



# TECHNICAL PAPER

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**Title:** Risk Assessment is Fuzzy Business – Fuzzy Logic Provides the Way to Assess Off-site Risk from Industrial Installations

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# Risk Assessment is Fuzzy Business – Fuzzy Logic provides the Way to Assess Off-site Risk from Industrial Installations

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## ABSTRACT

There is no such thing as an “exact” value of risk. Results of traditional quantitative risk assessments are usually qualified with a statement of uncertainties. This paper presents a novel approach to overcome the ‘fuzziness’ in traditional risk assessment, and a risk assessment model using fuzzy logic. The likelihood of occurrence of incidents is regarded as a function of the robustness of Safety Management System (SMS). Fuzzy logic is used to characterise the robustness of the SMS as the variable, which determines the likelihood of incidents. Fuzzy logic is used to characterise consequences and then fuzzy set operations are used to combine the severity of consequences and likelihood of occurrence to calculate risk. The model assesses risk of one major hazard at a time.

The advantage of the fuzzy approach is that it enables processing of vaguely defined variables, and variables whose relationships cannot be defined by mathematical relationships. Fuzzy logic can incorporate expert human judgement to define those variable and their relationships. The model can be closer to reality and site specific than that by some of the other methods.

The fuzzy risk model presented in this paper is the first of its kind. It is presented with the expectation that it can be developed and refined further with inputs from safety practitioners and experts.

## INTRODUCTION

*‘Everything is vague to a degree you do not realise till you have tried to make it precise’*  
- Bertrand Russell.

Risk assessment is an “assessment” of something hypothetical defined as “risk”, which must then be interpreted as “high”, or “low”, or “tolerable”. Such assessment, whether qualitative or quantified, requires analyst’s judgement, expert human knowledge and experience. Quantification of risk in scalar values is subject to uncertainties for many reasons including difficulties in defining the likelihood and consequence severity and the mathematics of combining them. Current approach to risk assessment of industrial installations uses Safety Reports focusing on Safety Management Systems to demonstrate that risks are low or tolerable.

Fuzzy logic and fuzzy set operations enable characterization of vaguely defined (or fuzzy) sets of likelihood and consequence severity and the mathematics to combine them using expert knowledge, to determine risk. The fuzzy risk model presented is the first of its kind. It is presented with the expectation that it can be developed and refined further with inputs from safety practitioners and experts.

## EVOLUTION OF RISK ASSESSMENT CONCEPTS

The quest for judging the safety of industrial installations in Europe in the 1970’s and 80’s led to the concept of off-site risks. Initially, risk assessments were qualitative and were seen by some to be subjective. The search for greater objectivity, led to the development of quantified risk analysis techniques, the concept of tolerability criteria and the concept of comparing the industrial risk with risks taken by people in everyday life. Quantitative techniques introduced three new concepts: individual risk of fatality, the exposed hypothetical individual and societal risk. This approach was considered to be more objective, although many practitioners question this.

The Seveso 1 Directive (1982) in Europe followed by the Seveso 2 Directive (1996) led to *Control of Major Accident Hazards 1999 Regulations* (COMAH) required plant operators to provide Safety Reports

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describing their Safety Management Systems (SMS), including justification and rationale of the safety measures and their reliability. In Australia, the *National Standard for the Control of Major Hazard Facilities* [NOHSC: 1014(1996)] was modelled on the same principles.

The focus on the SMS appears to be a move away from complex quantitative analysis, historical equipment failure rates and complex concepts. This approach to demonstrate that the risk is low appears suitable for communicating with the public and seems generally acceptable.

An important implication of the new approach is that risk is a function of the robustness of the SMS. Fuzzy logic provides the methodology for assessing the robustness of SMS and assessing off-site risk.

## **FUZZINESS AND FUZZY LOGIC**

In contrast to the true or false world of Boolean logic, fuzzy logic techniques allow the use of degrees of truth to calculate results. The expression “fuzziness” means a sense of vagueness in defining the measures rather than the lack of knowledge about the value of the variables and the causal relationships. However, fuzzy set theory provides a strict mathematical framework within which results are calculated. According to Zimmerman: “There is nothing fuzzy about fuzzy set theory” [1].

Fuzzy logic is justified because:

- It is tolerant of imprecisely defined data;
- It can model non-linear functions of arbitrary complexity; and
- It is able to build on top of the experience of experts.

