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Fuzzy FMEA application to improve purchasing process in a public hospital

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ABSTRACT

Failure mode and effects analysis (FMEA) is one of the well-known techniques of quality management that is used for continuous improvements in product or process designs. While applying this technique, determining the risk priority numbers, which indicate the levels of risks associated with potential problems, is of prime importance for the success of application. These numbers are generally attained from past experience and engineering judgments, and this way of risk assessment sometimes leads to inaccuracies and inconsistencies during priority numbering. Fuzzy logic approach is preferable in order to remove these deficiencies in assigning the risk priority numbers. In this study, a fuzzy-based FMEA is to be applied first time to improve the purchasing process of a public hospital. Results indicate that the application of fuzzy FMEA method can solve the problems that have arisen from conventional FMEA, and can efficiently discover the potential failure modes and effects. It can also provide the stability of process assurance.

1. Introduction

Today's hard economical conditions, in which health companies operate, force the managers of these companies to use various scientific methods and new technological equipments on the way to attain more productive usage of their resources. Particularly the situations such as increasing costs, limited budget, and severe competition require development of planning and supervisory activities. Among health companies the public hospitals are the foundations which are directly affected from these circumstances.

Public hospitals are also the organizations who work with limited resources. The allocative inefficiency is a fundamental flaw in the public hospitals and these inefficiencies drain the limited public resources allotted for health care [1]. The more rationally they manage their supplies, the less negative outcomes of deficiencies or corruptions exist. Extensive usage of medical technologies requires considerable amounts of resources to be consumed at temperate levels and where they are needed. It is clear that if equipment/material purchases are realized without making an evaluation of requirements and getting cooperation of the hospital management, then the capacities and the qualities of these purchased items could be so far away from meeting the hospitals real needs [2]. That is why the purchasing process is very important in hospitals and should be improved continuously.

Process improvement plays a key role in business process management for every organization as well as for health organizations. It is a series of actions taken to identify, analyze and improve existing processes within an organization to meet new goals and objectives. These actions often follow a specific methodology or strategy to create successful results.

Understanding processes so that they can be improved by means of a systematic approach requires the knowledge of a simple kit of tools or techniques. The effective use of these tools and techniques requires their application by the people who actually work on the processes, and their commitment to this will only be possible if they are assured that management cares about improving quality. Managers must show they are committed by providing the training and implementation support necessary.

The tools and techniques most commonly used in process improvement are: DRIVE (define, review, identity, verify, execute), process mapping, process flowcharting, force field analysis, cause and effect diagrams, pareto analysis, brainstorming charting, matrix analysis, spc, etc. Failure mode and effect analysis (FMEA) is one of these techniques. In the following sections, the FMEA based on fuzzy approach is to be applied first in a public hospital to improve its purchasing process. The paper is organized in such a way that FMEA and fuzzy FMEA is introduced in Sections 2 and 3, literature review is given in Section 4, purchasing process in hospitals is discussed in Section 5, and the fuzzy FMEA application is given thoroughly in Section 6. The paper ends with concluding remarks.

2. Failure mode and effect analysis (FMEA)

FMEA is an analytical technique that combines the technology and experience of people in identifying foreseeable failure modes

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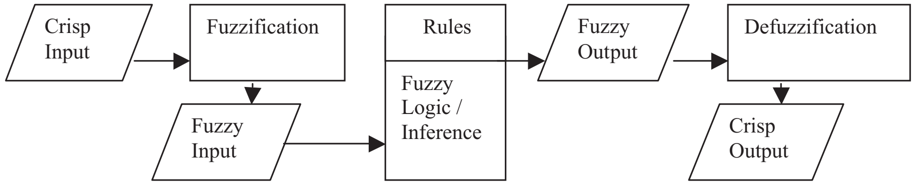

Fig. 1. Fuzzy logic process.

of a product or process and planning for its elimination [3]. It is widely used in manufacturing industries in various phases of the product life cycle and is now increasingly finding use in the service industry.

Traditional FMEA uses a risk priority number (RPN) to evaluate the risk level of a component or process. The RPN is obtained by finding the multiplication of three factors, which are the probability/occurrence of the failure (O), the severity of the failure (S) and the probability of not detecting the failure (D). Representing this mathematically will give:

$$\text{RPN} = O \times S \times D$$

Traditional FMEA uses five scales and scores of 1–10, to measure the probability of occurrence, severity and the probability of not detection.

In traditional FMEA, the RPN ranking system is used to evaluate the risk level of failures, to rank failures, and to prioritize actions. This approach is simple but it suffers from several weaknesses. The traditional FMEA has been criticized to have a number of drawbacks such as follows:

(1) The assumption that the RPN elements are equally weighted leads to over simplification [4]. It neglects the relative importance among O, S and D. The three factors are assumed to have the same importance. This may not be the case when considering a practical application of the FMEA process [5].
(2) The RPN elements have many duplicate numbers [4]. The method that the traditional FMEA employs to achieve a risk ranking is critically debated. The purpose of ranking risk in order of importance is to assign the limited resources to the most serious risk items. Various sets of O, S and D may produce an identical value of RPN; however, the risk implication may be totally different. For example, consider two different events having values of 3, 5, 2 and 2, 3, 5 for O, S and D, respectively. Both these events will have a total RPN of 12 ($\text{RPN}_1 = 3 \times 5 \times 2 = 30$ and $\text{RPN}_2 = 2 \times 3 \times 5 = 30$), however, the risk implications of these two events may not necessarily be the same. This could entail a waste of resources and time or in some cases a high-risk event going unnoticed [5].
(3) The RPN scale itself has some non-intuitive statistical properties. It is derived from only three factors mainly in terms of safety; and the conventional RPN method has not considered indirect relations between components [4].

When conducting an FMEA for safety assessment purposes, precision should not be forced where data is unreliable and scarce [5]. Hence, to ask an analyst or an expert to assign scores ranging from 1 to 10 (as done in the RPN method) for the different factors considered would produce a false and unrealistic impression. Though this simplifies the computation, converting the probability into another scoring system, and then finding the multiplication of factor scores are believed to cause problems. The relations between the probabilities and the factors are different (linear or nonlinear).

In an attempt to overcome the aforementioned weaknesses associated with the traditional RPN ranking system, we use fuzzy approach in this paper for RPN determination as was given in the following section.

3. Fuzzy approach to FMEA

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. The fuzzy logic variables may have a membership value of not only 0 or 1, but a value inclusively between 0 and 1. In fuzzy logic the degree of truth of a statement can range between 0 and 1 and is not constrained to the two truth values {true (1), false (0)} as in classic propositional logic [6]. Thus, the fuzzy logic provides a basis for approximate reasoning, that is, a mode of reasoning which is not exact or very inexact. It offers a more realistic framework for human reasoning than the traditional two-valued logic.

The term “fuzzy logic” emerged as a consequence of the development of the theory of fuzzy sets by Lotfi Zadeh. In 1965, Zadeh proposed fuzzy set theory [7], and later established fuzzy logic based on fuzzy sets. The process of fuzzy logic is given in Fig. 1.

