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Development of Risk Assessment and Occupational Safety Management Model for Building Construction Projects

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***Abstract*—**In order to be capable of dealing with uncertainties, subjectivities, including vagueness arising in building construction projects, the application of fuzzy reasoning technique based on fuzzy set theory is proposed. This study contributes significantly to the development of a fuzzy reasoning safety risk assessment model for building construction projects that could be employed to assess the risk magnitude of each hazardous event identified during construction, and a third parameter of probability of consequence is incorporated in the model. By using the proposed safety risk analysis methodology, more reliable and less ambiguities, which provide the safety risk management project team for decision-making purposes.

***Keywords*—**Safety risks assessment, building construction safety, fuzzy reasoning, construction risk assessment model, building construction projects.

I. Introduction

CONSTRUCTION industry has a poor record on safety risk management in comparison to other industries, and construction sites are dangerous places [1]-[5] because of their high accident, injury and fatality rates. The risks of fatal accidents in the construction industry are five times more probable than in other industries [6]. Building construction industry is also considered as a labour-intensive industry [5]. Additionally, quantitative risk data and documentation generated by industries are generally inadequate for determining the risks. However, many of safety risk assessment techniques currently used in the construction industry may not give satisfactory results because a hazardous event may be utterly difficult to conduct by a quantitative risk assessment due to the high level of uncertainty involved and incomplete risk information in determining the probability of a possible consequence scenario [2]. Furthermore, in many circumstances, the applications of current safety risk assessment techniques use two risk parameters, i.e., probability of occurrence and severity of consequence, to assess risk magnitude. This analysis is lack of confidence to determine risk level, which requires introducing a third parameter such as probability of consequence. Although the number of fatal occupational accidents in the construction industry worldwide is difficult to quantify as information on this issue is not available for most countries, it is reasonable to expect at least 55,000 deaths every year occurred on construction sites [7]. Compared to many other activities in other industry sectors, the construction activities are more dangerous due to the unique features of construction works, for example the high-risk characteristics of construction activities, which include steel erection, demolition, scaffolding, excavation, falsework, maintenance, roofwork, and site transport when people work at complex work sites. Specifically, the most frequent hazards in the construction projects identified by the health and safety executive (HSE) [8] provide useful information for risk analysis such as falling from height, falling objects and materials, electricity, trips, asbestos, manual handling, noise and vibration, chemicals, and mobile plants. Therefore, construction project risk assessment has been recognized as an obvious important issue to the safety risk management process in order to identify and assess the potential risks. Risk mitigation measures must be applied by reducing the probability of occurrence or controlling the possible consequence if a hazardous event has been identified and analysed with a high risk level. In many circumstances, many of safety risk assessment approaches are employed widely in building construction projects, for instance, Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Monte Carlo simulation, Consequence Analysis and Equivalent Fatality Analysis (EFA), and Sensitivity Analysis [3], [9]-[11]. Nonetheless, the applications of these techniques may be more difficult to address adequate liability to gratifying results because the safety risk data are often incomplete or the information may be extremely inadequate to determine risk level. Therefore, it is necessary to develop new safety risk assessment methods and models that can be used to estimate and assess the safety risks in building construction projects, for example, by using fuzzy reasoning techniques.

The fuzzy reasoning approach based on the principle of fuzzy set and fuzzy logic that was originally produced by Zadeh [12] offers advantages which can systematically measure both quantitative as well as qualitative information from available sources to simplify risk analysis. Additionally, this method can be used to effectively reduce the uncertainties, subjectivities, ill-defined problems, and vague information associated with building construction projects and activities.

This article presents the development of a fuzzy reasoning safety risk assessment model for building construction projects, which a third parameter of probability of consequence is incorporated in the model. By using the proposed methodology, more accurate and reliable results

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from safety risk analysis can be obtained, which can provide useful information to project managers and engineers to manage and control risks during the construction projects. This paper is organized as follows: In Section I, current practice of safety risk management in the construction industry is reviewed. Also, problems and challenges are addressed by using existing safety risk analysis methods. The third safety risk assessment parameter of probability of consequence is discussed in Section II. Section III presents a construction safety risk assessment model by using fuzzy reasoning approach. A case study is presented in Section IV, which demonstrates the effectiveness of the developed safety risk analysis model in construction safety risk analysis. The results of the risk assessment in the case study are represented as risk score, located in a defined range, and risk category with linguistic words associated with a belief of percentage. The advantages of using a fuzzy reasoning approach are also discussed and compared with conventional methods. Finally, Section V gives conclusions and a summary of the main benefits of using a fuzzy reasoning approach in the construction safety risk assessment process.

