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ORIGINAL ARTICLE

Fuzzy approach for safety integrity level evaluation to improve the safety of an industrial fired heater

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Abstract The study proposes an integrated frame implemented based on HAZOP and fuzzy evaluation of risk matrix (used to evaluate the safety integrity level), the aim is the improvement of an industrial fired heater safety. The determination of target SIL of any safety-instrumented function by the conventional methods such as Risk graphs, LOPA…may give imprecise values due uncertainties, in both parameters and models. Fuzzy theory is a useful mathematical approach to deal with the problem of uncertainties, by applying the membership principle introduced by L.A Zadeh. In this paper, we will use the Fuzzy theory to evaluate the target SIL for HAZOP recommended safety functions of a fired heater. The results will be compared with other SIL values (called calculated SIL and deduced using practical data of Probability of failure under Demand (PFD values). Depending on these comparison, recommendations for improvement are raised. In our case and from the overall study more safety functions should be added and the design of others have to be modified to respect the required safety level.

Keywords Fuzzy logic · Risks · HAZOP Hazard and Operability · SIL safety integrity level · Fired Heater

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1 Introduction

Chemical and petrochemical industrial plants are complex systems, designed to operate continuously for long periods. They consist of different kinds of equipment and devices interacting with each other (Ramzan et al. 2007a; Jose 2013). The configuration and the function of such type of plants leads to many difficulties in process control. These difficulties may generate deviations, which lead to abnormal situations characterized by the production of off-spec products i.e. products out of required specifications (Marhavilas et al. 2020a). It may also lead to shut downs and/or accidents causing damages to equipment operator's safety and health. Identifying hazards plays a very interested role in development of strategies to provide multiple plant's protection layers. In the last few decades, several techniques and standards have appeared in literature, to identify hazardous situations, and help companies to build up their own safety plans (Ramzan et al. 2007b). However, even the wide variety of provided techniques, they suffer from some limitations due to the limited application of some methods (taking into account the complexity of process and chemical industries) and the difficulties in generalization in other methods; hence an effective risk assessment process can be achieved only by the combination of different techniques. The idea of integrating different methods in one frame has been extensively presented in literature, the aim is to obtain results by covering the maximum drawbacks, and respect all site-specific factors (Hu et al. 2015 ; Nolan 2014 ; Riad et al. 2018; Jeerawongsuntorn et al. 2011). Another difficulty that faces the application of these methods is the existence of

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uncertainties in both the output of analysis and the furnished data from the site (Cheraghi et al. 2019). The uncertainties in the output of analysis means the differences between the key values in each risk assessment method and the true values. For example, in risk analysis we need to quantify the economic effect of an accident, or the number of fatalities... the fact that requires experimental data to validate the model and hence the results. which is not possible particularly in complex petrochemical plants (Bendib et al. 2019 ; Zhang et al. 2015 ; Chang et al. 2015). Where the uncertainties in the furnished data generally caused by the inability of performing adequate measurements due to sensors errors, or in some cases the operators' ignorance (Chang et al. 2015 ; Zhang et al. 2015; Bendib et al. 2019).

Furthermore, recent advancements in control systems have been marked by the integration of powerful tools based on artificial intelligence, providing innovative solutions to overcome the limitations of traditional control systems. Notably, one such tool gaining prominence is fuzzy logic, which is established upon the principles of fuzzy set theory (Mohan 2019).

This theory suggested that the membership principle is the key to decision making when faced with uncertainties. Mathematically the fuzzy logic is an extension of the classical binary logic (Cheraghi et al. 2022). Such that instead of exact or crisp values, membership functions with linguistic variables are used. The mechanism to deal with any real problem using Fuzzy logic should follow three main steps, the first is fuzzification which is the conversion from the exact or crisp measures to fuzzy and membership functions, the second is rule base implementation (inference) and the last is defuzzification, the reverse process of fuzzification (Kumar and Kaushik 2020). The recent researches show that the fuzzy logic is a powerful tool to deal with uncertainties (Wang 1997; Passino and Yurkovich 1998; Ross 2016), and it is even used in risk analysis methodologies (Chun and Ahn 1992; Dernoncourt 2013a, b; Kabir and Papadopoulos 2018).

Safety integrity level or SIL method (Cruz-Campa and Cruz-Gómez 2010; Cui et al. 2012) is a systematic method widely used by industrials to implement the safeguards used for mitigating any expected risk that may inflict the operation. The approach is divided into two main parts, the first is to define the required safety functions (SIFs) to bring the process to safe state, and the second it concerns the design of safety instrumented system (SIS) which include all sensors, logic solvers and final elements (valves, pumps…) used to achieve the specified function. The (ANSI/ISA S84.0 1996) and IEC 61508 (International Electro-Technical Commission IEC standards 2010) standards provide guidelines for design, installation, operation, maintenance, and test of safety instrumented systems. To implement an effective safety integrity level study, two SILs should be, defined, and compared. To give recommendations for safety improvement. The first is the Target SIL which is deduced from qualitative analysis based on quantifying the effects and the consequences on health, economic and environment raised when a safety function does not work (Ahn et al. 2019). The further is the Required SIL and this is deduced based on PFD (probability of failure under demand) of a SIS (Marszal and Scharpf 2002).

Based on the above in our study, we propose a new comprehensive integration framework that combines the Hazard and Operability (HAZOP) analysis with the Safety Integrity Level (SIL) and FTA methods. The aim is to get more advantages and to avoid drawbacks. The actual works and practice generally use only one method or different methods but each is presented separately.

Our approach involves the identification of Safety Instrumented Functions (SIFs) through the HAZOP analysis process. Subsequently, we determine the SIL target by constructing a FUZZY risk matrix to address the uncertainties present in conventional risk matrix. The obtained SIL target is then compared with the required SIL to assess adequacy. To demonstrate the effectiveness of our approach, we applied it to an existing industrial fired heater located in ADRAR Refinery, Algeria. Notably, in a previous study by (Riad et al. 2018), an integration framework based on conventional risk matrix analysis was proposed for the same fired heater.

2 Fuzzy logic

Fuzzy logic is a set of mathematical tools based on the membership degrees' principle; it can be defined as a generalization of classical binary logic, which admits only two logical states true or false. By adding degrees of truth between the extreme values. Whose basics were initiated by Lotfi Zadeh in mid-1960s (Voskoglou 2021), the main application of fuzzy logic is to model the problems in which imprecise and uncertain data exist (Cheraghi et al. 2022). Hence, by considering the difficulties mentioned before effective risk assessment strategies can be realized based on Fuzzy theory (Andrews and Dunnett 2000; Sal et al. 2017; Suresh et al. 1996; Kabir and Papadopoulos 2018). In this section, we will present some general and important aspects in FUZZY logic theory.

2.1 Fuzzy sets and membership functions

The difference between classical set (crisp values) and fuzzy set is presented by introducing the concept of membership function. Such that each element of any set will be characterized by a degree of membership expressed by a real number belongs to the interval [0 1] (Chun and Ahn 1992; Mendel

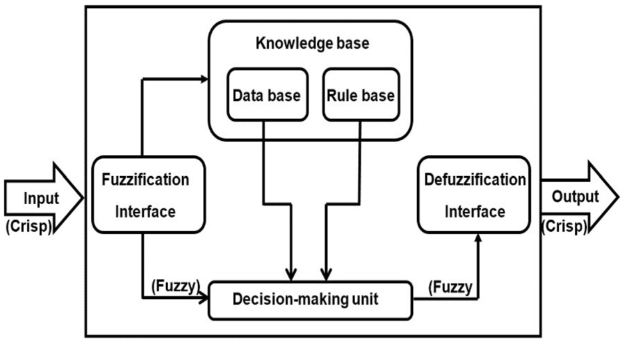


Fig. 1 Fuzzy inference engine

1995) (Voskoglou 2021). As a general conclusion from the use of this notion is that, the intersection between the set and its complement is not always an empty set as it is described in classical set theory.

2.2 Fuzzy inference system

Fuzzy inference is the process formulating the mapping from a given input to a given output using fuzzy logic. The functional block in Fig. 1 summarizes the different functions realized in an inference engine.

- *Fuzzification:* at this stage, the crisp (exact) inputs and outputs are converted to fuzzy quantities such that we specify the values of the input and output variables, transfer the range of these values into a corresponding universe of discourse, and convert them into linguistic variables (e.g. big, less…) (Mohan 2019).
- *Rule base:* which contains a number of fuzzy IF–THEN rules and according to these rules we will understand the behavior mechanism of the system. The rules are generally deduced from previous experiences, or using optimization methods (Hong and Lee 1996).
- *Data base:* It defines the number and shapes of membership functions. As a common practice in engineering, the membership functions have some specific shapes such as triangular, trapezoidal, Gaussian…the suited shape depends on the expert's knowledge on the application, some recent researches devoted to the use of some new optimization tools to find the optimal shapes (Kumar and Kaushik 2020).
- *Decision making unit*: which performs the inference operations such as: evaluation and aggregation of rules.
- *Defuzzification:* which transforms the fuzzy results of the inference into crisp output values. In literature different methods have been proposed such as: centroid, bisector… (Wang 1997; Simon 2002; Jin Zhao and Bose 2002; Jin Zhao and Bose 2002).

