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Article

Modified Fuzzy FMEA Application in the Reduction of Defective Poultry Products

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Abstract. Failure mode and effects analysis (FMEA) consists of the famous qualitative management methods used for improvements in management processes. This paper aims to determine the factors of defective products in the processing of poultry products in the industry. The causes of problems have been analyzed by systematic brainstorming of specialist consensus in the evaluation of problems to achieve unanimity on the violence level. The FMEA method uses the risk priority number (RPN), which indicates the priorities of risk problems and can evaluate three components: severity, occurrence and detection. Sometimes, this risk assessment leads to the wrong priorities. Therefore, we propose fuzzy FMEA methods for priority ranking of RPN and efficiently reducing poultry product defects, which are established based on fuzzy systems followed by comparison with conventional FMEA. The results indicate that the fuzzy FMEA method can efficiently and feasibly reduce poultry product defects.

Keywords: Risk priority number, failure mode and effect analysis, fuzzy logic.

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1. Introduction

Currently, the production process in the industry is very competitive. An organization that succeeds and survives in the situation of strong competitiveness requires the ability to reduce or control the production costs. Generally, production factors consist of manpower, machines, raw materials and cost. However, one additional factor that affects the cost of production is the existence of defects or errors within the production process. Thus, discovery and development of production processes, which are created to ensure the minimal defects and errors with tools such as samplings for inspection and final check. When production systems go into mass production, monitoring the quality of products cannot solve quality problems immediately. Therefore, the organization should manage the systems that prevent errors and ensure quality at all stages of production.

Total Quality Management (TQM) is a tool and important technique with the objective of increasing the quality of the product, improving the effectiveness of the organization and providing services to satisfy the customer [1]; it introduces techniques to control the production process by statistical process control (SPC) including seven quality control tools—checklist, histogram, Pareto diagram, cause and effect, scatter diagram, flowchart and control chart—to help control the quality of products [2-4]. However, production systems are currently changing from mass production to mass customization. Therefore, root cause analysis that contributes to solving problems directly affects the product quality improvement, including the responses of customer satisfaction. The method that analyzes the root cause is called failure mode and effect analysis (FMEA).

FMEA is the tool and method to analyze the causes of failure and to forecast the impact of factors. The main purpose of the FMEA is to assess the causes and consequences of failure modes in each component, specify the mode of failure that might occur, decrease the chance of failure modes and determine what can be eliminated. The RPN is applied in FMEA method to assess the cause of the failure, and contains three parameters: severity (S), occurrence (O), and detection (D). The results of the analysis can help fix the mistakes; show causes that harm in the process and resolve performance in every phase of the operation.

FMEA has been applied in many studies; for example, Chang [5] presented a risk assessment for preventive analysis on product design and management process by using the RPN methodology. Bas [6] developed a technical RPN of failure mode and effects analysis in planning investment to prevent injury to children and validate a reasonable period to prevent injury to children in each age group based on different situations. Xiao et al. [7] offered the analysis of multiple failure modes and weighted RPN evaluation in large and complex systems. Mariajayaprakash and Senthilvelan [8] presented failure detection and optimization method for sugar mill boilers using FMEA and Taguchi methods to solve a major problem with boilers in sugar mills that resulted in the loss of manufacturing processes for example electrical failure and temperature sensor failure. This may cause several problems and result in difficulty in the simultaneous assessment and prioritization of errors. Therefore, the use of the FMEA technique to solve problems involves multiplication by the weight parameters of S, O and D to provide similar weight values. However, several authors have reported problems in FMEA implementation: the values of S, O and D are inconsistent, depending on the FMEA reference manual used [9-10]; the failures are incompletely represented; there are some overlapping and a gap between the design and process of FMEA [11, 12]; etc. Therefore, the approach that has been suggested to improve the FMEA methodology is the fuzzy logic approach.

A fuzzy logic approach is used to manage the uncertainty that emerged from the fuzzy set [13], and it has been improved to investigate the relationship between the variables in the system observed in the existing data is individual and fuzzy [14]. Fuzzy logic is well known and has been used in a variety of fields. Some application results have emphasized efficiency of information and exploration of unknown information [15, 16]. Furthermore, it creates a powerful framework for modeling human's feelings, decision making and applied in the assessment of risk in many ways; for example, Singh and Markeset [17] presented a planning method to effectively monitor the level of risk and maintenance strategy of oil and gas pipes by using a fuzzy logic framework for the establishment of an RBI program and managed data with greater precision. It also helped the maintenance engineers in reducing difficulties in complex calculations, including the calculation method of the corrosion rate of CO_2 in the carbon steel pipe. Zhang et al. [18] conducted a risk assessment before an excavation in the South China Sea by using the AHP and fuzzy set theory to prevent accidents during excavation that would cause direct financial losses and thus improved the excavation efficiency to complement the engineers' work. Su and Wen [19] suggested the risk analysis and fuzzy mathematics methods to carry out an assessment of gravity dam instability by using membership functions to describe the scope of failure risk, which could improve the understanding of the problem and help dam engineers fix actual errors.

Lu et al. [20] studied the risk factors in railway reconstruction project in Taiwan by using the fuzzy MCDM technique to help generate awareness of authorities on the subject of risk factors. The assessment processes are dealt with using trapezoid fuzzy numbers. The result found that it enables to chart out the right strategy to build up the effectiveness. Rezakhani [21] introduced the fuzzy Multi-Criteria Decision Making method to select risk factors in construction projects. This approach can prioritize and select risks based on decisions made by specialists. Ighravwe and Oke [22] studied the fuzzy goal programming and big-bang big-crunch algorithm for maximizing efficiency improvement and minimizing workforce costs in small-scale sachet water production factories. Charongrattanasakul and Pongpullponsak [23] introduced the integrated model for fuzzy Weibull distribution using genetic algorithm. The consequence indicated that this model is applied to define the optimal values of six variables which cut down the fuzzy hourly cost.

From a review of past research and literature, it was found that most of them applied fuzzy FMEA to various industrial sectors as well as automotive and industrial electronic and computer parts, industrial machines, electrical appliance manufacturing, the development and design of products, management processes within the organization, medical applications, etc. For example, Yeh and Hsieh [24] presented a new risk assessment system based on fuzzy theory in a sewage plant by ranking the action. This method can reduce or eliminate the respective effects of the failures. Chin et al. [25] presented a method of evaluation for the basic idea of new product development by using fuzzy FMEA to increase the reliability for the improvement of the evaluation, alternative designs, selection of materials and expense estimate. Liu and Tsai [26] offered prevention techniques and improvement of occupational hazards in the construction industry by using a fuzzy analytic network process (FANP) to specify the hazard type and hazard causes and using FMEA techniques in risk assessment of hazard causes on fuzzy inference. Dinmohammadi and Shafiee [27] proposed the risk assessment method and analyzed the errors by using fuzzy offshore wind turbine FMEA. Kumru and Kumru [28] studied fuzzy FMEA to improve the procurement processes of public hospitals to reduce the cost of products purchased, reduce the cost of the purchase process to resolve the service to the customer/patient and minimize inventory investment; this stabilized the process and thus increased the efficiency of the assurance process. Yeh and Chen [29] proposed the linguistic fuzzy variables to replace the severity, occurrence and detection for calculating and ranking the wafer processes yield change in semiconductor wafer manufacturing processes. Nuchpho et al. [30] studied the failure mode of defective products at this stage of the plating bath product category page (K-160) of sanitary ware by using fuzzy FMEA to prioritize the risk of failure and reduce the defects in the products. Maranate et al. [31] studied the application of fuzzy FMEA to the medical diagnostic severity of obstructive sleep apnea (OSA), which was caused by 19 failures for suspected OSA patients in the sleep laboratory center of Siriraj Hospital by prioritizing the risk of OSA and using specialist consensus in the evaluation of the unanimity on the violence level.

Thailand is among the most significant manufacturers and exporters of food products in the world because of its availability of raw materials and its potential to tailor its quality and format to the needs of the market. As a result, Thailand is the top national exporter of processed food such as frozen chicken, frozen shrimp and mackerel. However, in the process of producing processed food, there are still many defects in products, and many industrial factories must control the quality of products by applying statistical principles to help in quality control. Therefore, in this study, the researcher was interested in studying the production process in the food processing industry; a case study was conducted on poultry products. The purpose of the study was to examine the impact and results of product errors of defects in the production process from many factors such as raw materials, man, machinery and the management process. In addition, there has been no study of the food processing industry using fuzzy FMEA. Thus may be due to delicate problems and a high defect rate.