II. Suggestion of the Third Parameter

The two fundamental risk parameters are commonly used to assess risk magnitude (RM) in safety assessment of a construction project in terms of probability of occurrence (PO) and severity of consequence (SC) [9]. The PO represents the likelihood of an event to happen. The SC defines the number of minor injuries, major injuries, and fatalities resulting from the occurrence of a particular event. Nevertheless, considering the magnitude of a particular risk also depends highly upon the probability that the accident will occur. These two parameters do not take into the probability of current consequence caused in the project safety risk assessment process consideration to gain the accuracy of the reliability results. Thus, a third parameter, named probability of consequence (PC) is proposed. The PC indicates the occurrence likelihood of the accident if an event becomes a reality in order to assess such a safety risk associated with the construction project's effectiveness and efficiency.

III. A Proposed Construction Safety Risk Assessment Model

The architecture of the construction safety risk assessment model is proposed as shown in Fig. 1, which includes the development of the qualitative descriptors for representing risk inputs, i.e. probability of occurrence (PO), severity of consequence (SC) and probability of consequence (PC), and risk outputs, i.e. risk magnitude (RM). The proposed model consists of three steps: risk data information collection and hazard identification, risk criteria calculation, and risk estimation. The details of the proposed safety risk assessment model are described in the following sections.

A. Step 1: Risk Data Information Collection and Hazard Identification

1. Establishing a Safety Risk Assessment Team

In order to identify safety hazards associated with a construction project, a safety risk assessment team composed of different disciplines/backgrounds needs to be established. The members in a safety risk assessment team must be carefully selected. The selected experts will have essential experience and high knowledge degree regarding the construction activity. The safety risk assessment team should include experts, for example, site construction managers, project managers, site engineers, safety officers, etc. The safety risk assessment team will undertake the review of safety hazard identification and risk data information.

2. Problem Definition

Safety risk assessment starts with problem definition that involves identifying the specific safety requirements at different levels of a project, e.g., at project level, sub-project levels, and element levels of a project. The requirements may include safety regulation and safety rules made by HSE and the company's policy.

3. Data and Information Collection

Once problem definition is completed, the safety risk assessment moves from the problem identification to the data and information collection. The data and information can be collected from previous similar projects, reports and databases. However, in any cases, if the statistic record does not exist, expert judgement needs to be applied. In addition, the data and information collection will be expressed as the qualitative descriptors and associated with parameters, i.e. PO, SC, and PC.

4. Safety Hazard Identification

All of potential safety hazards associated with a building construction project need to be classified and identified into different categories at different levels. The process of hazard identification must involve an investigation into all of the potential sources of project construction risk and their consequences. Many of the tools and techniques of hazard identification are widely used in the construction industry, which can be applied to identify hazards of a project, including checklist. What if, brainstorming approach, Failure Mode and Effect Analysis (FMEA), Hazard and Operability studies (HAZOP), Concept Hazard Analysis (CHA), Preliminary Hazard Analysis (PHA), Job Hazard Analysis (JHA), and Inherent hazard analysis (IHA) [10], [13], [14], [19], [20]. The information gained from hazard identification will be used in risk analysis.

B. Step 2: Risk Criteria Calculation

This step is to calculate the risk criteria, which consists of seven principal components: determining the risk criteria, determining fuzzy membership functions (MF_f), fuzzification, fuzzy aggregation, fuzzy inference, fuzzy rule base, and defuzzification.

