An alternative approach to criticality analysis of industrial risks

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*Abstract_* **The evaluation of the risk indicates a procedure based on the analysis of the risk. It is a question of considering the risks in order to treat on a hierarchical basis them and of comparing them with a level considered to be acceptable. This evaluation amount dimensioning each identified dangerous situation, at the same time compared to the gravity of its consequences and its frequency of occurrence. That supposes that it is necessary to define scales of quotation of the risk in term of frequency and gravity as well as a grid of criticality allowing the combination of these two parameters and clarifying the criteria of acceptability retained for the evaluation of the risk. However, knowledge of which we lay out concerning the probability of occurrence of the events and the gravity of their consequences is generally imperfect. The validity of the results of the evaluation depends on the taking into account total or partial of the imperfection of knowledge used. This work falls under a prospect for improvement of the conventional grids of criticality for a better control of the industrial risks. The objective being to show the interest of the fuzzy set theory in the assessment of the criticality of the risks in the presence of uncertain data.**

Keywords— Risk management, Grid of criticality, fuzzy Logic, industrial Risks.

I. INTRODUCTION

Risk assessment, primordial step in the process of risk management, is a procedure based on risk analysis to decide if the tolerable risk is reached or not [4]. It is often carried out in a semi-quantitative way starting from a level of probability that damage would occur as well as its severity level and must be done to prioritize identified risks and to compare them to a predefined level of security according to acceptability criteria. Consequently, the finesse when assessing the parameter of the risk depends partly on these criteria.

So, the evaluation of the risk criticality is defined as an operation of comparison implying the definition of the rating scales of the risk parameters in terms of frequency (F) and gravity (G), and as a structure of combination of these latter to make explicit the acceptability criteria retained for the evaluation. The positioning in a matrix allows the visualization of the criticality of the dangerous situations in order to judge the risk acceptability and to decide what improvement measures are to be taken to reduce it. It makes it possible to distinguish among the positioned situations which ones require an immediate improvement.

The conventional criticality matrix, although widely used in various industrial sectors, presents inherent deficiencies in the subjective nature of expert judgment and uncertainty of knowledge implied in risk assessment [8]. The used data is imprecise, uncertain and are not always quantitatively sufficient, thus not suitable in quantitative handling. The frequency and gravity are in fact expressed by linguistic qualifiers schematizing the real situation which is the cause of the differences in interpretation of the evaluation results [10]. Three main problems are then raised:

1. The first one concerns the process of the frequency, gravity and criticality quotation scales. It is observed that this type of scaling is defined in a straightforward manner by associating them with a numeric ordinal classification which does not match the uncertain and imprecise nature of information on the frequency and the gravity of real situations, especially with rare events or new systems under development. Moreover, this rating neglects the effects of confusion between categories (i.e., overlapping in intervals) reflecting the human reasoning.

2. The second is due to the discontinuity of the used rating scales leading to difficulties in interpretation of evaluation results.

3. The last one is relating to the rule of crossing of information on the F and G parameters to incorporate a score of criticality (risk index). The product R = F x G is often used but its significance is strongly contested for ordinal scales.

This can affect the quality devaluation by providing incorrect results on the criticality level of risk which may lead the analyst to decide inappropriate corrective measures for its management. Thus, to make the evaluation more accurate and reliable, it is necessary to manipulate consistently and logically the subjective, qualitative and quantitative information related to the analysis.

Fuzzy set theory due to Zadeh [16] seems to offer a very adequate framework for the evaluation of the criticality where imprecision, uncertainties, quantitative knowledge and symbolically expressed knowledge by qualifications in natural language, may be treated [1]. Fuzzy evaluation of the risks criticality presents the advantage of enabling the direct handling of the measures in the form of fuzzy sets, which allows the analyst to use natural and informative representations of expert judgment [2], [12]. On the basis of this knowledge, although qualitative and imprecise, one can undertake corrective actions enabling the control of the risks [15], [3]. In this context, many studies have developed fuzzy models to assess the criticality of risks [5], [7], [8], [10], [11], [13], [17].

This work is part of this context and aims to improve the conventional criticality matrixes describing them by an inference system based on fuzzy rules. Starting from a fuzzy representation with linguistic values of frequency, gravity and risk scales, fuzzy rule base is built. By using the operations of fuzzy logic, the data of frequency and gravity are applied to the system of fuzzy inference (SIF) to determine an index of criticality of the risk.

Prepare Y

I. Conventional Criticality Matrix (CCM)

The criticality matrix is a tool for decision support for [9]:

- the ranking of scenarios that could lead to a major accident;
- the definition of reduction measures of the risk at the source;
- the development of prevention and protection plans.

