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A FIS Approach to Prioritize Risks in a Chemical Industry

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Abstract: - In this paper, a Fuzzy Inference System (FIS) based risk analysis tool is presented to prioritize the identified potential risks at a chemical industry. The tool uses a Bow-tie analysis and a Fuzzy Inference System to analyze and prioritize a risk by computing its score. The risks, risk factors, and impacts are identified based on reported events and expert's knowledge. Bow-tie analysis is used to determine the factors that cause the occurrence of a risk and the impacts of a risk. Fuzzy estimates for the risk factors and impacts are obtained from an expert. The developed Mamdani FIS is used to compute the risk score. The developed FIS risk analysis tool is applied to assess the risks in a chemical industry. Based on the risk score, risks ranking is done in the chemical industry which helps in taking the required measures in advance to avoid the occurrence of risk events.

Key-Words: - Bow-Tie Analysis, Fuzzy Inference System, Risk Analysis, Risk Score

I. INTRODUCTION

In today's Manufacturing environment, Risk analysis plays an important role. The increasing variety of products manufactured by chemical process industries has made it more and more common for these industries to have serious consequences. One of the critical issues in the design and operation of chemical plants is safety. Unfortunately it has been overlooked for a very long time. The occurrence of catastrophic accidents such as Seveso in 1976, Bhopal in 1984, Flixborough in 1974, Piper Alpha in 1988, Longford in 1998 etc... resulted in lower public acceptance of chemical industry and led to a development of new safety standards and regulations. The science of risk assessment (RA) is defined as “a process, which includes both qualitative and quantitative determination of risks and their social evaluation” [5]. A large number of industries has been commissioned and many accidents came to light. This phenomenon increases the importance of RA.

Now it is necessary for chemical companies to conduct systematic analyses to convince regulatory agencies and the general public that their technologies are safe. This can be done by identifying the Crucial risks in the industry and design risk mitigation strategies in advance to avoid the occurrence of risk events. Risk management should be able to identify, measure and prioritize different risks in an industry, develop proper mitigation strategies, monitor and control these risks. Risk management provides processes for determining the risks and prepares the company to respond to them.

A. Risk Analysis

Occupational health and safety management program dedicates a substantial effort to risk analysis. This includes being conscious of risks, recognizing who might be at risk, deciding if existing control measures are satisfactory or if additional measures should be implemented, and protecting against injuries or illness. When executed at the designing or planning stage, prioritizing risks and the necessary control measures are essential to set up the plan. Many methods, such as: root cause analysis, failure mode effect analysis, Bow-tie analysis and others exist to perform risk analysis, [2], [4]. Bow-tie analysis is a risk analysis instrument based on the principles of event tree analysis and fault tree analysis [9]. Event tree analysis - "is a forward, bottom up, logical modelling technique for both success and failure that explores responses through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis". Fault tree analysis - "is a top down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine series of lower - level events" [1].

The components of Bow-tie analysis diagram are risk factors, risk events, impacts and risk reducers. The causes that initiate a risk event to happen in the system are risk factors. Risk impact is the consequence of a risk event on the system. Each risk event is occurred due to multiple risk factors and has a set of impacts. There are two types of risk reducers: preventive barriers and protective barriers. "Preventive barriers are used to reduce the probability of occurrence of a risk and protective barriers are used to minimize the impact of a risk event on the system" [1].