Fuzzy logic has an algorithm that is described in the following steps [8]:

1. Define the linguistic variables and terms (initialization).
2. Construct the membership functions (initialization).
3. Construct the rule base (initialization).
4. Convert crisp input data to fuzzy values using the membership functions (fuzzification).
5. Evaluate the rules in the rule base (inference).
6. Combine the results of each rule (inference).
7. Convert the output data to non-fuzzy values (defuzzification).

Linguistic variables are the input or output variables of the system whose values are words or sentences from a natural language, instead of numerical values. A linguistic variable is generally decomposed into a set of linguistic terms.

Membership functions are used in the fuzzification and defuzzification steps of a fuzzy logic system (FLS), to map the non-fuzzy input values to fuzzy linguistic terms and vice versa. A membership function is used to quantify a linguistic term. There are different forms of membership functions such as triangular, trapezoidal, piecewise linear, Gaussian, or singleton.

Fuzzy logic concept can be expressed mathematically as follows. Let X be a nonempty set. A fuzzy set A in X is characterized by its membership function $\mu_A : X \to [0, 1]$ and $\mu_A(x)$ is interpreted as the degree of membership of element x in fuzzy set A for each $x \in X$. It is clear that A is completely determined by the set of tuples $A = ((u, \mu_A(u))/u \in X)$. Frequently $A(x)$ is used instead of $\mu_A(x)$. The family of all fuzzy sets in X is denoted by $\mathcal{F}(X)$.

If $X = (x_1, \ldots\ldots, x_n)$ is a finite set and A is a fuzzy set in X then the following notation is often used.

$$A = \frac{\mu_1}{x_1} + \ldots\ldots + \frac{\mu_n}{x_n}. \tag{1}$$

where the term μ_i/x_i, $i = 1, \ldots, n$ signifies that μ_i is the grade of membership of x_i in A and the plus sign represents the union.

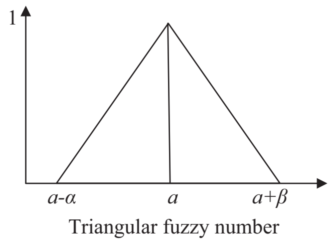

Fig. 2. Triangular fuzzy membership function.

From among various membership functions the triangular one is to be exemplified below.

A fuzzy set A is called triangular fuzzy number with peak (or center) a, left width $\alpha > 0$ and right width $\beta > 0$ if its membership function has the following:

$$A(t) = \begin{cases} 1 - (a - t)/\alpha & \text{if } a - \alpha \le t \le a \\ 1 - (t - a)/\beta & \text{if } a \le t \le a + \beta \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

and we use the notation $A = (a, \alpha, \beta)$. A triangular fuzzy membership function is depicted in Fig. 2.

A triangular fuzzy number with center a may be seen as a fuzzy quantity "x is approximately equal to a."

In a FLS, a rule base is constructed to control the output variable. A fuzzy rule is a simple IF–THEN rule with a condition and a conclusion. After evaluating the result of each rule, these results should be combined to obtain a final result. This process is called (fuzzy) inference. The results of individual rules can be combined in different ways (maximum, bounded sum, normalized sum). Depending on the form of the consequent, two main types of rule-based fuzzy models are distinguished [9]:

1. *Mamdani linguistic fuzzy model*: Both the antecedent and the consequent are fuzzy propositions.
2. *Takagi–Sugeno fuzzy model*: The antecedent is a fuzzy proposition; the consequent is a crisp function.

The most commonly used fuzzy inference technique is the so-called Mamdani method [10].

After the inference step, the overall result is a fuzzy value. This result should be defuzzified to obtain a final crisp output. This is the purpose of the defuzzifier component of a FLS. Defuzzification is performed according to the membership function of the output variable. There are different algorithms for defuzzification as well. These are Center of Gravity, Center of Gravity for Singletons, Center of Area, Left Most Maximum, and Right Most Maximum (see [11,12]). Among these algorithms the most popular one is the center of gravity (centroid) technique. It finds the point where a vertical line would slice the aggregate set into two equal masses. Mathematically this center of gravity (COG) can be expressed as:

$$\text{COG} = \frac{\int_a^b \mu_A(X) x dx}{\int_a^b \mu_A(X) x dx} \quad (3)$$

Centroid defuzzification method finds a point representing the center of gravity of the fuzzy set, A, on the interval, ab.

Fuzzy logic has been applied to diverse fields, from control theory to artificial intelligence. Without going further on fuzzy logic method at this stage, the reader is supposed to have a basic understanding thereon. For further reading see Klir and Yuan [13], and Zimmermann [12].

In the proposed approach, a fuzzy rule base is used to rank the potential causes identified within the FMEA, which would have identical RPN values but different risk implications. The approach then extends the analysis to include weighting factors for O, S and D using defuzzified linguistic terms.

The advantages of the proposed fuzzy rule base approach for application to FMEA can be summarized as follows:

- It provides an organized method to combine expert knowledge and experience for use in an FMEA study. This approach assumes that the relationship between the RPN score and the severity, occurrence, and not detection scores to be non-linear, instead of linear as in the conventional RPN model.
- The use of linguistic terms in the fuzzy approach allows for the experts to assign a more meaningful value for the factors considered, and hence improve the applicability of the FMEA. This ensures that identified events do not get overlooked (due to a low RPN) when considering the priority for attention.
- The flexibility of assigning weight to each factor in the FMEA provides a means of specifically identifying weak areas in the system/component studied [5].
- It considers the combination of the input factors (severity, occurrence, and not detection) in modeling. For example, a failure will only have a high RPN score if a certain combination of severity, occurrence, and not detection scores is fulfilled, which is described in the form of fuzzy IF–THEN rules. This can be a solution to situations whereby the RPN score does not reflect the true risk of failures.
- Fuzzy inference techniques can incorporate human/expert knowledge, whereby information is described by vague and imprecise statements during the modeling process. The behavior of fuzzy inference techniques is expressed with a language that is easily interpretable by humans. This leads to customization of the RPN model by FMEA users in an easy and straightforward manner [14].

FMEA is a widely used risk assessment tool to identify the potential failure modes of a product or a process. By ranking the priorities for corrective action according to the respective effects of the failures, the chance of the failures can be reduced or eliminated. However, there could be several difficulties during conducting conventional FMEA such as the subjective and qualitative description in natural language, the relative importance among the risk ratings, the difference of risk representation among the same ratings; and the knowledge shared among FMEA team members. Thus, a new risk assessment system based on fuzzy theory is proposed in this paper to deal with these difficulties. Furthermore, an FMEA is conducted for purchasing process of a public hospital to demonstrate the proposed fuzzy assessment of FMEA.