3 Hazardous and operability study (HAZOP)

The HAZOP (Hazard and Operability) method is a widely used technique in petrochemical industries, for identifying the hazards on process facilities (Marhavilas et al. 2020b). In HAZOP's the idea is the examination of malfunctions raised in the different part of a system by identifying in prior their causes, consequences and the safeguards. Finally, it depending on the analysis the engineer may recommends the addition of other measures to bring the process to a safe state. In HAZOP we follow PFDs (process flow diagram) and P&IDs (Piping and instrument diagrams) and divide the process into sections called nodes (Choi and Byeon 2020). In some cases, the PFD of a facility shows different streams and all of them should be considered. The malfunction or deviation are defined by some specific guide-words and parameters, Table 1 summarizes the guide words and the parameters that are generally considered in the field of petrochemical industries. (Dernoncourt 2013a, b; Crawley et al. 2008; Kletz 2018; Macdonald 2004).

3.1 Some useful definitions

Following terms are generally used in a HAZOP development

- *Nodes:* are sections of a P&ID (piping and instruments diagram). Usually the nodes are equipment items, however, if nodes are small so various devices may be joined in a single node.

Table 1 The HAZOP's guide words and deviation

Parameter	Deviation
Flow	No/less
	More
	Reverse
	Misdirected
Pressure	More
	Less
Temperature	More
	Less
Level	More
	Less
Phase/composition	Different
Operations	Star-up
	Maintenance
	Shut-down
	Sampling
Other	Instrument air failure
	Fire case
	Tube rupture

- *Deviation*: each line of the node is analyzed by applying certain deviations. These deviations result from the combination of a guide word with a specified parameter (generally used are pressure, temperature, flow, level) (Joubert et al. 2021).
- *Cause*: HAZOP Team brainstorms to identify possible causes for the considered deviation. All possible causes are recorded (e.g.: control loop failure, manual valve in wrong position, etc.).
- *Consequences:* Once the team is unable to find causes any longer for the considered deviation their likely consequences are studied in terms of severity of impact on people, plant and environment.
- *Safeguards:* It includes any technical, operational and organizational measures that can prevent, detect, protect or control a given scenario (Liu et al. 2020).

3.2 HAZOP methodology

HAZOP study needs to be accomplished by a multidisciplinary team of experts, to ensure benefiting from the experience of each one of the members. Depending on the plant situation, (whether it is a new or an existing one), the team may include process, instrumentation and safety engineers, as well as other independent experts. In construction contracts, the team will include both the contractor and owner experts and in some cases a third party (independent experts) (Nigel 2004).

The study begins first on the PFDs (Process flow diagrams) and P&IDs (Piping and instrumentation diagrams). The experts divide the plants into different streams and each stream to different nodes. After that, the study starts at each node by the analysis of possible deviations that raise from the application of different guidewords with the corresponding parameters (Cheraghi et al. 2019). The flowchart of Fig. 2 indicates the study's different steps, which can be summarized by taking any expected deviation, followed by listing of its possible causes and its consequences and finally the examination of existing safeguards that are originally proposed to mitigate the risks (Suzuki et al. 2021). In case it is not sufficient to let the process operate in safe state, recommendations for additional safeguards should be proposed.

A common practice, in HAZOP implementation the last section in the HAZOP report should include a recommendation sheet summarizes all raised recommendations. This sheet will be helpful later in the project realization stage to highlight the technical solutions to be followed in order to implement the recommendations. In case the mentioned recommendation is not possible to be realized (this situation happens generally in an existing plant case, ex in some situations we may find a recommendation to add some valves whereas the existing space is not sufficient) the contractor

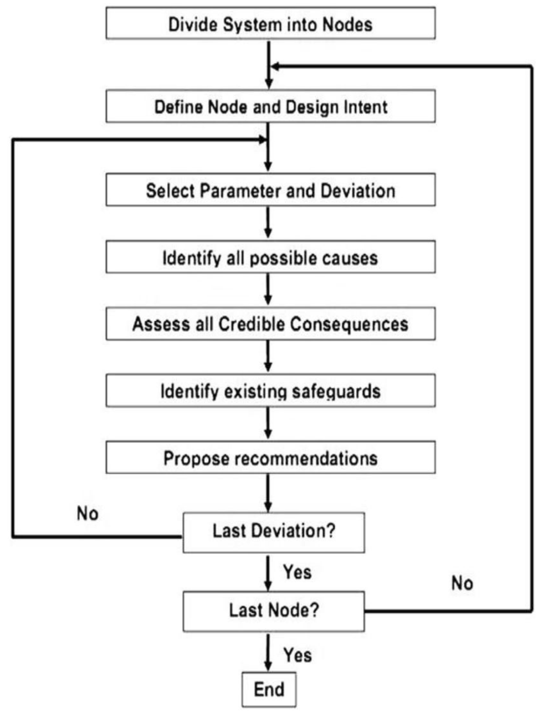


Fig. 2 HAZOP procedure

should propose other solutions (Suzuki et al. 2021 ; Joubert et al. 2021 ; Singh and Singh 2021a).

As it may be noticed that the analysis consumes a huge amount of efforts and time (hence money) particularly when the plant is complex (the case in petrochemical plants).

4 Safety integrity level

The purpose of any safety function is to achieve tolerable risk for a process hazard (Cui et al. 2019). The performance level needed from a safety function to realize the job is quantified using degrees called SILs or safety integrity levels, there are four integrity levels SIL1, SIL2...SIL4. On the other hand, these integrity levels are the measures of performance of any safety system in terms of probability of failure under demand PFD (Salaheldine Darwish et al. 2020), in such a way that higher the safety integrity level means lower the probability for the system to fail. From the above definition, we can define two types of SIL (Target and calculated SILs) (ANSI/ISA S84.01 1996).

4.1 Target SIL

This SIL is defined on the basis of the assessment of the likelihood, which an incident will occur, and its consequences (Ahn et al. 2019). The consequences are divided into three categories

Table 2 Risk matrix

Consequence category			Demand rate category				
S health and safety	E environment	L economic	D0	D1	D2	D3	D4
S0	E0	L0	–	–	–	–	–
S1	E1	L1	–	–	A1	A2	A2
S2	E2	L2	–	A1	A2	1	2
S3	E3	L3	–	A2	1	2	3
S4	E4	L4	–	1	2	3	4(X)
S5	E5	L5	–	2	3	4(X)	X

Table 3 Consequences categories as defined in IEC 61508

S0–No injury or health effect	E0–No effect	L0–No loss
S1–Slight injury or health effect	E1–Slight effect	L1–Slight loss (< 10 K USD)
S2–Minor injury or health effect	E2–Minor effect	L2–Minor loss (10–100 K USD)
S3–Major injury or health effect	E3–Localized effect	L3–Local loss (0.1–1 M USD)
S4–Between 1 and 3 fatalities	E4–Major effect	L4–Major loss (1–10 M USD)
S5–Multiple fatalities	E5–Massive effect	L5–Extensive loss (> 10 M USD)
D0 = Negligible	- = No safety requirement	
D1 = > 20 years	a1,a2 = No special safety requirement	
D2 = 4–20 years	1,2,3,4 = SIL value	
D3 = 0.5–4 years	4 (X) = SIL-4 functions are to be avoided	
D4 = 0–0.5 years		

- People
- Environment
- Economic

The likelihood of an incident depends on many factors such as, the frequency of process failure (demand rate), the exposure (Sotoodeh 2019)….

Final SIL classification is the maximum SIL between the ones deduced from the three categorizes (Raeesivand and Kasaeyan 2019). Risk matrix is used to specify the final risk for any safety function. Table 2 shows the risk matrix that defines the SIL of any safety integrity level as it is defined in (2003).

S0, S1…. S5 are consequences categories on health and safety of personnel, E0, E1…E5 are consequences categories on environment, L0, L1…L5 are consequences categories on economics and D0, D1…D4 the demand rate (Ahn et al. 2019). The equivalent interpretation of the previous parameters is clearly given in (IEC 61511-1: 2016) as it is summarized in Table 3.

When determining the effects on personal health and safety (Badida et al. 2019), the following factors are taken into account:

- Potential risk of human injury in the event of unsuccessful SIF in a dangerous situation

Table 4 risk reduction table for potential health and safety effects

Exposure				
F1	Very rare (< 10 man-minutes per day)			
F2	Occasional (< 6 man-hours per day)			
F3	Frequent to continuously (> 6 man-hours per day)			
Possibility to avert danger				
P1	In almost all circumstances			
P2	In some circumstances			
P3	Little or none			
Reduction in personnel health & safety consequence				
Possibility to avert danger	P3	− 1	0	0
	P2	− 1	− 1	0
	P1	− 2	− 1	− 1
	F1	F2	F3	
	Exposure			

- Exposure time
- Possibilities to avoid danger

Hence, the methods for alarming the person and the potential for escape (Singh and Singh 2021b). Conclusions are derived from the resulting risk reduction of the potential health and safety effects (Table 4).

4.2 Calculated SIL

Which relates the integrated level with the probability of failure under demand of the SIS (Safety Instrumented System) i.e. the components that are used to implement the safety function. The average PFD of any safety instrumented function is the sum of average PFDs of all sub systems i.e. the average PFD of the initiators + the average PFD of the logic solver + the average PFD of the final elements (Salaheldine Darwish et al. 2020; Joubert et al. 2021). Fault tree analysis method is used in the calculation of the corresponding average PFDs. OR and AND gates are used to define the relationship between different components (Akyuz et al. 2020). IEC 61508 defined clearly the relation between the Average PFD and SIL levels for both low demand and High demand as it is indicated in Table 5.