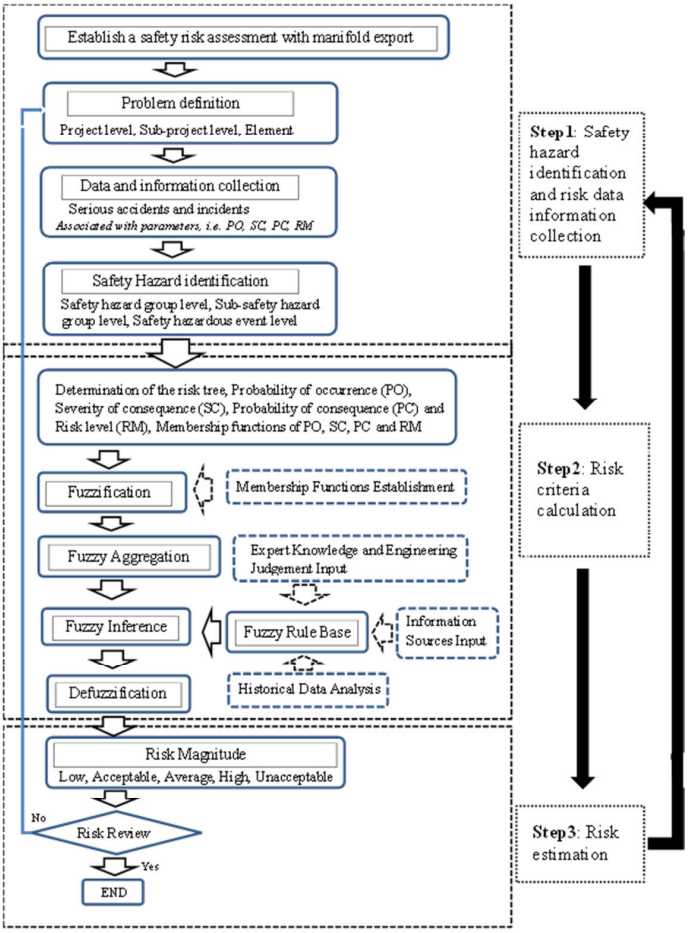

Fig. 1 Construction safety risk assessment model

1. Determining the Risk Criteria

The three fundamental risk parameters used to assess risk magnitude of safety construction industries, i.e., PO, SC as well as PC. The safety risk assessment team needs to discuss and decide a set of criteria for safety risk assessment. Risk criteria are standards, which define the scope of risk parameters of PO, SC, and PC.

Probability of occurrence (PO) refers to the number of times an event occurs or the failure frequencies in a certain time period, which may estimate PO as "*Very unlikely*", "*Unlikely*", "*Fairly unlikely*", "*Likely*", and "*Very likely*" as shown in Table I.

Severity of consequence (SC) refers to the number of minor injuries, major injuries, and fatalities resulting from the occurrence of a particular event. Three linguistic variables are used to describe consequence severity: "*Negligible*", "*Minor*", "*Moderate*", "*Major*", and "*Catastrophic*" to estimate SC as shown in Table II.

Probability of consequence (PC) is a new parameter which refers to the occurrence likelihood of the accident, seven linguistic variables are used in this research to describe PC as "*Highly unlikely*", "*Unlikely*", "*Reasonable unlikely*", "*Likely*", "*Reasonable likely*", and "*Highly likely*" as shown in Table III.

Five levels of risk magnitude (RM) in terms of linguistic variables are defined as "*Low*', "*Acceptable*", "*Average*", "*High*", and "*Unacceptable*". Their definitions are generally similar in the occupational health and safety management regulations published by HSE as shown in Table IV.

TABLE I
DEFINITIONS OF QUALITATIVE DESCRIPTORS OF PO

Qualitative Descriptors	Description	Range
Very unlikely	Failure is unlikely but possible during lifetime	0-1
Unlikely	Likely to happen once during lifetime	0.5-2
Fairly unlikely	Between unlikely and likely	1.5-3.5
Likely	Occasional failure	3-4.5
Very likely	Failure is almost unavoidable	4-5

2. Determining Fuzzy Membership Functions (MF_f)

In literature, linguistic variables are described by different types of fuzzy membership functions according to the situation of interested area, including triangular, trapezoidal, generalized bell-shaped, and S-shaped functions [9]. However, trapezoidal and triangular membership functions are the most

frequently used in construction project risk assessment practice. The selection of the form of MF_f by safety risk assessment team is generated usefulness the linguistic groups identified in the knowledge acquisition and consisting of a set of overlapping curves. Figs. 2-4 show MF_f of PO, SC, and PC.

TABLE II
DEFINITIONS OF QUALITATIVE DESCRIPTORS OF SC

Qualitative descriptors	Description	Range
Negligible	No injury	0-1
Minor	Minor injuries and/or < 3 days off work	0.5-2
Moderate	Multiple injuries and/or and or between 3 days and 1 months off work	1.5-3.5
Major	Severe injuries and/or > 1 month off work	3-4.5
Catastrophic	Fatality and/or large number of fatal injuries	4-5

TABLE III
DEFINITIONS OF QUALITATIVE DESCRIPTORS OF PC

Qualitative descriptors	Description	Range
Highly unlikely	The occurrence likelihood of accident is highly unlikely	0-1
Unlikely	The occurrence likelihood of accident is unlikely but possible given the occurrence of the failure event	0.5-2
Reasonable unlikely	The occurrence likelihood of accident is between unlikely and likely	1.5-3
Likely	The occurrence likelihood is likely	2.5-4.5
Reasonable likely	The occurrence likelihood of accident is between likely and highly likely	4-5.5
Highly likely	The occurrence likelihood of accident is very likely	5-6

TABLE IV
DEFINITIONS OF QUALITATIVE DESCRIPTORS OF RM

Qualitative descriptors	Description	Range
Low	Risk is low or insignificant and can be readily controlled.	0-1
Acceptable	Risk is acceptable.	0.5-2
Average	Risk is medium.	1.5-3.5
High	Risk is high. However, risk control should be undertaken if it is reasonably practicable to so.	3-4.5
Unacceptable	Risk is unacceptable. Proper action must be taken to eliminate or reduce the risk.	4-5

3. Fuzzification

Input data usually can be derived from several sources for example historical data, experts' judgements and experiences. The data format of the inputs can be a range of numbers, e.g., (3, 5), or a linguistic term, e.g., "Unlikely", or a numerical value, e.g., "5", or triangular fuzzy numbers, e.g., (1, 2, 3), or trapezoidal fuzzy numbers, e.g., (1, 2, 3, 4) (Table V).

