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Risk Analysis Using Fuzzy System Based Risk Matrix Methodology and Applications to Nuclear Facilities

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This paper proposes a new risk assessment methodology using fuzzy logic model based on the risk matrix information and applications to the nuclear facilities. The structure of the fuzzy Inference System (FIS) is formed in fuzzifier, knowledge base and defuzzifier. Applications of the fuzzy system involves analyzing and managing the risk in nuclear reactors based on the classification of the events information. The input and output of the fuzzy system are simulated in crisp value. The proposed fuzzy model; and operator experiences were the devices for making the rules and inherent connection between variables in fuzzy model. Fuzzy logic is one of the intelligence systems and it has wide range applications in fault analysis, event classification, accident analysis, safety and risk assessment. The structure of risk matrix reflects the shape of the membership functions and the If-Then rules of the fuzzy model design. The risk matrix is simulated in the fuzzy approach to make it easier as a model based on If-Then rules. Simulation results illustrated that fuzzy logic system gives many advantages for risk assessment such as the dynamic modeling in If-Then rules.

Keywords: *Risk analysis, Risk matrix methodology, Fuzzy system applications in risk analysis*

Introduction

The safety and security of critical infrastructures such as nuclear plants, petrochemical installations, underground transportation lines, and airports need an effective, fast, accurate and applicable risk analysis and assessment methods. The main objective of developing risk analysis methodologies is to provide a better understanding and a useful tool that can be used to guarantee the safety and security of environment, public and to secure the safety of the investments. The infrastructure may be destroyed either because of terrorist activities or safety rules violations. A nuclear power plant may blow up in a manner similar to Chernobyl and Fukushima accidents resulting in a release of radioactive material. A chemical plant may release toxic gases, or a natural disaster (hurricane, flood, tornado, volcano and fire) can cause a severe damage to the environment [1]-[2]. Generally, risk is defined as the effect of uncertainty on objectives, and it may result from different circumstances such as uncertainty in financial markets, supply chain disruptions, project failures, security breaches, quality and safety incidents, nuclear accidents, environmental causes and disasters as well as deliberate attack from an adversary or unpredictable root cause. It is therefore important to identify and assess risks in order to render them clearly understood and properly managed. According to Flanagan and Norman (1993), risk management is a process which aims to identify and quantify all risks to which the business is exposed, so that a conscious decision can be made to manage the risks. Risk management often includes risk identification, risk assessment, risk prioritization and risk mitigation strategies. Among them, risk identification is a fundamental phase to recognize the potential uncertainties and enables a decision maker or a group of decision makers to become conscious

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about the event that cause uncertainty (Hallikas et al. 2004) [3]-[4]. Several methodologies are used for risk identification such as risk mapping and event tree analysis. Risk assessment determines the quantitative or qualitative value of risk relating to a concrete situation, which is required to be able to choose suitable management actions for the identified risk factors according to the situation. There are many probability-based methods by which risk is assessed, but techniques based on possibility methods were developed since mathematical relations and parameters for risk assessment were difficult to model (Lees, 2001). Pokoradi (2002) defined the preliminary basis of risk assessments by possibility methods and fuzzy logic. Bowles and Pelaez (1995) evolved the use of fuzzy arithmetic and linguistic variables in risk assessments while characterizing the system reliability [5]. For a period of time, nuclear engineering systems were assessed through Fuzzy Inference System (FIS), particularly by Guimaraes and Lapa (2007). Karimi and Hüllermeier (2007) suggested a modular framework for risk assessment by fuzzy logic. They used possibility-probability distribution as a new approach for analyzing risks. Markowski and Mannan (2008, 2009a) and Markowski et al. (2009b) developed a risk matrix based on fuzzy thinking and described fuzzification of the frequency and severity of the consequences of an incident scenario as basic inputs for fuzzy risk assessment. In the addition, many attempts were made in the models at developing possibility-based risk assessments in environmental issues since there were many uncertainties and lack of information in environmental risk analysis. Applications of fuzzy logic in risk assessment have been discussed in following manuscript: Ma (2002), Dahab et al. (1994), Uricchio et al. (2004), McKone and Deshpande (2005), and Darbra et al. (2008b) established different FIS for evaluating risk in environmental issues. Kentel and Aral (2007) and Vemula et al. (2004) use a hybrid of probabilistic and fuzzy methods to analyze environmental risks [6]. In case of nuclear facilities with probability of risk exposure, the risks probability of risky parameters that need to be monitored makes in-depth risk analysis unaffordable, especially when there are coherent relationships among risk factors. Fuzzy model in fact build in rules that explicitly explain the interface between the model and the operator experience, dependence and relationships among modeled factors. It is helpful for identifying and managing the risk [5]. The fuzzy system is proposed to model the risk matrix and analyze the risk of infrastructure such as nuclear plant using the interference of operator experience and the availability of the tools. The risk matrix methodology is one of the risk analysis methodologies, which are used to identify the qualitative risk level.