The construction of the criticality matrix includes the following steps:

1. characterization of the gravity, the frequency, the risk and definition of quotation scales;
2. definition of the acceptability criteria of the risk;
3. graphical representation of the matrix.

The SONATRACH Company at Hassi R'mel uses for the risk assessment qualitative approach based on the matrix of figure 1, where the vertical axis relating to the gravity includes four categories of consequences (Negligible-I, Marginal-II, Critical-III, Catastrophic-Iv) and the horizontal axis which also includes four levels of frequency ranging from “I = Improbable” to “IV = frequent”.

		Improbable (I)	Rare (II)	Occasional (III)	Frequent (IV)
Negligible	(I)	1	2	3	4
Marginal	(II)	2	4	6	8
Critical	(III)	3	6	9	12
Catastrophic	(IV)	4	8	12	16

Fig. 1 — Criticality Matrix used by SH DP HR Company [14].

The relation between the categories of gravity and frequency is represented by a set of rules resulting from risk engineering (criteria of acceptability of the risk). The risk criticality level is obtained by the product of gravity levels by those of probability. So, to each box of the matrix corresponds a number characterizing the risk, this number varying between 1 (acceptable minimum risk) and 16 (unacceptable maximum risk). A zone of serious risks (the numbers 3, 4, and 6) between the two extreme zones (green zone for low risks and red zone for high risks) is taken into account by the matrix.

The scales of gravity (G), frequency (F) and criticality (C) to which we refer in the continuation of this work, arise in the following way (Tab.I).

TABLE I . Qualitative and quantitative definition of risk parameters.

Risk Parameters		Qualitative Description	Quantitative/ Score Description
Gravity (G)	Negligible	Superficial injuries Degradation of the installation capacity with less than 10%	1≤ G < 2
	Moderate	Minor injuries Degradation of the installation capacity with less than 50%	1< G < 3
	Critical	Serious injuries Stop of the unit	2 < G < 4
	Catastrophic	Death Stop of the unit	3 <G < 4
Frequency (*F*)	Improbable	Improbable to occur during the life of the installation	10-7≤ F ≤ 10-5, [10-7, 10-5] (/year)
	Rare	Can occur once during the life of the installation (1/50 years)	F ≤ 2*10-2,] 10-5, 2*10-2] (/year)
	Occasional	Can occur more than one time during the life of the installation (1/10 years)	F ≤ 1*10-1,] 2*10-2, 10-1] (/year)
	Frequent	Can occur several times during the life of the installation (1 year)	F ≤ 1,] 10-1, 1] (/year)
Criticality (C)	Acceptable	No necessary measurement	1 ≤ C ≤ 3 (1, 2, 3)
	Tolerable	Actions based on the ALARP principle	3 ≤ C ≤ 6 (3, 4, 6)
	Inacceptable	Immediate reduction (preventive and/or protection measures)	8 ≤ C ≤ 16 (8, 9, 12,16)

The matrix of figure 1 is widely used in various industrial sectors. However, we wonder some aspects of the method:

- The gravity scale is based on a discontinuous categorization but a situation of danger can present more gravity than another one although they are both classified in the same category. On the other hand, one situation cannot be classified in one category only.
- The matrix uses two ordinal scales for the qualitative evaluation of gravity and frequency. However, considering these two scales as two numeric scales and taking into account the FxG product, presents serious problems for the classification of the accident scenarios. For example, an improbable scenario (level 1) with catastrophic consequences (level 4) has the same risk level (equal to 4) as a frequent scenario (level 1) with negligible consequences (level 4). However, it seems difficult to admit that these two scenarios are similar to be managed in the same manner.
- The risk levels in the matrix belong to a discontinuous scale with the extreme values 1 and 16, in other words, many integers between these two values are the result of any product of the two risk parameters. This discontinuity makes it difficult to interpret the differences between the values of the scale. For example, the numbers 9, 12 and 16 are successive on the scale of criticality but the differences "15-12" and "12-9" cannot be considered as equal or different.
- The clear delimitation of frequency, gravity and risk acceptability levels is undoubtedly incompatible with the inaccuracy and the uncertainty by which the information on the occurrence and the gravity of dangerous situations is affected, especially in the presence of rare events or new systems under development.

All these arguments justify the need to use a fuzzy evaluation of risk criticality. This will be dealt with in the following section.

II. Development of the Fuzzy Criticality Matrix (FCM)

The proposed Fuzzy Criticality Matrix (FCM) is a model which will be exploited within a process of risk analysis based on scenarios (Scenario-based risk analysis approach).