4. Literature review

A number of investigations have been conducted to enhance the FMEA methodology using artificial intelligence techniques. Recently, many studies have been published in technical fields where FMEA was used together with fuzzy sets. For example, Xu et al. [15] implemented a fuzzy logic-based FMEA in diesel engine systems. Guimaraes and Lapa [16] applied fuzzy FMEA to PWR chemical and volume control system. The authors also applied a pure fuzzy logic system to FMEA of an auxiliary feedwater system in a nuclear power plant for risk ranking enhancement purpose (Guimaraes and Lapa [17]. Besides, Guimaraes and Lapa [18] used the fuzzy inference system in the production of nuclear energy as an alternative approach to risk analysis. To demonstrate their proposed fuzzy assessment of FMEA Yeh and Hsieh [19] conducted an FMEA for a sewage plant.

Some researchers have engaged with improving the FMEA methodology. Wang et al. [20] made risk evaluation in FMEA using

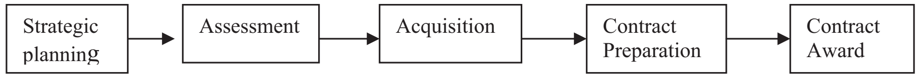

Fig. 3. Operational stages of hospital purchasing process.

fuzzy weighted geometric mean. To overcome the limitations of traditional FMEA Sharma et al. [21] developed a fuzzy logic-based decision support system. Tay and Lin [22] proposed a generic method to simplify the fuzzy logic-based FMEA methodology by reducing the number of rules that needs to be provided by FMEA users for the fuzzy RPN modeling process. They also developed fuzzy RPN models and evaluated their performance in a semiconductor manufacturing plant [23]. Application of the fuzzy cognitive map to FMEA was explored by Peláez and Bowles [24]. Fuzzy reasoning and gray relation with FMEA for marine industry was proposed to overcome the traditional FMEA weaknesses in failures risk evaluation [5]. Braglia et al. [25] used a fuzzy TOPSIS in FMEA. More recently, an alternative evaluation method for FMEA, which was based on the Fuzzy ART algorithm, was reported in [26].

Though FMEA has a wide range of application areas, its number of applications in process design/improvement is limited. Regarding the fuzzy logic applications in process design/improvement, some exemplary studies can be given here. Chin et al. [27] developed a fuzzy FMEA-based product design system. By using combined fuzzy FMEA and fuzzy AHP Abdelgawad and Fayek [28] implemented risk management in the construction industry.Tay and Lim [23] tried to enhance the FMEA methodology with fuzzy inference techniques to design new fuzzy RPN models. They evaluated the performance of the fuzzy RPN models by using a real-world case study pertaining to the test handler process in a semiconductor manufacturing plant. Hassan et al. [29] used QFD, FMEA, and ABC methods to improve conceptual process planning.

Most of the improvement studies that have been carried out in hospitals are related with service quality. Almost no improvement has been searched for technical or administrative processes. Rather than FMEA, other techniques have been used in hospitals for various reasons. For example, Hintzen et al. [30] explored the effect of lean process improvement techniques on a university hospital inpatient pharmacy. Nickel and Schmidt [31] presented a case study to support hospital planning for process improvement at a German university hospital with over 30 clinics and institutes. Szabo [32] examined the implementation of continuous process improvement in hospitals across the U.S., and showed that continuous process improvement improved the performance of health personnel. Uçkun and Erken [33] used analytic hierarchy process in medical equipment purchasing decisions in a university hospital, and determined the priorities of the medical equipments to be purchased.

To our knowledge, no research has been conducted for FMEA application in purchasing process improvement in general, and specifically for hospitals. Therefore, this study is the first one on this issue.

5. Purchasing process in hospitals

There is a whole process that hospitals must go through before they purchase one piece of hospital equipment. They do this process for several reasons and it can involve many different departments of the hospital. They have to make sure that every piece of equipment they buy is up to the standards of the technology they are using at the time in order to give the best and most accurate information to their patients that they can. They must also stick within their budget in order to keep the hospital up and running.

The process of purchasing hospital equipment follows five operational stages which are *strategic planning*, *assessment*, *acquisition*, *contract preparation*, and *contract award* (Fig. 3). It starts off with *strategic planning*, and this task is usually taken on by the higher ranking staff of the hospital. At this stage, the hospital management brainstorm in order to identify the types of services that the hospital offers, and the types of equipment they would be able to purchase to complement those services in order to make them better. They need to research on new innovative technology that is available to them to determine if it would be best for the services that they provide. They need to be constantly up-to-date on the new technologies that are out on the market. Second stage of the purchasing process involves the *assessment* phase where they discuss the cost efficiency and benefit that it would give to the hospital as a whole. This would involve more staff including the accountants. The *acquisition* stage is the next phase of the process and involves the creation of the proposals for the medical equipment and the purchasing negotiations with the medical equipment company that they have decided to buy from. The stage of *contract preparation* takes part after the acquisition stage, and finally the *contract award* stage which gives the medical company the green light in order to deliver the purchased equipment to the hospital.

This whole process that the hospital goes through in order to purchase medical equipment is a fairly long process and can take some time. If everything is not thought of properly, they could spend a lot of money on a piece of equipment that is not very useful to the services they give. Technology is the key word in this process along with the patient's welfare being the main concern. The hospital staff needs to make sure that the equipment will not only help to make their services more efficient and up-to-date, but also that the equipment will be cost effective for them and the patient [34].

The purchasing department is responsible for the procurement of all equipments, supplies and services required and authorized for use by the hospital and its owned, managed or affiliated clinics, and care centers. Hospitals apply different procurement methods which are:

(1) Simplified acquisitions, like micro-purchases, small purchases.
(2) Full and open competition, like bids, proposals.
(3) Other than full and open competition, like sole source [35].

5.1. Simplified acquisitions

These procedures are the procurement methods used for acquisitions that do not exceed a specific amount of money given in the state public procurement laws. Simplified acquisitions are equitably distributed among qualified suppliers in the local area, and purchases are not split to avoid the requirements for competition above the respective threshold. Minimal documentation is usually required, including a determination that the price is fair and reasonable; and material on how this determination was derived.

5.2. Full and open competition

For acquisitions exceeding the simplified acquisition threshold, the hospital is required to use a formal solicitation and selection, i.e. competitive procurement process based on competition in place. The competitive procurement methods available for use in fulfilling the requirement for full and open competition in the acquisition process are *sealed bidding* (relying on *bids*, also called *sealed bids*), *negotiated procurement* (relying on *competitive proposals)*; and *two-step sealed bidding* (a combination of *bidding* and *negotiating)*.

5.3. Other than full and open competition

Other non-competitive procurement methods are considered to be exceptions, and thus are used only under certain, well-defined conditions, and they are carefully and thoroughly justified and documented. Contracting without providing for *full and open competition* cannot be justified because of a failure to plan in advance, or concerns about the availability of related funds or budget. Sole source is an example of non-competitive procurement or purchase process accomplished after soliciting and negotiating with only one available and responsible source.

Improper purchasing activities in hospitals can lead to serious consequences which include lack of inventory control, missed contract compliance, excess inventory levels, frequent stock-outs and costly emergency deliveries, workflow interruptions and expensive rework, and increased health system labor requirements. Therefore, design of a right purchasing system and its improvement over time in compliance with changing conditions is very important. The right purchasing process design involves three components; technology, buyer experience, and change management.

