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Development of a Fuzzy Fire Risk Evaluation Model for Building Construction Sites in Hong Kong

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ABSTRACT

Earlier research works on fire risk evaluation indicated that an objective, reliable, comprehensive, and practical fire risk evaluation model is essential for mitigating fire occurrence in building construction sites. Nevertheless, real empirical studies in this research area are quite limited. This journal paper gives an account of the second stage of a research study aiming at developing a fuzzy fire risk evaluation model for building construction sites in Hong Kong. The empirical research findings showed that the overall fire risk level of building construction sites is 3.6427, which can be interpreted as "moderate risk". Also, the survey respondents perceived that "Restrictions for On-Site Personnel" is the most vital fire risk factor; with "Storage of Flammable Liquids or Dangerous Goods" being the second; and "Attitude of Main Contractor" the third. The proposed fuzzy fire risk evaluation model for building construction sites can be used to assess the overall fire risk level for a building construction site, and to identify improvement areas needed. Although the fuzzy fire risk evaluation model was developed domestically in Hong Kong, the research could be reproduced in other nations to develop similar models for international comparisons. Such an extension would provide a deeper understanding of the fire risk management on building construction sites.

1. Introduction

Among all types of accident in the construction industry, industrial practitioners intend to pay less attention to the construction site fire prevention. Though it is not likely for fires to occur frequently on construction sites, their consequences are often severe. The Hong Kong Labor Department [1] reported that while construction site fires happen, damage is very severe regarding fatalities and injuries, as well as serious project delay and financial loss to the projects affected. The occurrence of two severe construction site fires in Hong Kong illustrated these major risks [2,3]. There are numerous reasons why fires happen on building construction sites but a simple lack

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of awareness of the fire risk is certainly one. In fact, it is always for site supervisory teams not to have regular and formal fire risk evaluations. This may be because of a lack of a suitable fire risk evaluation model for assessing fire risks on construction site. In order to help conquer this shortcoming, this journal paper gives an account of the second stage of a research study aiming at developing an objective, reliable, comprehensive, and practical fuzzy fire risk evaluation model for building construction sites in Hong Kong. The proposed model can assist safety officers and related personnel to evaluate the overall fire risk level of an individual construction site objectively and to identify improvements areas needed. Despite the model was developed domestically in Hong Kong, the research method may be reproduced to other nations for the development of similar models and subsequently used for international comparisons.

2. Research Methodology

Overall Research Framework

The research methodology used in this study was adapted from Chan and other scholars' research work [4]. It is based on a (1) desk research (including (a) a thorough literature review on fire risk evaluation systems; and (b) studies of current practices and legislation in respect of fire safety in building construction sites); (2) structured face-to-face interviews with experienced site personnel; (3) two different sets of empirical questionnaire survey; (4) Reliability Interval Method for the first empirical questionnaire survey; and (5) fuzzy synthetic evaluation for the second empirical questionnaire survey. It is emphasized that the first four methods were conducted at the first research stage (excluding the second empirical questionnaire survey) and the remaining two methods (the second empirical questionnaire survey and the fuzzy synthetic evaluation) were conducted at this second stage of the research study. Figure 1 shows the flow of the overall research process.

Desk Research

The desk research included: (1) a thorough literature review of fire risk evaluation systems; and (2) studies of current practices and legislation in respect of fire safety in construction sites. A preliminary initial checklist of 10 fire risk factors and 52 fire risk sub-factors was developed after conducting the desk research [5].

Structured Face-to-Face Interviews with Experienced Site Professionals

An expert panel was invited for the structured face-to-face interviews to assist in complementing and refining the preliminary checklist of fire risk factors derived from the thorough literature review. The interviewees included two senior project building engineers, one senior project manager (civil engineer), one fire safety engineer, and one safety manager. All the interviewees had 10 to 25 years of experience of construction site management and/or safety. It is believed that all of them have good knowledge and abundant hands-on experience in evaluating building construction site fire risk. Thus, they should be able to identify fire risk factors towards an objective, reliable, comprehensive, and practical fire risk evaluation model for building construction sites in Hong Kong. A total of twelve interview questions were drafted based on the preliminary checklist of fire risk factors derived from the desk research. After conducting the structured face-to-face interviews, content analysis was used to identify the fire risk factors and sub-factors. The interview transcripts were sent back to all interviewees for approval before conducting further analysis. After analyzing the interview transcripts, the final checklist of 11 fire risk factors and 48 sub-factors was derived, which then formed the basis for production of the first empirical questionnaire form [6].