Following this introduction, this paper is structured as follows: section II explains the main concepts of the fuzzy logic system, while section III introduces the risk matrix methodology. Section IV develops the fuzzy system model for risk assessment and section V gives the conclusion of the application.

Fuzzy Logic System

The Fuzzy Logic system is a mathematical tool for dealing with uncertainty, introduced by Professor L. A. Zadeh who was the first pioneer of fuzzy as his seminal works (Zadeh, 1965, 1968, 1971, 1973, 1975) in the early 1970s.

Fuzzy sets and fuzzy logic theory have found a great variety of applications in control engineering, power systems, telecommunication, consumer electronics, information processing, pattern recognition, signal processing, machine intelligence, qualitative modeling, decision making, management, finance, medicine, the chemical industry, motor industry, robotics, nuclear reactors modeling and power control, risk assessment and management.etc [7]. The fuzzy theory provides a mechanism for representing linguistic constructs such as “very low (VL),” “low (L),” “medium (M),” “high (H),” “very high (VH), which reflects the Extreme (E) risk.” In general, the fuzzy logic provides an inference structure that enables appropriate human reasoning capabilities. On the contrary, the traditional binary set theory describes crisp events, events that either do or do not occur. It uses probability theory to explain if an event will occur, measuring the chance with which a given event is expected to occur [8]-[9]. The theory of fuzzy logic is based upon the notion of relative graded membership and so are the functions of cognitive processes. In the fuzzy logic system (FLS) the membership functions are utilized to find the degree of membership of the element in a given set. The utility of fuzzy sets lies in their ability to model uncertain systems, so often encountered in real life. Figure (1) illustrates the block diagram of the fuzzy inference system, which indicates how the input sensory (crisp or numerical) data are fed into Fuzzy Rule Based System (FRBS) where physical quantities are represented or compressed into linguistic variables with appropriate membership functions. These linguistic variables are then used in the *antecedents* (IF-Part) of a set of fuzzy rules within an inference engine to result in a new set of fuzzy linguistic variables or *consequent* (THEN-Part) [10]-[11]. Variables are then denoted in this figure by z , and are combined and changed to a crisp (numerical) output $y^*(t)$ which represents an approximation to actual output $y(t)$ Mamdani method was selected due to the reason that Mamdani is widely accepted for capturing expert knowledge and it allows us to describe the expertise in more intuitive, more human-like manner. On the other hand, Sugeno method is computationally efficient and works well with optimization and adaptive techniques, which makes it very attractive in control problems, particularly for dynamic nonlinear systems. The main Mamdani structure of a fuzzy inference consists of the following three steps: Fuzzification; Inference engine and Defuzzification [12]. The Matlab software package was used to apply the fuzzy logic system to model a fuzzy risk matrix assessment methodology

Risk Matrix Methodology

A risk may be viewed as the combination of the probability of an event (likelihoods) and its consequences, and in particular, its global impact. This combination can form the basis of a risk matrix such as that shown in Figure (2). This shows a common graphical approach to identifying the risks that are of particular concern in different conditions. Clearly there is a sense in which the most critical risks to nuclear plant (those that should be the focus of the most monitoring and mitigation efforts) are those that are both likely and damaging i.e. those found towards the top and right of the risk matrix. This is reflected via the coloration of the risk map, which depicts the upper right hand of the matrix in red. Those risks that, after consideration, are categorized as falling in the red area of the risk matrix would be the primary focus of a prudent project risk management team. A typical risk matrix associated with the plant would have a large number of risks (represented by their numbers) scattered across the matrix shown, rather than just a single number [13-14]. Risk assessment matrix is a tool to conduct a subjective risk assessment. The bases for risk matrix are the definition of risk as a combination of severity of the consequences occurring in a certain accident scenario and its frequency. Although the conventional Risk Matrix provides a standard tool for treating the relationship between the severity of consequences and the likelihood in assessing process risks, it has a disadvantage of uncertainties.