6. Application

6.1. The hospital and its purchasing problems

The proposed method was applied in the purchasing department of a public hospital located in Istanbul. The purpose of the study was to improve the hospital's purchasing process by examining the process itself and by determining the measures which reduce the procurement (lead) times and costs and eliminate the burden of unnecessary work. As it provides the necessary inputs for other processes, the improvement of the purchasing process would bring a positive impact on all the following processes, including the delivery of health service. For this reason, the FMEA method was applied in the hospital and it was based on fuzzy logic approach due to the lack of sufficient numerical data and expert opinion in determining some of the important criteria.

The hospital goes through the purchasing process explained in Section 5, and uses all three types of procurement methods (simplified acquisitions, full and open competition, and other than full and open competition). Simplified acquisitions are used for the amounts of acquisitions that do not exceed TL 5000 ($ 3000) (Public Procurement Law 4734/22). Sealed bidding, negotiated procurement, and two-step sealed bidding are used in full and open competition method for the amounts of acquisitions exceeding the simplified acquisition threshold. Other than full and open competition procurement methods are considered to be exceptions, and used only under certain, well-defined conditions, and they are carefully and thoroughly justified and documented.

Public procurement is regulated by the Public Procurement Law No. 4734, and different regulations are prepared for the procurement of goods, services, construction affairs and consulting services dealt with in this context. In the mentioned procurement law, along with the bidding (tendering) issues, issues related with direct and exceptional purchases are included as well. Purchases from the State Material Office are evaluated within the scope of the exception (Article 3). Compared to bidding (tendering) methods, direct supply is a more flexible and fast method for retrieval (purchasing) which can be used in the cases referred to in the Public Procurement Law, Article 22. In this kind of purchases, giving advertisements, preparation of tender documents, forming the tender commission and the contract are not necessary. The law provided permits the direct method of procurement (need to be met from a single person) in the cases about the need for a statutory right to have a single contractor, the amount of purchases to remain below the limit specified in the law, in case of an emergency supply of the product, and the need not to be stored.

The vast majority of materials purchased are medical supplies. More than half of the buying team is tasked to supply such materials. Therefore, the application was carried out on the purchase of this kind of material; other material purchases were assumed to be made in the same manner. The hospital staff who works in the purchasing department supported the study, and the service units using the material and the quality personnel were consulted in case of need. The methods of tender and direct procurement of medical equipment purchasing process of the hospital are shown in Fig. 4.

The purchasing process of the hospital was not properly operating. Most of the times failures were happening at different levels and magnitudes within the process and these failures were apparently leading to negative outcomes for the hospital. Detection and evaluation of these failures are to be searched in the next section.

6.2. Detection and evaluation of the failure modes

Examining the medical supplies' purchasing process, the modes of failures that may occur, their effects and the causes were identified by brainstorming technique, and the findings are given in Table 1.

When determining the failure types, the 6th and the 13th steps in the purchasing process were assessed together as they are similar. The types of failures were not defined in the steps 9 and 10, since they involve the process rather for contractors.

Among failure effects, prolongation of the procurement time and revocation of the contract are the most frequently emerging ones. Prolongation of the procurement time will also increase the total duration of purchasing. The effect of cancelation of the process will, at the same time, cause the time for contracting to increase. The impact of these failures depends on the level of inventory of the materials to be purchased and the ability of the administration to generate different alternatives. The matter of "how much the process will prolong" is to be discussed later when defining the failure effects and their associated scores. It is evident that the amount of prolongation will directly affect the score. Similarly, the time to be lost will be varying in cases of cancelation of the contract depending on its being at the first or last steps of the purchasing process, and so, the scores will also vary.

There is no direct regular control of failures over the process. The control is maintained by the person doing the job or by the person's supervisor. Since the control is exerted at every stage of the process, and as irregular, a separate control point was not defined in the manifest for each type of failure. However, the supervisor's approval, and at the same time, the contractors to see the tender documentation and notifying the tender results to all the contractors concerned can be assumed a kind of control point for the previous operational stages of the process

Here exists a need to eliminate the failures as many as possible, and by doing so to improve the purchasing process of the hospital. By process improvement the following objectives could be achieved:

- To reduce cost of products purchased.
- To reduce purchasing process costs.
- To improve service to customers/patients.
- To reduce inventory investment.

By conducting the FMEA on these process failures the aforementioned objectives were attained in the following parts. First, classical reasoning was used during the analysis, then, fuzzy