2. Research Methodology

2.1. Nomenclature

In this study, the following nomenclature has been used:

FMEA Approach

RPN	The measure used when assessing risk to help identify critical failure modes associated with process
S	Severity, which rates the severity of the potential effect of the failure
O	Occurrence, which rates the likelihood that the failure will occur

D Detection, which rates the likelihood that the problem will be detected before it reaches the end-user

Fuzzy Approach
X The universe of discourse
A The fuzzy set in X
$\mu_A(x)$ The degree of membership function of element x in fuzzy set A for each $x \in X$
$\mu_B(x)$ The degree of membership function of element x in fuzzy set B for each $x \in X$
x The membership of fuzzy set A
μ The grade of membership of x in A
a_1 The lower bounds of triangular fuzzy number
a_2 The middle point of triangular fuzzy number
a_3 The upper bounds of triangular fuzzy number
c The membership functions center
σ The membership functions width
COG Centroid defuzzification method finds a point representing the center of gravity of the fuzzy set, A, on the interval [a, b]

2.2. Failure Mode and Effects Analysis (FMEA)

FMEA is an important method for solving problems in the production process, identifying failure modes and damaging effects of factors, and prioritizing the risk management decisions required for corrective action [32]. In 1963, the FMEA methodology was suggested by The National Aeronautics and Space Administration, and then in the 1970s, it was first adopted and implemented by the automotive industry, aerospace and general manufacturing [33]. Currently, FMEA is used widely for industrial production of motors, mechanical equipment, machinery, electronics, etc. [34]. To analyze a system all failure modes of the systems or products should be identified by systematic brainstorming of expert teams from various departments (e.g., production, quality assurance, engineering, and maintenance). The process of FMEA is separated into the following steps: i) collect component function information, ii) determine failure modes and effects, iii) study of the effects of each mode errors, iv) list of present process control, v) determine the detection priority, vi) calculate the risk priority number (RPN), vii) correct the action properly, and viii) implement adaptation [35]. Conventional FMEA uses RPN, which is obtained by finding three factors, namely, severity (S), occurrence (O) and detection (D), to evaluate the risk level of failure. The RPN is calculated in Eq. (1).

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

To obtain the RPN of a failure mode, the three factors are evaluated using 5 scales and 10 scores from 1 to 10 to measure the severity of the failure and probability of the failure, and 10 scales with 10 scores are used to describe the probability of detection by a consensus of expert knowledge for different factors [5]. After the failure mode or effects are analyzed with the FMEA method, the processes that require priority action according to the failure modes with the higher RPN values are given more importance for improvement than lower RPN values. Table 1-3 show the scales that are used to measure the S, O and D.

Table 1. The criteria of severity evaluation for FMEA.

Severity of effect	The severity of the impact on the product	Rank
Very high	Product quality is impacted at a very high level; it causes waste that cannot be recovered. (The product is abandoned.)	10
High	Product quality is impacted at a high level; it causes some waste that can be recovered by selection. (Some may be abandoned.)	8, 9
Moderate	Product quality is impacted at a moderate level; it can be brought back immediately to be fixed by selection, and there are no wasted products.	6, 7
Low	Product quality is impacted at a low level; it can be accepted without being fixed, and there are no wasted products.	2, 3, 4, 5
None	Product quality is not impacted, and the product moves to the next process.	1

Table 2. The criteria of occurrence evaluation (chance of occurrence/frequency) for FMEA.

Chance of occurrence	Occurrence of causes	Rank
Very high	Occurs in more than 50% of the whole production.	9, 10
High	Occurs in 31-50% of the whole production.	7, 8
Moderate	Occurs in 11-30% of the whole production.	4, 5, 6
Low	Occurs in 1-10% of the whole production.	3
Very low	Occurs in less than 1% of the whole production.	2
Remote	No chance of occurrence.	1

Table 3. The criteria of detection evaluation (ability to control) for FMEA.

Detection	Detection control	Rank
Absolute uncertainty	No control/detection or monitoring.	10
Very remote	The action can be controlled by using random checks to detect failure.	9
Remote	The action can be controlled by employees with visual inspection methods or properties: pass/fail.	8
Very low	The action can be controlled by employees by using repeated detection with visual inspection methods or properties: pass/fail.	7
Low	The action can be controlled by a SPC chart.	6
Moderate	The action can be controlled by using measurement tools. The workpiece is measured before leaving the operating point, or the appropriate measurement tools are used for all work before leaving the operating point.	5
Moderately high	Error detection is performed in the next process or using a measurement instrument during the first job.	4
High	Error detection is performed at the operating point or in the next process by checking for job acceptance.	3
Very high	Error detection is performed at the operating point with the automatic control system to prevent defective products from advancing to the next process.	2
Almost certain	There is no chance of defect occurrence because the error protection system products are used to detect the error and notify employees (light, sound, etc.).	1

2.3. Fuzzy Approach to FMEA

Fuzzy logic technique is used to manage the uncertainty of the data. This method is determined as a set in the principles of mathematics, whose knowledge is based on degrees of membership functions instead of crisp values as in classical binary logic and emerges from the fuzzy set [13]. Fuzzy logic involves determining the degree of membership and member variables can be not only 0 or 1. (0 represents a non-member of the group, whereas 1 represents the members) but a value comprehensively between 0 and 1 (range from 0 and 1 representing increasing membership level) [36]. Thus, fuzzy FMEA can be divided into the following steps and illustrated in Figs. 1-2.

Step 1: Procedure of preparing relationship dataset. This procedure is to prepare the dataset of the relationship by using the 3 components of risk assessment; S, O and D.

Step 2: Determining the linguistic variable for input and output. The determination of the variable can help interpret human communication and translation to numerical values by using the membership function. The concept [37] can be illustrated as follows. Conditioned X as a nonempty set, then place fuzzy set A in X to be identified on membership function $\mu_A\colon X \rightarrow [0,1]$, and in other part, $\mu_A(x)$ to be interpreted to represent the degree of membership of element x in fuzzy set A for each $x \in X$. Therefore, A can be fully clarified by analyzed set of tuples as $A = \left(\left(u, \mu_A(u)\right)/u \in X\right)$. Generally, $A(x)$ is applied for $\mu_A(x)$.

Meanwhile, the correlation of all fuzzy sets in X is being indicated by equation of $F(X)$. As for that, if a set of $X = (x_1, \cdots, x_n)$ is finite, while A is a fuzzy set in X, thereon, the following notation is used regularly.

$$A = (\mu_1/x_1) + \cdots + (\mu_n/x_n), \tag{2}$$

where the term μ_1/x_1 , i = 1,…, n signifies that $\mu_1$is the grade of membership of x_1 in *A*, and the plus the sign represents the union.

Step 3: Procedure of conversion input and output data. On this step, the input function and construction of the membership function is converted to cover the data acquired. The number or each variable in set terms should be decided to ensure that the inference of the output value is most similar to the real data.

A connection between variables of data, in which intricate membership functions, can be designated as a triangular membership function, trapezoidal membership function and etc. In that case, triangular fuzzy number [38] is constituted by a fuzzy number of three parameters as follows:

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ (x-a_1)/(a_2-a_1), & a_1 \le x \le a_2 \\ (a_3-x)/(a_3-a_2), & a_2 \le x \le a_3 \\ 0, & x > a_3 \end{cases}, \tag{3}$$

where $a_1$and a_3 correspond to the lower and upper bounds of fuzzy number *A,* respectively, and a_2 is the middle point. The triangular fuzzy number is indicated as $A = (a_1, a_2, a_3)$. The Gaussian membership function [39] can be represented by

$$f(x; c, \sigma) = e^{\frac{-1}{2}\left(\frac{x-c}{\sigma}\right)^2}, \tag{4}$$

where σ represents the standard deviation, and c is the mean. The Gaussian membership function is nonzero at all points, and every membership function practically has a 50% overlap [40].

