A New approach to identify and analyze multi-leveled risks: Extension of the fuzzy FMEA method

Ahmed Badreddine [a,1], Nahla Ben Amor [a] and Taieb Ben Romdhane [b]
[a] *LARODEC, Institut Superieur de Gestion de Tunis, Le Bardo, Tunisie*
[b] *INSAT, Centre Urbain Nord BP 676 -1080, Tunisie*

Abstract. The evolution of the current industrial context and the increasing of competition pressure led the companies to adopt new concepts of management. In this context, we have recently proposed an integrated management system including Quality, Environment and Safety management systems [1] using the risk management as an integration factor. This paper proposes an implementation of the most important part of the plan phase, consisting in analyzing and selecting the most critical risks regarding all QSE objectives. To this end we propose to adapt the well known risk management approach *Fuzzy Failure Mode and Effects Analysis* (FMEA) in order to define for each risk a multi-leveled *Risk Priority Number* relative to different QSE objectives. Then, to select the most critical risks we propose to use a multicriteria approach which is the Analytic Hierarchical Process (AHP) in order to take into consideration the different values relative to each risk.

Keywords. Integrated QSE management system, Risk management, Fuzzy FMEA, Analytic Hierarchical Process.

Introduction

The risk management is defined as a set of principles and practices whose purpose is to identify, analyze, evaluate and treat each eventual existing risk factor [2]. The risk factors are seen as events hindering an organization to reach their objectives. The risk management in projects is currently one of the main topics of interest for researchers and practitioners working in the area of project management. In fact, it became an important factor to ensure the integration of the three most known management systems namely the Quality Management System (ISO 9001) [3], the Environmental Management System (ISO 14001) [4] and the Occupational Health and Safety Management System standard (OHSAS 18001) [5]. In fact, the same source of hazard can cause several risks relative to the three management systems (QSE). For instance, an explosion in a plant (as the AZF one) causes (i) a security problem since employees can be injured, (ii) an environmental problem since it can blow out the windows of nearby residents and pollute the air, and (iii) a quality problem since it can generate a supply disruption for customers.

[1] LARODEC, Institut Supérieur de Gestion Tunis
41, Avenue de la liberté, 2000 Le Bardo, Tunisie.; E-mail: badreddine.ahmed@hotmail.com.

This means that the risk management can be seen as a common factor that can be used to identify and evaluate different risk sources with a view to achieve different QSE objectives. In this context, we have recently proposed a new process based approach for integrating the Quality, Security and Environment (QSE) management system [1]. Our approach, illustrated by figure 1 covers the whole PDCA (Plan, Do, Check, Act) scheme also known as the Deming circle as detailed below:

Figure 1. Process-based approach for QSE-IMS

- *Plan phase*: this phase is composed of six steps: the first consists in setting up all quality, security and environment objectives issued from the requirements and the expectations of stakeholders (e.g. customers, employees, population, environment, etc.). In the second, we propose to deploy all these objectives on each process using the process cartography in order to identify the operational objectives and their related risks. In the fourth step, each risk has to be analyzed according to each related objective in order to evaluate the most critical of them in the fifth step. In the sixth step we have to define a global management plan QSE to implement selected treatments as preventive and corrective actions, in order to reduce levels of risks already identified and to improve the efficiency of the IMS. To this end, we have to consider the interaction between the different management areas; indeed some decisions can be beneficial for some management areas and harmful for others. Finally, the sixth step is devoted to the definition of an appropriate monitoring plan, in order to ensure the well implementation of the global management plan.

- *Do phase*: this phase has as input the global management plan QSE and the corresponding global monitoring plan generated from the *plan* phase and will implement the selected treatments. Note that we have to define the appropriate Scheduling to optimize the resources in order reach up the objectives more efficiently.
- *Check and Act phase*: once the do phase achieved, this phase will finalize the process of integration by the measure of the effectiveness of different decisions and their readjustments via three steps. In the first one, we have to measure all the indicators already defined in order to evaluate the effectiveness of selected treatments and to estimate the degree of achievement of objectives. For this reason, we have to aggregate the indicators of each objective. In the second step, a readjustment of the management plan will be done in order to satisfy unreached objectives. Although, some objectives may not be reached, that is why we should revise some of the initial assigned objectives in order to make their satisfaction possible, in this context we propose the third step (i.e. revision of objectives) in order to contribute to sustainable development.

This paper proposes an implementation of the most important part of the plan phase, consisting in analyzing and selecting the most critical risks regarding all QSE objectives. In the literature several approaches for risk management have been proposed. They can be divided into two categories:

- *Qualitative risk analysis*: The qualitative risk analysis aims to identify, analyze and treat each identified risk. Several methods have been proposed in this direction. Within the most important ones we can mention preliminary risk analysis (PRA) [6], the hazard and operability study (HAZOP) [7], and the failure mode and effects analysis (FMEA)[8]. The common factor between these methods is that they use a set of guide words (i.e. low, moderate, high etc.) to evaluate the level of risk. Except the FMEA, remaining method can not be used in any context. In fact, the PRA is mainly used as a prior conceptual phase, and the HAZOP is especially performed in the chemical field.
- *Tree-based risk analysis*: These techniques are mainly used to represent the whole scenario of a given risk in a graphical way. Within the most common ones, we mention bow tie diagrams [9], Markov modeling [10], dynamic event logic analytical methodology [11] and event tree analysis method [10].