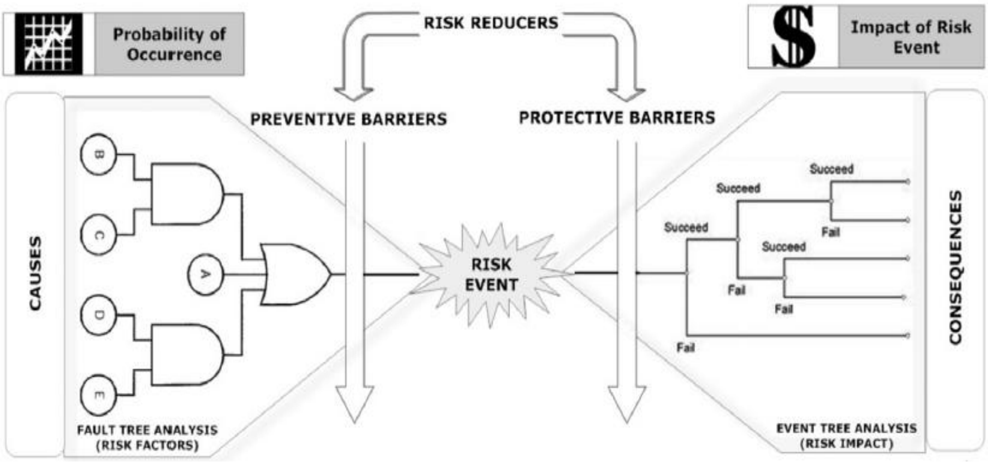

***Figure 1** Diagrammatic representation of the Bow-tie analysis [1].*

B. Fuzzy Logic

Today, intelligent system techniques from the soft computing field have proven to be very effective in solving many real-world problems. Zadeh in [10] proposed the concept of fuzzy logic. This multi valued logic is introduced to deal with vague data. This represents human thinking and interpretation when algorithm making decision is not possible; often decisions are made in a comparative and probabilistic manner. Fuzzy inference system uses the concepts of fuzzy sets, fuzzy if - then rules and fuzzy reasoning altogether. Some of the available and widely used intelligent techniques include: Artificial Neural Networks - (ANNs), Fuzzy Logic - (FL) and General Algorithms - (GAs), [3]. According to [10] "fuzzy set is a class of objects with a continuum of grades of membership and can be mathematically expressed as : If X is a collection of objects denoted generically by x, then a fuzzy set A in X is defined as a set of ordered pairs:

$$A = \{(x, \mu_A(x)) / x \in X\},$$

where $\mu_A(x)$ is called the membership function (MF) for the fuzzy set A. The MF maps each element of X to a membership grade (or membership value) between 0 and 1". In a classical set, the membership function value is strictly zero or one and has crisp boundaries. Whereas in fuzzy set, the value can be between zero to one and has fuzzy boundaries [10]. "As the complexity of a system increases, our ability to make precise and yet significant statements about its behaviour diminishes until a threshold is reached beyond which precision and significance become almost mutually exclusive characteristics" [3]. Due to this belief, Zadeh [10], suggested the concept of linguistic variables. The concept of linguistic variable is explained by using the following example.

Example:
X(temperature) = {less high, high, more high}
Y (room feels) = {less warm, warm, more warm}

In this example, "temperature" and "room feels" are linguistic variables and the linguistic values are "less high", "high", "more high", "less warm", "warm", "more warm". Each linguistic value is defined by a fuzzy set. These fuzzy sets are defined by the characterized membership functions. "A fuzzy set is completely characterized by its Membership Function (MF)" [10]. They can be defined either in one dimension or in two dimension depending upon the type of problem. The work reported herein used Gaussian membership function. The main element in fuzzy logic to express the pieces of human knowledge is fuzzy rule. Fuzzy rules are similar to "IF….THEN" rules. The format of a fuzzy rule is as follows [3]:

"IF x is A THEN y is B",

where A and B are linguistic values defined by fuzzy sets [3]. The antecedent is "x is A" and the consequence is "y is B". These rules are defined based on the available expert knowledge or historical data or literature available in a particular research area. If a system is designed with more number of fuzzy rules from various resources, then the uncertainties in that system can be reduced [3].

The basic components of a Fuzzy inference system are Rule base, data base and reasoning mechanism [3].

Rule base - This contains a set of well defined fuzzy if-then rules.

Data base - It defines the different membership functions that are used in the Fuzzy if-then rules.

Reasoning Mechanism - This performs the inference procedure upon the rules and given facts to derive a conclusion.

FIS takes either fuzzy inputs or crisp inputs. The FIS output can be either crisp or fuzzy depending upon the type of FIS. In this research, Mamdani FIS was used. It takes both crisp inputs and fuzzy inputs but gives only fuzzy sets as output. Hence defuzzification is required to obtain a crisp value that best represents the output fuzzy set. This work used centroid defuzzification method. Many decision making methodologies are based on Fuzzy Logic. Fuzzy Inference Systems - (FIS) have the ability to handle real world problems that are based on user knowledge and experience and can also deal with uncertain, incomplete and vague data [1]. The purpose of selecting intelligent techniques is to create a convenient user interface and reduce the work done by the user.