The standardised trapezoidal fuzzy number (STFN) is employed to convert the judgement of expert into a universal format for the composition of group preferences. A STFN can be defined as X= (a, b, c, d) with its membership function indicates the degree of preference [9], [10], that is defined as

$$\mu_A(x)=\begin{cases}0, x\le a\\ (x-a)/(b-a), x\in(a,b)\\ 1, x\in(b,c)\\ (d-x)/d-c), x\in(c,d)\\ 0, x\ge d\end{cases} \quad (1)$$

where A set of real numbers (a, b, c, d) with the relationship's satisfaction $a \le b \le c \le d$ determine the x coordination of the four points of a trapezoidal MF_f.

4. Aggregated STFN of PO, PC, and SC

The fuzzy aggregation of STFN scores can be carried out from applying the fuzzy weighted trapezoidal averaging operator, which is defined by

$$\text{Fuzzy aggregated score } (F_{agg}) = STFN_{1i} \times c_1 + STFN_{2i} \times c_2 \ldots + STFN_{ni} \times c_n \quad (2)$$

where F_{agg} is the fuzzy aggregated score, $STFN_{1i}$, $STFN_{2i}$,…, $STFN_{ni}$ are the STFN scores of parameter i measured by experts respectively, and c_n are contribution factors allocated to experts, for example, c_1 assigned to $Expert_1$, and $c_1+c_2+\ldots, c_n = 1$

It should be noted that if some experts provide zero scales [10] the aggregation of STFN scales is defined as:

$$\text{Fuzzy aggregated score } (F_{agg'}) = \frac{STFN_{1i} \times c_1 + STFN_{2i} \times c_2 \ldots + STFN_{ni} \times c_n}{1-\sum c_n} \quad (3)$$

where $F_{agg'}$ is the aggregated fuzzy scale and c_n is the contribution of experts who provide zero scales.

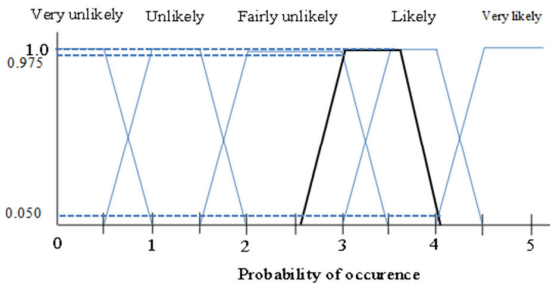

Fig. 2 Fuzzy probability of occurrence definition

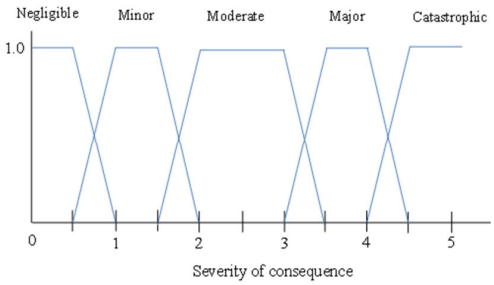

Fig. 3 Fuzzy severity of consequence definition

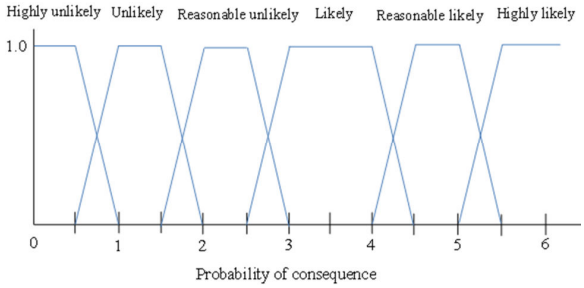

Fig. 4 Fuzzy probability of consequence definition

5. Calculation of Fuzzy Values (STFN)

Assume A_{PO}, A_{SC}, and A_{PC} are three STFN of PO, SC, and PC of a safety hazardous event, respectively [10]. A_{PO}, A_{SC}, and A_{PC} are defined as