## **THE PRINCIPLES INCORPORATED IN THE RISK MODEL**

The fuzzy risk model is built on the following principles:

- That the robustness of the Safety Management System (SMS) is an indicator of likelihood of incidents. The idea of robustness of SMS incorporates people, competences, procedures and culture. This is generally recognised [2, 3 and 4] and justified by the modern approach and regulations;
- That off-site consequences involving injuries and death to people can be caused by one major incident alone. Therefore, off-site risk is based on consideration of one major incident at a time;
- That quantification of severity of consequences and their effects on humans give us ranges of results for any selected scenario, not necessarily absolute and correct scalar values;
- That the risk, related to the one major incident, is assessed in terms of the level of injuries and death to people at their actual location because almost all the time, wind blows in one direction or the other, varying with seasons. In the event of a release, dispersion will occur in the downwind direction and affect people in its path until dilution to harmless concentrations.

## **THE FUZZY RISK MODEL**

The steps involved in constructing a fuzzy model [5, 6 and 7] are shown in Figure 1.

- Two inputs are defined as: Robustness of SMS (as an indicator of the likelihood) and severity of consequence;
- Valid ranges of the inputs are considered and divided into classes, or fuzzy sets. For example, robustness of SMS can range from ‘less than adequate’ to ‘excellent’ with other values in between. Consequence severity of the release of a toxic gas can range from ‘minor injuries’ to ‘serious injuries and death’. We cannot specify clear boundaries between classes. The degree of belongingness of the values of the variables to any selected class is called the degree of membership;
- The output is risk and is defined in fuzzy sets like ‘tolerably low’ to ‘unacceptably high’;
- Expert knowledge is used to characterise inputs and outputs and connect the inputs and outputs by a set of inference rules using if/then statements; and
- The fuzzy output set is then defuzzified to arrive at a scalar value.

A simplified model is presented in this paper having two inputs and one output with 12 inference rules. In reality, there are no limits on the number of inputs, or outputs or the number of rules or the number of classes used to define the range of a variable. The model can be refined by adding more inputs and more rules. The modelling process is made convenient by proprietary software [7].

## A CASE STUDY

A fuzzy risk assessment model is presented for a plant, which has a 25 m<sup>3</sup> capacity bulk storage tank for chlorine, stored as liquid under pressure, and a variable number of standard 920 kg drums, which also store chlorine as liquid under pressure. A small bore outlet pipe supplies chlorine to the user plants via isolating valves, remote operated valves and automatic shut off valves. The site is separated from the nearest residential zone by about 500 m. The wind direction is often towards the residential area.

A leak directly from the bulk tank is identified as the source of off-site risk as it cannot be stopped if it occurred and its effects cannot be controlled easily.

In the simplified model, the range of robustness is described in the following three fuzzy sets, shown in Figure 2. Audits using detailed questionnaires and checklists are used to assess factors which collectively characterise the robustness of the SMS at the site [3, 4 and 8]. A detailed checklist is based on the types of safeguards, and weights assigned to them according to their effectiveness, as shown in Table 1.

**Inadequate:** Describes a system where there is no formal safety policy and no evidence of serious attempt to implement critical safety procedures and training in safety procedures. On a scale of 0 – 100, most independent assessors would give it an overall score of less than 25 - 40 and consider it inadequate.

**Good:** Describes a system where there is a declared safety policy, engineered protection systems with evidence of a high level of compliance with the safety procedures but less than adequate level of training and skills in safety. On a scale of 0 – 100, most independent assessors would give it an overall score of 45 – 75 and consider it good or passable for the site.

**Excellent:** Describes a system where there is a clear safety policy which is well integrated into the organisation at all levels. Accountabilities and responsibilities of personnel are defined and taken seriously. There is evidence of management interest and positive reinforcement of safe behaviour, while unsafe behaviour is dealt with appropriately and immediately. Engineered systems are supported by well trained personnel and well defined procedures with an accent on preventing the hazards and measures for controlling the harmful effects. On a scale of 0 – 100, most independent assessors would give it an overall score of greater than 80 - 85 and consider it excellent.

Severity of consequence of exposure of people to chlorine cannot be clearly defined. There are many different methods for dispersion analysis, many different methods for assessing effects on people and there are variations in effects across the population. Therefore, the severity of exposure of people to chlorine at their residence in the downwind direction is described by Gaussian shaped membership functions in the following five fuzzy sets, depicted in Figure 3:

**Category 1:** Chlorine concentration / exposure time to which people may be subjected would not cause any harm, with a probability of nuisance only. Chlorine concentrations would not exceed 50 PPM and would exist for short periods. On a scale of 0-100, this category would rate 0 – 12.