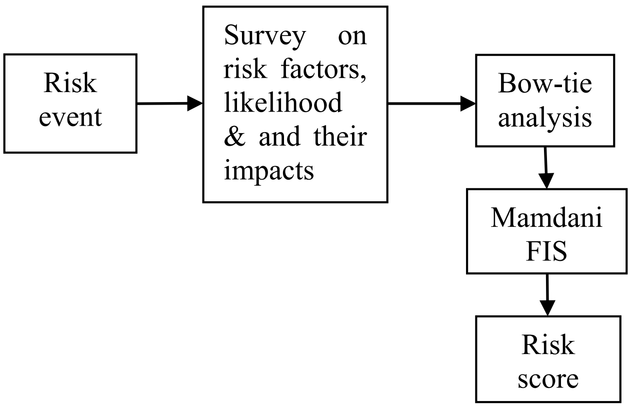

Figure 2 *Steps involved in FIS risk analysis tool*

II. PROPOSED FRAMEWORK

Risk event is caused by a set of risk factors and impact factors. Risks occur because of uncertainty in future. The level of uncertainty depends upon the amount and type of information available on the likelihood and impact of risks.

Reducing the uncertainty has an economic value. It also improves the risk management decisions. To reduce the uncertainty, a fuzzy inference system was used in the framework. The framework to develop the FIS risk analysis tool is shown in Fig. 2.

The steps involved in designing the FIS risk analysis tool are as follows:

A. Identification of risk events (RE), risk factors (RF) contributing the risk events and risk impacts (IMP)

In this step, major risk events that can occur in the industry are identified. Identification of risk events can be done in many ways, e.g. based on the history of risk events that happened in the industry previously or by conducting interviews to the experienced employees working in the industry or from the available literature resources. After identifying the risk events, major risk factors that contributes to the risk event and impacts of the corresponding risk events are gathered. Each risk event can have one or more risk factor and also one or more impact. Bow-tie analysis is performed. Bow-tie diagrams are used to show the links between the risk factors, risk event and impacts. It is the best way to communicate risk assessment in a simple and effective manner.

B. Risk score calculation using Fuzzy inference system (FIS)

After identifying risks, it is important to control and monitor those risks for the smooth function of the industry. For each risk factor a fuzzy estimate of risk probability (likelihood) and risk impact are obtained from the experts. Risk score of a risk event is the combination of Probability of occurrence score and impact score. Calculating the risk score helps in prioritizing the risks and appropriate mitigation plans can be implemented. This work considers both risk factors and impacts of a risk event to calculate risk score using Mamdani fuzzy inference system. By using MATLAB 2010 a package [7], a Mamdani FIS is applied in different scenarios. Each FIS shown in the Figures 3, 4, and 5 has different rules from each other that are based on their function. All the membership functions are Gaussian, [3], and the de-fuzsification method is the centroid area. The Risk score calculation involves following steps:

Step - 1

Probability of occurrence score of a risk event is calculated by giving probability of occurrence of its risk factors as inputs to the Mamdani FIS. FIS gives the output based on the fuzzy IF-THEN rules that are defined based on the human expertise. Suppose a Risk event RE- 1 is caused due to two risk factors, RF-1 and RF-2, then the design to compute probability of occurrence score is as shown below Fig. 3.

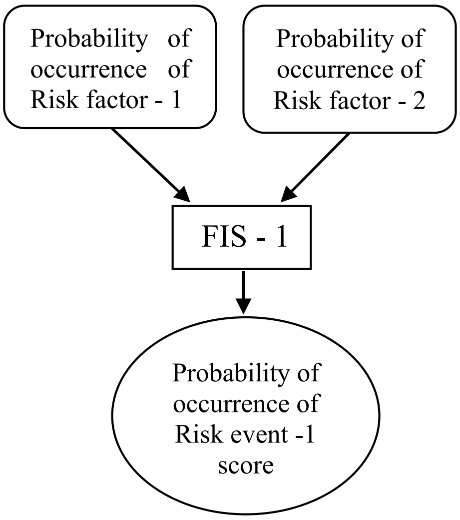

Figure 3. *Probability of occurrence score calculation of a risk event considering probability of occurrence of corresponding risk factors - Left side: inputs, Right side: output*

Step - 2

Impact score of a risk event is calculated by giving the intensity level of each impact as inputs to the FIS. The output is computed based on the defined fuzzy if-then rules. Suppose the Risk Event RE-1 has two Impacts, IMP-1 and IMP-2, then the Impact score of a RE-1 is computed as below.