$$A_{PO}= \{(u, \mu A_{PO}(u) | u \in U = [0,u], \mu A_{PO}(u) \epsilon [0,1]\} \quad (4)$$

$$A_{SC}= \{(v, \mu A_{SC}(v) | v \in V = [0,v], \mu A_{SC}(v) \epsilon [0,1]\} \quad (5)$$

$$A_{PC}= \{(w, \mu A_{PC}(w) | w \in W = [0,w], \mu A_{PC}(w) \epsilon [0,1]\} \quad (6)$$

where, μA_{PO}, μA_{SC}, and μA_{PC} are trapezoidal MF_f of A_{PO}, A_{SC}, and A_{PC} and u, v, and w are input variables in the universal of discourse U, V, and W of PO, SC, and PC, respectively.

TABLE V
EXPERTS' JUDGEMENT AND CORRESPONDING STFN

Input type	Description	Input values	Example	STFN
A numerical value	….is *a*	*a*	2	(2,2,2,2)
A range of number	….is between *a* and *b*	(*a*, *b*)	(2,3)	(2,2,3,3)
A linguistic term #1	….is High	High	High	(4,4.5,5,6)
A linguistic term #2	….is about *c*	About *c*	About 4	(3,4,4,5)
Triangular Fuzzy number	….is between *a* and *c* and most likely to be *b*	(*a*, *b* , *c*)	(2,3,4)	(2,3,3,4)
Trapezoidal Fuzzy number	….is between *a* and *d* and most likely to be *b* and *d*	(*a*, *b*, *c*, *d*)	(2,3,4,5)	(2,3,4,5)

6. Fuzzy Reasoning Evaluation

The Mamdani's method is employed to develop fuzzy reasoning process which rules are relevant to the current situations of the project for calculating the fuzzy output. The fuzzy rule base comprises the following fuzzy if-then rules [9], [10], [15], [16].

$$R_i: \text{If } u \text{ is } Q^i_{PO} \text{ and } v \text{ is } Q^i_{SC} \text{ and } w \text{ is } Q^i_{PC}, \text{ then } x \text{ is } Q^i_{RM} \quad (7)$$

where, $i = 1,2,3\ldots,n$ and u, v, w, and x are variables in the universe of discourse U, V, W, and X of PO, SC, PC, and RM, and Q^i_{PO}, Q^i_{SC}, Q^i_{PC}, and Q^i_{RM} are qualitative descriptors of PO, SC, PC, and RM , respectively.

The firing strength of α_i of the ith rule with input fuzzy sets A_{PO}, A_{SC}, and A_{PC} are calculated using fuzzy intersection operation as

$$\alpha_i = \min[\max\left(\mu A^i{}_{PO}(u) \cap \mu Q^i{}_{PO}(u)\right), \max\left(\mu A^i{}_{SC}(v) \cap \mu Q^i{}_{SC}(v)\right), \max(\mu A^i{}_{PC}(w) \cap \mu Q^i{}_{PC}(w)] \quad (8)$$

where $\mu A^i{}_{PO}(u)$, $\mu A^i{}_{SC}(v)$ and $\mu A^i{}_{PC}(w)$ are the MF_f of fuzzy sets A_{PO}, A_{SC} and A_{PC}, respectively.

The control output of fired rules R_i is obtained by

$$\mu Q^i{}_{RM'}(x) = \alpha_i \cap \mu Q^i{}_{RM} \quad (9)$$

where α_i is the firing strength of rule R_i, μQ^i_{RM} is the membership functions of fuzzy set A_{PO}, A_{SC}, and A_{PC}, respectively.

The Mamdani combination is used, the maximum operator can be used to calculate the total relation by [10]

$$\mu Q^i{}_{RM'}(x) = \max\{\min(\mu Q^i{}_{RM1}, \mu Q^i{}_{RM2}, \ldots, \mu Q^i{}_{RMn})\} \quad (10)$$

The $\mu Q^i_{RM'}(x)$ is the output fuzzy membership function after aggregation.

7. Defuzzification

The defuzzifier is defined as the output of the fuzzy inference engine to crisp point. Conceptually, the task of this step is an importance procedure to convert the aggregated result to a crisp number. The centre average method is the most commonly employed for defuzzification [10], [16]. Assume the output of fuzzy inference engine is obtained as:

$$\mu RM = \{(x, \mu RM(x)) | x \in X, \mu RM(x) \in [0,1]\} \quad (11)$$

and RM can be calculated as

$$RM = \frac{\sum_{i=1}^{n} Ci \mu RM(Ci)}{\sum_{i=1}^{n} \mu RM(Ci)} \quad (12)$$

where $i = 1,2,3, \ldots, n$. c_i denoted the centre of fuzzy term set i of RM, and $\mu RM(c_i)$ denoted the membership function of the fuzzy term set of RM.