Characteristics of risk matrices

Risk matrices are structured to be easily used for assessment. They can create liability issues and give a false sense of security. Risk ranking matrix should have the following features to be effective:

- It should be simple to use and understand;
- It must not require extensive knowledge of the use of quantitative risk analysis;
- It should be clear to applicability;
- It must consist of the likelihood ranges that cover the full spectrum of potential scenarios;
- It should include a detailed description of the consequences that relate to each consequences range;
- It must clearly define tolerable and intolerable risk level;
- It must show those scenarios that are at an intolerable risk level can be mitigated to a tolerance level on the matrix;
- It provides a clear guidance on what action is necessary in order to mitigate the scenarios with intolerable risk levels [15].

Advantages and disadvantages of risk assessment matrix

The risk assessment matrix has the following advantages:

1. It is a useful guide for risk engineering practice;
2. It is a standard tool for establishing the connection between consequences and probabilities in risk assessment of a given exposure to risk;
3. It disables the acceptance of unacceptable risk and enables making operating decisions, improving the distribution of resources to mitigate the loss.

Disadvantages and limitations of the risk assessment matrix can be considered as follows:

1. The possibility of applying only identified hazards (not a tool for the identification of hazards);
2. Subjectivity;

3. The possibility of a comparative risk analysis only [15].

Fuzzy Model of Risk Matrix

Different people have different perceptions about risk and the association of its dependent variables. Fuzzy logic provides an excellent framework for risk assessment and management. The fuzzy if-then rules are to be built on the human experience. The key idea in that process is to capture knowledge needed from risk managers and safety experts and form if-then rules in a FIS to automate the risk assessment [16-17]. Figure (2) illustrates the risk matrix structure, which consists of likelihood and consequences or the impact as two inputs of the risk matrix and the output is the severity of the risk. The severity of the risk equals the likelihood multiplied by its impact. Figure (3) indicates another image of the matrix of qualitative risk analysis (risk levels).

Table (1) summarizes the classification and description of the risk levels defined and included in the risk matrix. Table (2) gives the risk categories in fuzzy if then rules, which reflects the main idea of the risk matrix in fuzzy logic system [18]. The structure of the risk matrix indicates the different levels of both likelihood and consequence, which varies between (almost certain, likely, possible, unlikely and rare) for the risk matrix input and (insignificant, minor, moderate, major and catastrophic) for the risk matrix consequence. Application of modeling the risk matrix in fuzzy logic facilitates the analysis and assessment processes and simulates the output in three dimensions image. Figure (4) shows the membership function of the first input of the risk matrix designed based on fuzzy logic system relative to the likelihood of risk in five-degree (very low, low, medium, high, very high) level.

Figure (5) illustrates the membership function of the second input of the risk matrix designed based on fuzzy system in five degrees relative to the consequences (impact). Figure (6) represents the third element or the membership function of the fuzzy system model of risk matrix. Figure (7) indicates the fuzzy model rules viewer of assessment condition (case1), and indicates that low probability and low impact means low severity of risk. Figure (8) shows the fuzzy model rules viewer of the risk assessment condition (case2), which means medium risk severity. Figure (9) illustrates the fuzzy model rules viewer of the risk assessment condition (case3).

Table (3) summarizes the simulation results of different values of the fuzzy model-based risk matrix methodology, which indicates the grading of the risk severity based on the likelihood and consequences. Figure (10) illustrates the surface view of Mamdani fuzzy inference system model for risk assessment based on risk matrix. It is noted that the risk is ranging from the very low level to extreme level. The design of rule base (if then rules) of the previous risk matrix depends on the definition of qualitative risk analysis matrix or the level of risk to reflect the real image of the risk level [19]-[20].