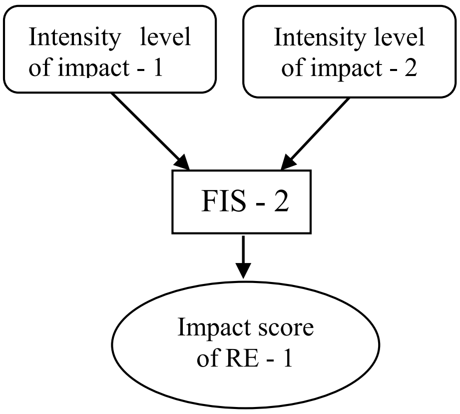

Figure 4*. Impact score calculation of a risk event considering Intensity levels of the corresponding risk event impacts- Left side: inputs, Right side: output*

Step – 3

Finally, Risk score is calculated by using Probability of occurrence score and Impact score as inputs to Mamdani FIS.

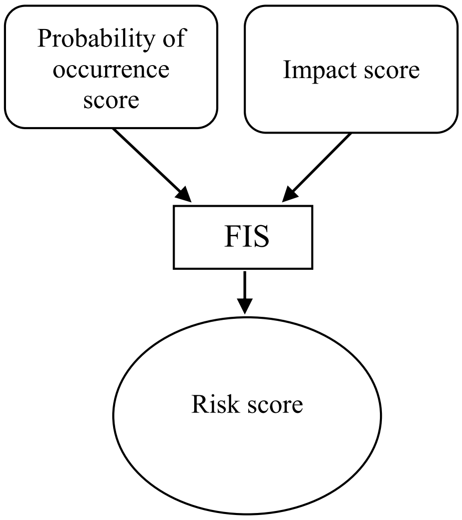

Figure 5 *score calculation of a risk event considering both Probability of occurrence score and Impact score- Left side: inputs, Right side: output*

C. Prioritization and monitoring risks

A case study in [1], on a chemical process industry has been considered in this paper. There are many risks, risk factors and impacts in a chemical industry. Hence there are many blocks as explained above for calculating Probability of occurrence score, Impact score and Risk score. All these blocks are integrated into a single framework, which is explained in the Appendix section. It is important to notice that 15 FIS have been developed. The last FIS-15,that calculates the Risk Score considers the outputs for the 7 FIS that evaluate the Risk factors; and 7 FIS that evaluate the Risk Impacts. Based on the computed risk score, the risks are prioritized. Risk events with high risk scores are identified, and proper mitigation strategies are applied in order to avoid the risk events to happen in the industry.

III. CASE STUDY

The proposed FIS risk analysis tool was applied on a paint manufacturing industry. The data required to implement the FIS risk analysis tool is acquired from the journal "Integrating lean principles and fuzzy Bow-tie analysis for risk assessment in chemical industry" [1].

A. Identification: In [1] it is identified seven potential risks in the chemical process industry based on the questionnaires and interviews held to five different workers at various levels. The identified potential risks are as follows:

- Non-confirming Product – R1
- Personal Injuries – R2
- Fire risk – R3
- Exposure to toxic materials – R4
- Leakage of chemicals – R5
- Explosion Risk – R6
  The Tables 2 & 3 shows the fuzzy estimates for risk likelihood, Impact and Risk score. Risk Probability and impact score for each

Based on the expert's Knowledge and survey, the risk factors and impact factors for the identified risks are listed in the Table 1.

Estimating the impact and likelihood values is often not accurate due to the difficulty in acquiring the adequate data. For this reason fuzzy sets and fuzzy inference system is used to improve the accuracy of the estimates.The Tables 2 & 3 shows the fuzzy estimates for risk likelihood, Impact and Risk score. Risk Probability and impact score for each identified risk in the industry is estimated by taking risk factors and impacts respectively as inputs to the Mamdani fuzzy inference system as shown in Fig. 6.