Within these methods, the *Failure Mode and Effects Analysis* (FMEA) [8,12] appears as one of the most popular and diffused risk management methods. Moreover, several researches have been carried out to enhance its performance by introducing fuzzy logic concepts to evaluate the risk level in a more flexible way, such a new version is called fuzzy FMEA [12,13,14,15]. The fuzzy FMEA was initially designed to assign to each risk a unique *Risk Priority Number* (RPN) which is not adapted to our case since each risk will have an impact on several management areas.

Thus, our idea in this paper is to extend the existing fuzzy FMEA by defining for each risk a multi-leveled *Risk Priority Number* relative to different QSE objectives. Then, to ensure the selection phase of the most critical risks regarding different QSE objectives, we propose to use a multicriteria approach which is the *Analytic Hierarchical Process* (AHP) [16].

The remainder of this paper is organized as follows: Section 1 recalls the principle of the Fuzzy Failure Mode and Effects Analysis. Section 2 presents our new approach to evaluate multi-leveled risks. Finally, Section 3 presents an illustrative example in the petroleum field involving the selection of the most critical risks for TOTAL TUNISIA company.

1. Fuzzy Failure Mode and Effects Analysis

Initially proposed by the US military in 1962 as a process tool, the *Failure Mode and Effects Analysis* (FMEA) has became one of the most popular risk management tools to identify, analysis and treat each identified risk in many industrials fields such as manufacturing, assembly processes, products and equipment. That is why it was easily spread into industry and widely known within the quality community as a total quality management tool in the 1980s and as a six sigma tool in the 1990s [17]. The FMEA is based on a ranking of different risks on the basis of their *Risk Priority Number* (RPN). In fact for each risk R_j it associates a *Risk Priority Number* $RPN_j = O_j * S_j * D_j$ such that:

- *Occurrence* O_j: is the rate at which R_j will occur before any additional process controls are applied. This can be done by looking at similar products or processes and the failure modes that have been documented for them.
- *Severity* S_j: evaluates the seriousness of an effect of R_j.
- *Detection* D_j: is relative to the likelihood that the detection methods will detect R_j (A high detection number indicates that the chances of detection are low).

To evaluate these three parameters, linguistic scales should be defined in order to convert their qualitative descriptions given by the expert to a quantitative one. Table 1 shows an example of a linguistic scale with five levels describing the occurrence (O), severity (S) and detectability (D). For example if the expert evaluates the occurrence as moderate then the variable (O) will be equal to 3.

Table 1. Linguistic scale

Rank	Description	Occurrence (O)	Severity(S)	Detectability (D)
1	Remote	Unlikely	No effect	Certainly detected fail
2	Low	Relatively few	Slight annoyance	Major defects are detected
3	Moderate	Occasional	Severus deterioration	Some defects are detected
4	High	Repeated	Very severs deterioration	Few defects are detected
5	Very high	Almost inevitable	The whole system is affected	Detection is impossible

The first problem with the classical FMEA consists in the parameters estimation which is not an easy task since in real world problems O, S and D are pervaded with uncertainty which is not well described by qualitative linguistic scales. Moreover, to compute RPN values the FMEA neglects the relative importance among O, S and D since it assumes that they are equally important (by aggregating them via a simple multiplication) which is not always true. For instance, in nuclear and chemical plants, the severity is much more weighted than the occurrence and the detectability. To overcame this weaknesses several researchers propose to introduce fuzzy logic concepts [18] to evaluate the risk level. The new version, called Fuzzy FMEA, has been widely used in many industrial applications as in marine industry [19], engine system [20] and auxiliary feed water system in a nuclear power plant [15]. For each risk, Fuzzy FMEA, has as input a linguistic description of its occurrence, severity and Detectability, then it proceeds through a fuzzy logic system [18] with three main phases (i.e. Fuzzification, Fuzzy inference system and Defuzzification) in order to compute its *Risk Priority Number* (RPN) [12,14,15]:

1. **Fuzzification**: in this phase, experts are invited to define membership functions and the values in the universe of discourse using the interpretations of the linguistic terms. The shape of these functions can be diverse but the most used are triangles and trapezoids. Note that linguistic terms describing inputs and output (i.e. RPN) can be different. For example figure 5 shows a set of four triangular membership functions defined by fuzzy number (a, b, c) expressing the proposition *close to b* [21], these functions describe the linguistic scale of table 1 relative to O, S and D.