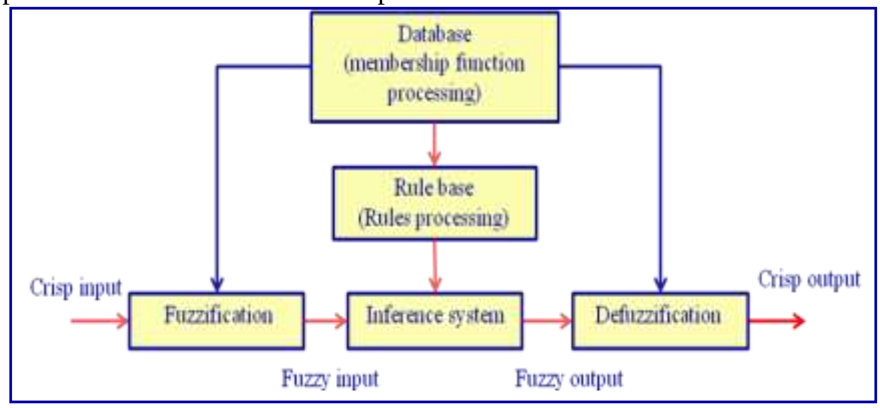

Figure (1): Main structure of fuzzy inference system

Likelihood	Consequences					
		Insignificant	Minor	Moderate	Major	Catastrophic
	Almost certain	Medium	High	High	Extreme	Extreme
	Likely	Medium	Medium	High	High	Extreme
	Possible	Low	Medium	Medium	High	Extreme
	Unlikely	Low	Low	Medium	Medium	High
	Rare	Low	Low	Low	medium	High

Figure (2): Risk matrix construction [13]-[14]

Likelihood	Consequences					
		Insignificant	Minor	Moderate	Major	Catastrophic
	A	High	High	Extreme	Extreme	Extreme
	B	Medium	High	High	Extreme	Extreme
	C	Low	Medium	High	Extreme	Extreme
	D	Low	Low	Medium	High	Extreme
	E	Low	Low	Medium	High	High

Figure (3): Matrix of qualitative risk analysis (risk levels) [15]

Table (1): Classification and description of the risk levels

Level	**Description**	
A	**Almost certain**	is expected to occur in most circumstances/commonly repeating
B	**Likely**	is expected to occur in most circumstances
C	**Possible**	Will probably occur in most circumstances
D	**Unlikely**	might occur in some time
E	**Rare**	may occur only in exceptional circumstances

Table (2): Risk categories based fuzzy model

Severity	Likelihood					
		VL	L	M	H	E
	VL	VL	VL	L	L	M
	L	VL	L	M	M	H
	M	L	M	M	H	H
	H	L	M	H	H	E
	E	L	H	H	E	E