Table 1 Risk factors and impacts

Risks	Risk factors	Risk impacts
R1	F11 = Release of wrong raw materials F12 = Addition of wrong chemical into certain batch by mistake F13 = Insufficient cleaning of tanks & pipes	L11 = Customer dissatisfaction L12 = Loss of reputation L13 = Waste of money
R2	F21 = Safety procedures not followed by an employee F22 = Lack of awareness and supervision	L21 = Absence of work L22 = Compensation L23 = Medication costs
R3	F31 = A cigarette lighted by a visitor in production area F32 = Electrostatic spark F33 = Electrical spark	L31 = Fire L32 = Explosion
R4	F41 = Dealing with hazardous chemicals for long time F42 = Safety equipment not wore by worker	L41 = Infection to operators L42 = Compensation L43 = Medication
R5	F51 = Float valve didn't close F52 = Unfastened cam lock F53 = Clogged filter or pipeline	L51 = Loss of money because of spills L52 = Severe injuries due to slipping
R6	F61 = Flammable materials storage under direct sun	L61 = Explosion due to reactivity under direct sun
R7	R71 = Extreme bending R72 = Lifting of heavy materials	L71 = Absence of work L72 = Decrease of productivity L73 = Compensation

B. FIS to Estimate Probability of Occurrence Score and Impact Score

Fuzzy scale ratings which were used in this study to reduce the uncertainty in risk estimates are shown in the Tables 2 & 3.

Table 2 Linguistic variables and fuzzy numbers for FIS 1, FIS 3, FIS 5, FIS 7, FIS 9, FIS 11, FIS 13

Linguistic variables	Fuzzy numbers
Expected	(0.7,0.9,1.0)
Possible	(0.5,0.7,0.9)
Unlikely	(0.3,0.5,0.7)
Very unlikely	(0.1,0.3,0.5)
Not expected	(0.0,0.1,0.3)

Table 3 Linguistic variables and fuzzy numbers for FIS 2, FIS 4, FIS 6, FIS 8, FIS 10, FIS 12, FIS 13

Linguistic variables	Fuzzy numbers
High	(7,9,10)
Medium	(5,7,9)
Low	(3,5,7)
Very low	(1,3,5)
Not effect	(0,1,3)

C. FIS to Estimate Risk Score

The inputs for the risk factors and impacts from the expert knowledge is tabulated in Table 4. The Risk probability and impact score for each risk is given as an input to the Mamdani Fuzzy inference system to estimate the risk score. The risk score was calculated separately for each risk by using FIS 15. Based on the risk score, ranking was done.

As in [1] i.e., the Lean Fuzzy Bow-tie analysis, the risks were categorized as high, medium and low range. From Table 4 it is clearly seen that RE-1, RE-2, RE-4, RE-5, RE-6 and RE-7 are categorized in the medium range. But by using the proposed framework i.e., FIS risk analysis tool, the risks were assigned with an unique number and based on the number, ranking was done. This helps the risk managers to take care of highest ranked risks first. Also, for each change in the expert's input, a lot of computations should be performed in the in the Lean Fuzzy Bow-Tie analysis method; whereas it is not necessary in the proposed Framework.

" RPN = rate of occurrence (O) x severity (S) x ease of detection (D)" [8].

The occurrence score, severity score and detect ability score for each identified risk event was obtained from the expert knowledge and Risk Priority Number (RPN) was calculated. Table 5 shows the comparison of FMEA and FIS risk analysis tool results on a chemical industry.

Table 4 Probability of occurrence score, impact score and risk score for the identified risks in chemical industry

Risk event no.	Risk factors	Occurrence score	FIS occ score	Impacts	Impact score	FIS impact score	Risk score	FIS risk score	Risk rank
RE1	0.5,0.4,0.6	(0.51,0.79,0.94)	0.514	7.6,6.8,6	(4.58,6.17,7.6)	5.01	Medium	42.7	6
RE2	0.8,0.86	(0.76,0.88,0.97)	0.588	5,5,5	(3.86,5.63,7.23)	4.92	Medium	41.7	7
RE3	0.175,0.35,0.5	0.20,0.51,0.8)	0.506	9,10	(7,9,10)	8.88	**High**	**73.6**	1
CRE4	0.8,0.7	(0.58,0.85,0.96)	0.599	8.8,5,6	(3.22,4.93,6.75)	5.12	Medium	45.9	4
CRE5	0.8,0.7,0.8	(0.78,0.94,0.99)	0.53	5,4.7	(3.67,5.62,7.35)	6.85	Medium	47.5	3
CRE6	0.6	(0.2,0.4,0.6)	0.59	7	(5,7,8.20)	6.82	Medium	59.9	2
CRE7	0.6,0.5	(0.3,0.58,0.8)	0.51	6,7,6.5	(3.71,5.34,7.13)	5.61	Medium	44.8	5