**Category 2:** Chlorine concentration / exposure time to which people may be subjected would not cause any more than a nuisance with low probability of minor injuries. Chlorine concentrations could be 100 PPM for very short periods. On a scale of 0-100, this category would rate 12 – 37.

**Category 3:** Chlorine concentration / exposure time to which people may be subjected would cause minor injuries with low probability of acute injuries. Chlorine concentrations would be less than 100 PPM and would not exist for more than 10 minutes. On a scale of 0-100, this category would rate 37 – 62.

**Category 4:** Chlorine concentration / exposure time to which people may be subjected would cause acute injuries with a relatively low probability of fatality. Chlorine concentrations would be less than 200 PPM and would not exist for more than 10 minutes. On a scale of 0-100, this category would rate 62 – 87.

**Category 5:** Chlorine concentration / exposure time to which people may be subjected would cause death with a high probability (say >50%). Chlorine concentrations greater than 200 PPM would exist for more than 10 minutes. On a scale of 0-100, this category would rate 87 – 100.

The output of risk is defined in the following five classes and shown in Figure 4:

**Unacceptability High:** High probability that the consequence severity will cause deaths in the residential area.

**High:** Low probability of deaths in the residential area but high probability of acute injuries.

**Moderate:** Probability of deaths or acute injuries in the residential area is virtually nil. Probability of minor injuries remains.

**Low:** There is no risk of deaths or any type or injuries to residents.

**Negligible:** There is no risk to residents at all. Consequences do not extend beyond the site boundary.

Twelve (12) inference rules, which relate inputs and output are:

1. If <consequence is **Category 5**> and <SMS is **Inadequate**> then <Risk is **Unacceptable**>
2. If <consequence is **Category 5**> and <SMS is **Good**> then <Risk is **High**>
3. If <consequence is **Category 5**> and <SMS is **Excellent**> then <Risk is **Moderate**>
4. If <consequence is **Category 4**> and <SMS is **Inadequate**> then <Risk is **High**>
5. If <consequence is **Category 4**> and <SMS is **Good**> then <Risk is **Moderate**>
6. If <consequence is **Category 4**> and <SMS is **Excellent**> then <Risk is **Low**>
7. If <consequence is **Category 3**> and <SMS is **Inadequate**> then <Risk is **Moderate**>
8. If <consequence is **Category 3**> and <SMS is **Good**> then <Risk is **Low**>
9. If <consequence is **Category 3**> and <SMS is **Excellent**> then <Risk is **Negligible**>
10. If <consequence is **Category 2**> and <SMS is **Good**> then <Risk is **Low**>
11. If <consequence is **Category 2**> and <SMS is **Excellent**> then <Risk is **Negligible**>
12. If <consequence is **Category 1**> then <Risk is **Negligible**>

Figure 5 is a three-dimensional depiction of the set of rules as a check on consistency.

A number of inference methodologies exist for combining inputs and outputs. The method used in the proposed model is that of Mamdani [7] as it is considered the most appropriate.

Applied to the case study, a simplified explanation is illustrated in Figure 6, showing the application of only the rules 5 and 6 from the list above. From dispersion analyses for the selected incident followed by an assessment of effects on people due to the ranges of possible concentrations and durations of exposure in the residential area, it is concluded that the consequence score is 65 on a scale of 0-100, which falls in the lower side of Category 4. From an audit of the facility by three independent experts, using the template shown in Table 1, robustness of the SMS is found to be 75, on a scale of 0-100, which is in Classes Good and Excellent. For scores of 65 and 75 respectively in consequence severity and SMS robustness, rules 5 and 6 are invoked. AND combination means an intersection of fuzzy sets and gives the fuzzy output sets of risk on the right hand side of the figure. A union of the two output sets gives the aggregated output shown in the bottom right of the figure. Centroid of this output fuzzy set gives a scalar value of 43, the value of risk, which falls in the lower part of risk class defined as Moderate. Proprietary software [7] gives results derived from comprehensive computations and presents graphic results. Results of any subsequent changes in the system can be seen immediately.

## CONCLUSION

Risk assessment is based on imprecisely defined inputs. Current approaches based on Safety Reports focus on the Safety Management Systems and imply that the likelihood occurrence of incidents is a function of the robustness of the SMS. Fuzzy logic methodology provides a way to characterize the imprecisely defined variables, define relationships between variables based on expert human knowledge and use them to compute results. A model is presented for assessing robustness of SMS. Consequence severity can be characterized from quantified results and our knowledge of harmful effects. Risk is computed by fuzzy set operations. The proposed model can be built upon and refined over time with inputs from experts.