4.3 SIL verification

Lastly, the designer should check whether the existing components of SIS meet necessary risk reduction. This can be done via the calculation of the PFD of each SIF and comparing the results with the target SIL deduced from above considerations (Singh and Singh 2021a). In case where the calculated SIL is lower than the target SIL recommendations for design modification is generated (by modifying the components of the SIS or adding new SIF) (Chen et al. 2022).

4.4 Fault tree analysis for calculated SIL specification

The fault tree analysis is a very structured and rigorous method developed in the 1960 by Bell Laboratories in the United States (Liu et al. 2020). It was used in military and aerospace application in the beginning, and it was adapted by other industries such as refining, oil, papers…. later. The FTA is a diagrammatic deductive engineering technique. Widely used in safety and reliability studies. The main advantage is its capability to quantify the safety systems and by this way it generates a solid interaction between the actions taken to improve safety or production and the actual events (Kumar and Kaushik 2020; Akyuz et al. 2020).

Building a fault tree comes down to answering the question "how can such an event happen?", Or " what are all the possible sequences that can lead to this event?. Fig. 3 shows the implementation of safety instrumented function TAHH-1 (description of this SIF is given in the next sections) using FTA. As it is indicated in the figure the final elements are generally safety valves where two components (Solenoid+ Valve) related with an OR gate are used to represent the final elements, the logic solver is a programmable logic controller (PLC) and initiators are transmitters.

Table 5 PFD versus safety integrity levels (low demand case)

Safety integrity level (SIL)	Range of PFDavg	Risk reduction factor (Range of RRF)
4	$10^{-5} < PFD < 10^{-4}$	10.000 < RRF < 100.000
3	$10^{-4} < PFD < 10^{-3}$	1000 < RRF < 10.000
2	$10^{-3} < PFD < 10^{-2}$	100 < RRF < 1000
1	$10^{-2} < PFD < 10^{-1}$	10 < RRF < 100

5 Fuzzy logic for risk matrix evaluation

The flow chart of Fig. 4 indicates a global philosophy that we propose in this work, where the aim is to implement an effective safety strategy in an industrial plant. This global philosophy is based on the integration between the most known methods in the field of petrochemical studies,

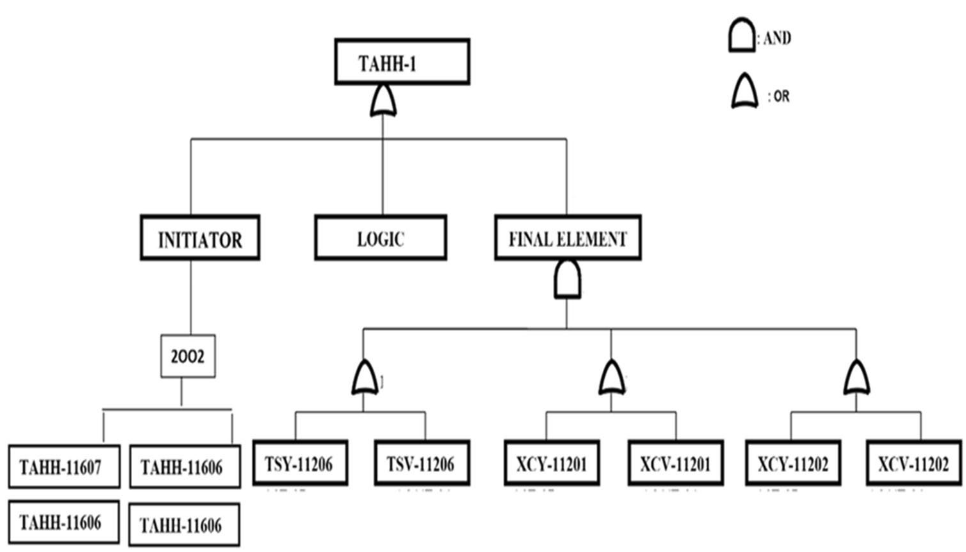


Fig. 3 Implementation of SIF TAHH-1 using FTA

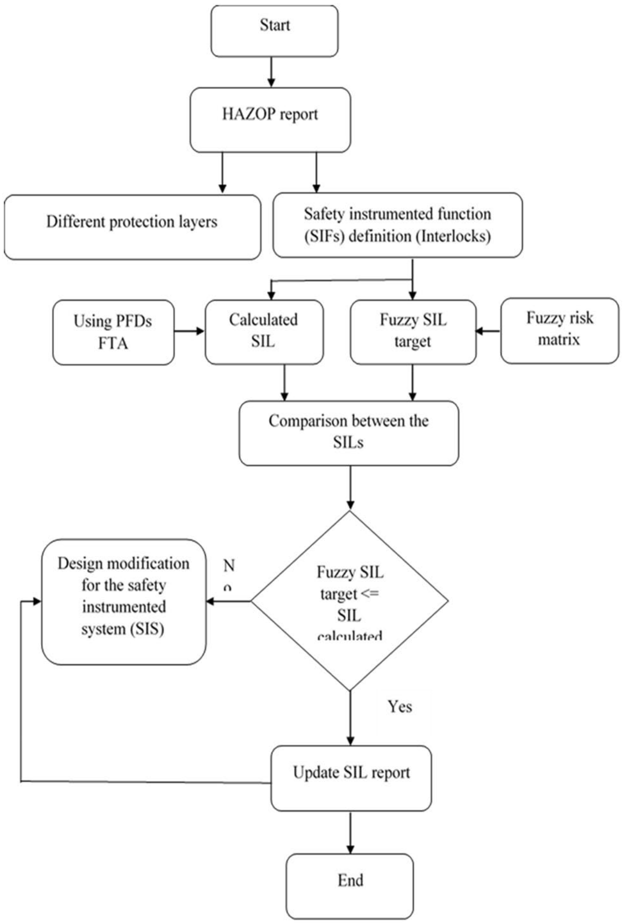


Fig. 4 Effective safety strategy based on fuzzy logic for risk assessment in an industrial plant

which are HAZOP and SIL. Such that we first define the safety instrumented functions required to bring the operation to a safe state using HAZOP study, and we will investigate the ability of the SIS to realize the safety goals using SIL. As it is mentioned in the previous sections two values of safety integrity levels should be defined, the first is the target SIL and we will use fuzzy inference engine to specify these values, after that we consider the calculated SIL which results from calculating the average PFD of the corresponding SIS. In the last stage, we will compare the results and hence whenever the target SIL is greater than the calculated SIL a design modification is required to meet to safety requirements (our design modification should lead a target SIL smaller or equal from the required SIL).

5.1 Fuzzy risk matrix implementation

The block diagram of Fig. 5 shows a general structure of a fuzzy controller that represents the fuzzy equivalent of the risk matrix

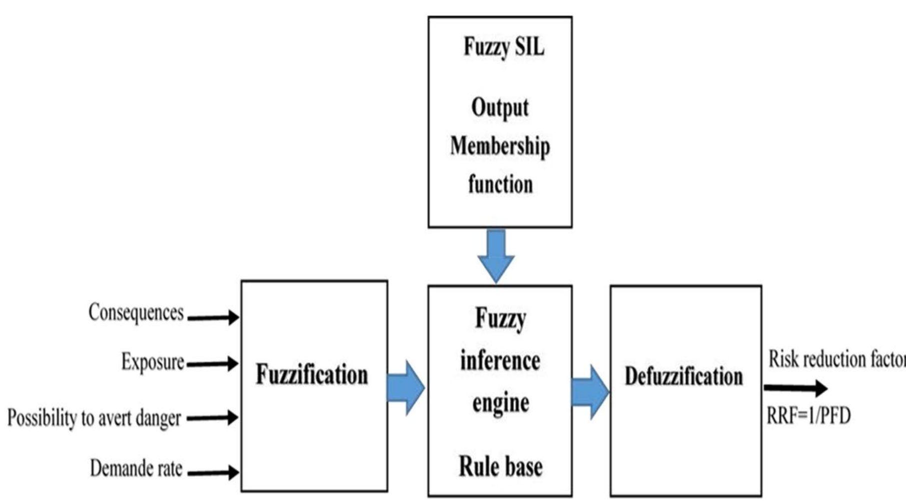
5.1.1 Scaling, fuzzy interval construction and membership function's shape determination

It should be mentioned that before implementing the algorithm and as it is a common practice in the design of a fuzzy logic controllers, for each linguistic variable a universe of discourse and a range of variations should be assigned. In this case the scaling of the intervals should be done to avoid computational errors and hence, bad interpretations of results.

Another important thing, the shape of any membership function is deduced based on many important factors in our case we choose the trapezoidal shape as a base shape (Fig. 6).