C. Step 3: Establishment of Risk Estimation

The outcomes of risk assessment are represented as the risk level such as low, acceptable, average, high and unaccepted risk that provide safety officers, risk analysts, engineers and project managers for risk response decision making. However, the results need to be reviewed by experts and risk analysts by the safety risk assessment group.

IV. CASE EXAMPLE

A case example of falling from height in a building construction project is presented to demonstrate the proposed safety risk assessment model. Falls from height are considered as major injuries and crucial risk to undertake risk assessment

in most of projects and proper risk management is required [17]. In many cases, a worker falls from height due to improper scaffold construction, inadequacy of the edge protection, unprotected openings in buildings, lack of edge protection for working on roofs, dangerous demolition work and inappropriate use of ladders and hoists [21]-[23]. However, the fuzzy reasoning approach technique based on the principle of fuzzy set and fuzzy logic offers advantages which can be employed to reduce the uncertainties and vague information associated with building construction projects and activities. The application of the proposed methodology consists of three stages as stated in section III which can be described as follows.

A. Safety Hazard Identification and Analysis

A safety risk assessment group is established to undertake the review of safety risks in a building construction site. The safety risk assessment group consisting of five experts is required knowledge and qualification. A contribution factor is allocated to each expert as shown in see Table VI.

TABLE VI
EXPERTS' CONTRIBUTION FACTOR

Experts	Background	Contribution factor
E_1	Safety manager	0.25
E_2	Project manager	0.23
E_3	Senior safety officer	0.20
E_4	Safety officer with 15 years' experience	0.17
E_5	Site engineer with 15 years' experience	0.15

B. Risk Criteria

1. Determination of PO, SC, PC, RM, and Membership Functions of PO, SC, PC, and RM

The three fundamental risk parameters of PO, SC, and PC are used to assess risk magnitude of such a construction project. Five levels of linguistic variables of PO are used for expression of RM as very unlikely, unlikely, fairly unlikely, likely, and very likely. The PC is classified into six levels as highly unlikely, unlikely, reasonable unlikely, likely, reasonable likely, and highly likely; the SC is described by negligible, minor, moderate, major, and catastrophic, and the RM is classified into five levels as low, acceptable, average, high, and unacceptable as shown in Tables I-IV, respectively. PO, PC, SC, and RM are defined by trapezoidal MF_f as shown in Figs. 2-6, respectively.

2. Fuzzy Aggregation

Experts in the safety risk assessment team can provide a numerical value, a linguistic term, a range of number, a triangular fuzzy number and a trapezoidal fuzzy number to describe a particular identified hazard. In this case example, Expert E_1 uses a range of number, E_2 uses a numerical value, and E_4 uses a triangular fuzzy number while E_3 and E_5 provide linguistic term as shown in Table VII to describe the hazardous event of falls from height.

The aggregations of PO scores can be calculated by

$$\begin{aligned}\text{Probability of occurrence } \mu(x) &= ((2,2,4,4) \times 0.25 + (3,3,3,3) \times 0.23 \\ &+ (3,4,4,5) \times 0.20 + (2,3,3,4) \times 0.17 \\ &+ (3,3.5,4,4.5) \times 0.15) \\ &= (2.58,\ 3.03,\ 3.60,\ 4.05)\end{aligned}$$

Similarly, other aggregated scores of SC and PC can be also being obtained as shown in Table VII.

3. Fuzzy Inference

This step is to convert the aggregated of PO, SC, and PC into matching fuzzy sets for fuzzy inference. For example, the aggregated STFN of PO = (2.58, 3.03, 3.60, 4.05) as shown in Fig. 2 (the thick segments), then the matching fuzzy set PO is obtained by intersections between the STFN and fuzzy sets of PO, i.e.

$$PO = \{(Fairly\ unlikely,\ 0.975),\ (Likely,\ 1.000),\ (Very\ likely,\ 0.050)\}$$

$$PC = \{(Likely,\ 1.000),\ (Reasonable\ likely,\ 0.760)\}$$
$$SC = \{(Major,\ 0.728),\ (Catastrophic,\ 1.000)\}$$

Likewise, SC and PC can be obtained, the matching fuzzy sets of SC and PC are.

The safety risk assessment team produces 150 rules in the fuzzy rule base that are used in this study as shown in Fig. 5. The rules are interpreted thus: If PO is *very unlikely* and SC is *negligible* and PC is *highly unlikely,* then RM is *Low*; and if PO is *very likely* and SC is *catastrophic* and PC is *highly likely*, then RM is *Unacceptable.*

The min-max implication is then employed in this case example to calculate fuzzy preference. The fuzzy inference can be broken down into four phases as described below [18].