Step 4: Deduce the concluded fuzzy logic relationship from Mamdani-style inference by using a fuzzy rule composed of IF and THEN [41]. A number of rules based on dependent variables and values in the state will be limited by the selection of the necessary regulations. The Mamdani-style inference can be represented by

The operation of OR in the fuzzy set has been performed as follows:

$$\mu_{A \cup B}(x) = max[\mu_A(x), \mu_B(x)]. \tag{5}$$

The operation of AND using an intersection operator is performed as follows:

$$\mu_{A \cap B}(x) = min[\mu_A(x), \mu_B(x)]. \tag{6}$$

After evaluated the other rules and the rule result is not equivalent to zero, then it will be convened by the membership function. With reference to the output, it then will be convened by union, and the result of aggregation will be used further to convert into a single number, which will be used later for data processing. Defuzzification is the process of conversion in the crisp values using the center of gravity (COG). [42] as presented in Eq. 7:

$$COG = \frac{\int_a^b \mu_A(X)x dx}{\int_a^b \mu_A(X) dx} \tag{7}$$

Step5: Consideration of error improvement. After the completion of the fuzzy FMEA.

Step6: Comparison between the conventional FMEA and fuzzy FMEA methods. Using expert team consensus, fuzzy FMEA is then applied.

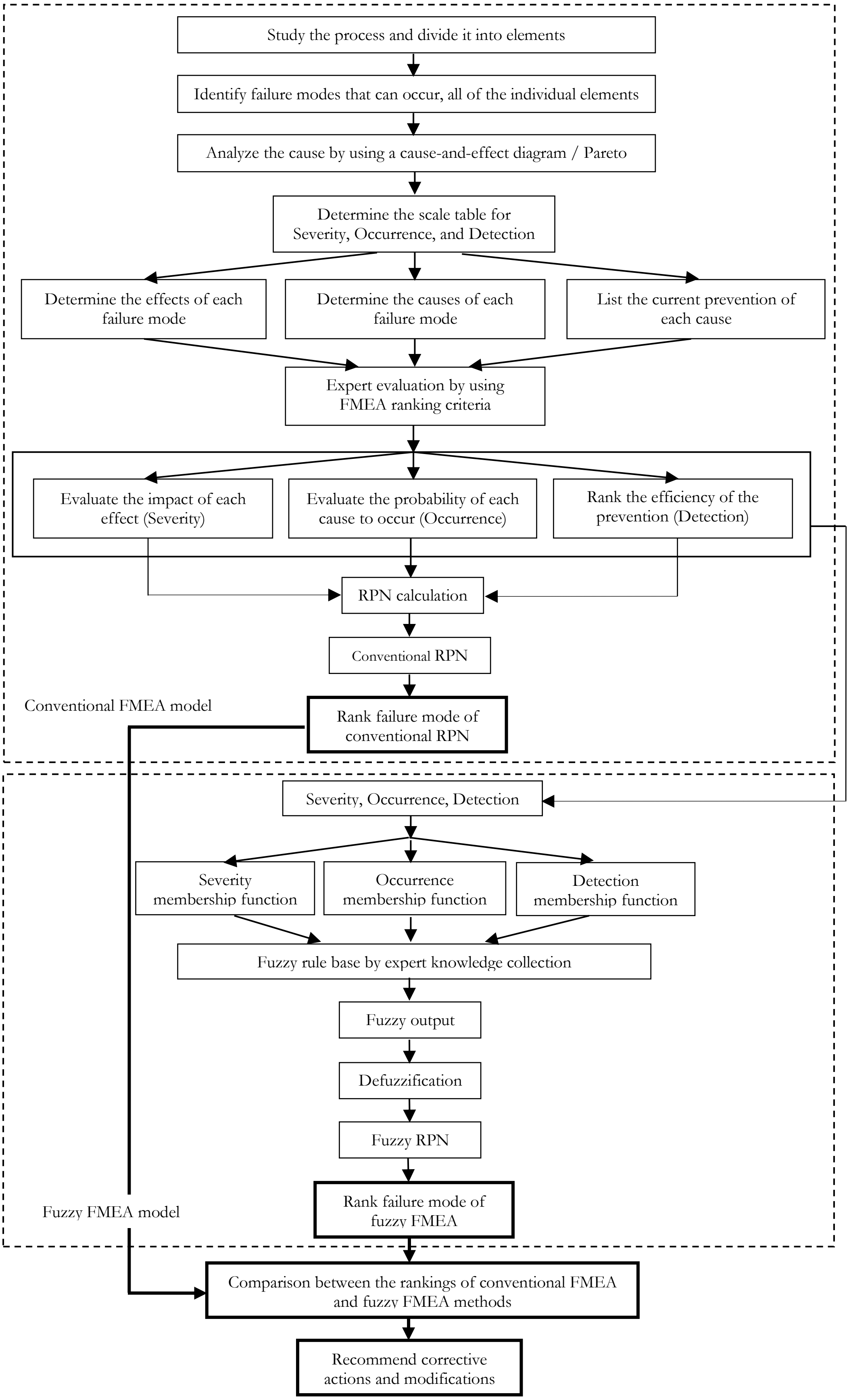

Fig. 1. Procedure of conventional FMEA and fuzzy FMEA models.

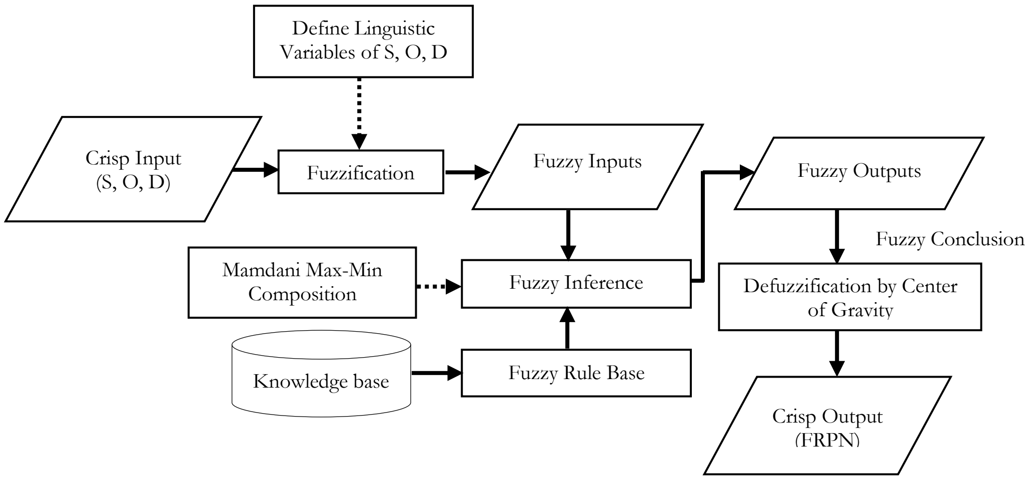

Fig. 2. The process of fuzzy systems.

3. Results

3.1. Production process of poultry products

There are three main poultry production processes: the process of low risk, process of high risk and process of medium risk. The steps in the process of low risk start with the receiving of raw material at the slaughterhouse: weight/piece, raw marks, temperature of material, temperature of storage materials. Step2 is the selection of raw material by workers: raw marks, adulterated product. Step3 is chilling: temperature of meat, chill time before marinating meat. Step4 is marinating: pressure, speed, time. Step5 is tumbling: temperature of marinade solution, treatment, time to chill meat, marinade recipes, temperature of tumbling. Step6 involves the loader machine, which arranges chicken pieces along the belt. Step7 is flattening: thickness. The last step is pre-cooking: temperature, steam flow, high fan/low fan, cooking time. In the process of high risk, step1 is cooking/ steaming in the cooker machine: temperature of meat before cooking, weight/piece and raw marks after tumbling, treatment, ripening conditions and central temperature after cooking. Step2 is searing by a set bar mark machine: heating coil, belt speed, distance of the threaded nut; the slices are placed diagonally 45 degrees before reaching the bar mark machine. Step3 is freezing: central temperature after freezing, weight/piece and raw marks, sampling to detect, and sampling test kitchen. Step4 is plastic bag packing: weight/bag, quality sealed bags. The last step is metal detection.