The linguistic term associated with this type is defined by the following Eq. (1) (Markowski et al. 2009):

Fig. 5 Fuzzy risk matrix implementation



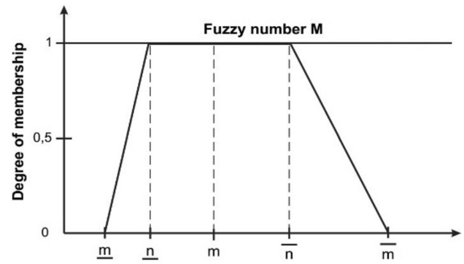


Fig. 6 Trapezoidal membership function

$$\mu_M(x) = \left\{ \begin{array}{cc} 0, & x \leq \underline{m} \\ \frac{x-\underline{m}}{\underline{n}-\underline{m}} & \underline{m} \leq x \leq \underline{n} \\ 1 & \underline{n} \leq x \leq \overline{n} \\ \frac{\overline{m}-x}{\overline{m}-\overline{n}} & \overline{n} \leq x \leq \overline{m} \\ 0 & \overline{m} \leq x \end{array} \right\} \quad (1)$$

The exact shape i.e. the edge calculation (defining the parameters (m, n, m, $\overline{n}$, *and* $\overline{m}$,) is based on the calculation of the fuzzy intervals.

In computing the fuzzy intervals, the following steps should be followed:

1. The determination of a scaled risk matrix since all needed values are well defined in the conventional risk matrix.
2. The transformation from ordinary matrix (values) to fuzzy intervals. (which is the reverse procedure of fuzzy interval mean value determination).

***Remark*:** The mean value of a fuzzy interval Q is well defined by (Dubois and Prade 1987). As follows: it is a closed interval bounded by the expectations calculated from its upper and lower distribution functions.

The above procedure is repeated with the risk matrix parameters (S, L, E, D, F, SIL), knowing that each parameter corresponds to fuzzy set with more than three linguistic variables (ex. S (six), L (six), E(six) F(three), D (three), and SIL (six)).

The definitions of S,L,E,D,F,SIL are previously given in Sect. 4.

The exact shapes are shown in the next sections.

5.1.2 The fuzzy system parameters

The following parameters should be specified,

- *The system's inputs*: four inputs for our algorithm are considered, these inputs are chosen following the guidelines for constructing the conventional risk matrix. These parameters are:
- *Consequences:* which means the resulted consequences when the safety instrumented function does not work, there are three categories of these consequences.

The first is (S), the effect on people where six linguistic variables are considered, S0, S1…. S5 the corresponding membership functions are given in Fig. 7

The second is the economic effects (L) and in this case six linguistic variables are considered which are L0, L1…L5, the membership functions are shown in Fig. 8.

Finally, the third parameter is the environmental effects (E) which also contains six linguistic variables E0, E1… E5, the corresponding membership functions are shown in Fig. 9.

Exposure (F): Duration of presence (exposure) of personnel in the area affected by the hazardous situation, three linguistic variables are assigned to this input F1, F2, F3 the corresponding membership functions are shown in Fig. 10.

Possibility to avert the danger (P): means Possibilities for the person(s) who may be injured to avert the hazardous situation. This considers the existence of alarming tools and possibility of escape from the area. Three linguistic variables are considered P1, P2 and P3 the corresponding membership functions are shown in Fig. 11.

Demand rate(D): this factor means the rate by which the demand is placed on the safety instrumented function or SIF. Five linguistic variables are considered D1, D2…D4. The corresponding membership functions are shown in Fig. 12.

The system's output: the output of our system is the safety integrity level and six linguistic variables are considered SIL1, SIL2, SIL3, SIL4, a (no special safety requirements) and NR (situation to be avoided). The corresponding membership functions are shown in Fig. 13.

5.1.3 The rule base

The rules base is constructed following the logical sequence of the conventional SIL table (Table 2) by translate it into fuzzy thinking (if ... then ... rule). A set of fuzzy IF-THEN rules forms the rule base engine. In fuzzy logic this engine serves as the brain of the fuzzy system, all other elements are used to execute these principles in a sensible and effective way. In our case for example for the personal health effect, the rule base engine is as follows:

IF the consequence S is S2 AND the exposure F is F2 AND the possibility to avert P is P3 AND Demand rate D is D4 THEN the outcome SIL is SIL2. And so on with all the rules.

The same for the economic effects, the rule base engine is constructed as follows:

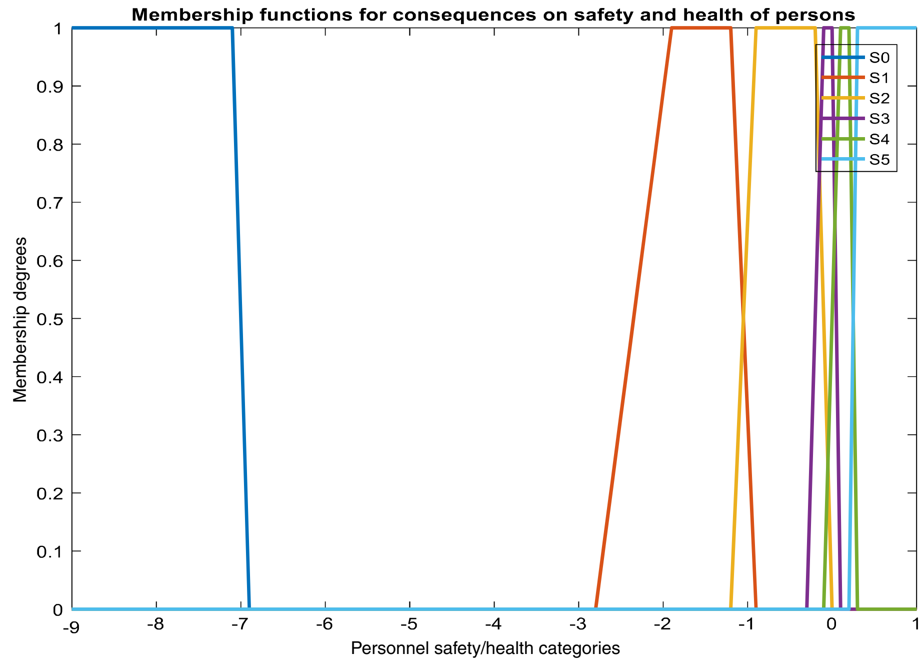


Fig. 7 Membership functions for consequences on safety and health of persons

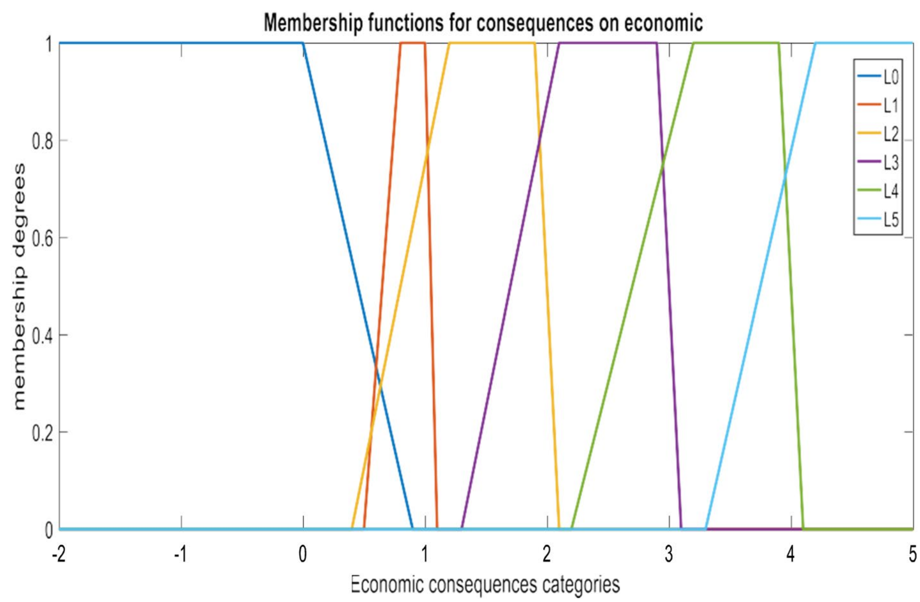


Fig. 8 Membership functions for consequences on economy

IF the consequence L is L2 AND demand rate D is D3 THEN the outcome SIL is SIL1.

Same for the Environment effects:

IF the consequence E is E2 AND demand rate D is D3 THEN the outcome SIL is SIL1.

Tables 6, 7 and 8 summarize the chosen rules.