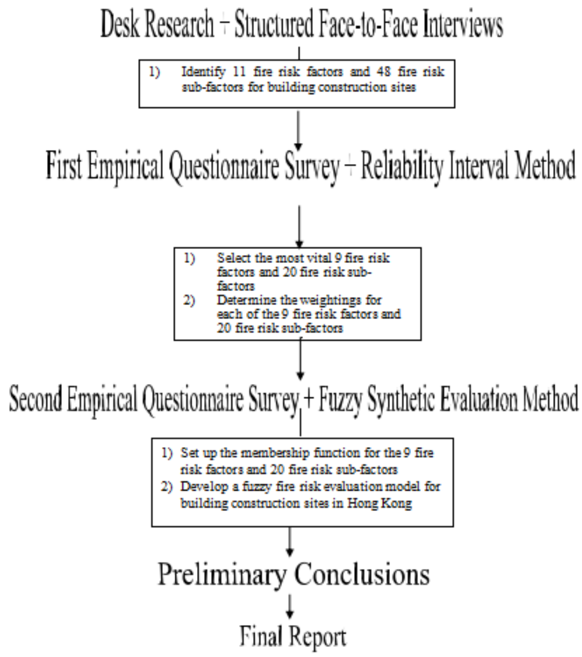

Figure 1. Overall Research Framework for this Study

Two Different Sets of Empirical Questionnaire Survey

Based on the final checklist of 11 fire risk factors and 48 fire risk sub-factors derived from the results of the literature review and the structured face-to-face interviews, the first empirical questionnaire was developed. The survey results were used to develop suitable weightings for various fire risk factors and sub-factors by using Reliability Interval Method (RIM). To assess the weighting for each fire risk factor and sub-factor, a proper weighting assessment method is required considering a good practice of adopting interval grading in this research [7,8]. The subsequent section presents the most suitable weighting assessment method.

After determining the weightings, relative importance and rankings of various fire risk factors and sub-factors by means of RIM, the second empirical questionnaire survey was developed to establish an objective, reliable, comprehensive, and practical fire risk evaluation model for building construction sites in Hong Kong. Two major sections were included in the second empirical questionnaire survey, including (1) background information of survey respondents; and (2) evaluation of level of likelihood of occurrence and severity of fire risk factors and sub-factors for building construction sites in Hong Kong. A total of around 500 self-administered blank questionnaires were sent to target industrial practitioners via email and by hand (during a seminar) and 149 completed questionnaires were returned, which represented an acceptable response rate of 29.8%. The professional affiliation for the 149 survey respondents encompassed architects (2.7%), building surveyors (1.4%), quantity surveyors (7.5%), project managers (16.3%), engineers (19%), builders (19%), safety officers (17%), and others (17%). A majority of them worked in main contractors and they held vital roles in construction site management because they monitored the daily operations of construction sites and one of their main job duties was to take care of site safety (including construction site fire safety). Therefore, they were believed to possess rich knowledge and abundant hands-on experience to handle site fire safety [6].

Reliability Interval Method

It is vital to select the suitable weighting assessment method because this affects the accuracy of the fire risk evaluation directly [9]. There were two weighting assessment methods considered in this research. They are: (1) the Analytical Hierarchy Process (AHP) and (2) the Reliability Interval Method (RIM). The AHP is a measurement theory using pair-wise comparisons. It depends on the expert judgments to obtain priority scales [10]. Yiu et al. [11] reported that there were two main limitations for AHP. Firstly, it is unavoidable to have inconsistency between pair-wise comparisons even though evaluators have thorough explanations of the factors and sub-factors. Secondly, assessors are difficult to set an exact weighting for some factors because they are fuzzy in nature. The two limitations make AHP difficult to adopt to fire risk evaluation.

On the basis of Moore's [12] research study, Lo et al. [7] developed RIM to evaluate fire risk for high-rise buildings. By using RIM, the expert is allowed to assign a grade range rather than a fixed integer score. This enables the expert to have flexibility in assigning a fuzzy range of importance for each factor [7,10]. In fact, it is especially useful for RIM to deal with imprecise information. Assessors are required to weigh a factor adopting a fuzzy range of numbers. If the weighting for a fire risk factor is higher, its influence on fire safety is greater. Since there is no need for pair-wise comparisons in this evaluation method, it is eliminated for the problem of inconsistency arising from pair-wise comparison. Such a method can also determine the degree of reliability on the basis of center variance (CV) and interval variance (IV). According to Lo et al. [8], the degree of reliability is the proportion of the ranges weighted by the evaluators which falls within the average range. IV and CV show the consistency of opinions among survey respondents. Yiu et al. [11] adopted RIM to set suitable weightings for various decision criteria and their sub-criteria in assessing cost estimator's performance. Lo et al. [8] viewed that this method is especially feasible when there are large numbers of factors and sub-factors as the adoption of pair-wise comparisons in AHP may result in a lengthy questionnaire. According to the above discussion, RIM was selected for this study as the most suitable weighting assessment method to set the weightings of each fire risk factor and sub-factor [6].