## REFERENCES

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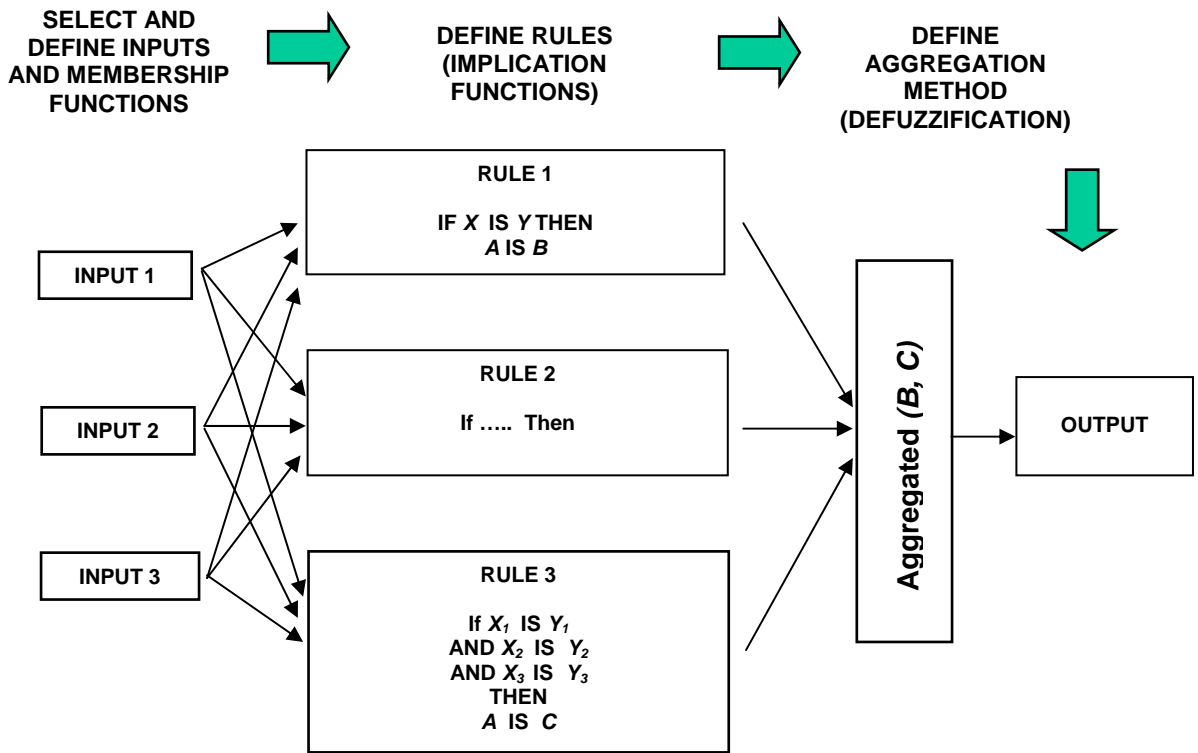