The FCM methodology is based on fuzzy sets theory [16], gravity (G) and frequency (F) are inputs variables which will be fuzzified by using adequate membership function. Resulting fuzzy G and fuzzy F sets, are introduced in inference engine (C-FIS) based on the application of knowledge rules IF – THEN resulting from engineering knowledge and expert judgment. The criticality index of the risk is single output variable. The output of the model is a fuzzy index of risk whose defuzzification makes it possible to obtain a single value representing its criticality level.

The relation: Risk = Frequency * Gravity, where (*) is generally the product, is transformed into a rule of the type:

"If Frequency is A and Gravity is B, then Criticality is C",

where A, B and C are, respectively, the qualitative descriptors of the linguistic variables F, G, and C. The global structure of the proposed FCM model is illustrated by figure 2.

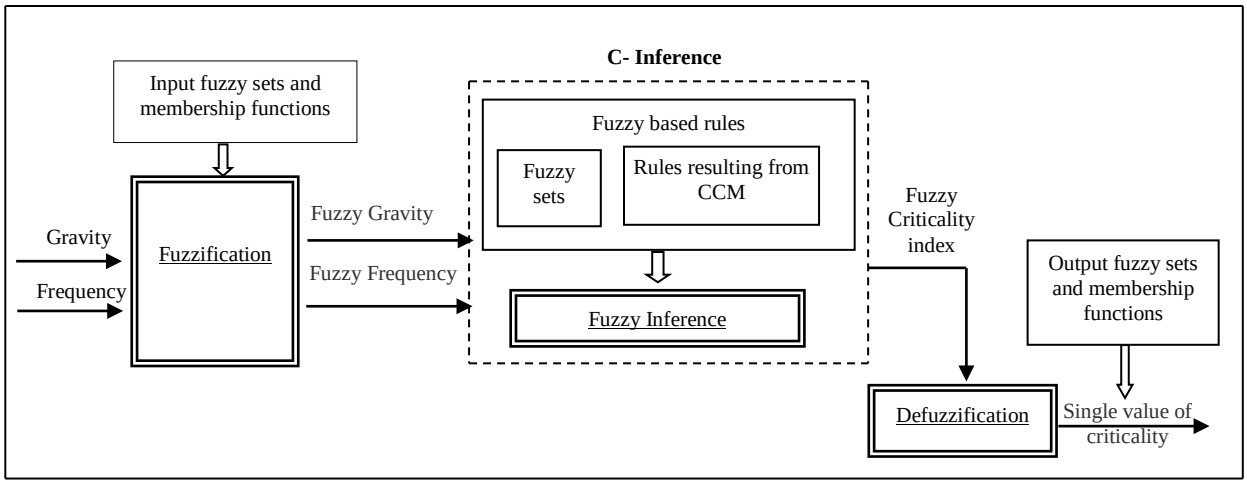

Fig 2: Overall procedure of fuzzy criticality assessment.

The implementation of the FCM shows three major modules constituting the inference system of Mamdani min-max that can be described as follows [6]:

A. *Fuzzification:*

The fuzzification is the process of converting an input ordinary data f0 and g0 in its symbolic representation, by calculating the degree of membership µA (f0), µB (g0).

B. *Fuzzy Inference:*

The inference engine transforms the input fuzzy sets (resulting from the operation of fuzzification) into output fuzzy sets by using the basis of linguistic rules and the fuzzy implication operations. The fuzzy output is obtained by the max-min inference method according to the following sub-steps:

(I) Identification of the level of activation of each rule: The truth value allocated to the "antecedent" (premise) of each rule is calculated and then applied to the "conclusion" of this rule. The calculation is done as follows:

$$\alpha_i = \min(\mu_A(f_0), \mu_B(g_0)) \qquad (1)$$

(II) Inferencing: In the step of inference, the output of rule Ri is calculated using the conjunction operator (min) where:

$$\mu C'(C) = \min(\alpha, \mu_c(r)) \qquad (2)$$

(III) Aggregation: To obtain the global output of the system, specific outputs for each rule are combined using the operator disjunction max. Thus, that is to say:

$$\mu_{C'agr}(r) = \max_{i=1,\dots,n} \mu_{C'i}(r) \quad (3)$$

C. Defuzzification:

The step of defuzzification allows transforming the fuzzy output into a digital value vo representative of Y in B'. Different defuzzification algorithms have been developed and there is no one best algorithm for all applications, however, "average of maximum" method and "center of gravity" method are most frequently used. According to this latter, the representative value is given by:

$$r_0 = \frac{\int_{r\in w} \mu_{E'_{agr}}(r)\cdot r \cdot dr}{\int_{r\in w} \mu_{E'_{agr}}(r)\cdot dr}. \quad (4)$$

III. Criticality index assessment (C-FIS)

A. Establishment of the fuzzy partitions (*Fuzzufication*):

The gravity, frequency and criticality scales to which we refer are given in table 1. Gravity and criticality scales are continuous ordinal scales regularly partitioned. The orders of magnitude of the frequency scale result from an expert testimony. The number of linguistic values allotted to each input and output variable describe the totality of the universe of discourse of this variable. The fuzzy partitions associated with the data of table 1 are visualized in figure 3.