Fuzzy Synthetic Evaluation

Fuzzy synthetic evaluation is an approach to evaluate numerous criteria decision-making [12]. In this research, the calculation of the Fire Risk Index (FRI) of a particular fire risk factor and the Overall Fire Risk Index (OFRI) of building construction sites in Hong Kong is used.

There are three basic elements for a fuzzy synthetic evaluation model [13]:

(1) A set of fire risk sub-factors $\pi = \{f_1, f_2, ..., f_m\}$;

(2) A set of grade alternatives $E = \{c_1, c_2, ...c_n$; $e_1, e_2, ...e_n\}$; e.g. c_1= very very low; c_2= very low; c_3= low; c_4= medium; c_5= high; c_6= very high; and c_7= very very high; (for risk probability) e_1= very low; e_2= low; e_3= medium; e_4= e_2= high; and e_5= very high (for risk severity) (it is noted that for risk evaluation, the rating of risk impact of a particular fire risk factor/sub-factor is calculated as the product of the rating of its associated risk

severity and the rating of its associated risk probability [14,15].

(3) For every object $u \notin U$ (which implies that the fuzzy subset u does not belong to the fuzzy set U). There is an evaluation matrix $R = (r_{ij})_{m \times n}$. r_{ij} is the degree to which alternative e_j satisfies the fire risk sub-factor f_j under the fuzzy environment. It is illustrated by the fuzzy membership function of grade alternative e_j regarding the fire risk sub-factor f_j. With the previous three elements, for a given $u \notin U$, its assessment result can be obtained (Figure 2).

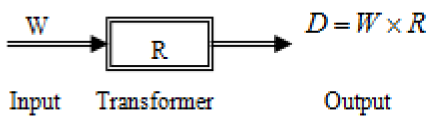

Figure 2. The Process of Fuzzy Synthetic Evaluation

Where W is the Input Information (it represents the parameters measured in the second empirical questionnaire survey in this research study) (the parameters mean different alternatives e_j with respect to different fire risk sub-factors f_j);

R is the Transformer in which it transforms the Input into the Output (i.e. it is the evaluation matrix and the evaluation matrix is the Model 3 mentioned in the main text on page XX);

D is the Output Information (it represents the membership function (both risk probability and risk severity) of each fire risk factor/sub-factor (Tables X and X) derived from the second empirical questionnaire survey in this research study)

Fire risk evaluation often involves numerous fire risk factors and sub-factors. All the fire risk factors and sub-factors are scrutinized so as to ensure effectiveness during the evaluation process. Therefore, if a synthetic evaluation method is adopted to tackle this multi-factor and multi-level problem, it will be more appropriate. As an application of Fuzzy Set Theory, Fuzzy Synthetic Evaluation has been used in a number of fields. Lu et al. [16] used Fuzzy Synthetic Evaluation to analyze reservoir water quality. Sadiq and Rodriguez [17] also adopted this approach to resolve the health risks on disinfection by-products. Hsu and Yang [18] established a Fuzzy Synthetic Decision system for adoption in human resources management. Zhao et al. [19] developed a Fuzzy Integrative Evaluation Method for evaluating the risk factors of a project. Based on these earlier research studies, it can be known that Fuzzy Synthetic Evaluation (FSE) has advantages in dealing with complex assessment with multi-factors and multi-levels. As a matter of fact, the adoption of fuzzy synthetic evaluation (as a kind of fuzzy logic/fuzzy set approach) could assist in evaluating more quantifiable risks [13]. As fire risk evaluations are always fuzzy and multi-layered in nature, which require evaluators' subjective judgment, it is suitable to use the Fuzzy Synthetic Evaluation Method to propose a fuzzy fire risk evaluation model in this study.