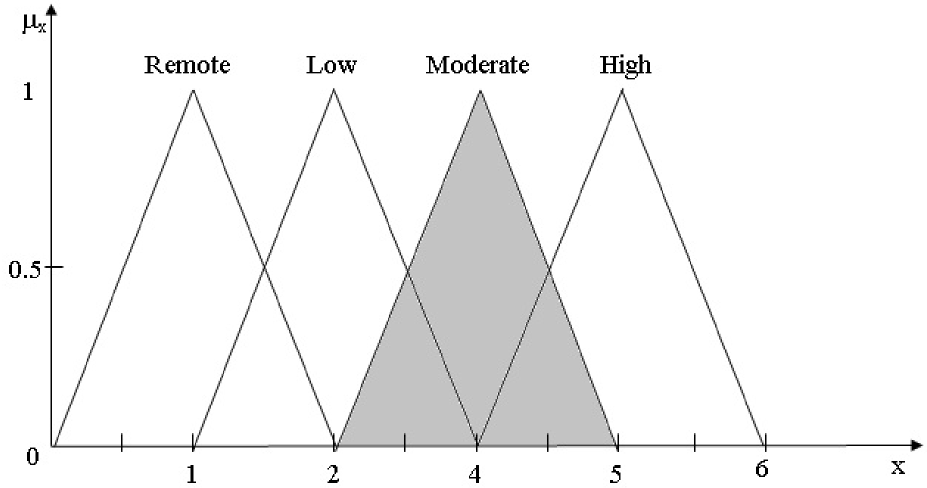

Figure 2. Set of four membership functions

2. **Fuzzy inference system**: Membership functions derived from experts are used to generate a fuzzy rule base [22] where rules are in the form *R1: IF (O is Low) AND (S is Moderate) AND (D is Minor) THEN (RPN is moderate), R2:IF (O is Moderate) AND (S is Low) AND (D is Minor) THEN (RPN is moderate), etc.*. Thus, the parameters relative to each risk can be merged via an inference system (e.g. *max-min* or *max-prod* [18]) into a fuzzy output. For instance, if O =Low, S = Moderate and D=Minor, then the application of R1 generates the colored surface in figure 5.
3. **Defuzzification**: in this last step, the aggregated fuzzy output is converted into a crisp number. Defuzzification is defined as a function F^{-1} mapping a fuzzy set to a certain element x of the support of the output. Several defuzzification methods have been proposed as the *centroid method*, *center of area*, and *maxima methods* [18] and the selection of the appropriate one should be based on the properties of the defuzzification method and the requirements of the system.

Despite its success, fuzzy FMEA is restricted by the qualitative linguistic description of the parameters and also by its restriction to a unique severity value regarding the whole studied system. In fact, in our case we handle several QSE objectives so that any risk can alter the realization of these objectives in different ways and the definition of its severity by a single value is a real limitation. We show now how to adapt fuzzy FMEA to our requirements.

2. Multi-leveled Fuzzy FMEA

In this section, we propose to extend the existing fuzzy FMEA in order to deal with several QSE objectives. In fact, in accordance with our QSE integrated management system (figure 1), we propose to evaluate the impact of each risk regarding different QSE objective in order to select the most critical of them as shown in figure 3.

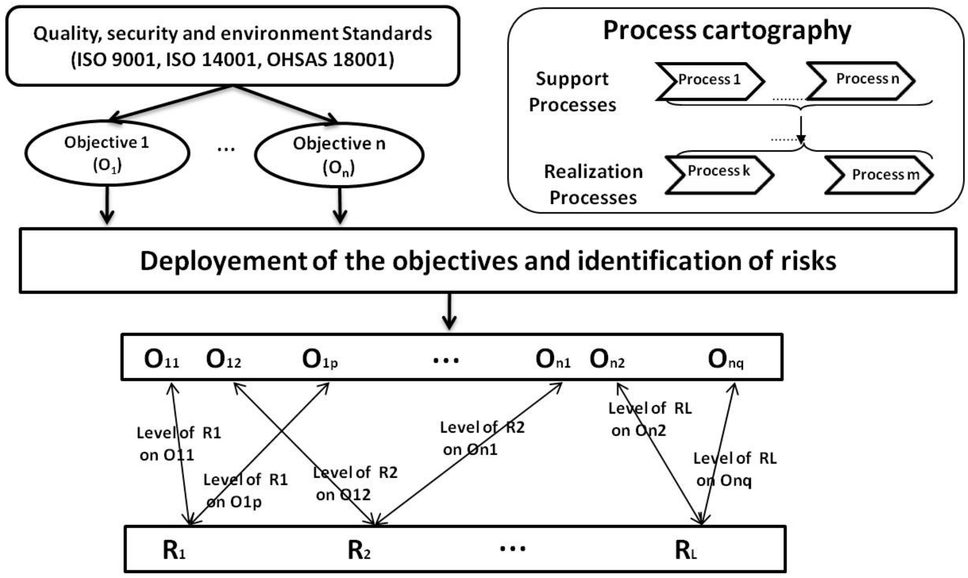

Figure 3. Risk identification phase

The principle of our approach, named multi-leveled Fuzzy FMEA (MLF-FMEA), is outlined in figure 4. First we propose to overcome the problem related to the parameters estimation by replacing the simple qualitative linguistic description to a quantitative one in the unit interval. To this end, we propose to define indicators relative to the occurrence (O), detectability (D) and also to exploit the severity parameters to quantify the impact of each risk R_j on any QSE objective O_i (i.e. S_{R_j/O_i}). Then an implementation of a fuzzy system on the basis of the three main steps of F-FMEA described above (i.e. fuzzification, fuzzy inference system and defuzzification) is proposed in order to compute for each risk R_j a Risk Priority Number related to each QSE objective O_i (i.e. RPN_{ji}). Finally, these RPNs are used as input of multicriteria analysis, based on the Analytic Hierarchical Process (AHP), in order to rank the different risks and to select the most critical ones.