B. Establishment of the fuzzy rules (Inference)

After establishing the fuzzy scales, the corresponding fuzzy sets are associated with premises and conclusions of rules for constructing the fuzzy rule base and this, by reference to the matrix of criticality of figure 1.

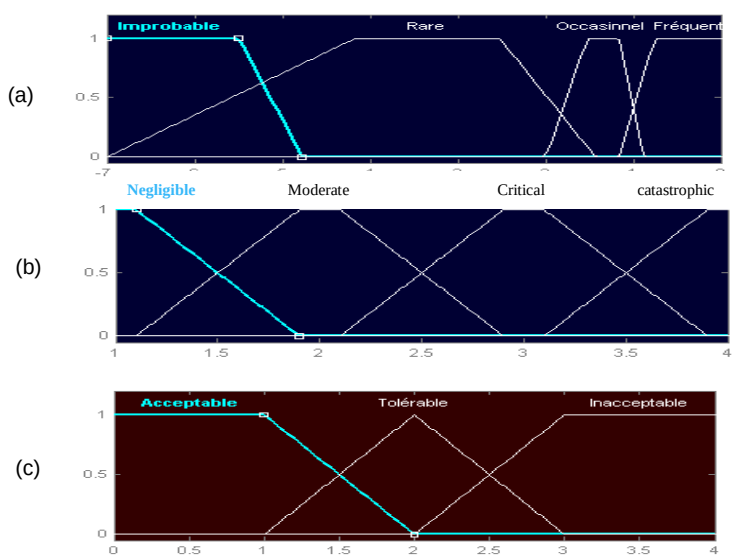

Fig.3: Membership functions generated for: (a) frequency, (b) gravity and (c) criticality.

Table (II) shows combination rules of F and G parameters. Rule 1, for example, must be read as follows:

"If the Frequency is improbable and Gravity is negligible, then the Risk is acceptable"

The surface of criticality, resulting from all the rules is given by figure 4.

TABLE II . RULES OF COMBINATION OF RISK PARAMETERS

Rule#	*Frequency*	*Gravity*	*Criticality*
1	Improbable	Negligible	Acceptable
2	Improbable	Moderate	Acceptable
3	Improbable	Critique	Tolérable
4	Improbable	Catastrophic	Tolérable
5	Rare	Negligible	Acceptable
6	Rare	Moderate	Tolérable
…	…	…	…

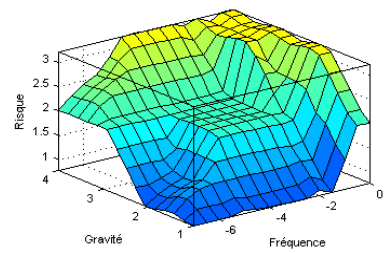

Fig. 4: Fuzzy criticality Surface.

IV. CASE STUDY

In order to illustrate the applicability of fuzzy matrix and show the contribution of fuzzy sets theory to the reduction of uncertainty related to the data used in the criticality assessment of risks, our case study has focused on a furnace of the MPP3-plant at Hssi R'Mel (South Algeria). The furnace is one of the most significant systems of SONATRACH Company, being able to generate, in the case of failure, critical and catastrophic consequences on human, material and environment.

The MPP3 Plant, one of the three zones of the complex Hassi R'Mel is a northern compression and treatment plant which recuperate heavy hydrocarbons (condensed and LPG) of crude gases collected from many oil wells and to produce treated gases (gas of sale or gas of re-injection).

Regarding the selection criteria of scenarios to be studied, we retain only those whose consequence lead to the stop of the unit.

Three scenarios are retained (Tab.III) according to following methodology:
- Development of the scenarios of accident by HAZOP method
- Estimate of the probability of the accidental scenarios identified by Event tree method (ET).

TABLE III. ACCIDENTS SCENARIOS RETAINED

Scenario	Consequence	Probability
1	Damage of the serpentine (fire), stop of the unit, possible stop of the module	6.60E-07
2	Damage of the serpentine (fire), stop of the unit, possible stop of the module	3.20E-06
3	High temperature at the exit of H-101, posclble damage of the serpentine (fire), stop of the unit, possible stop of the module.	1.00E-05

Using the Matlab simulator, the range of inferences operations is done automatically. The following figure (5) illustrates the fuzzy inference process. Table (IV) shows the values of the criticality index.