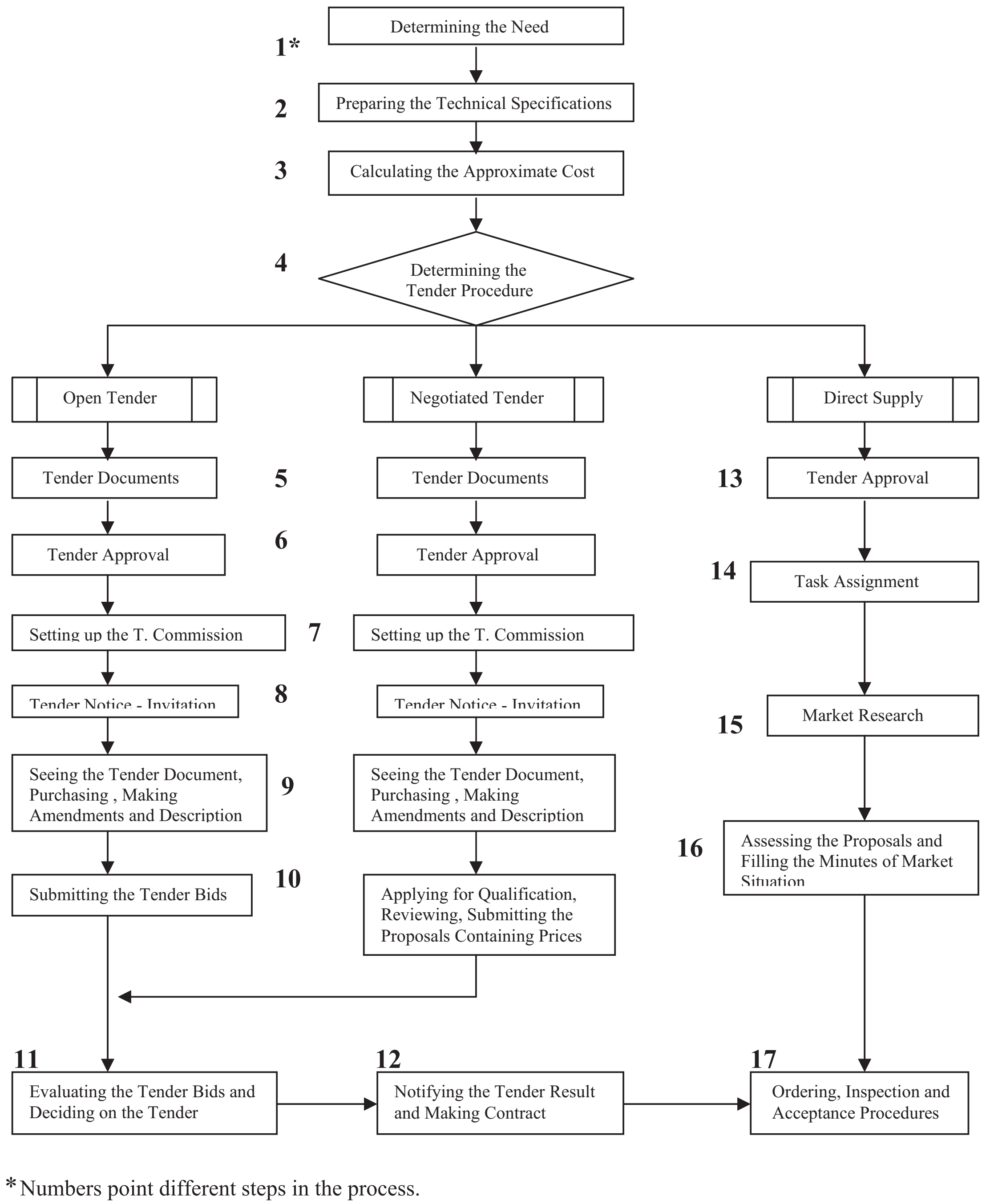

Fig. 4. Purchasing process of medical equipments.

approach was applied to the same set of failures, and their results were compared with those of the classical reasoning.

6.3. *Analyzing the failure modes by classical FMEA and fuzzy FMEA and finding the respective RPN numbers*

6.3.1. *Classical FMEA application*

Using classical understanding the FMEA analysis was carried out on the purchasing process of the hospital and the associated RPN numbers were calculated. Results are given in Table 2.

The evaluation of the failure modes is carried out by scoring the respective risk factors of occurrence, severity, and not detection. For this purpose, usually 10-level scales are being used. While scoring the risk factors a variety of statistical techniques or expert opinion is referred to. In this study, all the risk factors were based on expert opinion because there was not enough data on risk factors, and some of the factors were uncertain.

For the reasons expressed earlier, different values were given to the effect of “cancelation of the contract” defined with the same failure effect when determining the severity of failures. This situation is not contradictory to the principle of “the failure modes having the same effect get the same severity value”. Because if the tender is revoked at the last stages, the time and work force to be lost will be more with respect to the first stages. In the same way, a number of failures were defined as “procurement time prolongation”. Here, different scores of severity have been given according

Table 1
Probable failure modes, failure effects and failure causes.

Process no.	Failure no.	Failure mode	Failure effect	Failure cause
1	1	Need to be determined later	Procurement period gets longer	Some materials are forget during transactions
	2	Missing to be identified	Proc. period gets longer	The annual consumption guess cannot be done
	3	Purchase request form filled out incorrectly	Proc. period gets longer	Poor performance of personnel
	4	Request form and tech. spec to be delivered late	Proc. period gets longer	Waiting for technical specification
2	5	False identification of need	Small allergy, etc. over patient	Not having enough knowledge about the production
	6	Prohibitive substances for competition and violation of regulations	Cost rise or time extension	Technical properties of the products on the market are not known
3	7	Wrong about the preparation of approximate cost	Cost rise or time extension	Technical specifications not to be sent to the firms
	8	Taking long time	Proc. period gets longer	Firms respond late or give no response
4	9	Incorrect determination of the tender procedure	Administrative penalty/rarely proc. time extension	Incorrect calculation of the approximate cost or the properties of the product are not known
5	10	Introduction of administrative provisions are missing or wrong	Contract may be canceled or may experience problems during the execution of the work	Lack of knowledge and experience of staff
	11	Prohibitive definitions for competition and violation of regulations	Contract may be canceled and the cost rises	Lack of knowledge and experience of staff
6,13	12	Approval to work without compensation	Administrative penalty/contract cancelation	The status of allowance not checked prior to appropriation
7	13	Late establishment	Contract to be canceled	Lack of knowledge or negligence of staff
	14	Missing number	Contract to be canceled	Lack of knowledge or abstraction of staff
8	15	Missing information	Contract to be canceled	Lack of knowledge, experience, and abstraction of staff
	16	Conflicting statements about tender document	Contract to be canceled	Lack of knowledge, experience, and abstraction of staff
	17	Time is short	Contract to be canceled	Lack of knowledge, experience, and abstraction of staff
11	18	Incorrect assessment	Contract to be canceled or corrective action	Sample examination according to specific criteria
	19	To be decided later	Proc. period gets longer	Long duration of the sample and document control
12	20	Underreporting	Proc. period gets longer	Lack of knowledge or abstraction of staff
	21	Late notification	Proc. period gets longer	Lack of knowledge or abstraction of staff
14	22	No assignment of expert	Proc. period gets longer/Treatment to be prolonged, etc.	Since materials to be purchased are standard, no need the idea of assigning specialist
15	23	Not made adequate research	Cost rise	Materials not to reach a sufficient number of related firms or the period of time to be short
16	24	Taking long time	Proc. period gets longer	Elongation phase of the sample examination
17	25	Not reach the order to the contractor	Proc. period gets longer	Contractor's fax ready to be busy or faulty
	26	Late orders	Proc. period gets longer	Failure to properly inventory control
	27	Acceptance of nonconforming product	Treatment to be prolonged allergic effect and so on, minor problems	Commission members not to allocate sufficient time due to their high workload
	28	Late meeting of Medical Commission	Proc. period gets longer	Official duties of members not to be treatment and the intensity of these duties

As the steps 6 and 13 are very similar, they were evaluated together. The steps 9 and 10 were not taken into account to identify the failure due to the process of interest rather than bidders.

to how much would prolong the process. When defining the failure modes the terms such as "much or less prolongation of the process" have not been used. Because those terms are in the opinion of experts and that will need again expert opinion to export them to 10-level scales, which will raise the share of mistake.

Because of not having enough data and some of the factors being vague, expert opinion (fuzzy logic) was used here. For example, when determining the failure effects in the process, it cannot be stated clearly how many days a failure will prolong the process. However, the available variables like "prolongs less" or "prolongs much" can be used. At these kind of ambiguous situations, and to remove the subjectivity in the expert opinion, the fuzzy logic approach is to provide great benefits.

6.3.2. Fuzzy FMEA application

The fuzzy logic toolbox of Matlab software program has been used in calculating the values of RPN. A model was established for the FMEA technique having 3 inputs and 1 output variable, and given in Fig. 5. The RPN values were calculated by combining the associated 3 input factors. For the input variables of occurrence, severity and not detection a 5-level; and for the output variable RPN a 10-level triangular membership functions were used (Figs. 6 and 7).

As can be seen from the figures, while creating membership functions for input values the 10-level scale is divided into 5 different regions. Being represented by triangular membership functions, these sub-regions respectively are *almost none, low, medium, high and very high.* For the output variable RPN, the

Table 2
RPN numbers with respect to Occurrence, Severity, and not Detection scores by Failure Modes.