Phase 1 is to determine which rule is on the rule base. From the mapping of inputs of *PO*×*SC*×*PC*, the following 12 rules are fired contributing to the actual evaluation process. These 12 rules are:

Rule #106: If PO is FU_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is A
Rule #107: If PO is FU_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is H
Rule #112: If PO is LI_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is H
Rule #113: If PO is LI_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is H
Rule #118: If PO is VL_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is H
Rule #119: If PO is VL_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is U
Rule #136: If PO is FU_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is H
Rule #137: If PO is FU_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is H
Rule #142: If PO is LI_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is H
Rule #143: If PO is LI_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is U
Rule #148: If PO is VL_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is U
Rule #149: If PO is VL_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is U

where FU_{PO}, LI_{PO}, and VL_{PO} are the qualitative descriptors, "*Fairly unlikely*", "*Likely*", and "*Very likely*" of PO, respectively and MA_{SC}, CA_{SC} are the qualitative descriptors, "*Major*", "*Catastrophic*" of SC and LI_{PC}, RL_{PC}, are the qualitative descriptors, "*Likely*" ,"*Reasonable likely*" of PC, respectively.

TABLE VII
EVALUATION AND STFN OF PO, SC, AND PC

Experts	Evaluation					
	Probability of occurrence		Severity of consequence		Probability of consequence	
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN
E_1	(2,4)	(2,2,4,4)	(4,5)	(4,4,5,5)	(3,4)	(3,3,4,4)
E_2	3	(3,3,3,3)	5	(5,5,5,5)	4	(4,4,4,4)
E_3	About 4	(3,4,4,5)	About 4.5	(3.5,4.5,4.5,5)	About 4.5	(3.5,4.5,4.5,5.5)
E_4	(2,3,4)	(2,3,3,4)	(3,4,5)	(3,4,4,5)	(4,5,6)	(4,5,5,6)
E_5	Likely	(3,3.5,4,4.5)	Major	(3,3.5,4,4.5)	Likely	(2.5,3,4,4.5)
Aggregated STFN		(2.58, 3.03, 3.60, 4.05)		(3.81, 4.26, 4.58, 4.93)		(3.43, 3.87, 4.27, 4.72)

Phase 2 is to apply the minimum operator to calculate the strength of the fired rules, the process is shown as follows:

$$Rule\ \#106: \alpha_{106} = \mu FU(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(0.975, 0.728, 1.000) = 0.728$$
$$Rule\ \#107: \alpha_{107} = \mu FU(PO) \cap \mu MA(SC) \cap \mu RL(PC) = min(0.975, 0.728, 0.760) = 0.728$$
$$Rule\ \#112: \alpha_{112} = \mu LI(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(1.000, 0.728, 1.000) = 0.728$$
$$Rule\ \#113: \alpha_{113} = \mu LI(PO) \cap \mu MA(SC) \cap \mu RL(PC) = min(1.000, 0.728, 0.760) = 0.728$$
$$Rule\ \#118: \alpha_{118} = \mu VL(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(0.050, 0.728, 1.000) = 0.050$$
$$Rule\ \#119: \alpha_{119} = \mu VL(PO) \cap \mu MA(SC) \cap \mu RL(PC) = min(0.050, 0.728, 0.760) = 0.050$$
$$Rule\ \#136: \alpha_{136} = \mu FU(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(0.975, 1.000, 1.000) = 0.975$$
$$Rule\ \#137: \alpha_{137} = \mu FU(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(0.975, 1.000, 0.760) = 0.760$$
$$Rule\ \#142: \alpha_{142} = \mu LI(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(1.000, 1.000, 1.000) = 1.000$$
$$Rule\ \#143: \alpha_{143} = \mu LI(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(1.000, 1.000, 0.760) = 0.760$$
$$Rule\ \#148: \alpha_{148} = \mu VL(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(0.050, 1.000, 1.000) = 0.050$$
$$Rule\ \#149: \alpha_{149} = \mu VL(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(0.050, 1.000, 0.760) = 0.050$$