IV. COMPARISON OF FIS RISK ANALYSIS TOOL RESULTS WITH FMEA RESULTS

Failure Mode Effects Analysis (FMEA) is one of the risk analysis method which is widely used in non - health care industries, [8]. In FMEA risks are treated as failure modes. For each of the identified failure mode, three measures were done. They are "rate of occurrence", "severity" and "ease of detection", [8]. Each failure mode was assigned with a Risk Priority Number (RPN). Based on the RPN, the criticality of the failure modes were identified. Risk priority number is calculated as follows:

Table 5 RPN for the identified risks in the chemical process industry

Risk event	O	S	D	RPN	FMEA rank	FIS rank
CR1	3	4	3	36	6	6
CR2	4	2	4	32	7	7
CR3	5	5	4	100	1	1
CR4	5	4	4	80	3	4
CR5	4	5	3	60	4	3
CR6	4	5	4	90	2	2
CR7	4	3	4	48	5	5

From the Table 5 it is clear that the results from the FMEA method are in agreement with the FIS risk analysis tool results. FIS risk analysis tool considers the risk factors and impacts of each risk event to compute the risk score and whereas FMEA method does not consider them. This is the reason for the difference in ranking for the risk events CR4 and CR5 on applying these two methods.

The advantages of the combination of Fuzzy Inference systems and Bow-tie analysis over FMEA are as follows:

• Normally, the FMEA assigns same Risk Priority Number (RPN) to different risks irrespective of the severity, occurrence, and detection of ability scores. Whereas FIS risk analysis tool assigns a different risk score to each risk event. This makes easier for an organization to choose the mitigation strategies.

• The proposed FIS risk analysis tool assigns risk score to each risk event by considering both risk factors and impacts of a risk based on the expert's knowledge.

• The risk analysis tool proposed in this Paper is very useful as it provides an outlook of errors happening in the chemical process industry.

V. CONCLUSIONS

In this Paper, an integrated framework is presented for risk assessment in a chemical manufacturing industry using Bow-tie analysis and a Mamdani Fuzzy Inference System (FIS). To calculate the risk score for each identified risk event, a Mamdani FIS was developed with the help of expert's knowledge. Risk ranking is done among the identified seven potential risks in the Industry. Based on the ranking, Risk mitigation strategies can be developed by the industry in advance. Afterwards, a FMEA method was applied on the chemical industry and its results were compared with FIS risk analysis tool results. This study can be extended by considering other factors like risk controllability and risk mitigation probability in the final FIS i.e., FIS-15 in the case study to calculate the better risk score.

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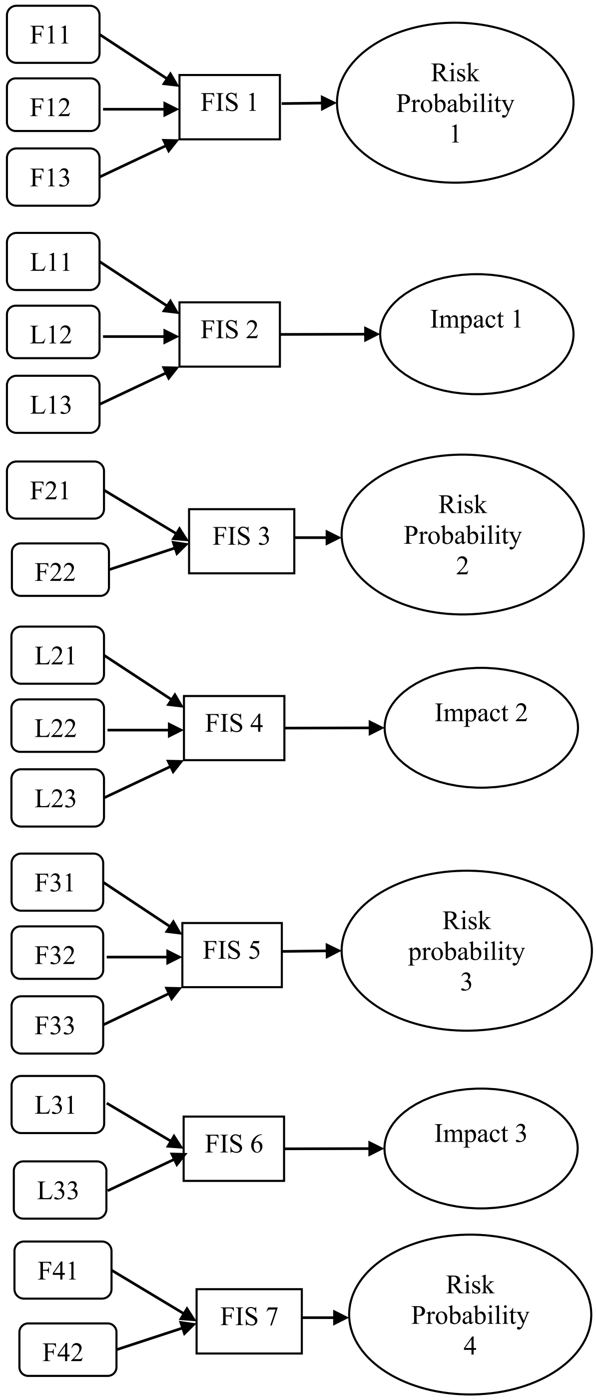
APPENDIX