Failure No.	Failure Mode	O	S	D	RPN
1	Need to be determined later	6	8	9	432
2	Missing to be identified	5	6	7	210
3	Purchase request form filled out incorrectly	1	3	2	6
4	The request form and technical specification to be delivered late	4	6	3	72
5	False identification of need	4	6	6	144
6	Prohibitive substances for competition and violation of regulations	3	6	5	90
7	Wrong about the preparation of approximate cost	2	6	6	72
8	Taking long time (prolonged)	6	6	4	144
9	Incorrect determination of the tender procedure	1	4	7	28
10	Introduction of administrative provisions are missing or wrong	1	6	5	30
11	Prohibitive definitions for competition and violation of regulations	1	6	5	30
12	Approval to work without compensation	1	7	3	21
13	Late establishment	1	6	1	6
14	Missing number	1	6	1	6
15	Missing information	1	8	2	16
16	Conflicting statements about tender document	1	8	2	16
17	Time is short	1	8	2	16
18	Incorrect assessment	3	9	2	54
19	To be decided later	8	8	3	192
20	Underreporting	1	6	2	12
21	Late notification	1	6	1	6
22	No assignment of expert	1	7	2	14
23	Not made adequate research	3	3	3	27
24	Taking long time	5	7	4	140
25	Not reach the order to the contractor	2	6	4	48
26	Late orders	1	6	6	30
27	Acceptance of nonconforming product	1	5	6	30
28	Late meeting of Medical Commission	4	5	2	40

10-level scale (the decimal scale) is divided into 10 different parts. These are, respectively, *none, very-low, low, high-low, low-medium, medium, high-medium, low-high, high and very high.*

The occurrence, severity and not detection values of the failures were identified with the help of expert opinions and by using a database of 125 decision rules (see Appendix A) determined specifically. The rules were designed to take into account all possible situations. Here are given some of the rules as an example.

IF occurrence IS almost none AND severity IS almost none AND not detection IS almost none (found) then RPN IS none (no risk), IF occurrence IS almost none AND severity IS medium AND not detection IS very high then RPN IS high low.

IF occurrence IS very high AND severity IS medium AND not detection IS very high then RPN IS high medium, IF occurrence IS very high AND severity IS very high AND IF not detection IS almost none then RPN IS high medium.

Mamdani min/max method of inference mechanism (input method: min; aggregate method: max) was used and the results were defuzzified by center of gravity method.

As to the types of failure, the fuzzy RPN values provided in the model are given in a descending order in Table 3 in comparison with the RPN values of classical FMEA. The failure types containing the same RPN values were arranged according to the values of occurrence, severity and not detection (priority queues). The average number of RPN was found to be 3.98 (high low–low medium).

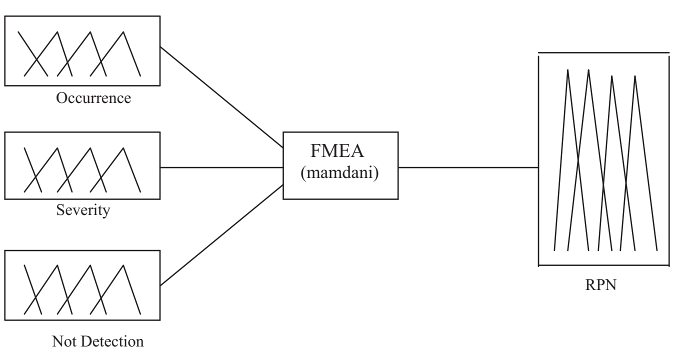

Fig. 5. The Fuzzy FMEA model.

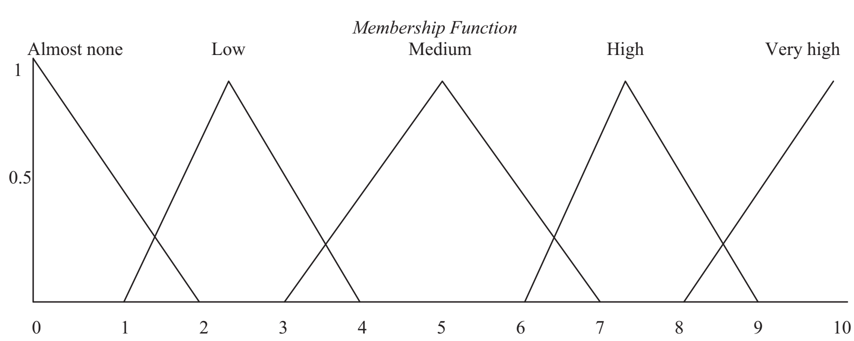

Fig. 6. Input variables' membership function.

Table 3
Prioritization of failure modes.

Failure no.	Failure mode	RPN	Prioritization	Fuzzy RPN	Prioritization
1	Need to be determined later	432	1	7.69	1
2	Missing to be identified	210	2	7.69	2
5	False identification of need	144	4	6.50	3
8	Taking long time (prolonged)	144	5	6.50	4
19	To be decided later	192	3	5.49	5
7	Wrong about the preparation of approximate cost	72	8	5.49	6
6	Prohibitive substances for competition and violation of regulations	90	7	5.49	7
25	Not reach the order to the contractor	48	11	5.49	8
4	The request form and technical specification to be delivered late	72	9	5.49	9
18	Incorrect assessment	54	10	4.50	10
24	Taking long time	140	6	4.50	11
28	Late meeting of Medical Commission	40	12	4.50	12
15	Missing information	16	20	3.39	13
16	Conflicting statements about tender document	16	21	3,39	14
17	Time is short	16	22	3.39	15
12	Approval to work without compensation	21	19	3.39	16
22	No assignment of expert	14	23	3.39	17
9	Incorrect determination of the tender procedure	28	17	3.39	18
10	Introduction of administrative provisions are missing or wrong	30	13	2.50	19
11	Prohibitive definitions for competition and violation of regulations	30	14	2.50	20
26	Late orders	30	15	2.50	21
20	Underreporting	12	24	2.50	22
27	Acceptance of nonconforming product	30	16	2.50	23
23	Not made adequate research	27	18	2.50	24
3	Purchase request form filled out incorrectly	6	28	2.50	25
13	Late establishment	6	25	1.46	26
14	Missing number	6	26	1.46	27
21	Late notification	6	27	1.46	28

6.4. *Evaluation of results and suggestions for improvement*

It was decided to take preventive measures absolutely for the failure types having risk levels low-medium or higher (i.e., the fuzzy RPN number 3.5 or over). However, for the failure types having RPN values below this level, some simple corrective actions were determined. In this sense, for 8 of the 28 failures identified no improvement was suggested, but for the remaining 20 failures improvement suggestions were made. Recommendations have been set in related fields; particularly the creation of data bank for medical supplies, personnel, operations, communications and documentation. Some of the recommendations were implemented during the project while an implementation plan was prepared for the rest of the suggestions. Those failure types to be decided to take preventive measures and the types of measures taken are given in Table 4.

For the failure types with numbers 15, 16, 17, 20 and 21 staff training was envisaged. These types of failures had low RPN values as their occurrence values were high whereas not detection values were low. Having been subjected to training formerly, the team that work in purchasing operations had also a positive impact on the existence of low RPN levels. The lack of information that may cause to formation of these failures could be removed in a total of 2–3 min of training. When the aforementioned types of failures (in question) were detected during the application, the team was warned about the rules.