$$Rule\ \#106: \alpha_{106} \cap \mu V(RM) = min\ (0.728, \mu V(RM))$$
$$Rule\ \#107: \alpha_{107} \cap \mu H(RM) = min\ (0.728, \mu H(RM))$$
$$Rule\ \#112: \alpha_{112} \cap \mu H(RM) = min\ (0.728, \mu H(RM))$$
$$Rule\ \#113: \alpha_{113} \cap \mu H(RM) = min\ (0.728, \mu H(RM))$$
$$Rule\ \#118: \alpha_{118} \cap \mu H(RM) = min\ (0.050, \mu H(RM))$$
$$Rule\ \#119: \alpha_{119} \cap \mu U(RM) = min\ (0.050, \mu U(RM))$$
$$Rule\ \#136: \alpha_{136} \cap \mu H(RM) = min\ (0.975, \mu H(RM))$$
$$Rule\ \#137: \alpha_{137} \cap \mu H(RM) = min\ (0.760, \mu H(RM))$$
$$Rule\ \#142: \alpha_{142} \cap \mu H(RM) = min\ (1.000, \mu H(RM))$$
$$Rule\ \#143: \alpha_{143} \cap \mu U(RM) = min\ (0.760, \mu U(RM))$$

Phase 3 is to determine the control fired rules in outputs:

$$Rule\ \#148: \alpha_{148} \cap \mu U(RM) = min\ (0.050, \mu U(RM))$$
$$Rule\ \#149: \alpha_{149} \cap \mu U(RM) = min\ (0.050, \mu U(RM))$$

It should be noted that the following rules including *Rule* #107, *Rule* #112, *Rule* #113, *Rule* #118, *Rule* #136, and *Rule* #137 are included into *Rule* #142; *Rule* #119, *Rule* #148, and *Rule* #149 are included into *Rule* #143.

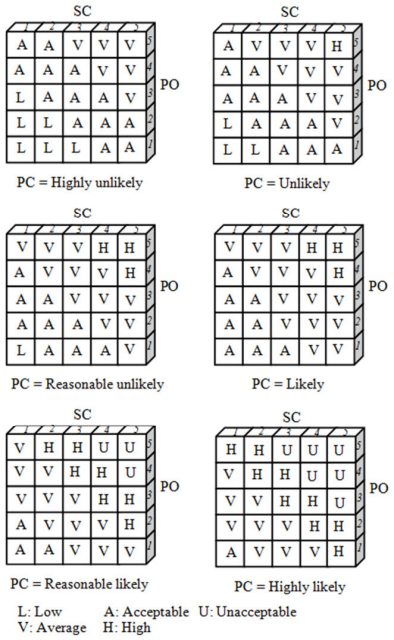

Fig. 5 Fuzzy rule base matrixes (adapted from [10])

Taking the maximum operator to calculate:

$$\mu Q^{i}{}_{RM'}(x) = \max\{\min(0.728, \mu V(RM)), \min(1.000, \mu H(RM)), \min(0.760, \mu U(RM))\}$$

Phase 4 of defuzzification is to convert the fuzzy output RM into a matching numerical value of RM. By using centre average calculation method, the crisp value is obtained RM= 4.013, which gives the position of RM estimation in the axis of the risk magnitude as shown in Fig. 6.

$$RM = \frac{3 \times 0.728 + 4 \times 1.00 + 5 \times 0.760}{0.728 + 1.000 + 0.760} = 4.013$$

C. Risk Estimation

The overall safety risk magnitude is 4.013 under defined scale system of RM, i.e. the safety risk of falling from height is between *High* and *Unacceptable* with a belief of 97.4% (μ = 0.974) for *High* and 2.6% (μ = 0.026) for *Unacceptable*. This value requires risk reduction measures to be taken to reduce the risk level of falling from height on building construction project and provides useful information for safety managers,

safety officers and safety analysts to carry out safety-based decision making. The appropriate corrective and preventive actions in this building construction project management are provided.

V. Conclusion

This paper presents a proposed safety risk assessment model using fuzzy reasoning technique, which can be used to assess both quantitative and qualitative risk data and information for building construction projects. A third parameter of probability of consequence (PC) is incorporated into the model in order to gain more accurate and reliable results of safety risk analysis. The results of the case example of safety risk analysis was presented to illustrate the application of the proposed safety risk analysis methodology, which the information of both safety risk score and types of risk with a belief of percentage can be obtained that can be used for decision-making purpose. Most importantly, it can assist the project managers, safety officers and engineers to manipulate and control risks in their safety risk management and improve safety standard operation procedures during the construction projects.

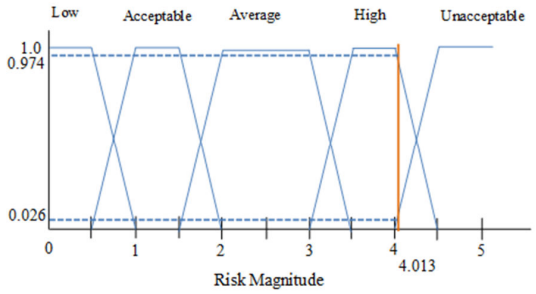

Fig. 6 Defuzzification of RM

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