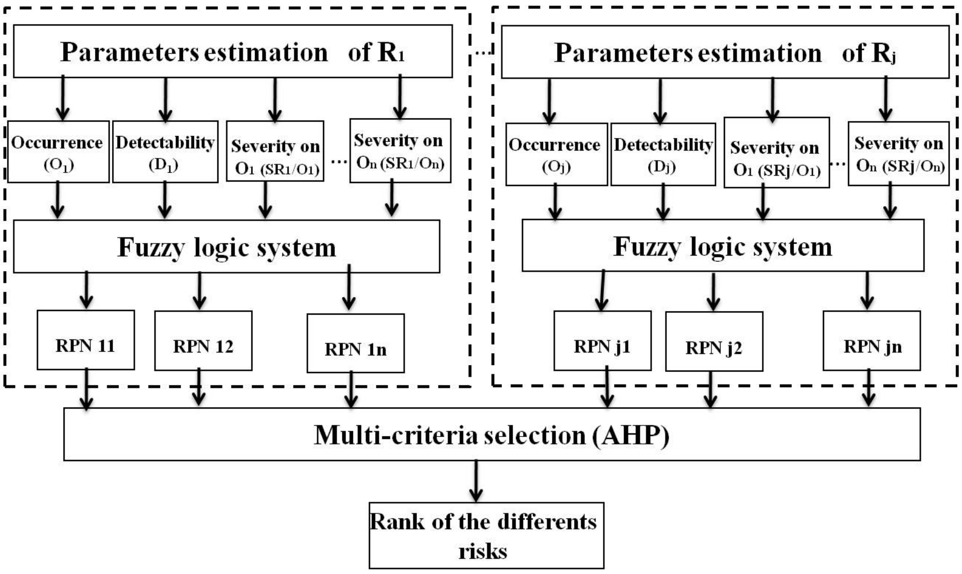

Figure 4. Overall view of MLF-FMEA

2.1. Parameters estimation

In this phase we propose to replace the simplest qualitative linguistic description of fuzzy FMEA by a quantitative one using the unit interval [0 1]. Several indicators may relate to our approach, we can retain the following basic ones:

- *Occurrence*: within the multiple indicators developed for the quantification of the occurrence, we can mention the *Mean Time Between Failure* [23] which is a basic measure of a system's reliability.
- *Detectability*: this parameter can easily be computed by a ratio of the detecting occurrence rate of the risk and its occurrence rate.
- *Severity*: to quantify the severity of each risk R_j on the objective O_i (i.e. S_{R_j/O_i}), we propose to compute a ratio between the measure of the objective O_i and the measure of the risk R_j on O_i. In fact, from a formal point of view, an objective can be seen through a set of expected values associated with a variable or factor since the three management systems (ISO 9001, ISO 14001, OHSAS 18001) require that each objective should be quantified and expressed by numerical values which can be expressed from customers requirement, standards or even regulations. Regarding the measure of the risk on the objective it can be provided by physical sensors or by experts.

2.2. Fuzzy logic system

Thus given m risks and n QSE objectives, the parameters estimation phase will provide O_j, D_j and S_{R_j/O_i} ($i \in \{1..n\}$, $j \in \{1..m\}$,). These parameters will be handled via a fuzzy logic system following the same principle than fuzzy FMEA:

- *Fuzzification*: In order to fuzzify different inputs, experts have first to define different membership functions (number, form) using the linguistic design. Since we propose a quantitative description of different parameters in the unit interval [0 1], membership functions should be defined on this interval. For example figure 5 shows a set of trapezoidal membership functions for a three level fuzzification relative to a linguistic scale with three levels (i.e. Low, Moderate and High) that we suppose valid for input and output variables. Note that contrary to fuzzy FMEA where the quantification is done via linguistic terms, the input values here can be defined in [0 1] in a *crisp* or *uncertain* manner as illustrated by figure 5.

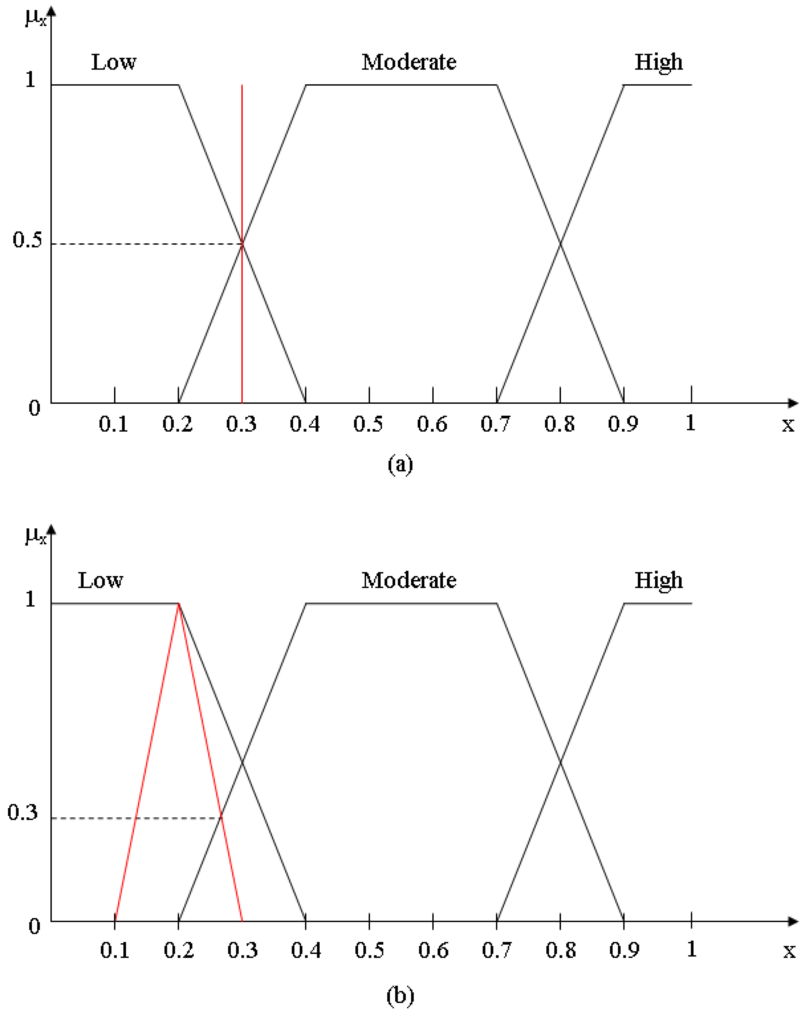

Figure 5. (a) Fuzzification of a crisp input (x=0.3): 0.5 Low, 0.5 Moderate, 0 High
(b) Fuzzification of uncertain input (x= [0.1 0.3]): 1 Low, 0.3 Moderate, 0 High