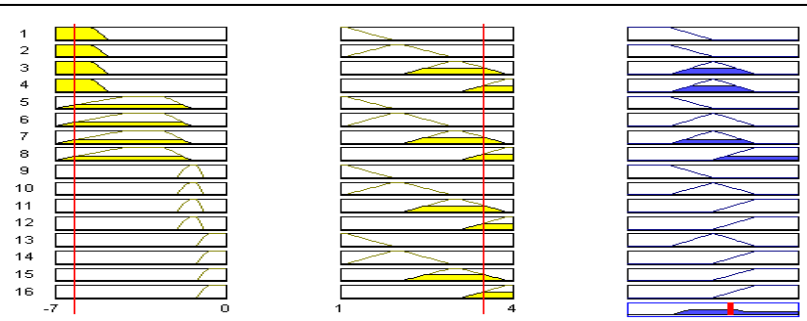

Fig.5 : Inference Process of the fuzzy rules (C-FIS): Case of scenario 1.

TABLE IV. COMPARISON OF THE CRITICALITY ASSESSMENT RESULTS OBTAINED BY CCM AND FCM.

Scenario	***Entrées***			***Sortie (Index de criticality)***	***Interpretation***
	F	***G***	***MCC***	***MCF***	
Scenario 1	6,60E-07	3.50	T (2)	2.46 (T-0.54, NA-0.46)	Under-estimation
		3.75	T (2)	2.39 (T-0.61, NA-0.39)	Under-estimation
		4.00	T (2)	2.38 (T-0.62, NA-0.38)	Under-estimation
Scenario 2	3,20E-06	3.50	T (2)	2.64 (T-0.36, NA-0.64)	Under -estimation
		3.75	T (2)	2.58 (T-0.42, NA-0.58)	Under -estimation
		4.00	T (2)	2.57 (T-0.43, NA-0.57)	Under -estimation
Scenario 3	1,00E-05	3.50	T (2)	2.64 (T-0.36, NA-0.64)	Under -estimation
		3.75	T (2)	2.86 (T-0.14, NA-0.86)	Under -estimation
		4.00	T (2)	2.86 (T-0.14, NA-0.86)	Under -estimation

C. Interpretation of results

The comparison of results of the two approaches for evaluating the criticality, i.e., the CCM and FCM, is done by putting the fuzzy index which represents the value closest to the real state, as the index reference, one can conclude that:

• Considering the results obtained, we can formulate as first conclusion that the difference between the two approaches is translated, as shown in table IV, by an under/over estimation of the criticality of the scenarios selected. Indeed, the CCM give completely tolerable value (T) for scenario 1 whereas the FCM reveals the unacceptable level (NA) with degrees of membership 46%).

• The output of the FIS is characterized by a gradual belonging to more than one category. For example, the index 2.84 (for scenario 3) belongs simultaneously to tolerable and unacceptable categories with membership degrees respectively, 0, 14 and 0,86. Those gradual belonging possible values are decreasing in the first and increasing in the second. For the CCM approach, there is only one total belonging of only one category.

• Using the FIS for assessing the criticality scenarios S1 and S2, it was found that their criticality is characterized according to two levels tolerable and unacceptable membership with divergent degrees. This implies a revision of the means of prevention and protection established for the management of these risks. Practically speaking, it is recommended to the company to proceed for an immediate reduction of this risk.

VI. CONCLUSION

The purpose of this work was to demonstrate the opportunity of the proposed approach in the criticality assessment of the industrial risks, enabling firstly, a consideration of the imprecise and uncertain aspects of the expert judgment and secondly, a better characterization of the dangerous situations.

An application on an operational system was used as support with the illustration of the fuzzy inference system. The results of the practical study validate the proposed approach and show its importance for criticality analysis of industrial risks.

The criticality assessment of risk based on fuzzy rules as an alternative to the conventional criticality matrix presents several advantages:

- To avoid the operation of the multiplication of risk parameters whose the significance is highly contested for ordinal scales, and to provide a more flexible structure to combine these parameters;
- To use the linguistic variables associated with fuzzy intervals instead of unique numbers generally incompatible with the imprecision of human perception;
- To use fuzzy continuous scales this will eliminate the problem of interpretation of results.

Compared to the conventional matrix, the proposed fuzzy model presents a very clear advantage allowing a decision making on the basis of a precise index of criticality and consequently to carry out a process to reduce risks through a rational investment.

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