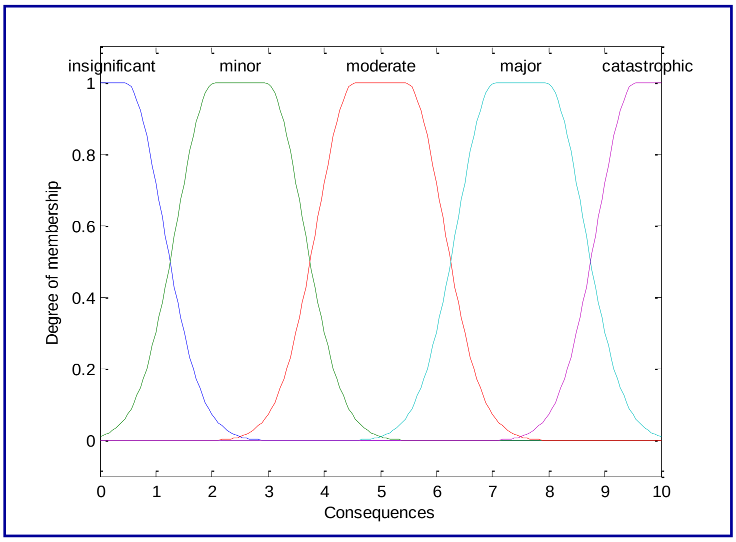

Figure (4): Input1 membership function

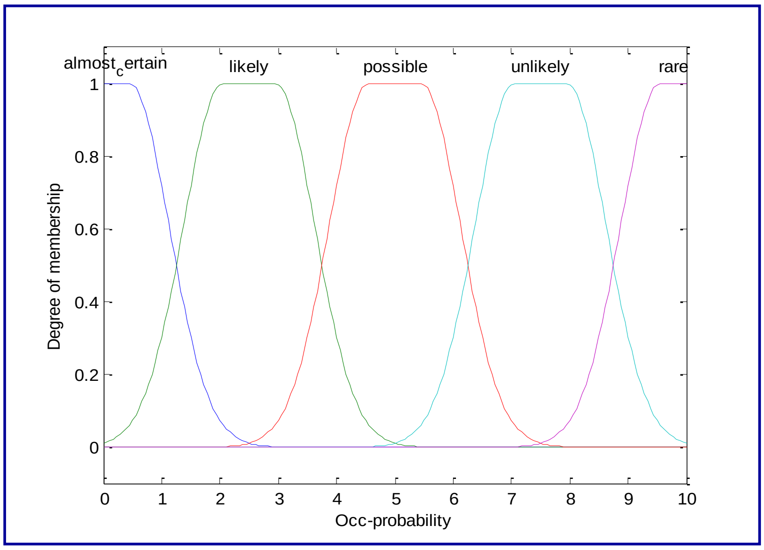

Figure (5): input 2 membership function

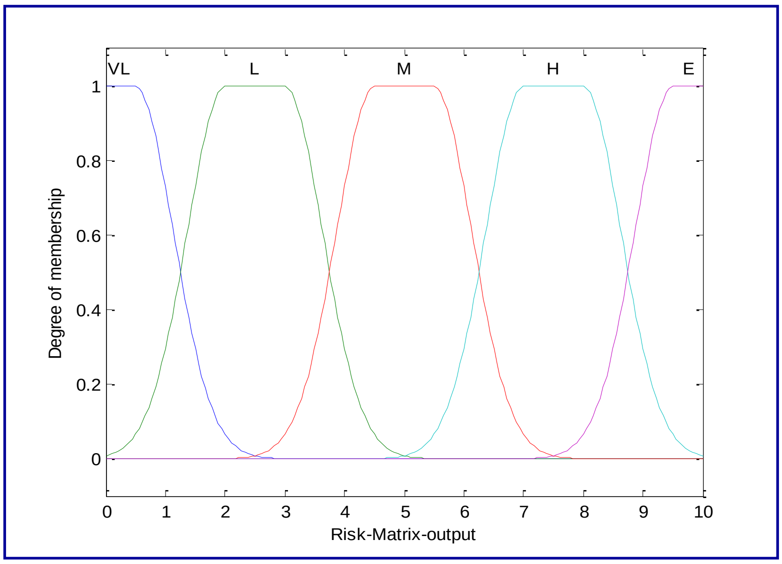

Figure (6): Risk matrix output membership function

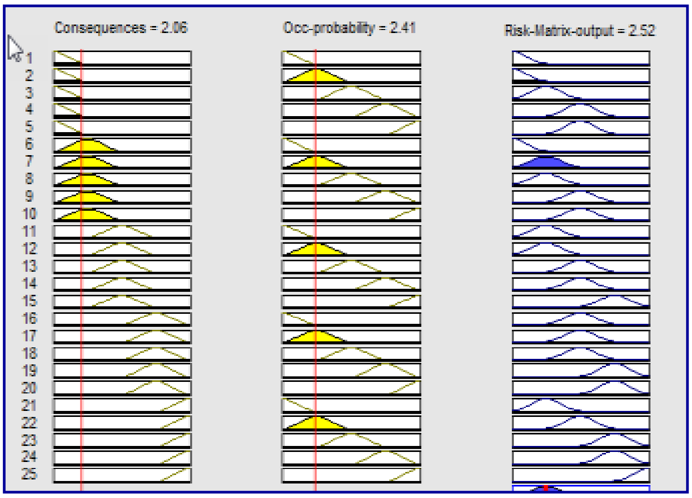

Figure (7): Rules view of fuzzy based risk matrix model (case1)

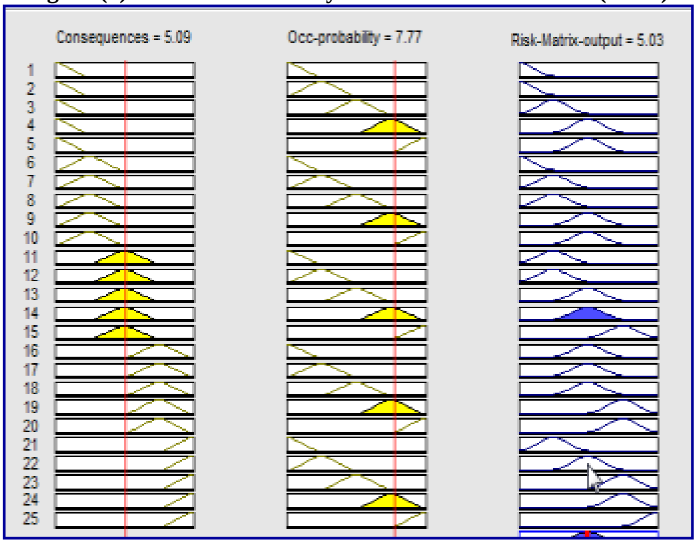

Figure (8): Rules view of fuzzy based risk matrix model (case2)