6 Application for fired heater F-201101 CDU-unit, Adrar refinery Algeria

The under study fired heater belongs to ADRAR refinery located in the south of Algeria. The most important unit in this refinery is the CDU (crude distillation unit). The unit has a mission to separate the components of crude oil, and producing three semi-final products (Gases, Naphtha and Residues). Separation of these products is done in

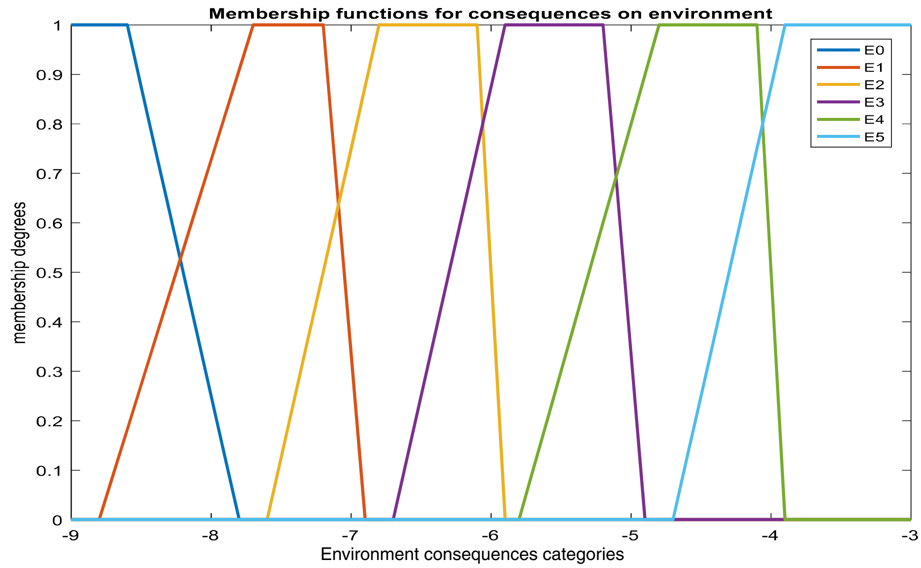


Fig. 9 Membership functions for consequences on environment

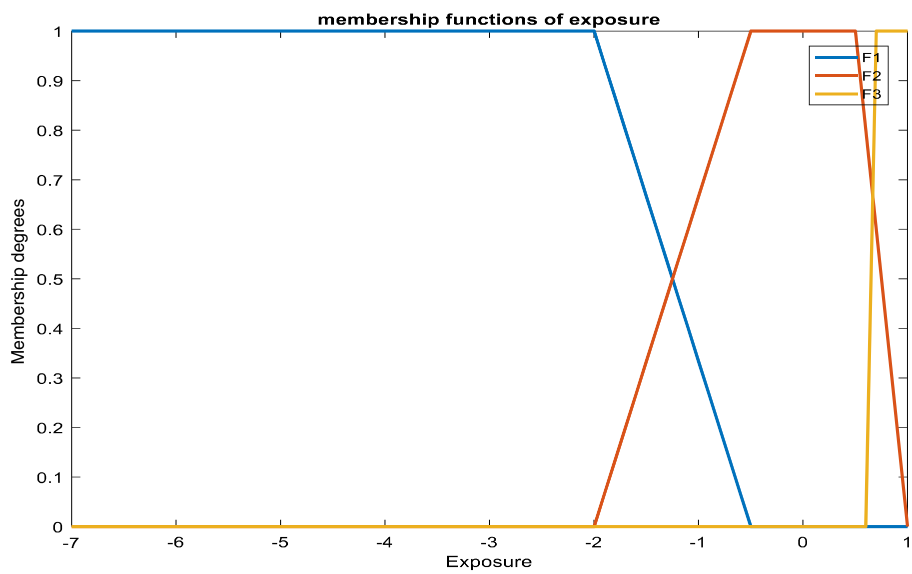


Fig. 10 Membership functions of exposure

distillation towers; the crude is heated to reach 365 °C in the Fired Heater F-201 101and after that is pumped to the distillation column through feed tray N°:14 (Bendib 2017)

6.1 Fired heater operation philosophy

In petrochemical refineries, fired heaters (Fig. 14) are used to heat up the crude to reach high temperatures (in our case 365 °C). For safe operation, the following parameters should be controlled:

- The product flow in each pass (in our case, the heater has two passes). The control is realized through simple control loops FIC (Flow Indicator Controller). In some heaters the flow in each pass combined with the skin temperature of the corresponding tubes are both used to control the flow. In this case we use ratio control principle.
- The temperature for both product and internal tubes: Concerning the product, this temperature should be controlled such that the set point is 365 °C, and this is done by the use of a cascade type controller, that controls the outlet temperature through the burners fuel gas pressure. For the tubes' temperature, special type sensors are used which called skin points. The skin temperatures are in direct relation with the product's flow inside the tubes in case there is no flow or less flow in the tubes, the skin temperature increases automatically.
- Pressure: fuel gas pressure in both burner and pilot lines and the pressure inside the heater's combustion room.

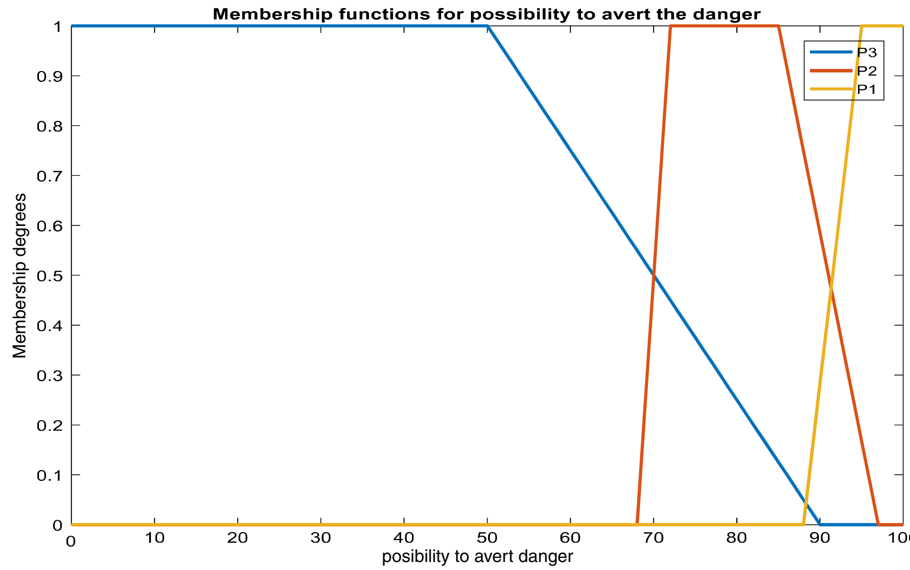


Fig. 11 Membership functions for possibility to avert the danger

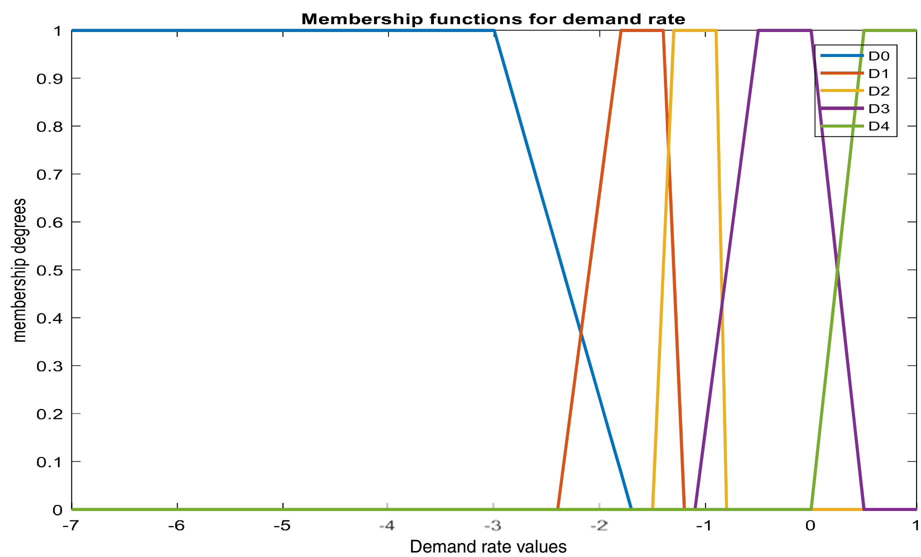


Fig. 12 Membership functions for demand rate

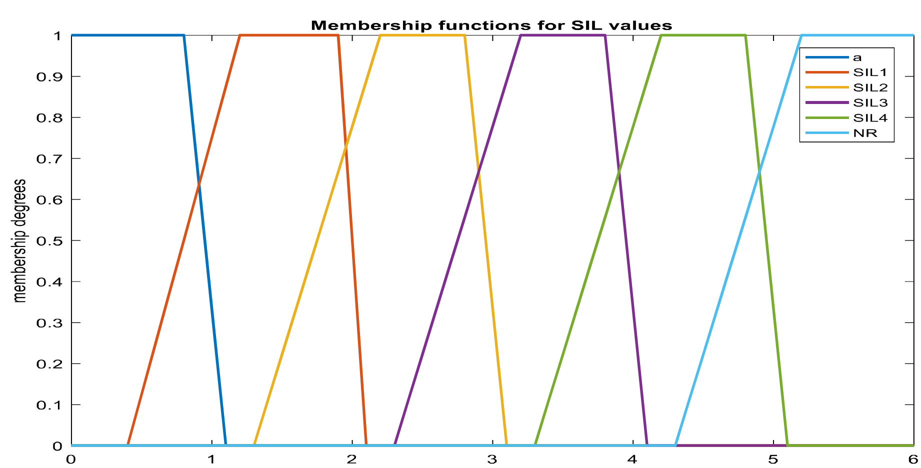


Fig. 13 Membership functions for SIL values

Table 6 Rule base engine for fuzzy risk matrix- Personal health effect

Rule	Consequences	Exposure	Possibility to avert	Demand rate	SIL
1	S2	F2	P3	D4	SIL2
2	S2	F3	P3	D4	SIL2
3	S2	F3	P2	D4	SIL2
4	S3	F2	P3	D4	SIL2
5	S3	F3	P3	D4	SIL3
6	S3	F3	P2	D4	SIL3
7	S3	F2	P3	D3	SIL2
8	S3	F3	P3	D3	SIL2
9	S3	F3	P2	D3	SIL2
10	S3	F1	P3	D4	SIL2
11	S3	F1	P2	D4	SIL2
12	S3	F2	P2	D4	SIL2
13	S3	F2	P1	D4	SIL2
14	S3	F3	P1	D4	SIL2
15	S4	F2	P3	D2	SIL2
16	S5	F2	P3	D1	SIL2
17	S5	F3	P3	D1	SIL2
18	S5	F3	P2	D1	SIL2
19	S5	F2	P3	D2	SIL2
20	S5	F3	P3	D2	SIL3
21	S5	F3	P2	D2	SIL3