3. Research Findings and Discussions

Identification of 11 Fire Risk Factors and 48 Fire Risk Sub-Factors for Building Construction Sites in Hong Kong (Reported in [6])

At the first research stage, the research team had identified 11 fire risk factors and 48 fire risk sub-factors [6].

Selection of the Most Vital 9 Fire Risk Factors and 20 Fire Risk Sub-Factors for Building Construction Sites in Hong Kong

After conducting the first empirical questionnaire survey, the survey results indicate that the first three vital fire risk factors are 1. "fire services equipment and installations"; 2. "means of escape"; and 3. "attitude of main contractor" [6]. It should pay attention that the fire risk factor of "attitude of main contractor" was worked out through structured face-to-face interviews. This fire risk factor was ranked high reflects the fact that the respondents believe that it is not enough to only consider fire safety installations and equipment in order to achieve a favorable construction site fire safety level. It should also pay attention to human factors. Yiu et al. [11] did an analysis on performance evaluation for cost estimators and they suggested that when using the RIM, it could be viewed as very good when there was an achievement of 65% in reliability. They also considered that if the values of average center and interval variances are less than 0.65 and 2.10 respectively, only slight inconsistencies in opinions happen among clients. Accordingly, the fire risk evaluation model was developed by using the cut-off values of 0.65 for reliability, 0.65 for center variance (CV) and 2.20 for internal variance (IV) respectively. Attention needs to be paid the cut-off value of 2.10 for IV was too severe so a slightly revised value 2.20 was chosen. It was worth eliminating for any fire risk factor or sub-factor beyond these values. Altogether, 9 fire risk factors and 20 fire risk sub-factors met those requirements, in which they were chosen to develop the fire risk evaluation model of this research [6].

Development of Suitable "Normalized" Weightings for the 9 Fire Risk Factors and 20 Fire Risk Sub-Factors

As mentioned earlier, the survey results indicate the respondents' weightings of the 9 fire risk factors and 20 fire risk sub-factors [6]. A series of "normalized" weighted fire risk factors and sub-factors were established on the basis of the weightings of these fire risk factors and sub-factors. The "normalized" weightings for each of the 9 fire risk factors and 20 fire risk sub-factors were computed by using Equation 1 [20,21]:

$$W_i = \frac{M_i}{\sum_{i=1}^{9} M_i} \quad \text{(Equation 1)}$$

Where W_i represents the "normalized" weighting of a particular fire risk factor/sub-factor;

M_i represents the weighting of a particular fire risk factor/sub-factor;

$\sum M_i$ represents the summation of weightings of all the fire risk factors/sub-factors.

Table 1 shows the 9 fire risk factors and 20 fire risk sub-factors together with their corresponding "normalized" weightings.

Determination of the Membership Function for Each Fire Risk Factor/Sub-Factor

As mentioned previously, 20 fire risk sub-factors in total were identified for evaluating the overall fire risk level of building construction sites in Hong Kong. Suppose that the set of fire risk sub-factors in fuzzy risk evaluation model to be $\pi = \{f_1, f_2, ..., f_{17}\}$; and the grades for selection are defined as $E = \{c_1, c_2, ...c_n; e_1, e_2, ...e_n\}$; For each particular fire risk sub-factor, the membership function can be formed by the evaluation of survey experts. For instance, the survey results on "Fire Alarm" showed that 2% of the respondents opined the probability of occurrence of this risk as very very low, 10.1% as very low; 27.5% as low; 22.1% as medium; 20.1% as high; 8.7% as very high; and 9.4% as very very high, therefore the membership function of Fire Alarm (risk probability) is given by Equation 2:

$$C1 = \frac{0.020}{veryverylow} + \frac{0.101}{verylow} + \frac{0.275}{low} + \frac{0.221}{medium} + \frac{0.201}{high} + \frac{0.087}{veryhigh} + \frac{0.094}{veryveryhigh}$$

$$= \frac{0.020}{1} + \frac{0.101}{2} + \frac{0.275}{3} + \frac{0.221}{4} + \frac{0.201}{5} + \frac{0.087}{6} + \frac{0.094}{7} \quad \text{(Equation 2)}$$

It can also be written as (0.020, 0.101, 0.275, 0.221, 0.201, 0.087, 0.094). Similarly, the survey results on the "Fire Alarm" indicated that 1.3% of the respondents viewed that the severity of this risk as very low, 11.4% as low, 27.5% as medium, 43.6% as high, and 16.1% as very high, thus the membership function of Fire Alarm (risk severity) is given by Equation 3:

$$C1 = \frac{0.013}{verylow} + \frac{0.114}{low} + \frac{0.275}{medium} + \frac{0.436}{high} + \frac{0.161}{veryhigh}$$

$$= \frac{0.013}{1} + \frac{0.114}{2} + \frac{0.275}{3} + \frac{0.436}{4} + \frac{0.161}{5} \quad \text{(Equation 3)}$$