The last process is the process of medium risk, which consists of packaging: quality bags, number of bags/ boxes, arrangement of products, accuracy of boxes, quality of seal, and packed storage temperature. The last step of the process of medium risk is storage: cold storage temperature. The production process is shown in Fig. 3.

3.2. Conventional FMEA Methodology

Observing at different parts of a defective product in the manufacturing procedure, most of them were poultry products. We have determined the numbers and types of defective parts from January to September 2017, as shown in Table 4.

From Table 4, the total production value was about 110,540.77 kg. Most defective parts were rejected, with defective parts representing 2.51% of the total product value. The bar mark consists of the bar mark having sufficient coverage on less than 60% of the meat/ insufficient bar mark with a percentage of 1.50%, bar mark burning with a percentage of 0.54% and long bar mark/back bar mark/straight bar mark with a percentage of 0.48%. The second is rejection of shred meat/shred tail, with a percentage of 1.27%, the third is CT under standard, with a percentage of 0.87%, etc. Therefore, the highest priority of the manufacturer was to resolve the problem. The Pareto chart was plotted by MINITAB 16 [43] and is shown in Fig. 4.

The bar mark is the first feature of defective products, which included bar mark on less than 60% of the meat/insufficient bar mark, bar mark burning and long bar mark/back bar mark/straight bar mark in the production process, as shown in Fig. 5.

The brainstorming technique was used to seek out the main cause of the problem. Experts in the production, quality assurance, quality control departments and operating workers involved in the brainstorming with expertise person in operation. All ideas shared during the brainstorm are summarized in the cause-and-effect fishbone diagram shown in Fig. 6.

The failure mode consists of the raw material, man machinery and management process. The RPN enabled us to prioritize the leading causes of the failure effect (bar mark burning, bar mark is less than 60% of meat/insufficient bar mark and long bar mark/back bar mark/straight bar mark), which are 16 failure causes. The prioritization of failure causes, for which No.1 would show the priority of the highest risk, and No.16 would reflect the priority of the lowest risk is shown in Table 5.

Fig. 3. Production process of poultry products.

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Table 4. The features of defective products and percentage of defect during January to September 2017.

Prioritization	Feature of defective product	Defective product (kg)	Reject: defective product (%)	Reject: Total production volume (%)
1	Bar mark	2,775,68	48.96	2.51
	▪ Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	1,652.94	29.15	1.50
	▪ Bar mark burning	592.32	10.45	0.54
	▪ Long bar mark/ back bar mark/straight bar mark	530.42	9.36	0.48
2	Shred meat/ shred tail	1407.71	24.83	1.27
3	CT under standard	965.40	17.03	0.87
4	Fall to the floor	221.87	3.91	0.20
5	Fall to the tray	158.20	2.79	0.14
6	Fall below the belt	74.44	1.31	0.07
7	Others (small pieces, a bit of chicken, broken tail, fall under the outfeed, and green fragment)	66.44	1.17	0.06
Total		**5,669.74**	**100.00**	**5.13**

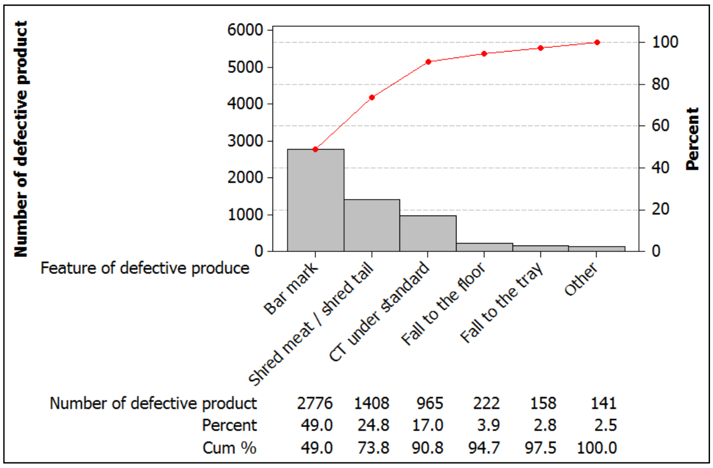
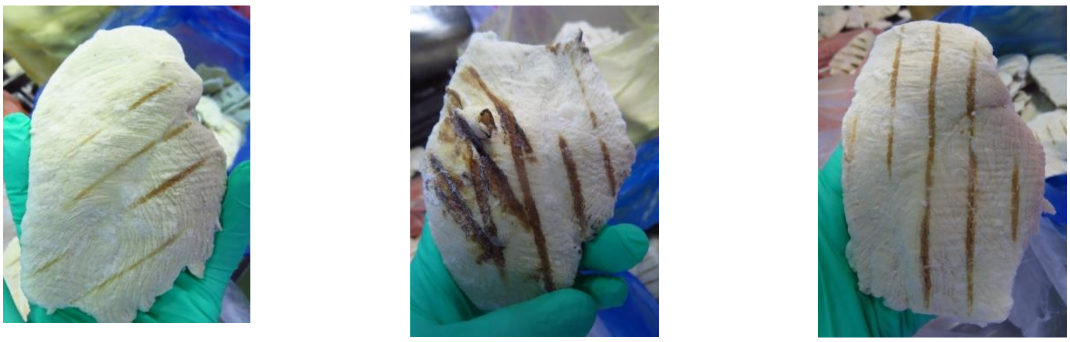


Fig. 4. Pareto chart of features of defective product.



(a) bar mark coverage sufficient on less than 60% of meat/ insufficient

(b) bar mark burning

(c) long bar mark/back bar mark /straight bar mark

Fig. 5. The features of defective production.

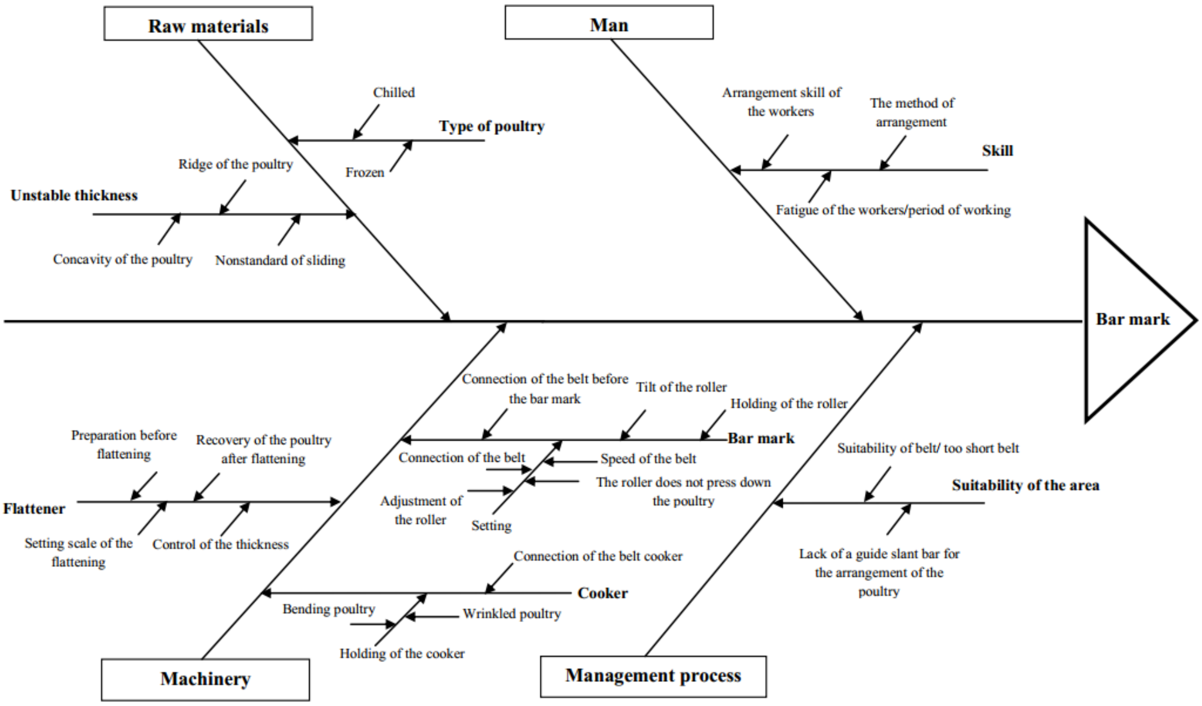


Fig. 6. The cause-and-effect fishbone diagram for bar marks.