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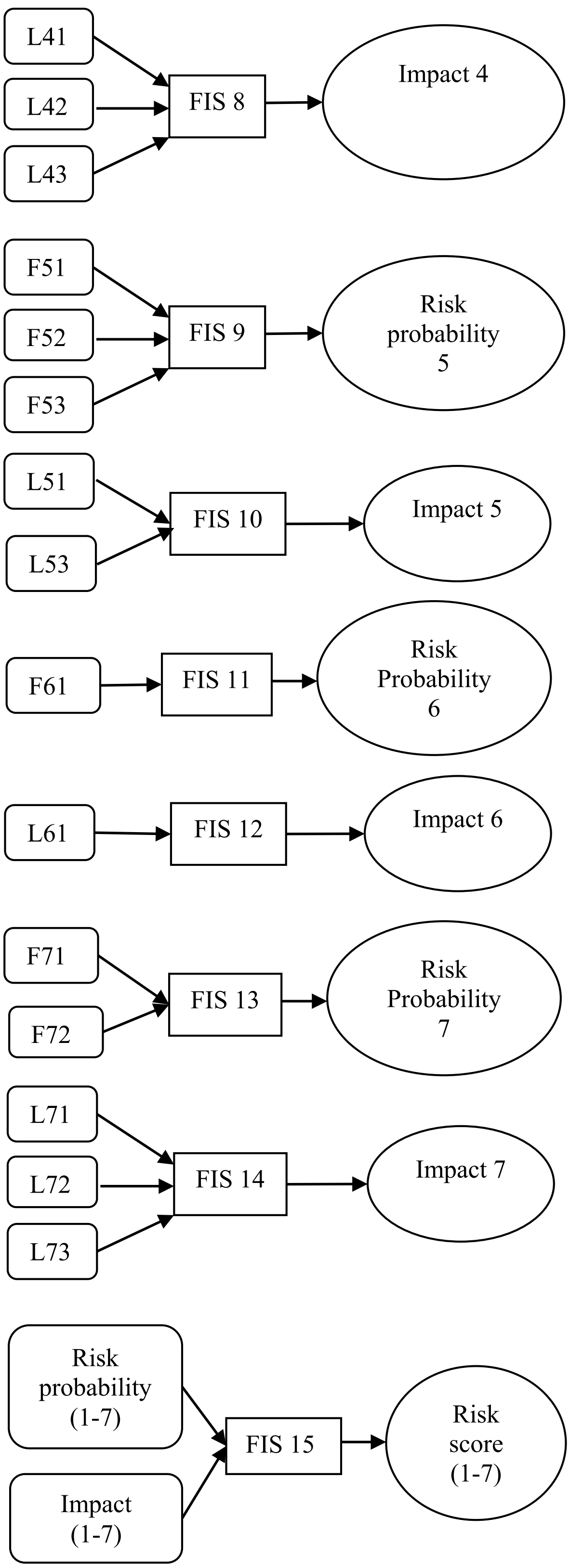

Figure 6 *FIS models to calculate probability of occurrence score and Impact score of all risks considering their risk factors and impacts in chemical industry*