- Fuzzy inference system : in order to ensure this phase, experts should first define the fuzzy rule base [22] and select the inference engine (i.e. *max-min* or *max-prod*) in order to get the fuzzy output. Figure 6 illustrates the application of the max-min inference mechanism with two fuzzy rules *R1: IF (O is Low) AND (S is Low) THEN (RPN is Low)* and *R2=IF (O is Low) AND (S is Moderate) THEN (RPN is Moderate)* with two inputs $O = 0.1$ and $S = 0.25$. From the fuzzification phase we μ_O corresponds to 1 Low, 0 Moderate and 0 High and μ_S to 0.8 Low, 0.2 Moderate and 0 High. This means that using R1, we have RPN=min(1, 0.8)=0.8 Low (illustrated by (a)) and then using R2, we have RPN=min(1, 0.2)=0.2 Moderate (illustrated by (b)). Finally the max operator is applied to get the final output illustrated by (c).

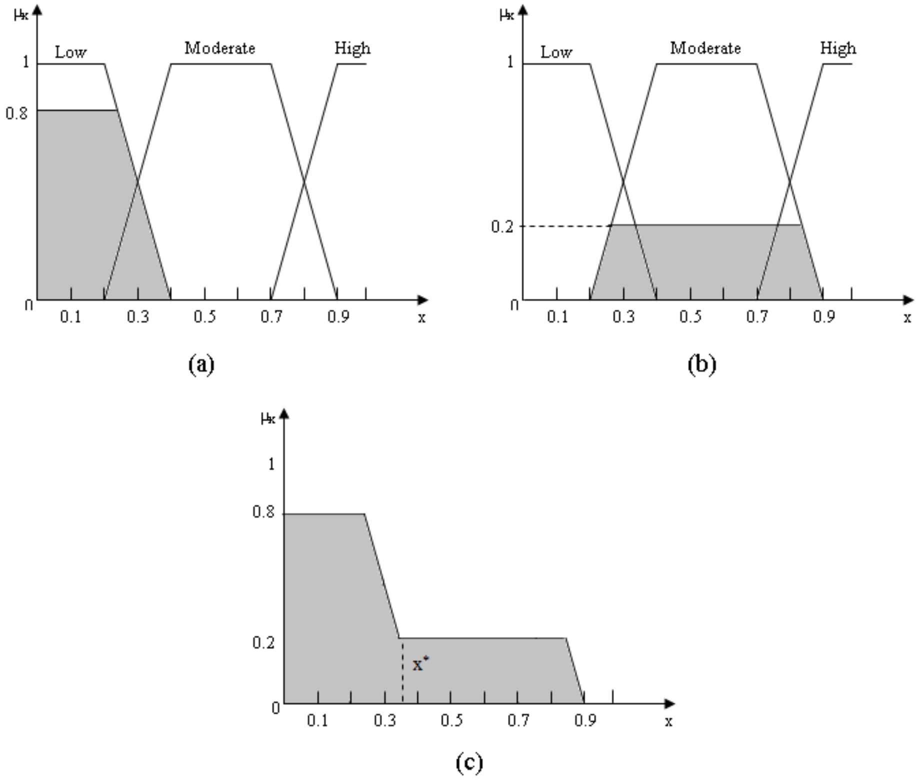

Figure 6. Example of the application of the max-min inference mechanism

- Defuzzification: the defuzzification process proposed in this work is the *centroid method* based on the computation of the center of gravity (COG) of the area delimited by the membership function of the output set using the following equation:

$$x^* = \frac{\int \mu_i(x) x dx}{\int \mu_i(x), dx} \tag{1}$$

where x^* is the defuzzified output, $\mu_i(x)$ is the aggregated membership function and x is the output variable. In figure 6 the COG of the area in (c) is equal to $x^* = 0.36$.
This final step allows the computation of different RPN values.

2.3. Multicriteria selection of the most critical risks

In order to select the most critical risks, we have to compare them regarding their impact on the set of fixed QSE objectives. This is clearly a multiobjective problem. In the literature we can distinguish a variety of multicriteria approaches such as weighting methods, outranking methods and interactive methods. We propose here to use the standard weighting method, which is the analytic hierarchical process (AHP) [16] since it can be easily adapted to our requirements. The AHP is a tool for quantifying decision-making processes with multiple criteria. It helps analysts to organize the critical aspects of a problem by decomposing it into a multi-level hierarchical structure corresponding to a tree structure where the first level (i.e root) corresponds to the objectives, the last one (i.e the leaves) to the alternatives (i.e possible solutions) and the intermediate ones to the different criteria and their sub-criteria. For each level of this tree (expect the root) we should define one or several decision matrices (DM) based on pairwise comparisons. Thus, for each level l with n elements (criteria or alternatives) we should define m decision matrices ($n*n$), where m is the number of elements (i.e criteria) of level $l-1$. Each value a_{ij} ($i \in \{1..n\}, j \in \{1..n\}$) of a matrix DM relative to the criteria C_i defines the importance degree between i and j in the context of C_i. Such a value can be depicted from Saaty's scale of measurement given in table 2. Note that a_{ij}=a_{ji} which means that all decision matrices are symmetric.