Figure 1: Building a Fuzzy Model

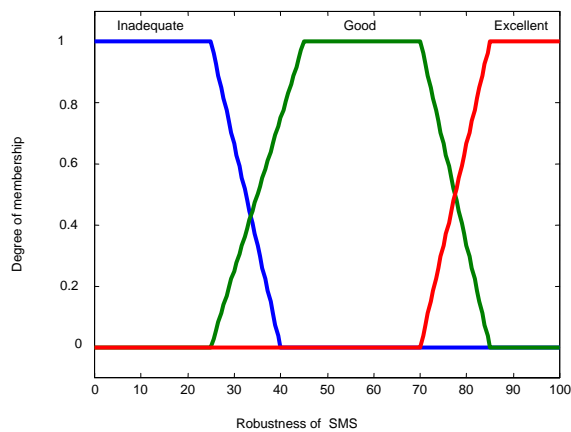


Figure 2: Range and classes of robustness of SMS

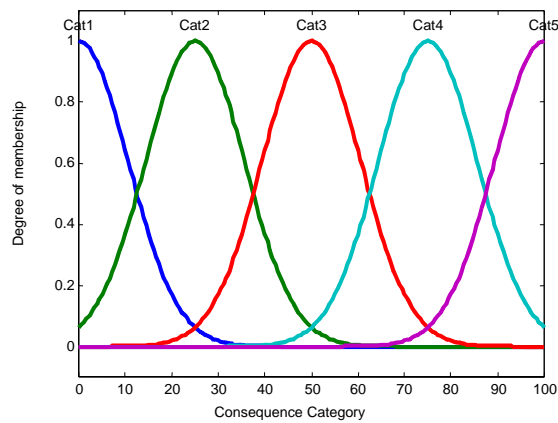


Figure 3: Range and classes of consequence severity

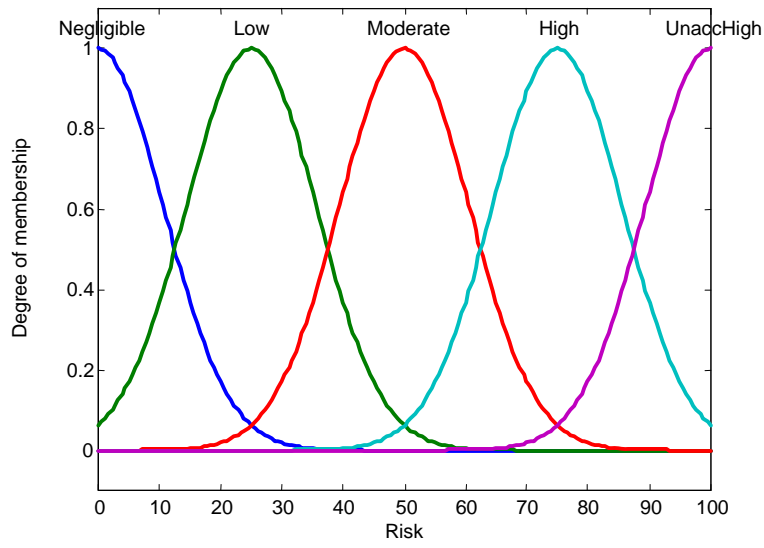


Figure 4: Range and classes of risk

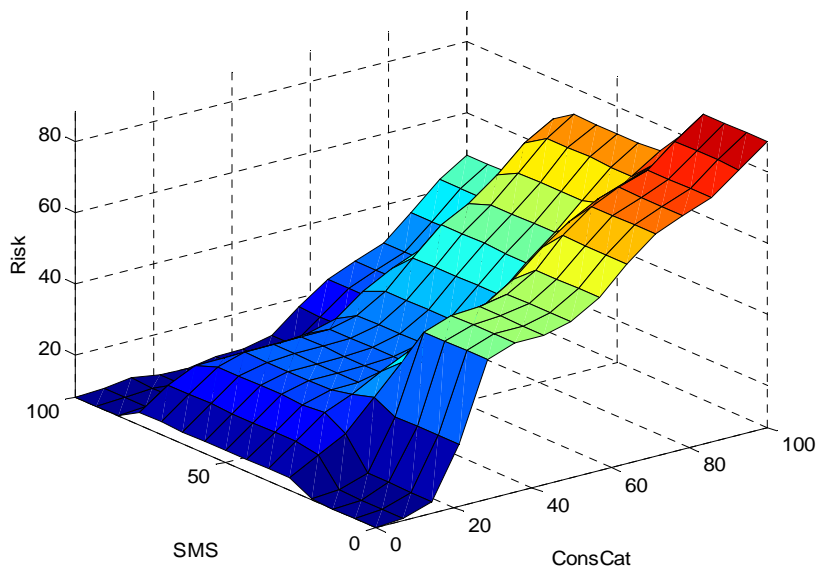


Figure 5: Three-dimensional depiction of inference rules

Acknowledgement Figure3, 4, 5 and 6: MathWorks. (1995). *Fuzzy Logic Toolbox for use with MATLAB*