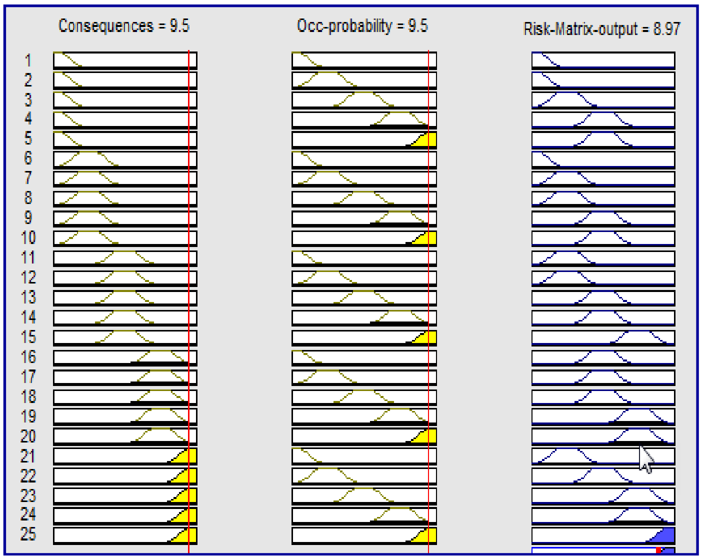

Figure (9): Rules view of fuzzy based risk matrix model (case3)

Table (3): Simulation results of fuzzy model at different inputs and output conditions

Simulation number	Consequences	Probability	Risk level
1	2.06	2.41	2.52
2	5.09	7.77	5.03
3	9.5	9.5	8.97

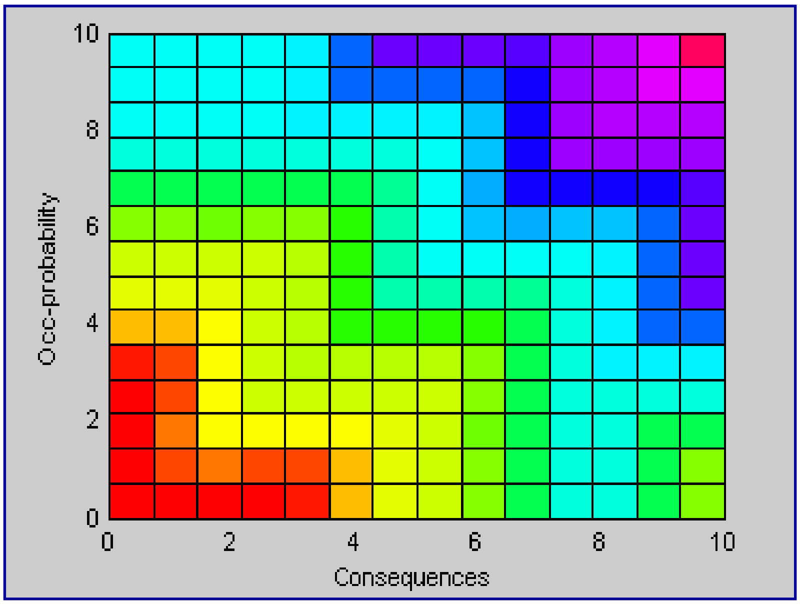

Figure (10): Surface view of Mamdani fuzzy inference system model for risk assessment-based risk matrix methodology

Conclusion

This paper demonstrated that the fuzzy logic theory can be used in risk analysis as an assessment tool. The fuzzy system is successfully used to analyze the risk based on risk matrix methodology and consider both the effect of risk likelihood and severity on the structure of the risk matrix. This application illustrated that the fuzzy logic is useful when applied to conventional risk matrix for risk analysis and assessment. This application of the fuzzy based risk matrix has illustrated the applicability of Mamdani FIS for collection the expert knowledge and allowing description of the expertise in more intuitive, more human like manner. Surface viewer is used to show the effectiveness of each parameter of the fuzzy system model-based risk matrix. Mapping the analysis using the proposed methodology is easier because of the fuzzy Mamdani model advantages and the free software tools in Matlab

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