Table 2. Saaty's scale of measurement [16]

Intensity of importance	Significance
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgments

The decision matrices are used to evaluate the global scores relative to different elements in each level in a top-down manner until reaching the alternatives level. More precisely, for each element i in a level l we should compute a global score W_i relative to each criterion C_i (pertaining to level $l-1$) using the DM relative to this criterion as follows:

$$W_i = \frac{1}{n} \frac{1}{\sum_{j=1}^{n} a_{i_1}} \frac{1}{\sum_{j=1}^{n} a_{i_2}} \cdots \frac{1}{\sum_{j=1}^{n} a_{i_n}} * a_{i_1} a_{i_2} \ldots a'_{i_n} \tag{2}$$

It is important to note that we should ensure the coherence of each defined DM by its consistency ratio expressed by:

$$CR = \frac{CI}{RI} = \frac{\frac{\lambda_{max}-K}{K-1}}{RI} \tag{3}$$

where K and λ_{max} are respectively the number of compared elements and the maximum eigenvalue of the considered DM and where RI is the random index value defined according to the number of criteria given in table 3 [16].

Table 3. Table of random index [16]

Number of criteria	2	3	4	5	6	7	8	9
RI	0	0.58	0.9	1.12	1.24	1.45	1.49	1.51

Values of CR $<= 0.1$ are typically considered acceptable, otherwise, the decision matrix should be revised [16].

In order to select the most critical risks we propose to use a three-levels hierarchical structure (see figure 7) having as a main objective the ranking of different risks. The second level relative to comparative criteria concerns QSE objectives ($O_1 \ldots O_n$), and the last one identified risks ($R_1 .. R_m$). Thus as a first step, we should compare the different objectives in order to obtain their relative weights using Saaty's scale measurement. Then the different values of RPN_{ji}, obtained from the previous step, will be calibrated in Saaty's scale by a pairwise comparisons. More precisely, for each pair of risks $\{R_j, R_k\}$, for each objective O_i, we propose to compute the impact of R_j on O_i w.r.t. R_k by dividing RPN_{ji} on RPN_{ki} (resp. RPN_{ki} on RPN_{ji}) if $RPN_{ji} \geq RPN_{ki}$ (resp. otherwise) and by rounding the obtained result by a value α in order to fit to the semantic of Saaty's scale.

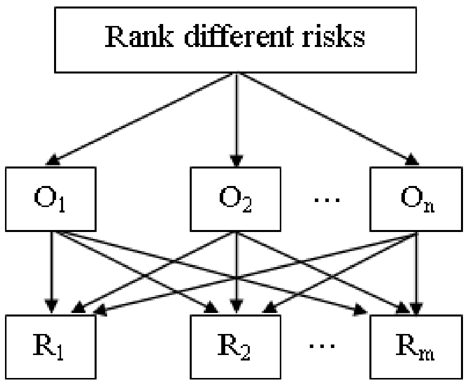

Figure 7. The hierarchical model to select critical risks

3. Illustrative example

In order to illustrate our method, we will present in this section an application released in the petroleum field involving a part of a decision problem faced during the identification of the most critical risks in TOTAL TUNISIA company (certified for quality, security and environment management systems). Due to the lack of space we will only consider three QSE objectives (O_1 (Quality) : Gain market share by providing superior all round by decreasing the product of non conformity level service to the customer, O_2 (Environement): Minimize the environmental waste by respecting the contamination rate of the air, water and ground according to the requirements and international standards, and O_3 (Security) : Increase safety staff by decreasing the number of day off of employees) and three risks (R_1: A major fire and explosion on tanker truck carrying hydrocarbon, R_2: A fire in container and R_3: the passage of a product in the discharge circuit from the separator to the sea). Note that O_2 is deployed into two sub-objectives (i.e. O_{21} Carbon concentration on the air <= 10000 ppm and O_{22} Fuel concentration on the sea <= 25000 ppm) but since R_1 and R_2 concern O_{21} and R_3 concerns O_{22}) we can use O_2 instead of O_{21} and O_{22} without any confusion.

Figure 8 illustrates the membership functions defined by experts and used for both inputs and outputs (since they are defined by the same linguistic description and the same universe of discourse). Regarding the fuzzy rule base, we have to define 4^3= 64 rules for each risk of the form (For the lack of space we cannot provide all of them):

IF (O_1 is minor) AND (S_{R_1/O_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is minor)
IF (O_1 is low) AND (S_{R_1/O_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is minor)
IF (O_1 is moderate) AND (S_{R_1/O_1} is minor) AND (D_1 is minor) THEN (RPN_{11} is low)
IF (O_1 is high) AND (S_{R_1/O_1} is high) AND (D_1 is minor) THEN (RPN_{11} is low)
...

Note that we can reduce the number of fuzzy rules as described in [24].

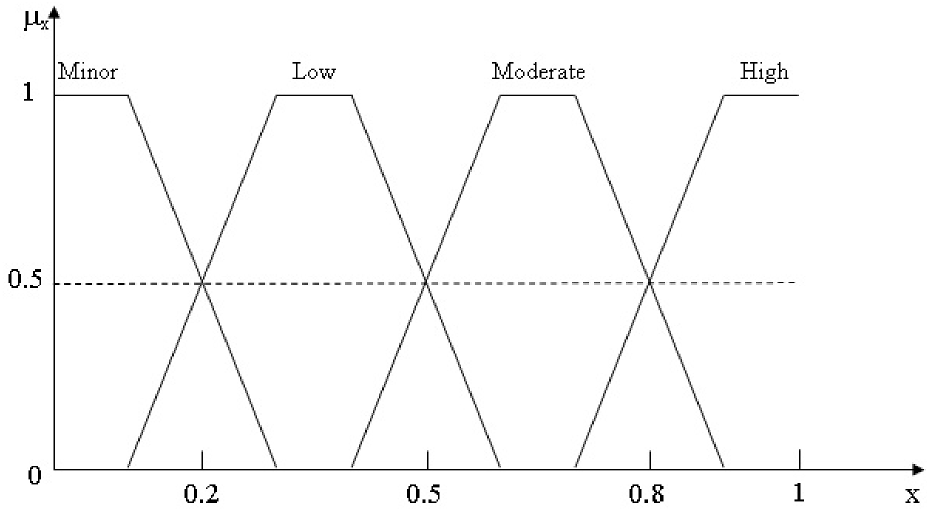

Figure 8. Constructed membership functions

The quantification of different inputs is provided in tables 4,5 and 6 relative to the occurrence, severities and detectability of each risk, respectively.