The amount of materials to be used in the next period is currently estimated according to the data of the previous period. However, these estimates are not healthy due to the reasons such as changes in the number of physicians in certain branches, entry of the hospital in the same district to the earthquake renovation etc. If estimates were done in conjunction with the other departments' personnel, then more reliable results could be obtained. Department managers were aware of the changes that may happen at least in the short term.

In order to be able to remove most of the failures creation of a data bank addressing to the medical supplies were proposed. The proposed data bank would consist of 2 parts. The first part would be devoted to the preparation of the product lists used in the hospital. It was planned to specify in these lists, which is called medical equipment catalog, the stock codes of the materials, their full names and branch codes in National Data Bank system. These lists could be prepared within 15 days. But in addition to this list, establishment of the second part of the data bank, which would include the technical specifications of each product, could be completed within 1 month at the earliest. While establishing the 2nd part which is called technical specifications file, the technical specifications used in other hospitals and the technical specifications still used in this

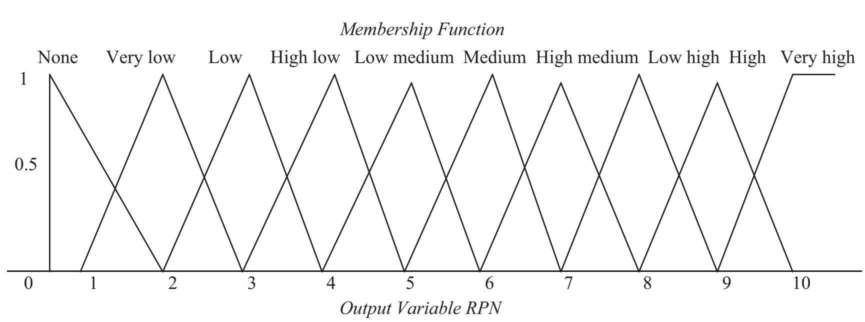

Fig. 7. Output variable membership function.

Table 4
Corrective actions recommended.

F. no.	Failure mode	Failure cause	Fuzzy RPN	Corrective action	Due date
1	Need to be determined later	Some materials are forget during transactions	7.69	The creation of data bank for medical supplies	01.06.2010
2	Missing to be identified	The annual consumption	7.69	Considering the historical data evaluation of the needs by service and warehouse	01.05.2010
5	False identification of need	Not having enough knowledge about the production	6.50	The creation of data bank for medical supplies	01.06.2010
8	Taking long time	Firms respond late or give no response	6.50	The publication of technical specifications on the web site of the hospital or on the free auction sites and the use of previous purchases	01.06.2010
19	To be decided later	Long duration of the sample and document control	5.49	Request samples from bidders before the tender date	Since the first purchase
7	Wrong about the preparation of approximate cost	Technical specifications not to be sent to the firms	5.49	The publication of technical specifications on the web site of the hospital or on the free auction sites and the use of previous purchases	
6	Prohibitive substances for competition and violation of regulations	Technical properties of the products on the market are not known	5.49	The creation of data bank for medical supplies	01.06.2010
25	Not reach the order to the contractor	Contractor's fax ready to be contractor	5.49	Be confirmed by telephone	Started to be implemented
4	Request form and tech. Specifications to be delivered late	Waiting for technical specification	5.49	The creation of data bank for medical supplies	01.06.2010
18	Incorrect assessment	Sample examination according to specific criteria	4.50	Deficiency to be confirmed by information given to the bidder with inappropriate sample	Since the first purchase
24	Taking long time	Elongation phase of the sample examination	4.50	Not to request to sample the products previously used	Started to be implemented
28	Late meeting of Medical Commission	Official duties of members not to be treatment and the intensity of these duties	4.50	The appointment of business density less persons in commission	Started to be implemented
15	Missing information	Lack of knowledge, experience and abstraction of staff	3.39	Training of personnel	Completed
16	Conflicting statements about tender document	Lack of knowledge, experience, and abstraction of staff	3.39	Training of personnel	Completed
17	Time is short	Lack of knowledge	3.39	Training of personnel	Completed
12	Approval to work without compensation	The status of allowance not checked prior to appropriation	3.39	Appropriation status to be updated every 3 months in the second half of the year and notification to staff	01.03.2010
22	No assignment of expert	Since materials to be purchased are standard, no need the idea of assigning specialist	3.39	The appointment of at least one expert for each material	Started to be implemented
20	Underreporting	Lack of knowledge or abstraction of staff	2.50	Training of personnel	Completed
23	Not made adequate Research	Materials not to reach a sufficient number of related firms or the period of time to be short	2.50	Free use of auction sites	01.06.2010
21	Late notification	Lack of knowledge or abstraction of staff	1.46	Training of personnel	Completed

hospital would be utilized together. There were technical specifications for approximately 75% of the materials used already in the hospital. However, these specifications were being maintained in different departments of the hospital and most of them were not having any electronic record. Collection and transfer of these specifications to electronic media and then the rearrangement of these specifications after comparison with the specifications gathered from other public institutions would require a period of at least 3 months. After this study is finished, the specifications together with the numbers assigned to each of them could be published on the website of the hospital. Hence, the hospital's medical supplies would have been compiled on a regular basis, defined and easily accessible. After the data bank (knowledge base) is created, the service personnel will request the materials from among a list of items, and thus, the probability of some products' being forgotten will be reduced too.

Since the technical specifications in the current system do not exist in electronic format they should be faxed to the bidders. Sometimes the specifications in excess of 20 pages have to be faxed to 10–15 bidders at the same time. This situation time by time led to the specifications not to be faxed and to deal with the unnecessary workload. With the publication of the specifications on the website the need for faxing would be greatly reduced. In addition, by transferring the necessary specifications to the electronic environment, the publication of direct supplies on free internet sites would be facilitated. By these sites a large number of desirous companies could easily be reached as well. Because of the benefits mentioned, the creation of the data bank would facilitate the preparation of the approximate cost and market research, and bring more effective results. Since the technical specifications would be continuously open to bidders, possible nonconformities that will take place in these specifications could be removed over time through the feedback taken from the potential bidders.

Purchasing data/file is kept in current system in the department concerned. Beginning the regular recording of these data about 3 years ago made the data become newly available for use. With this data, the cost of some products can be estimated without market research. However, there are some problems with these records. Though products are registered by name, unfortunately the data/information is not used efficiently due to registration of the same material with different names or false recording of the name of the material. This data will be more useful when purchase information is recorded with stock codes.

The main reason for the time interval in the process of bids evaluation is the long time consuming process of trial sampling. In the current system purchase is made via tender. First, arrivals in the tender documents are checked, then, the appropriate firms/bidders are requested to give samples. This application increases competition but also prolongs the time of procurement. Instead, for the products with low prices it is proposed to receive the samples on tender day and the stages of document review and execution of the evaluation phase to be realized simultaneously. However, when sufficient time exists and in the absence of undesirable prolongation of the bidding process, it is more appropriate to continue the current practice. Another method to decrease the assessment phase of the sample is not to request sample from the brands that have been purchased but never caused any problem. In such cases, the opinion of the experts and end users must be taken into account.