3.3. Fuzzy FMEA Methodology

The risk priority number (RPN) was computed by merging the associated 3 inputs to the output; the inputs were (S, O and D) and output variables of failures were identified with the advice of expert knowledge by using a database of 300 decision rules (5 S × 6 O × 10 D). The input variable membership functions of S have a 10-level scale divided into 5 different regions. These sub-regions of S are none, low, moderate, high and very high. The inputs of O have a 10-level scale divided into 6 different regions. These sub-regions of O are remote, very low, low, moderate, high and very high. For input of D has a 10-level scale divided into 10 different regions. These sub-regions of D are almost certain, very high, high, moderately high, moderate, low, very low, remote, very remote and absolute uncertainty. The output variable membership functions have a 10-level scale ranging from 0,1,2,…,10, representing none, very low, low, high low, low moderate, moderate, high moderate, low high, high and very high, respectively.

Tables 6–9 show the linguistic terms and fuzzy numbers used to evaluate the three components (S, O and D), and the construction of the membership function of the input and output is visualized in Figs. 7–10. All computations and figures are run in MATLAB7.6.0 (R2009a) [44].

The fuzzy rule base was designed to find all possible failures according to the expert knowledge based on the significance of S, O and D. For example, in some rules based on expert opinions shown in Fig. 8, IF S is none (N), AND O is very high (VH), AND D is very high (VH), and output is very low (VL). The fuzzy inference systems use the method of Mamdani max–min composition consisting of three input variables (S, O and D), and the output variable is defined to represent the fuzzy set. This system will convert the crisp input into linguistic variables by using the membership functions kept in the knowledge base of the fuzzy system and then compare the input value with the membership functions. The operational rules (If–Then) were applied to generate a result for each rule before combining the results of the rule or converting the fuzzy input into a fuzzy output. From the example of the Mamdani-based rule viewer, the 18 rules of unstable thickness: nonstandard sliding are rule 156, rule 157, rule 166, rule 167, rule 176, rule 177, rule 216, rule 217, rule 226, rule 227, rule 236, rule 237, rule 276, rule 277, rule 286, rule 287, rule 296 and rule 297, as represented in Figs 9–10. All computations and figures are run in MATLAB 7.6.0(R2009a) [42]. The resulting fuzzy FMEA is shown in Table 10.

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Table 5. Detailed FMEA analysis of unit.

Failure mode	Failure causes	Failure effect	S	O	D	RPN	Prioritization
Raw material	1. Type of poultry (chilled, frozen)	Bar mark burning	6.8	5	6	204	8
	Unstable thickness						
	2. Ridge of the poultry	Bar mark burning	8.8	6.2	6.6	360	3
	3. Concavity of the poultry	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	9	6.6	6.8	404	2
	4. Nonstandard sliding	Bar mark burning	9.4	6.8	6.4	409	1
Man	5. Arrangement skill of the workers	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	7.4	6	6	226	6
	6. The method of arrangement	Long bar mark/back bar mark/ straight bar mark	9	5.8	5.6	292	5
	7. Fatigue of the workers/period of working	Long bar mark/back bar mark/ straight bar mark	7.8	3.8	5.2	154	14
Machinery	Process of the flattener						
	8. Preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening	Bar mark burning	8.6	4.8	4.4	182	10
	Process of the bar mark						
	9. Tilt of the roller	Bar mark burning	8.4	5.2	4.4	192	9
	10. Connection of the belt before the bar mark	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	7	5.2	4	146	15
	11. Holding of the roller	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	6.6	4.8	4.4	139	16
	12. Setting (speed of the belt, connection of the belt, adjustment of the roller, the roller does not press down the poultry)	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	7.6	5.2	4.4	174	12
	Process of the cooker						
	13. Holding of the cooker (wrinkled poultry, bending poultry	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	8	4.4	5	176	11
	14. Connection of the belt cooker	Long bar mark/back bar mark/ straight bar mark	6.6	4.2	5.6	155	13
Management process	Suitability of the area						
	15. Suitability of the belt/too short belt	Long bar mark/back bar mark/ straight bar mark	8.2	6.6	5.8	314	4
	16. Lack of a guide slant bar for the arrangement of the poultry	Long bar mark/back bar mark/ straight bar mark	7	5.6	6	235	7

Table 6. Fuzzy input for the severity (S) of failure.

Effect	Criteria: severity of effect	Fuzzy number (σ, c)
Very high (VH)	Product quality is impacted at a very high level; it causes waste that cannot be recovered. (The product is abandoned.)	(0.5, 10)
High (H)	Product quality is impacted at a high level; it causes some waste that can be recovered by selection. (Some may be abandoned.)	(0.83, 8.5)
Moderate (M)	Product quality is impacted at a moderate level; it can be brought back immediately to be fixed by selection, and there are no wasted products.	(1, 6.5)
Low (L)	Product quality is impacted at a low level; it can be accepted without being fixed, and there are no wasted products.	(1.66, 3.5)
None (N)	Product quality is not impacted, and the product moves to the next process.	(0.5, 1)

Table 7. Fuzzy input for the occurrence (O) of failure.

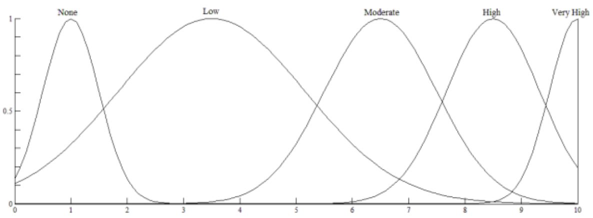
Probability of failure	Possible failure rates	Fuzzy number (σ, c)
Very high (VH)	Occurs in more than 50% of the whole production.	(1.33, 10)
High (H)	Occurs in 31–50% of the whole production.	(0.83, 7.5)
Moderate (M)	Occurs in 11–30% of the whole production.	(1.33, 5)
Low (L)	Occurs in 1–10% of the whole production.	(0.33, 3)
Very low (VL)	Occurs in less than 1% of the whole production.	(0.5, 2)
Remote (R)	No chance of occurrence.	(0.5, 1)

Table 8. Fuzzy input for the detection (D) of failure.

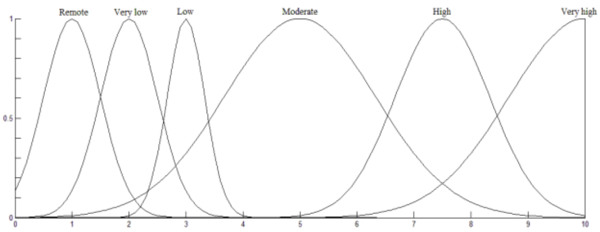
Detection	Criteria: detection control	Fuzzy number (a_1, a_2, a_3)
Absolute uncertainty (AU)	No control/detection or monitoring	(9, 10, 10)
Very remote (VR)	The action can be controlled by using random checks to detect failure.	(8, 9, 10)
Remote (R)	The action can be controlled by employees with visual inspection methods or properties: pass/fail.	(7, 8, 9)
Very low (VL)	The action can be controlled by employees by using repeated detection with visual inspection methods or properties: pass/fail.	(6, 7, 8)
Low (L)	The action can be controlled by a SPC chart.	(5, 6, 7)
Moderate (M)	The action can be controlled by using measurement tools. The workpiece is measured before leaving the operating point, or the appropriate measurement tools are used for all work before leaving the operating point.	(4, 5, 6)
Moderately high (MH)	Error detection is performed in the next process or using a measurement instrument during the first job.	(3, 4, 5)
High (H)	Error detection is performed at the operating point or in the next process by checking for job acceptance.	(2, 3, 4)
Very high (VH)	Error detection is performed at the operating point with the automatic control system to prevent defective products from advancing to the next process.	(1, 2, 3)
Almost certain (AC)	There is no chance of defect occurrence because the error protection system products are used to detect the error and notify employees (light, sound, etc.).	(0, 1, 2)

Table 9. Fuzzy output for the relative importance of risk factor.