Table 4. Occurrence values

	Risk occurence	$\Delta t(Days)$	Occurrence (O_j)
R_1	[1 2]	3650 (10 years)	[0.0002 0.0005]
R_2	3	3650 (10 years)	0.0008
R_3	[1 2]	1825 (5 years)	[0.0005 0.0001]

Table 5. Severity values

	Measure of risk on objective	Severity
O_1: Gain market share by providing superior all-round service to the customer (Measure of objective : <= 10 hours work stoppage)		
R_1/O_1	2.5 hours work stoppage	$S_{R_1/O_1} = 0.25$
R_2/O_1	3.5 hours work stoppage	$S_{R_2/O_1} = 0.35$
R_3/O_1	6 hours work stoppage	$S_{R_3/O_1} = 0.6$
O_2: Minimize the environmental waste (Measure of objective » O_{21} Carbon concentration on the air <= 10000 ppm » O_{22} Fuel concentration on the sea <= 25000 ppm		
R_1/O_2	Carbon concentration on the air = 6500 ppm	$S_{R1/O2} = 0.65$
R_2/O_2	Carbon concentration on the air = 6500 ppm	$S_{R_2/O_2} = 0.65$
R_3/O_2	Fuel concentration on the sea = 6250 ppm	$S_{R_3/O_2} = 0.25$
O_3: Increase safety staff (Measure of objective : A total of 15 days off))		
R_1/O_3	A total of 6 days off for injured staff	$S_{R_1/O_3} = 0.4$
R_2/O_3	A total of 4 days off for injured staff	$S_{R_2/O_3} = 0.26$
R_3/O_3	A total of 0 days off for injured staff	$S_{R_3/O_3} = 0$

Table 6. Detectability values

	Detecting risk number	Risk occurrence	Detectability (D_j)
R_1	1	[1 2]	[0.5 1]
R_2	2	3	0.66
R_3	1	[1 2]	[0.5 1]

Then, for each risk R_j (j=1..3) and each objective O_i (i=1..3), we compute RPN_{ij} given in table 7 using the max-min inference method and the centroid method for the defuzzification step.

Table 7. Different RPN_{ij} values

	O_1	O_2	O_3
R_1	0.65	0.38	0.71
R_2	0.38	0.35	0.66
R_3	0.29	0.74	0.18

Finally these values, are aggregated using the three-levels hierarchical structure of figure 7 as described above. To this end, we use the decision matrix relative to QSE objectives given in table 8. We can for instance note that O_3 has a moderate importance w.r.t O_1 and a stronger importance w.r.t O_2 etc. On the basis of these values, we can define the relative weight concerning each objective. Thus, we can conclude that O_2 is the most important criteria followed by O_1, and finally O_3. Once the criteria's weights are defined, the different values of RPN_{ji} will be re-scaled in Saaty's scale by computing for each couple $\{R_j, R_k\}$, for each objective O_i, RPN_{ji}/RPN_{ki} if $RPN_{ji} \geq RPN_{ki}$ and RPN_{ji}/RPN_{ki} otherwise. Then the ratio values are rounded using a threshold α

(in what follows we use $\alpha = 0.3$). Table 9 illustrates this transformation wich is used to construct the decision matrices relative to different risks regarding each objective (see table 10). Using these values, table 11 represents the different risk weights according to each objective. For instance, regarding the objective O_1, the risk R_1 is the most important ($W_1 = 0.498$), followed by R_2 ($W_2 = 0.268$) and R_3 ($W_3 = 0.203$).

Table 8. Decision matrix relative to QSE objectives

$-$	O_1	O_2	O_3	Weights
O_1	1	$1/3$	4	0.28
O_2	3	1	5	0.63
O_3	$1/4$	$1/5$	1	0.09

Table 9. Transformation of RPN_{ji} values into Saaty's scale

O_1			O_2			O_3		
R$_j/R_k$	$\frac{RPN_{j1}}{RPN_{k1}}$	Saaty value	R$_j/R_k$	$\frac{RPN_{j2}}{RPN_{k2}}$	Saaty value	R$_j/R_k$	$\frac{RPN_{j3}}{RPN_{k3}}$	Saaty value
R_1/R_2	1.71	2	R_1/R_3	1.94	2	R_1/R_2	1.07	1
R_1/R_3	2.24	2	R_3/R_2	2.11	2	R_1/R_3	3.94	4
R_2/R_3	1.31	2	R_1/R_2	1.08	1	R_2/R_3	3.66	4

Table 10. Decision matrices relative to risks

	O_1			O_2			O_3		
$-$	R_1	R_2	R_3	R_1	R_2	R_3	R_1	R_2	R_3
R_1	1	2	2	1	2	2	1	1	4
R_2	$1/2$	1	2	$1/2$	1	1	1	1	4
R_3	$1/2$	$1/2$	1	$1/2$	1	1	$1/4$	$1/4$	1