It can also be written as (0.013, 0.114, 0.275, 0.436, 0.161). Similarly, the membership functions of all the other fire risk sub-factors can be obtained in the same way (Tables 2 and 3) respectively. Attention should be paid that the membership functions of all the fire risk sub-factors are obtained from the Model 3 (Model 3: M $(\bullet, \oplus)$, $bj = \min(1, \sum_{i=1}^{m} wi \times rij) \forall bj \in B$) mentioned below.

Take the fire risk factor "Fire Services Equipment and Installations" (including sub-factors: Fire Alarm, Fire Hydrant Riser, Periodical Inspection, Provision in Area of Spraying Flammable Liquids, and Under Good Condition) as an instance; its membership function (risk probability) is shown in Table 2.

Similarly, the Membership Function of Fire Service Equipment and Installations (risk severity) is shown in Table 3.

Developing a Fuzzy Fire Evaluation Model for Building Construction Sites in Hong Kong

Having developed suitable "normalized" weightings for the 9 fire risk factors and 20 fire risk sub-factors, and subsequent establishing fuzzy membership functions for each fire risk factor and each fire risk sub-factor (both risk probability and risk severity), 4 models in total were considered to determine the results of the evaluation [9]. The reasons why the 4 models proposed by Lo [9] were considered are mainly because they are the typical models for assessing fire risk/fire safety involving fuzziness.

Model 1: M $(\wedge, \vee)$, $bj = \bigvee_{i=1}^{m} (wi \wedge rij) \quad \forall bj \in B$

Model 2: M $(\bullet, \vee)$, $bj = \bigvee_{i=1}^{m} (wi \times rij) \quad \forall bj \in B$

Since only the major criteria are considered and other minor criteria are ignored, Lo [9] stated that Models 1 and 2 are appropriate for single-item problems under this situation. Since it involves multi-factors for calculating the Overall Fire Risk Index (OFRI), Models 1 and 2 are considered not appropriate for this research.

Model 3: M $(\bullet, \oplus)$, $bj = \min(1, \sum_{i=1}^{m} wi \times rij) \quad \forall bj \in B$

Table 1. "Normalized" Weightings for the 9 Fire Risk Factor and 20 Fire Risk Sub-Factors

Fire Risk Factor/Sub-Factor	for both Risk Probability & Risk Severity			
	Weighting for Each Fire Risk Sub-Factor	**"Normalized"Weighting for each Fire Risk Sub-Factor**	**Weighting for Each Fire Risk Factor**	**"Normalized" Weighting for each Fire Risk Factor**
Fire alarm	0.02018	**0.209**		
Fire hydrant riser	0.02011	**0.204**		
Periodical inspection	0.02082	**0.200**		
Provision in area of spraying flammable liquids	0.02177	**0.194**		
Under good condition	0.02123	**0.193**		
Fire Services Equipment and Installations			0.09872	**0.117**
Adequate emergency lighting	0.02439	**0.551**		
Adequate width of means of escape	0.01987	**0.449**		
Means of Escape			0.09763	**0.116**
High level of commitment to fire safety system	0.02324	**0.354**		
High level of concern for main contractor about the probability of fire occurrence	0.02160	**0.329**		
Reasonable budget spent on site fire safety	0.02089	**0.318**		
Attitude of Main Contractor			0.09708	**0.116**
Use of earth leakage circuit breakers	0.02310	**1**		
Electricity Management			0.09324	**0.111**
Enforcement of smoking prohibition	0.02374	**0.517**		
Use of hot work procedures	0.02218	**0.483**		
Restrictions for On-Site Personnel			0.09310	**0.111**
Flammable liquids in spraying area stored in metal container with self-closing lid	0.02096	**0.348**		
Reasonable quantity of flammable liquids in spraying area	0.01974	**0.336**		
Removal or disposal of combustible materials after use	0.02177	**0.316**		
Storage of Flammable Liquids or Dangerous Goods			0.09173	**0.109**
Provision of firefighting & rescue staircase	0.02232	**1**		
Means of Access for Firefighting & Rescue Purpose			0.09077	**0.108**
Designated staff (e.g. wardens) help evacuation in fire situation	0.02008	**0.469**		
Planned evacuation route	0.02273	**0.531**		
Procedures Implemented in the Site			0.09063	**0.108**
Peer relationship of individuals	0.01967			
Behavior of On-Site Staff		**1**	0.08748	**0.104**
Total				