Table 7 Rule base engine for fuzzy risk matrix-economic effects

Rule	Consequences	Demand rate	SIL
1	L2	D3	SIL1
2	L3	D4	SIL2
3	L3	D2	SIL1
4	L3	D3	SIL2
5	L4	D4	SIL3
6	L4	D1	SIL1
7	L4	D2	SIL2
8	L5	D3	SIL3
9	L5	D1	SIL2
10	L5	D2	SIL3

The above parameters are used as key words in HAZOP study to describe the safety-instrumented functions- SIFs-. Following the flow chart described in the above section, application of HAZOP study will give the safety-instrumented functions mentioned in Table 9. The case status in Table 7 means whether the function already exists in the plant or it is just a HAZOP recommendation for future work. A more detailed HAZOP report is given in (Bendib 2017) (Riad et al. 2018), where all guidewords are considered along with different scenarios.

Table 8 Rule base engine for fuzzy risk matrix- Environment effects

Rule	Consequences	Demand rate	SIL
1	E2	D3	SIL1
2	E2	D4	SIL2
3	E3	D2	SIL1
4	E3	D3	SIL2
5	E3	D4	SIL3
6	E4	D1	SIL1
7	E4	D2	SIL2
8	E4	D3	SIL3
9	E5	D1	SIL2
10	E5	D2	SIL3

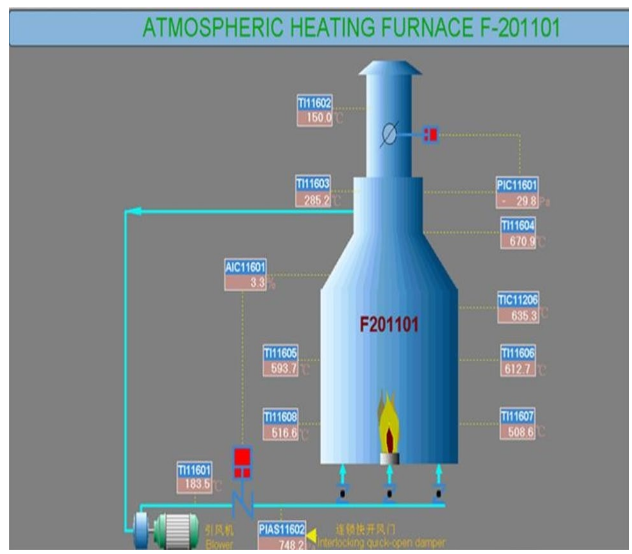


Fig. 14 Fired Heater F201101

6.2 The heater's emergency shutdown philosophy

Heater's safety is designed to simultaneously realize the following sequences in case of any deviation (through the activation of at least one of the previous safety functions)

1. Stop the feed of fuel gas by the closure the safety valve XCY-11201(fully closing)
2. Stop the product feed by the closure of the safety valve XCV-11202.
3. Full opening of the heater damper TSV-11206

Figures 3, 15 and 16 illustrate the implementation of the safety functions TAHH1, PAHH-2 and PAHH-3 using FTA analysis.

The PFD (the instruments' probability under demand) values for the existing instruments as furnished in the

Table 9 Deduced SIFs from HAZOP report

SIF	Definition	Status	Scenario
PS11203	Low/low pressure in the fuel gas and pilot gas lines	Existing	Burner can extinguish at low fuel gas pressure and possible flammable material accumulation inside the heater. There is a possibility of explosion during heater restart-up. The existing protection to avoid this scenario is explosion windows of the heater
TAHH 1	Skin temperature high/high in the tube	New	High/high temperature in the tube may lead to tube failure and explosion in case where the tube is damaged (presence of hydrocarbons with fire). The existing protection is the low pressure vapor to extinguish the fire inside the heater
FS11204 FS11205	Low/low flow of the crude in each pass	Existing	Low/low flow of the product in each pass will lead to increase in the skin temperature of the corresponding heater tube which will lead to tube damage. Fire and explosion is expected
PAHH-2	High/High alarm in the pressure of both fuel gas and pilot lines	New	Burner can extinguish at high/high fuel gas pressure as a result of gas blowing, and possible flammable material accumulation inside the heater. There is a possibility of explosion during heater restart-up
TS11207	High/High temperature in the heater box	Existing	Prolonged exposure to high temperature may cause tube failure which will lead to explosion and unit shutdown. High temperature of the crude may lead to perturbation of distillation column operation, and it may cause harm for the column internal in future
PAHH-3	High/High pressure in the heater box	New	Increasing the pressure inside the heater box may lead to explosion. The existing physical protection is the explosion windows

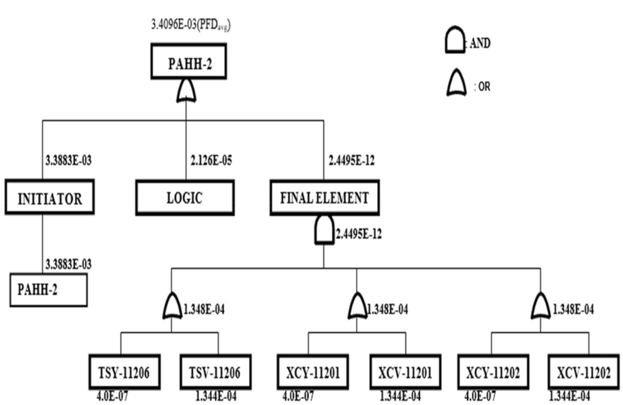


Fig. 15 Implementation of SIF PAHH-2 using FTA

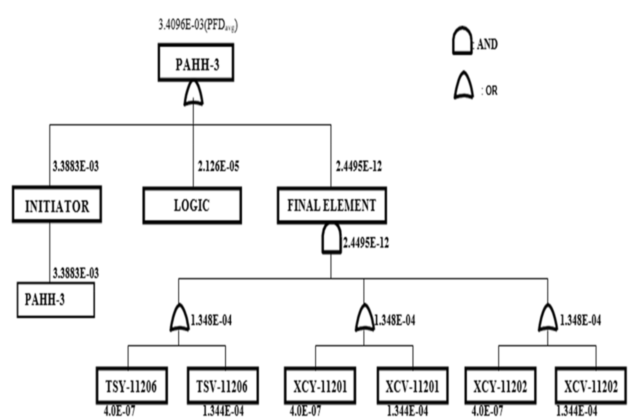


Fig. 16 Implementation of SIF PAHH-3 using FTA

Refinery documents (Report 2007) are summarized in Table 10. (Riad et al. 2018).

Remark Above values are used in to define the calculated SIL based on the calculation of the PFD average for each safety instrumented function. Table 7 summarizes the calculated SILs for all defined SIFs. Knowing in case of On–off valves (safety valves) we consider both values for PFD (PFD for the solenoid and the valve), which can be achieved using an OR logic function.

6.3 The fuzzy required SIL for the defined safety functions

In defining the required fuzzy (target) SIL the following tasks are performed (Ross 2016):

1. Using MAMDANI (min/Max) inference engine, we evaluate the rules
2. The aggregation between the rules is done via MAMDANI's rule

Table 10 PFD values for the existing instrument

Initiators		Logic solver		Final elements	
Type	PFD	Type	PFD	Solenoid valve	Valve
Pressure Transmitter	Simple 3.3883E-03 Voting 2oo3 8.1873E-06	TRICONEX TMR Triple Modular redundant	2.125E-05	High flow direct acting valve 4.0E-07	On–off valve 1.344E-04
Differential pressure transmitter (Flow)	Simple 6.7746E-03 Voting 2oo3 7.7764E-05				
Temperature	Simple 2.5411E-03 Voting 2oo3 6.0662E-06				

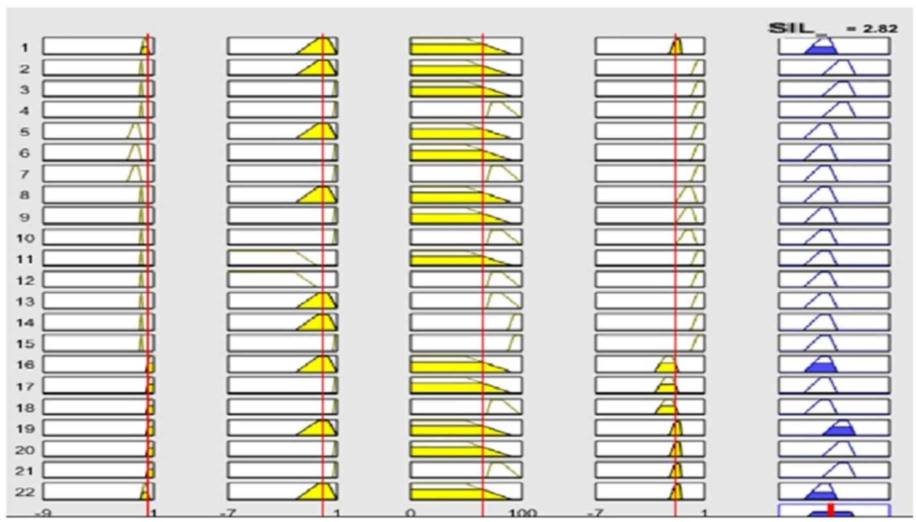


Fig. 17 The inference Engine for SIL determination (Rule base evaluation)-Personal health effect

3. At the end, the CENTROID is used in the defuzzification step to find the exact SIL values.
4. The Fuzzy toolbox in MATLAB is used to implement the algorithm.