Table 11. Risk weights

R_i	O_1 (0.28)	O_2 (0.63)	O_3 (0.09)	Weights
R_1	0.5	0.5	0.443	0.498
R_2	0.25	0.025	0.443	0.268
R_3	0.125	0.25	0.114	0.203

4. Conclusion

In this paper we have proposed an extension of the fuzzy FMEA risk analysis method in order to ensure the implementation of the most important part of the plan phase relative to the QSE integrated management system [1]. The basic idea is to estimate for each identified risk its occurrence, several severities degrees relative to different QSE objectives and its detectability. The use of the fuzzy logic allows the manipulation of uncertain values in a suitable way. The multi-leveled *Risk Priority Numbers* are then used in order to select the most critical risks via a multicriteria analysis based on the analytic hierarchical process (AHP) [16]. The proposed method is illustrated on a real case study in the petroleum field involving a part of a decision problem faced during the identification of the most critical risks in TOTAL TUNISIA company and that obtained results were validated by their experts confirming its coherence and efficiency. It is important to note that this method can be applied in other fields where many objectives should be considered.

As future work we propose to evaluate selected critical risk in order to assist the decision maker to define the appropriate preventive and corrective actions. A first study in this direction using a bayesian extension bow-ties diagrams as risk analysis tool is proposed in [25].

ACKNOWLEDGMENTS

We thank Total Tunisia for the valuable assistance in the preparation of the illustrative example.

References

[1] N. Ben Amor A. Badreddine, T. Ben Romdhane. A new process based approach for implementing an integrated management system: Quality, security, environment. In *International Conference on Industrial Engineering*, pages 1742–1747, 2009.

[2] R. Scheines P. Spirtes, C. Glymour. *Causation, Prediction and Search*. The MIT Press, 2000.

[3] Quality management system and requirements. Technical report, International Organization for Standardization, 2008.

[4] Environmental management system. requirements with guidance for use. Technical report, International Organization for Standardization, 2004.

[5] Occupational health and safety management systems-specification. Technical report, British standard institution, 2007.

[6] R. Hall R. Fullwood. *Probabilistic Risk Assessment in the Nuclear Power Industry*. Pergamon Press, 1988.

[7] T. Kletz. The origins and history of loss prevention. *Process Safety and Environmental Progress*, (77):109–116, 1999.

[8] Procedures for performing a failure mode, effects and criticality analysis. Technical Report MIL-STD-1629A, United States Department of Defense, 1980.

[9] A. Tripathi J.C. Couronneau. Implementation of the new approach of risk analysis in france. In *41st International Petroleum Conference*, pages 149–158, 2003.

[10] A. Amendola. Accident sequence dynamic simulation versus event trees. *Reliability Engineering and System Safety*, (22):3–25, 1988.

[11] P.C. Cacciabue G. Cojazzi. The dylam approach for the reliability analysis of dynamic systems. *Reliability Engineering and System Safety*, (53):181–352, 1996.

[12] P. Kumar R.K. Sharma, D. Kumar. Systematic failure mode effect analysis (fmea) using fuzzy linguistic modelling. *International Journal of Quality and Reliability Management*, (22(9)):986–1004, 2005.

[13] A. Badreddine T. Ben Romdhane, F. Ben Ammar. Une approche par la logique floue pour l'optimisation multicritère de la prise de décision appliquée à l'amdec. *Journal of Decision Systems*, (16(4)):505–545, 2007 (French).

[14] C.P. Lim K.M. Tay. Fuzzy fmea with a guided rules reduction system for prioritization of failures. *International Journal of Quality and Reliability Management*, (23(8)):1047–1066, 2006.

[15] C.M.F. Lapa A.C.F. Guimares. Fuzzy fmea applied to pwr chemical and volume control system. *Progress in Nuclear Energy*, (44(3)):191–213, 2004.

[16] T. Saaty. *The Analytic Hierarchy Process*. McGraw-Hill, 1980.

[17] S. Pollock. Create a simple framework to validate fmea performance. *ASQ Six Sigma Forum Magazine*, (4(4)):27–34, 2005.

[18] L. Zadeh. Fuzzy sets. *Information and Control*, (8(3)):338–353, 1965.

[19] J. Wang A. Pillay. Modified failure mode and effects analysis using approximate reasoning. *Reliability Engineering and System Safety*, (79):69–85, 2003.

[20] M. Xie S.L. Ho M. L. Zhu K. Xu, L.C. Tang. Fuzzy assessment of fmea for engine systems. *Reliability Engineering and System Safety*, (75):17–29, 2002.

[21] G.J. Klir and B. Yuan. *Fuzzy Sets and Fuzzy logic: Theory and Application*. Prentice Hall, 1995.

[22] S.L. Trubatch R.C. Berkan. *Fuzzy systems Design Principles: Building Fuzzy IF-THEN Rule Bases*. Wiley-IEEE Press, 1997.

[23] Nash F.R. Pecht, M.G. Predicting the reliability of electronic equipment. *Proceedings of the IEEE*, (82(7)):992 – 1004, 2002.

[24] D. Simon. Design and rule base reduction of a fuzzy filter for the estimation of motor currents. *International Journal of Approximate Reasoning*, (25(2)):145–167, 2000.

[25] N. Ben Amor A. Badreddine, T. Ben Romdhane. A multi-objective approach to implement an integrated management system: Quality, security, environment. In *Lecture Notes in Electrical Engineering (LNEE), Electronic Engineering and Computing Technology*, 2010.