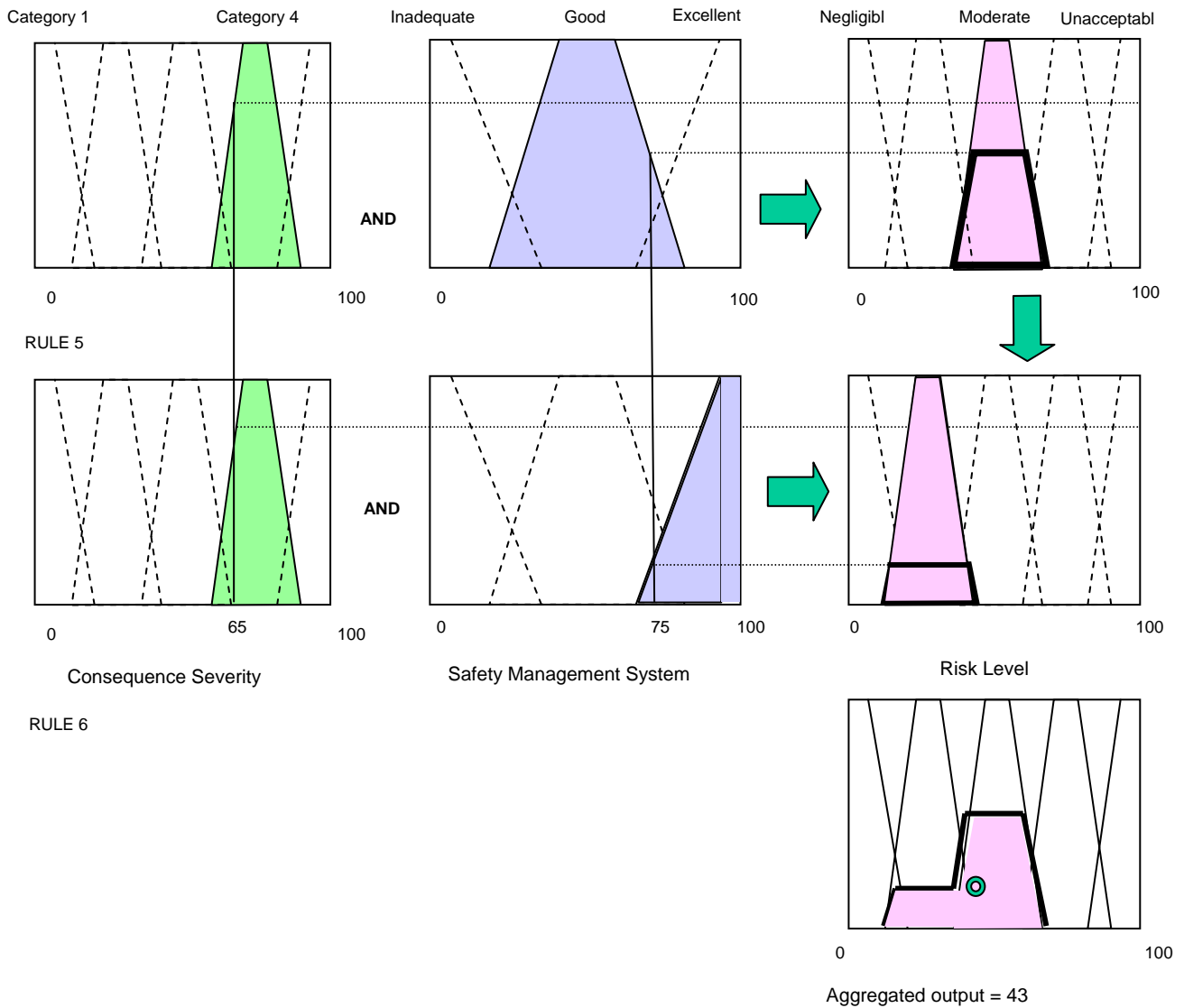


Figure 6: Mamdani Method for computing Output

Table 1 – Assessment of SMS Robustness

Safeguard Type and assigned weights	Safeguard Type Engineered measures Weight 0.6		Safeguard Type Measures that depend on people Weight 0.4	
	Rating %	Weighted Rate	Rating %	Weighted Rate
Prevention and early detection measures Weight 0.5	$M_{1E}$	$M_{1E} \times 0.5 = M_{1Ew}$	$M_{1P}$	$M_{1P} \times 0.5 = M_{1Pw}$
Control measures Weight 0.3	$M_{2E}$	$M_{2E} \times 0.3 = M_{2Ew}$	$M_{2P}$	$M_{2P} \times 0.3 = M_{2Pw}$
Protection measures Weight 0.2	$M_{3E}$	$M_{3E} \times 0.2 = M_{3Ew}$	$M_{3P}$	$M_{3P} \times 0.2 = M_{3Pw}$
Weighted type score		$M_E = M_{1Ew} + M_{2Ew} + M_{3Ew}$		$M_{Pw} = M_{1Pw} + M_{2Pw} + M_{3Pw}$
Weighted type score		$M_{EW} = M_E \times 0.6$		$M_{Pw} = M_P \times 0.4$
SMS Score				$M_{SMS} = M_{EW} + M_{Pw}$