The above steps are repeated for Personal, Economic and Environment effects of any safety- instrumented function. Figures 17, 18, 19 show the application the fuzzy engine to determine the Required SILs for the Safety function TAHH-1.

For other safety functions the results for the fuzzy target SIL are included in Table 11.

The following assumptions are considered in SIL determination process:

- In calculating the target SIL, the maximum value among the personal, economic and environment effects is chosen as the overall SIL. However, in case the results contain decimal numbers the value is rounded to the nearest one (if it is greater than 0.5 it is rounded to 1, whereas in case it is smaller than 0.5 it is rounded to zero).
- The tag number of the new SIFs are chosen randomly depending on its existence in the HAZOP report.

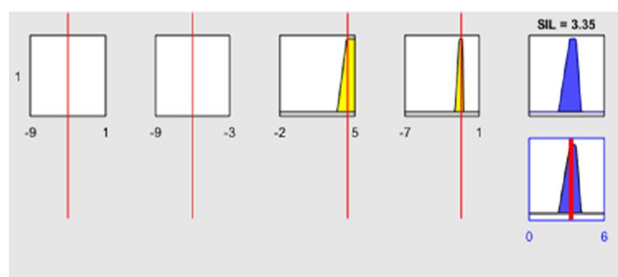


Fig. 18 The inference Engine for SIL determination (Rule base evaluation)-Economic effects

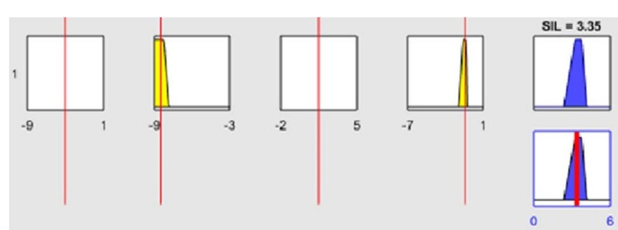


Fig. 19 The inference Engine for SIL determination (Rule Base evaluation)-Environment Effects

Table 11 PFD the calculated SIL versus Target SIL

SIF	Calculated SIL		Fuzzy Target SIL				Recommendations
	PFD	SILcal	Health	Economic	Environ ment	Over all SIL	
PS11203	3.4096E-03	2	0.48	2.35	0.474	2	Since the Target SIL equals to the calculated SIL, hence no design modification on the SIF component is required
TAHH 1	2.2431E-05	3	2.82	3.35	3.35	3	The same remark as above, no design modification is required
FS11204 FS11205	6.7959E-03	2	3	3.35	0.474	3	The calculated SIL is smaller than the Target SIL hence design modification is required. In this case, we recommend the use of voting system (2oo3), which designed using threeinitiators
	2oo3 vote 1.0E-04	3					The condition is satisfied the target SIL equals the calculated SIL
PAHH-2	3.4096E-03	2	0.502	2.35	0.469	2	Since the Target SIL equal to the calculated SIL so no design modification on the SIF component is required
TS11207	3.5624E-03	2	2.47	2.35	0.518	2	Since the Target SIL equal to the calculated SIL so no design modification on the SIF component is required
PAHH-3	3.409E-03	2	2.82	3.35	0.469	3	The calculated SIL is smaller than the Target SIL hence design modification is required in this case we recommend the use of the vote (2oo3) between three initial sensors
	2oo3 vote 2.95E-05	3					The condition is satisfied SIL target equal SIL calculated

- For the SIF TAHH-1 the initiator is chosen as 2oo2 (two out of two) voting configuration, because generally when we deal with the skin points temperature, the tube's temperature is measured in both the input and the output of each pass

7 Conclusion

In this paper, we have introduced a comprehensive framework for conducting risk assessments in industrial plants, with a primary focus on safety. This innovative approach combines three well-established methods, namely HAZOP (Hazard and Operability Study), SIL (Safety Integrity Level), and FTA (Fault Tree Analysis). By integrating these methods, we can effectively identify potential hazards, determine the necessary safety integrity levels for different safety-instrumented functions, and make informed decisions regarding the architecture of the safety-instrumented system. To address uncertainties that often arise due to the lack of information or data during the SIL target evaluation stage, we have employed advanced Fuzzy logic methods in the construction of the Risk matrix. Fuzzy logic proves to be a powerful tool in dealing with these uncertainties, particularly when expert judgment plays a crucial role, and the nature of each safety level is described in approximate terms within industry standards, based on potential accident consequences. By integrating these scientific methodologies, our framework offers a robust and comprehensive approach to risk assessment in industrial plants, promoting safety measures and more effective decision-making processes. The proposed approach has been implemented to enhance the safety measures of a fired heater situated within the ADRAR refinery, located in the southern region of Algeria. When dealing with risk assessment in fired heaters, it is crucial to pay special attention due to the existence of three elements necessary for the occurrence of a fire or explosion: oxygen, energy, and hydrocarbons. A detailed HAZOP report for the understudy fired heater is indicated in the study conducted by (Bendib 2017), where all the required safety instrumented function to ensure a safe operation of the fired heater are listed. The MAMDANI inference engine is used in the rule base calculation, and target SIL determination for each SIF. Whereas the FTA method is used in the calculated SIL determination. The PFDs of each component are defined in the Refinery construction report (Report 2007 the instruments data sheets). The comparison between the values of the calculated SIL and target SIL, and HAZOP recommendations give the following results:

- More safety-instrumented functions should be implemented in the emergency shutdown system, such as TAHH1, PAHH2 and PAHH3.
- A design modification should be added in some of the existing instrumented functions to meet the SIL requirement (FS11204, FS11205), here we recommend the use of three sensors with a voting configuration 2out of 3.
- For the new SIF PAHH3 three initiators with a voting 2oo3 configuration should be envisaged.
- For the new SIF TAHH-1 two sensors with a 2oo2 vote configuration (one in the entrance and the other in the output of each pass) should be considered

Finally, it is important to highlight that the approach presented herein holds significant potential as a robust tool for enhancing the safety of industrial plants. However, further theoretical analysis is warranted to refine and enhance the approach, particularly considering the presence of uncertainties. These uncertainties can arise not only in the determination of the risk matrix but also in the construction of the Fault Tree Analysis (FTA). To address these uncertainties, the application of fuzzy logic in the FTA construction stage (as suggested by Kumar and Kaushik in 2020) or the utilization of fuzzy logic in the HAZOP study (as proposed by Cheraghi et al. in 2022) may prove beneficial.

By incorporating these theoretical advancements, the approach can be strengthened, allowing for more accurate and effective safety assessments in industrial plants. This, in turn, will contribute to mitigating risks and ensuring the overall safety of industrial operations.

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Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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References

Ahn J, Noh Y, Joung T et al (2019) Safety integrity level (SIL) determination for a maritime fuel cell system as electric propulsion in accordance with IEC 61511. Int J Hydrogen Energy 44:3185–3194. https://doi.org/10.1016/j.ijhydene.2018.12.065

Akyuz E, Arslan O, Turan O (2020) Application of fuzzy logic to fault tree and event tree analysis of the risk for cargo liquefaction on board ship. Appl Ocean Res 101:102238. https://doi.org/10.1016/j.apor.2020.102238

Andrews JD, Dunnett SJ (2000) Event-tree analysis using binary decision diagrams. IEEE Trans Reliab 49:230–238. https://doi.org/10.1109/24.877343

Badida P, Balasubramaniam Y, Jayaprakash J (2019) Risk evaluation of oil and natural gas pipelines due to natural hazards using fuzzy fault tree analysis. J Nat Gas Sci Eng 66:284–292. https://doi.org/10.1016/j.jngse.2019.04.010

Bendib R, Zennir Y, Mechhoud E-A, Bouziane S (2019) Risk assessment for a steam generator (1050 G1) Skikda refinery Algeria, using HAZOP and RQA methods. In: 2019 International Conference on Advanced Systems and Emergent Technologies (IC_ASET). pp 262–267

Bendib R (2017) Optimization and improvement of the overall performance of an industriale Plant. PHD thesis M'hamed Bougara university Algeria

Chang K, Kim S, Chang D et al (2015) Uncertainty analysis for target SIL determination in the offshore industry. J Loss Prev Process Ind 34:151–162. https://doi.org/10.1016/j.jlp.2015.01.030

Chen L, Fan D, Zheng J, Xie X (2022) Functional safety analysis and design of sensors in robot joint drive system. Machines 10:360. https://doi.org/10.3390/machines10050360

