters. Fuzzy rule based allows experts to construct the more realistic and logical rules. By using the fuzzy set and membership function, the imprecise information is improved to reflect the real situations. Using the fuzzy IF-THEN, the collected rules from experts, experts' knowledge, and experience are incorporated in the risk assessment tool. It is more convenient to differentiate the risk representations among the failure modes having the same RPN. Through the building knowledge-based model, the expert's knowledge and judgment are reserved efficiently. Furthermore, the information of each failure is revised or updated by experts. The proposed assessment model is continuously improved. The most critical disadvantage of the tradition FMEA is that the various combinations of the three parameter ratings produces an identical value of RPN; however, the risk representations is thoroughly different. In this paper, fuzzy based risk assessment technique was implemented in the case study to resolve the difficulties arisen in conducting the procedure of the traditional FMEA.

References

[1] Yeh, R. H., & Hsieh, M. H. (2007). Fuzzy assessment of FMEA for a sewage plant. *Journal of the Chinese institute of industrial engineers*, *24*(6), 505-512.

[2] Xu, K., Tang, L. C., Xie, M., Ho, S. L., & Zhu, M. L. (2002). Fuzzy assessment of FMEA for engine systems. *Reliability engineering & system safety*, *75*(1), 17-29.

[3] [3] Guimarães, A. C. F., & Lapa, C. M. F. (2004). Fuzzy FMEA applied to PWR chemical and volume control system. *Progress in Nuclear Energy*, *44*(3), 191-213.

[4] Xu, K., Tang, L. C., Xie, M., Ho, S. L., & Zhu, M. L. (2002). Fuzzy assessment of FMEA for engine systems. *Reliability engineering & system safety*, *75*(1), 17-29.

[5] Bell, D., Cox, L., Jackson, S., & Schaefer, P. (1992, January). Using causal reasoning for automated failure modes and effects analysis (FMEA). *Proceedings of annual reliability and maintainability symposium* (pp. 343-353). Las Vegas, NV, USA, USA: IEEE.

[6] Wang, J., Ruxton, T., & Labrie, C. R. (1995). Design for safety of engineering systems with multiple failure state variables. *Reliability engineering & system safety*, *50*(3), 271-284.

[7] Bowles, J. B., & Peláez, C. E. (1995). Fuzzy logic prioritization of failures in a system failure mode, effects and criticality analysis. *Reliability engineering & system safety*, *50*(2), 203-213.

[8] Quin, S., & Widera, G. E. O. (1996). Uncertainty analysis in quantitative risk assessment. *Journal of pressure vessel technology*, *118*(1), 121-124.

[9] El-Shal, S. M., & Morris, A. S. (2000). A fuzzy rule-based algorithm to improve the performance of statistical process control in quality systems. *Journal of intelligent & fuzzy systems*, *9*(3, 4), 207-223.

[10] He, D., & Adamyan, A. (2001, December). An impact analysis methodology for design of products and processes for reliability and quality. *Proceedings of the ASME design engineering technical conference* (pp. 209-217). Pittsburgh, PA, United States.

[11] Capunzo, M. A. R. I. O., Cavallo, P. I. E. R. P. A. O. L. O., Boccia, G. I. O. V. A. N. N. I., Brunetti, L. U. I. G. I., & Pizzuti, S. A. N. T. E. (2004). A FMEA clinical laboratory case study: how to make problems and improvements measurable. *Clinical leadership and management review*, *18*(1), 37-41.

[12] Lee, B. H. (2001). Using Bayes belief networks in industrial FMEA modeling and analysis. *Proceedings of annual reliability and maintainability symposium. International symposium on product quality and integrity* (pp. 7-15). Philadelphia, PA, USA, USA: IEEE.

[13] Dittmann, L., Rademacher, T., & Zelewski, S. (2004, August). Performing FMEA using ontologies. *18th international workshop on qualitative reasoning* (pp. 209-216). Northwestern University, Evanston, Illinois, USA.

[14] Kandel, A. (1986). Fuzzy mathematical techniques with applications. Addison-Wesley.

[15] Quin, S., & Widera, G. E. O. (1996). Uncertainty analysis in quantitative risk assessment. *Journal of pressure vessel technology*, *118*(1), 121-124.