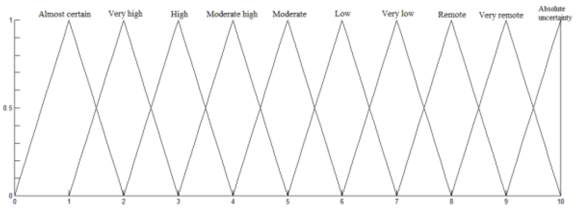
Linguistic term	**Fuzzy number** (a_1, a_2, a_3)
Very high (VH)	(9, 10, 10)
High (H)	(8, 9, 10)
Low high (LH)	(7, 8, 9)
High moderate (HM)	(6, 7, 8)
Moderate (M)	(5, 6, 7)
Low moderate (LM)	(4, 5, 6)
High low (HL)	(3, 4, 5)
Low (L)	(2, 3, 4)
Very low (VL)	(1, 2, 3)
None (N)	(0, 1, 2)



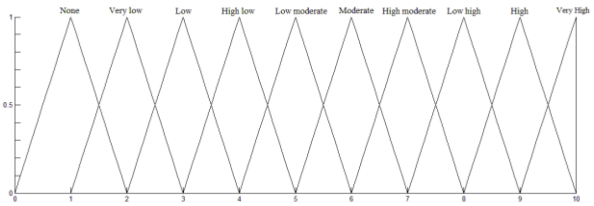
Input variable membership function of severity.



Input variable membership function of occurrence.

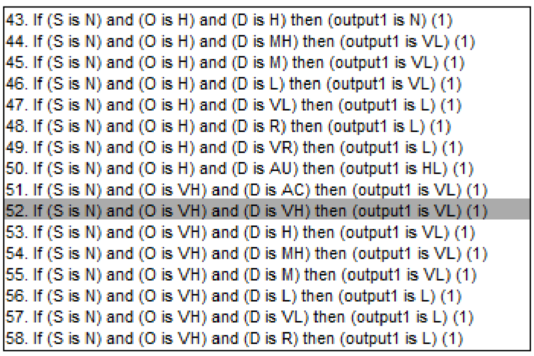


Input variable membership function of detection.



Output variable membership function.

Fig. 7. Input and output membership function.



43. If (S is N) and (O is H) and (D is H) then (output1 is N) (1)
44. If (S is N) and (O is H) and (D is MH) then (output1 is VL) (1)
45. If (S is N) and (O is H) and (D is M) then (output1 is VL) (1)
46. If (S is N) and (O is H) and (D is L) then (output1 is VL) (1)
47. If (S is N) and (O is H) and (D is VL) then (output1 is L) (1)
48. If (S is N) and (O is H) and (D is R) then (output1 is L) (1)
49. If (S is N) and (O is H) and (D is VR) then (output1 is L) (1)
50. If (S is N) and (O is H) and (D is AU) then (output1 is HL) (1)
51. If (S is N) and (O is VH) and (D is AC) then (output1 is VL) (1)
52. If (S is N) and (O is VH) and (D is VH) then (output1 is VL) (1)
53. If (S is N) and (O is VH) and (D is H) then (output1 is VL) (1)
54. If (S is N) and (O is VH) and (D is MH) then (output1 is VL) (1)
55. If (S is N) and (O is VH) and (D is M) then (output1 is VL) (1)
56. If (S is N) and (O is VH) and (D is L) then (output1 is L) (1)
57. If (S is N) and (O is VH) and (D is VL) then (output1 is L) (1)
58. If (S is N) and (O is VH) and (D is R) then (output1 is L) (1)

Fig. 8. Example of the rule base of expert opinions (rule 52).

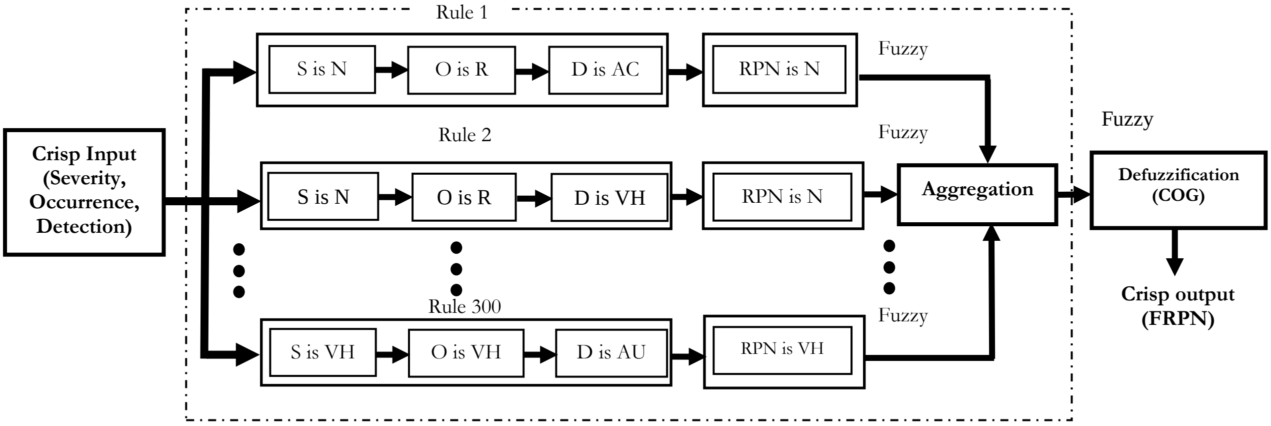


Fig. 9. Mamdani max–min composition style.

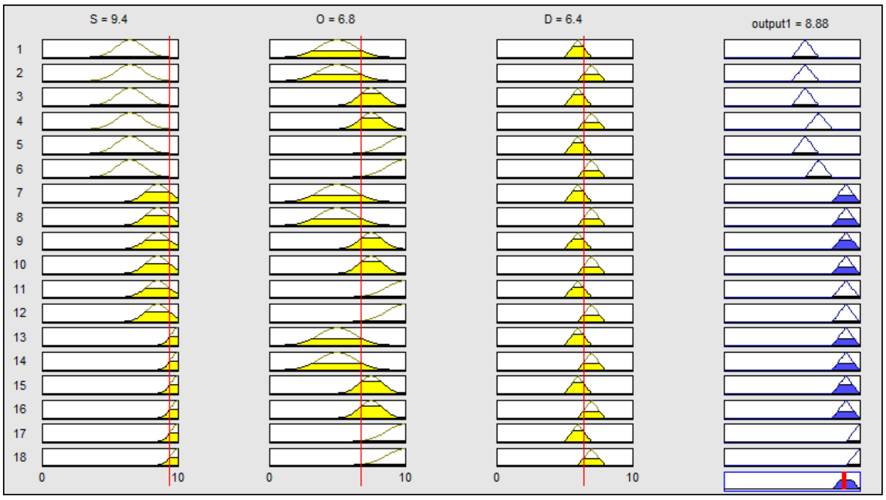


Fig. 10. Example of Mamdani-based rule viewer of unstable thickness: nonstandard sliding (18 rules).

3.4. Comparison between Conventional FMEA and Fuzzy FMEA

If using the principles of logic, it indicated that the priority has been changed. Two methods of the errors created the differences between the priorities of minor components, such as suitability of the belt/too short belt, the method of arrangement, arrangement skill of the workers, lack of a guide slant bar for the arrangement of the poultry, etc. Moreover, there are some sub-assemblies with the same priority such as nonstandard sliding, concavity of the poultry, ridge of the poultry, tilt of the roller, setting (speed of the belt, connection of the belt, adjustment of the roller, the roller does not press down the poultry), connection of the belt before the bar mark and holding of the roller. The results also showed that the risk priority changes from a sequence of high risk to low risk. These most obvious changes were in failure cause numbers 1, 5, and 16: the type of poultry (chilled, frozen), arrangement skill of the workers and lack of a guide slant bar for the arrangement of the poultry, respectively.

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Table 10. Prioritization of conventional FMEA and fuzzy FMEA.