Cheraghi M, Eslami Baladeh A, Khakzad N (2019) A fuzzy multi-attribute HAZOP technique (FMA-HAZOP): application to gas wellhead facilities. Saf Sci 114:12–22. https://doi.org/10.1016/j.ssci.2018.12.024

Cheraghi M, Eslami Baladeh A, Khakzad N (2022) Optimal selection of safety recommendations: a hybrid fuzzy multi-criteria decision-making approach to HAZOP. J Loss Prev Process Ind 74:104654. https://doi.org/10.1016/j.jlp.2021.104654

Choi J-Y, Byeon S-H (2020) HAZOP methodology based on the health, safety, and environment engineering. IJERPH 17:3236. https://doi.org/10.3390/ijerph17093236

Chun M-H, Ahn K-I (1992) Assessment of the potential applicability of fuzzy set theory to accident progression event trees with phenomenological uncertainties. Reliab Eng Syst Saf 37:237–252. https://doi.org/10.1016/0951-8320(92)90130-D

Crawley F, Preston M, Tyler B (2008) HAZOP : guide to best practice: guidelines to best practice for the process and chemical industries. IChemE

Cruz-Campa H, Cruz-Gómez M (2010) Determine sis and SIL using HAZOPS. Process Saf Prog 29:22–31. https://doi.org/10.1002/prs.10293

Cui L, Shu Y, Wang Z et al (2012) HASILT: an intelligent software platform for HAZOP, LOPA, SRS and SIL verification. Reliab Eng Syst Saf 108:56–64. https://doi.org/10.1016/j.ress.2012.06.014

Cui Z, Tian W, Wang X et al (2019) Safety integrity level analysis of fluid catalytic cracking fractionating system based on dynamic simulation. J Taiwan Inst Chem Eng 104:16–26. https://doi.org/10.1016/j.jtice.2019.08.008

Dernoncourt F (2013a,b) Introduction to fuzzy logic, Lecture notes MIT. USA

Dubois D, Prade H (1987) The mean value of a fuzzy number. Fuzzy Sets Syst 24:279–300. https://doi.org/10.1016/0165-0114(87)90028-5

Hong T-P, Lee C-Y (1996) Induction of fuzzy rules and membership functions from training examples. Fuzzy Sets Syst 84:33–47. https://doi.org/10.1016/0165-0114(95)00305-3

Hu J, Zhang L, Cai Z, Wang Y (2015) An intelligent fault diagnosis system for process plant using a functional HAZOP and DBN integrated methodology. Eng Appl Artif Intell 45:119–135. https://doi.org/10.1016/j.engappai.2015.06.010

(2003) IEC 61511–1:2016 IEC Webstore cyber security, functional safety, smart city, smart manufacturing, industrie 4.0, industry 4.0, automation. https://webstore.iec.ch/publication/24241. Accessed 24 Dec 2022
Jeerawongsuntorn C, Sainyamsatit N, Srinophakun T (2011) Integration of safety instrumented system with automated HAZOP analysis: an application for continuous biodiesel production. J Loss Prev Process Ind 24:412
Jose LD (2013) Integral management of abnormal situations in complex process plants. PHD thesis Poltecnica university Madrid. PhD thesis
Joubert F, Steyn E, Pretorius L (2021) Using the HAZOP method to conduct a risk assessment on the dismantling of large industrial machines and associated structures: case study. J Constr Eng Manag 147:05020021. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001942
Kabir S, Papadopoulos Y (2018) A review of applications of fuzzy sets to safety and reliability engineering. Int J Approximate Reasoning 100:29–55. https://doi.org/10.1016/j.ijar.2018.05.005
Kletz TA (2018) Hazop & Hazan: identifying and assessing process industry hazards, 4th edn. CRC Press, Boca Raton
Kumar M, Kaushik M (2020) System failure probability evaluation using fault tree analysis and expert opinions in intuitionistic fuzzy environment. J Loss Prev Process Ind 67:104236. https://doi.org/10.1016/j.jlp.2020.104236
Liu C, Yang S, Cui Y, Yang Y (2020) An improved risk assessment method based on a comprehensive weighting algorithm in railway signaling safety analysis. Safety Sci 128:104768. https://doi.org/10.1016/j.ssci.2020.104768
Macdonald D (2004) Practical hazops. Elsevier, Trips and Alarms
Marhavilas PK, Filippidis M, Koulinas GK, Koulouriotis DE (2020a) A HAZOP with MCDM based risk-assessment approach: focusing on the deviations with economic/health/environmental impacts in a process industry. Sustainability 12:993. https://doi.org/10.3390/su12030993
Marhavilas PK, Filippidis M, Koulinas GK, Koulouriotis DE (2020) An expanded HAZOP-study with fuzzy-AHP (XPA-HAZOP technique): application in a sour crude-oil processing plant. Safety Sci 124:104590. https://doi.org/10.1016/j.ssci.2019.104590
Markowski AS, Mannan MS, Bigoszewska A (2009) Fuzzy logic for process safety analysis. J Loss Prev Process Ind 22:695–702. https://doi.org/10.1016/j.jlp.2008.11.011
Marszal EM, Scharpf EW (2002) Safety Integrity Level Selection - Systematic Methods Including Layer of Protection Analysis. ISA: The Instrumentation, Systems, and Automation Society (May 1, 2002) ISBN-10: 1556177771.
Mendel JM (1995) Fuzzy logic systems for engineering: a tutorial. Proc IEEE 83:345–377. https://doi.org/10.1109/5.364485
Mohan C (2019) An introduction to fuzzy set theory and fuzzy logic, Second Edition, New edition, Second. MV Learning
Nigel H (2004) Guidelines for process hazards analysis, hazards identification and risk analysis, 1st edn.
Nolan DP (2014) Safety and security review for the process industries: application of HAZOP, PHA, what-IF and SVA reviews, 4th edn. Gulf Professional Publishing, Amsterdam
Passino KM, Yurkovich S (1998) Fuzzy control. Addison-Wesley, Menlo Park, Calif
Raeesivand A, Kasaeyan M (2019) New fuzzy uncertainty assessment approach of target SIL evaluation by risk graph optimization. Life Cycle Reliab Saf Eng 8:291–302. https://doi.org/10.1007/s41872-019-00093-0
Ramzan N, Compart F, Witt W (2007a) Application of extended Hazop and event-tree analysis for investigating operational failures and safety optimization of distillation column unit. Process Saf Prog 26:248–257. https://doi.org/10.1002/prs.10202
Ramzan N, Compart F, Witt W (2007b) Methodology for the generation and evaluation of safety system alternatives based on extended Hazop. Proc Safety Prog 26:35–42. https://doi.org/10.1002/prs.10161
Report (2007) Report- SONATRACH Algeria -Adrar Refinery Project and operation Manual
Riad B, Hamid B, Hind R, Youcef Z (2018) Design Of an integration Frame HAZOP-SIL for safety Optimization of a Fired Heater. In: 2018 international conference on electrical sciences and technologies in maghreb (CISTEM). pp 1–6
Ross TJ (2016) Fuzzy logic with engineering applications, 4th edn. Wiley
Sal R, Nait-Said R, Bourareche M (2017) Dealing with uncertainty in effect analysis of test strategies on safety instrumented system performance. Int J Syst Assurance Eng Manag 8:1945–1958
Salaheldine Darwish A, Salem Mansour M, Farag H, Ezzat KH (2020) Applying LOPA and fuzzy logic to identify SIL requirement for safety critical functions in a direct reduction iron industry. Alex Eng J 59:3575–3585. https://doi.org/10.1016/j.aej.2020.06.003
Simon D (2002) Sum normal optimization of fuzzy membership functions. Int J Unc Fuzz Knowl Based Syst 10:363–384. https://doi.org/10.1142/S0218488502001533
Singh P, Singh LK (2021a) Engineering education for development of safety-critical systems. IEEE Trans Educ 64:398–405. https://doi.org/10.1109/TE.2021.3062448
Sotoodeh K (2019) Safety integrity level in valves. J Fail Anal Preven 19:832–837. https://doi.org/10.1007/s11668-019-00666-2
Suresh PV, Babar AK, Raj VV (1996) Uncertainty in fault tree analysis: a fuzzy approach. Fuzzy Sets Syst 83:135–141. https://doi.org/10.1016/0165-0114(95)00386-X
Suzuki T, Izato Y, Miyake A (2021) Identification of accident scenarios caused by internal factors using HAZOP to assess an organic hydride hydrogen refueling station involving methylcyclohexane. J Loss Prev Process Ind 71:104479. https://doi.org/10.1016/j.jlp.2021.104479
Voskoglou M (ed) (2021) Fuzzy sets, fuzzy logic and their applications 2020. MDPI - Multidisciplinary Digital Publishing Institute, Basel
Wang L-X (1997) A course in fuzzy systems and control. Prentice Hall PTR, Hoboken
Zhang Y, Zhang W, Zhang B (2015) Automatic HAZOP analysis method for unsteady operation in chemical based on qualitative simulation and inference. Chin J Chem Eng 23:2065–2074. https://doi.org/10.1016/j.cjche.2015.10.004
Jin Zhao, Bose BK (2002) Evaluation of membership functions for fuzzy logic controlled induction motor drive. In: IEEE 2002 28th annual conference of the industrial electronics society IECON 02 1:229–234. https://doi.org/10.1109/IECON.2002.1187512

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