7. Conclusion

Traditional FMEA determines the RPN by finding the multiplication of factor scores that are converted from the probability or degree of problem occurrence without considering the relative importance of factors. This study applied fuzzy theory to eliminate the conversion debate by directly evaluating the linguistic assessment of factors to obtain RPN by assigning relative weighting coefficient.

Fuzzy FMEA was applied first time to improve purchasing process in a public hospital. After the implementation of fuzzy FMEA method to the purchasing process for medical supplies in a public hospital, several corrective actions were recommended. For 20 of the 28 failures observed improvement suggestions were made while for the remaining 8 failures no improvement was suggested. Some of these recommendations which were related particularly with the creation of medical supplies data bank, other fields of personnel, operations, communications, and documentation were realized during the project activity period. For the remaining failures an implementation plan was made to be activated in the future. Since the plan required a long time (about 6 months) the project could not be completed within the period of study. Therefore, at this stage, the average improvement in the RPN could not be clearly identified. However, with the implementation of all measures, it is expected to have a decline about 20% in procurement time, and 15% in time spent by the workforce. Besides, competition will increase among suppliers and the purchases will be made more transparent. Results indicate that the application of fuzzy FMEA method can solve the problems that have arisen from conventional FMEA, and can efficiently discover the potential failure modes and effects. It can also provide the stability of product and process assurance.

This study is the first authentic example of how fuzzy FMEA approach might be helpful to the management processes. Similarly, in all other management processes in manufacturing and service sectors it is quite possible to use this technique successfully.

Appendix A. Rule base for fuzzy output.

No	Occurrence	Severity	Not detection	Fuzzy output
1	Almost none	Almost none	Almost none	None
2	Almost none	Almost none	Low	None
3	Almost none	Almost none	Medium	Very low
4	Almost none	Almost none	High	Low
5	Almost none	Almost none	Very high	Low
6	Almost none	Low	Almost none	Very low
7	Almost none	Low	Low	Low
8	Almost none	Low	Medium	Low
9	Almost none	Low	High	High low
10	Almost none	Low	Very high	Low medium
11	Almost none	Medium	Almost none	Very low
12	Almost none	Medium	Low	Low
13	Almost none	Medium	Medium	Low
14	Almost none	Medium	High	High low
15	Almost none	Medium	Very high	High low
16	Almost none	High	Almost none	Low
17	Almost none	High	Low	High low
18	Almost none	High	Medium	Low medium
19	Almost none	High	High	Medium
20	Almost none	High	Very high	High medium
21	Almost none	Very high	Almost none	High low
22	Almost none	Very high	Low	Low medium
23	Almost none	Very high	Medium	Medium
24	Almost none	Very high	High	High medium
25	Almost none	Very high	Very high	High
26	Low	Almost none	Almost none	None
27	Low	Almost none	Low	None
28	Low	Almost none	Medium	Very low
29	Low	Almost none	High	Low
30	Low	Almost none	Very high	Low
31	Low	Low	Almost none	Very low
32	Low	Low	Low	Low
33	Low	Low	Medium	High low
34	Low	Low	High	Low medium
35	Low	Low	Very high	Medium
36	Low	Medium	Almost none	High low

No	Occurrence	Severity	Not detection	Fuzzy output
37	Low	Medium	Low	Low medium
38	Low	Medium	Medium	Medium
39	Low	Medium	High	High medium
40	Low	Medium	Very high	Low high
41	Low	High	Almost none	Low medium
42	Low	High	Low	Medium
43	Low	High	Medium	High medium
44	Low	High	High	Low high
45	Low	High	Very high	High
46	Low	Very high	Almost none	Low medium
47	Low	Very high	Low	Low medium
48	Low	Very high	Medium	Medium
49	Low	Very high	High	High
50	Low	Very high	Very high	High
51	Medium	Almost none	Almost none	Very low
52	Medium	Almost none	Low	Very low
53	Medium	Almost none	Medium	Low
54	Medium	Almost none	High	High low
55	Medium	Almost none	Very high	Low medium
56	Medium	Low	Almost none	Low
57	Medium	Low	Low	High low
58	Medium	Low	Medium	Low medium
59	Medium	Low	High	Medium
60	Medium	Low	Very high	High medium
61	Medium	Medium	Almost none	Low medium
62	Medium	Medium	Low	Medium
63	Medium	Medium	Medium	High medium
64	Medium	Medium	High	Low high
65	Medium	Medium	Very high	High
66	Medium	High	Almost none	Low
67	Medium	High	Low	High low
68	Medium	High	Medium	Low medium
69	Medium	High	High	High medium
70	Medium	High	Very high	Low high
71	Medium	Very high	Almost none	Low high
72	Medium	Very high	Low	Medium
73	Medium	Very high	Medium	High medium
74	Medium	Very high	High	Low high
75	Medium	Very high	Very high	High
76	High	Almost none	Almost none	None
77	High	Almost none	Low	Very low
78	High	Almost none	Medium	Low
79	High	Almost none	High	Low
80	High	Almost none	Very high	High low
81	High	Low	Almost none	Very low
82	High	Low	Low	Low
83	High	Low	Medium	High low
84	High	Low	High	Low medium
85	High	Low	Very high	Medium
86	High	Medium	Almost none	Low
87	High	Medium	Low	High low
88	High	Medium	Medium	Low medium
89	High	Medium	High	Medium
90	High	Medium	Very high	High medium
91	High	High	Almost none	Low medium
92	High	High	Low	Medium
93	High	High	Medium	High medium
94	High	High	High	Low high
95	High	High	Very high	High
96	High	Very high	Almost none	Medium
97	High	Very high	Low	High medium
98	High	Very high	Medium	Low high
99	High	Very high	High	High
100	Very high	Very high	Very high	Very high
101	Very high	Almost none	Almost none	Very low
102	Very high	Almost none	Low	Very low
103	Very high	Almost none	Medium	Low
104	Very high	Almost none	High	Low
105	Very high	Almost none	Very high	High low
106	Very high	Low	Almost none	Low
107	Very high	Low	Low	High low
108	Very high	Low	Medium	High low
109	Very high	Low	High	Low medium
110	Very high	Low	Very high	Medium
111	Very high	Medium	Almost none	High low
112	Very high	Medium	Low	High low
113	Very high	Medium	Medium	Low medium
114	Very high	Medium	High	Medium
115	Very high	Medium	Very high	High medium
116	Very high	High	Almost none	Low medium
117	Very high	High	Low	Medium
118	Very high	High	Medium	High medium
119	Very high	High	High	Low high
120	Very high	High	Very high	High
121	Very high	Very high	Almost none	High medium
122	Very high	Very high	Low	Low high
123	Very high	Very high	Medium	High
124	Very high	Very high	High	Very high
125	Very high	Very high	Very high	Very high

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