Failure mode	Failure causes	Failure effect	Fuzzy FMEA (1–10)	Prioritization of fuzzy FMEA
Raw material	1. Type of poultry (chilled, frozen)	Bar mark burning	6.13	13
	Unstable thickness			
	2. Ridge of the poultry	Bar mark burning	8.46	3
	3. Concavity of the poultry	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	8.62	2
	4. Nonstandard sliding	Bar mark burning	8.88	1
Man	5. Arrangement skill of the workers	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	7.04	9
	6. The method of arrangement	Long bar mark/back bar mark/ straight bar mark	8.37	4
	7. Fatigue of the worker/period of working	Long bar mark/back bar mark/ straight bar mark	7.15	7
Machinery	Process of the flattener			
	8. Preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening	Bar mark burning	7.25	6
	Process of the bar mark			
	9. Tilt of the roller	Bar mark burning	7.04	9
	10. Connection of the belt before the bar mark	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	5.45	15
	11. Holding of the roller	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	5.18	16
	12. Setting (speed of the belt, connection of the belt, adjustment of the roller, the roller does not press down the poultry)	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	6.32	12
	Process of the cooker			
	13. Holding of the cooker (wrinkled poultry, bending poultry)	Bar mark coverage sufficient on less than 60% of meat/ insufficient bar mark	7.15	7
	14. Connection of the belt cooker	Long bar mark/back bar mark/ straight bar mark	5.55	14
Management process	Suitability of the area			
	15. Suitability of the belt/too short belt	Long bar mark/back bar mark/ straight bar mark	7.77	5
	16. Lack of a guide slant bar for the arrangement of the poultry	Long bar mark/back bar mark/ straight bar mark	6.43	11

When considering each failure cause, the expert thought that the type of poultry (chilled, frozen) was the first factor that entered the production process. If the type of poultry (chilled, frozen) did not have the desired standard, it would affect the occurrence of defective products. The experts also placed importance on the failure causes of the arrangement skill of the workers and lack of a guide slant bar for the arrangement of the poultry, owing to the array of products that must be used and the good skills and experience that the workers must have. If there is no slant arrangement of the guide bar for poultry, it would affect the occurrence of defective products because people are the variable factors at any time. Therefore, the experts estimated that there are 3 high-risk failure causes.

However, when using the fuzzy FMEA method, it showed that the priority of the FMEA risk was lower than that of the conventional method. This indicated that, in fact, the surveillance was unnecessary, and if an error occurred, it did not cause damage or was not as important as expected. In contrast, the experts expressed their opinions that some failure causes were not as important as expected, so they evaluated the priority at a lower risk. When using the fuzzy FMEA method, it showed that the priority of risks was higher than that of the conventional FMEA method. The most obvious failure causes were 7, 8, and 13: fatigue of the workers/period of working, process of the flattener (preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening) and holding of the cooker (wrinkled poultry, bending poultry), respectively.

When considering each failure cause, the expert opinion was that the fatigue of the workers/period of working was less important because the production process will have to determine the period of time between work for workers, and the experience and expertise of the workers were quite high, so it resulted in the fewest defective products. Regarding the failure causes of preparation before flattening, the setting scale of the flattener, control of the thickness, recovery of the poultry after flattening and holding of the cooker (wrinkled poultry, bending poultry), the experts opined that the workers had experience in arranging the raw materials before entering into the machine. In addition, in the production, the machine was set up and controlled. The employees also monitored the machine to ensure that the products were not stuck in the machine. In addition, the engineers immediately examined the machine in the case of malfunction during the manufacturing process. Thus, these mentioned factors caused defective products at a low level.

For other failure causes, it was found that there was no difference in the priority risk between the conventional FMEA method and the fuzzy FMEA method. Therefore, the failure cause, which has been changed from low risk to high risk, requires a solution for the process improvement at that point along with surveillance and minimal occurrence of defective products. The prioritization of conventional FMEA and fuzzy FMEA is shown in Tables 11.

4. Conclusions and Discussion

Conventional FMEA is an important analytic instrument that is used widely in the manufacturing industries of motors, mechanical equipment, electronics, etc. However, it has been criticized because of its problems. RPN in FMEA is not a reliable indicator of the corresponding risks. FMEA has no effect on the main product / key process. The failures are shown incompletely by the method of FMEA. There is some overlapping. Normally, there is a gap between design and process FMEA, etc. Therefore, this study has proposed the fuzzy FMEA method, which was established based on fuzzy systems to evaluate the linguistic terms of factors to obtain RPNs (severity × occurrence × defection) by using the brainstorming system of specialist consensus to improve defects and reduce the risk of the poultry product process. A comparison between conventional FMEA and fuzzy FMEA can be summarized and discussed as follows:

The conventional FMEA method was used to analyze the cause of the failure mode, which calculated the RPN based on the evaluation and the decision of the five experts. It was found that the averages of S, O, and D were 7.89 (SD = 0.927), 5.39 (SD = 0.896) and 5.41 (SD = 0.890), respectively. Therefore, the evaluation would be different with different opinions. This probably depended on their basic knowledge, skills, work experiences and other environmental factors during the different performance, so the evaluation score was different as a result.

- The fuzzy FMEA—owing to the new assessment of the priority obtained from the experts' opinions by the consensus of the occurrence of each failure—could be helpful in the management and improvement process of defects in the production process.
- Failure causes that should be among the top three in surveillance included the following: 1) nonstandard sliding, causing bar mark burning; 2) concavity of the poultry, causing bar mark coverage

of less than 60% of the meat/insufficient bar mark; and 3) ridge of the poultry, causing bar mark burning. When comparing the conventional FMEA and the fuzzy FMEA methods, the priority of the risk method was not different. This showed that the experts noticed the problems of all three failures that affected the occurrence of product defects at a high level when performing analysis using fuzzy FMEA.

- Other failure causes that changed the priority of risk from low risk to high risk included the method of arrangement, fatigue of the workers/period of working, preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening and holding of the cooker. Therefore, the production process of poultry products should include surveillance of the failure causes with changing priority of risk to reduce defective products.
- This study can be used as a guideline to improve the production of poultry products and implement surveillance to minimize the occurrence of defective products, thus increasing efficiency helping reduce the cost of production in the food industry. In addition, this approach can be applied to other industries that have similar production processes. This method is appropriate for mid-sized manufacturing industries because the factors of defective products must be studied, and a long period of time was used to determine the root of the problem.

Table 11. Comparison of prioritization between conventional FMEA and fuzzy FMEA.

Prioritization	Conventional FMEA	Fuzzy FMEA
1	Nonstandard sliding	Nonstandard sliding
2	Concavity of the poultry	Concavity of the poultry
3	Ridge of the poultry	Ridge of the poultry
4	Suitability of the belt/too short belt	The method of arrangement
5	The method of arrangement	Suitability of the belt/too short belt
6	Arrangement skill of the workers	Preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening
7	Lack of a guide slant bar for the arrangement of the poultry	Fatigue of the workers/period of working holding of the cooker (wrinkled poultry, bending poultry)
8	Type of poultry (chilled, frozen)	-
9	Tilt of the roller	Arrangement skill of the workers Tilt of the roller
10	Preparation before flattening, setting scale of the flattener, control of the thickness, recovery of the poultry after flattening	-
11	Holding of the cooker (wrinkled poultry, bending poultry)	Lack of a guide slant bar for the arrangement of the poultry
12	Setting (speed of the belt, connection of the belt, adjustment of the roller, the roller does not press down the poultry)	Setting (speed of the belt, connection of the belt, adjustment of the roller, the roller does not press down the poultry)
13	Connection of the belt cooker	Type of poultry (chilled, frozen)
14	Fatigue of the workers/period of working	Connection of the belt cooker
15	Connection of the belt before the bar mark	Connection of the belt before the bar mark
16	Holding of the roller	Holding of the roller

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References

[1] A. Ghobadian and D. N. Gallear, "Total Quality Management in SMEs," *Omega*, vol. 24, no. 1, pp. 83–106, 1996.

[2] M. Zairi, *Total Quality Management for Engineers*. Cambridge, UK: Woodhead Publishing Limited, 1991.

[3] D. C. Montgomery, *Introduction to Statistical Quality Control*, 6th ed. USA: John Wiley & Sons and Arizona State University, 2009.

[4] A. Pongpullponsak, *Statistical Quality Control*. Bangkok, Thailand: Jaransanitwong Kanpim Co. Ltd., 2013.

[5] K.-H. Chang, "Evaluate the orderings of risk for failure problems using a more general RPN methodology," *Microelectronics Reliability*, vol. 49, no. 12, pp. 1586-1596, 2009.

[6] E. Bas, "An investment plan for preventing child injuries using risk priority number of failure mode and effects analysis methodology and a multi-objective, multi-dimensional mixed 0-1 knapsack model," *Reliability Engineering and system Safety*, vol. 96, no. 7, pp. 748-756, 2011.

[7] N. Xiao, H.-Z. Huang, Y. Li, L. He, and T. Jin, "Multiple failure modes analysis and weighted risk priority number evaluation in FMEA," *Engineering Failure Analysis*, vol. 18, no.4, pp. 1162-1170, 2011.

[8] A. Mariajayaprakash and T. Senthilvelan, "Failure detection and optimization of sugar mill boiler using FMEA and Taguchi method," *Engineering Failure Analysis*, vol. 30, pp. 17-26, 2013.

[9] W. Gilchrist, "Modelling failure modes and effects analysis," *International Journal of Quality and Reliability Management*, vol. 10, no. 5, pp. 16-23, 1993.

[10] P. Palady, *Failure Modes and Effects Analysis: Predicting & Preventing Problems Before They Occur*. Florida, USA: PT Publications Inc., 1995.

[11] S. Kmenta, "Advanced failure modes and effects analysis: A method for predicting and evaluating failures in products and processes," Ph.D. dissertation, Mechanical Engineering, Stanford University, California, USA, 2000.

[12] S. J. Rhee and K. Ishii, "Using cost based FMEA to enhance reliability and serviceability," *Advanced Engineering Informatics*, vol. 17, no. 3-4, pp. 179-188, 2003.

[13] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, 1965.

[14] M. Negnevitsky, *Artificial Intelligence: A guide to Intelligent Systems*, 2nd ed. UK: Pearson Education, 2005.

[15] C.–H. Yeh, H. Deng, and Y.-H. Chang, "Fuzzy multicriteria analysis for performance evaluation of bus companies," *European Journal of Operational Research*, vol.126, no. 3, pp. 459-473, 2000.

[16] L. Baron, S. Achiche, and M. Balazinski, "Fuzzy decision support system knowledge base generation using a genetic algorithm," *International Journal of Approximate Reasoning*, vol. 28, no. 2-3, pp. 125-148, 2001.

[17] M. Singh and T. Markeset, "A methodology for risk-based inspection planning of oil and gas pipes based on fuzzy logic framework," *Engineering Failure Analysis*, vol.16, no.7, pp. 2098-2113, 2009.

[18] H. Zhang, D. Gao, and W. Liu, "Risk assessment for Liwan relief well in South China Sea," *Engineering Failure Analysis*, vol. 23, pp. 63-68, 2012.

[19] H. Su and Z. Wen, "Interval risk analysis for gravity dam instability," *Engineering Failure Analysis*, vol. 33, pp. 83-96, 2013.

[20] S.-T. Lu, S.-H. Yu, and D.-S. Chang, "Using fuzzy multiple criteria decision-making approach for assessing the risk of railway reconstruction project in Taiwan," *The Scientific World Journal*, vol. 2014, Article ID 239793, pp. 1-14, 2014.

[21] P. Rezakhani, "Fuzzy MCDM model for risk factor selection in construction projects," *Engineering Journal*, vol. 16, no. 5, pp. 79-94, 2012.

[22] D. Ighravwe and S. Oke, "A combined fuzzy goal programming and Big-Bang Big-Crunch algorithm for workforce optimisation with facility layout consideration," *Engineering Journal*, vol. 19, no. 2, pp. 71-98, 2015.

[23] P. Charongrattanasakul and A. Pongpullponsak, "Optimizing the cost of integrated model for fuzzy failure Weibull distribution using genetic algorithm," *Engineering Journal*, vol. 21, no. 2, pp. 253-268, 2017.

[24] R. H. Yeh and M.-H. Hsieh, "Fuzzy assessment of FMEA for a sewage plant," *Journal of the Chinese Institute of Industrial Engineer*, vol. 24, no. 6, pp. 505-512, 2007.

[25] K.-S. Chin, A. Chan, and J.-B. Yang, "Development of a fuzzy FMEA based product design system," *International Journal of Advanced Manufacturing Technology*, vol. 36, no. 7, pp. 633-649, 2008.

[26] H.-T. Liu and Y.-L. Tsai, "A fuzzy risk assessment approach for occupational hazards in the construction industry," *Safety Science*, vol. 50, no.4, pp. 1067-1078, 2012.

[27] F. Dinmohammadi and M. Shafiee, "A fuzzy-FMEA risk assessment approach for offshore wind turbines," *International Journal of Prognostics and Health Management*, vol. 4, pp. 59-68, 2013.
[28] M. Kumru and P. Y Kumru, "Fuzzy FMEA application to improve purchasing process in a public hospital," *Applied Soft Computing*, vol. 13, no. 1, pp. 721-733, 2013.
[29] T.-M. Yeh and L.-Y Chen, "Fuzzy-based risk priority number in FMEA for semiconductor wafer processes," *International Journal of Production Research*, vol. 52, no. 2, pp. 539-549, 2014.
[30] P. Nuchpho, S. Nansaarn, and A. Pongpullponsak, "The fuzzy FMEA method to improve the defects in sanitary ware manufacturing process," in *Proceedings of the International Conference on Applied Statistics 2014*, Khon Kaen, Thailand, 2014, pp. 198-205.
[31] T. Maranate, A. Pongpullponsak, and P. Ruttanaumpawan, "Fuzzy FMEA application for variables in factor analysis to prioritize suspected OSA patients for sleep study," in *Proceedings of the 3rd International Conference on Computer Engineering and Mathematical Sciences*, Langkawi, Malaysia, 2014, pp. 111-119.
[32] D. H. Stamatis, *Failure Mode and Effect Analysis: FMEA from Theory to Execution*, 2nd ed. American Society for Quality, Quality Press, United States of America, 2003.
[33] R. K. Sharma, D. Kumar, and P. Kumar, "Systematic failure mode and effect analysis using fuzzy linguistic modeling," *International Journal of Quality and Reliability Management*, vol. 22, no. 9, pp. 986–1004, 2005.
[34] A. Scipioni, G. Saccarola, A. Centazzo, and F. Arena, "FMEA methodology design, implementation and integration with HACCP system in a food company," *Food Control*, vol. 13, no. 8, pp. 495-501, 2002.
[35] A. Pillay and J. Wang, "Modified failure mode and effects analysis using approximate reasoning," *Reliability Engineering and System Safety*, vol. 79, no. 1, pp. 69-85, 2003.
[36] P. Halfarová, T. Ustyugová, and D. Vykydal, "The application of fuzzy FMEA," in *Proceedings of the Metal 2013: 22 International Conference on Metallurgy and Materials*, Brno, Czech Republic, EU, 2013.
[37] T. J. Ross, "Logic and fuzzy systems," i*n Fuzzy Logic with Engineering Applications,* 3rd ed. London, UK: John Wiley & Sons, 2010a, ch. 5, pp. 117-173.
[38] T. J. Ross, "Logic and fuzzy systems," i*n Fuzzy Logic with Engineering Applications,* 3rd ed. London, UK: John Wiley & Sons, 2010b, ch. 7, pp. 213.
[39] T. J. Ross, "Logic and fuzzy systems," i*n Fuzzy Logic with Engineering Applications,* 3rd ed. London, UK: John Wiley & Sons, 2010c, ch. 7, pp. 212.
[40] K. M. Tay and C. P. Lim, "Fuzzy FMEA with a guided rules reduction system for prioritization of failure," *International Journal of Quality & Reliability Management*, vol. 23, no. 8, pp. 1047-1066, 2006.
[41] T. J. Ross, "Logic and fuzzy systems," i*n Fuzzy Logic with Engineering Applications,* 3rd ed. London, UK: John Wiley & Sons, 2010d, ch. 5, pp. 148-152.
[42] T. J. Ross, "Logic and fuzzy systems," in *Fuzzy Logic with Engineering Applications*, 3rd ed. London, UK: John Wiley & Sons, 2010e, ch. 4, pp. 99.
[43] MINITAB Thailand, *MINITAB 16 Order Number 100004968850, Single License*. February 2, 2010.
[44] MathWorks, *The Math WorksTM. MATLAB 7.6.0(R2009a). License Number 350306.* February 12, 2009.