Table 2. The Membership Function of all Fire Risk Sub-Factors (Risk Probability)

No.	Fire Risk Sub-Factor	"Normalized" Weighting	Membership Function of Level 3	Membership Function of Level 2
C1	Inadequate provision of fire services equipment in areas with flammable liquids	0.209	(0.020, 0.101, 0.275, 0.221, 0.201, 0.087, 0.094)	**(0.020, 0.108, 0.259, 0.282, 0.186, 0.098, 0.048)**
C2	Fire services equipment and installations are in poor condition	0.204	(0.007, 0.161, 0.262, 0.255, 0.188, 0.094, 0.034)	
C3	Inadequate inspection of fire services equipment	0.200	(0.013, 0.094, 0.188, 0.362, 0.195, 0.121, 0.027)	
C4	Inadequate provision of fire alarms	0.194	(0.013, 0.060, 0.262, 0.349, 0.181, 0.107, 0.027)	
C5	Inadequate provision of fire hydrant risers	0.193	(0.047, 0.121, 0.309, 0.228, 0.161, 0.081, 0.054)	
C6	Inadequate provision of emergency lighting	0.551	(0.034, 0.094, 0.255, 0.295, 0.221, 0.074, 0.027)	**(0.028, 0.103, 0.246, 0.295, 0.212, 0.083, 0.033)**
C7	Inadequate width of means of escape	0.449	(0.020, 0.114, 0.235, 0.295, 0.201, 0.094, 0.040)	
C8	Low level of commitment for main contractor to establish and implement a fire safety system	0.354	(0.013, 0.168, 0.215, 0.242, 0.228, 0.128, 0.007)	**(0.024, 0.118, 0.220, 0.248, 0.239, 0.141, 0.011)**
C9	Low level of concern by main contractor about the probability of fire occurrence	0.329	(0.034, 0.081, 0.255, 0.228, 0.242, 0.148, 0.013)	
C10	Insufficient budget for construction site fire safety provisions	0.318	(0.027, 0.101, 0.188, 0.275, 0.248, 0.148, 0.013)	
C11	Improper use of earth leakage circuit breakers	1	(0.007, 0.181, 0.289, 0.255, 0.188, 0.060, 0.020)	**(0.007, 0.181, 0.289, 0.255, 0.188, 0.060, 0.020)**
C12	Inadequate enforcement of smoking prohibition for on-site personnel	0.517	(0.000, 0.067, 0.128, 0.208, 0.215, 0.255, 0.128)	**(0.003, 0.061, 0.147, 0.231, 0.244, 0.229, 0.085)**
C13	Improper use of hot work procedures for on-site personnel	0.483	(0.007, 0.054, 0.168, 0.255, 0.275, 0.201, 0.040)	
C14	Improper treatment of combustible materials after use	0.348	(0.000, 0.047, 0.201, 0.282, 0.215, 0.228, 0.027)	**(0.005, 0.071, 0.228, 0.225, 0.261, 0.188, 0.023)**
C15	Flammable liquids are not stored in metal container with self-closing lid	0.336	(0.007, 0.054, 0.262, 0.215, 0.282, 0.148, 0.034)	
C16	Excessive quantity of flammable liquids in working areas	0.316	(0.007, 0.114, 0.221, 0.174, 0.289, 0.188, 0.007)	
C17	Inadequate provision of firefighting and rescue staircases	1.00	(0.040, 0.121, 0.248, 0.342, 0.174, 0.054, 0.020)	**(0.040, 0.121, 0.248, 0.342, 0.174, 0.054, 0.020)**
C18	Designated staff are not provided to help evacuation in case of fire	0.469	(0.034, 0.094, 0.262, 0.376, 0.161, 0.067, 0.007)	**(0.034, 0.140, 0.298, 0.322, 0.140, 0.060, 0.007)**
C19	Inadequate provision of planned evacuation routes	0.531	(0.034, 0.181, 0.329, 0.275, 0.121, 0.054, 0.007)	
C20	Poor working relationship between various trade workers	1	(0.034, 0.121, 0.201, 0.396, 0.161, 0.081, 0.007)	**(0.034, 0.121, 0.201, 0.396, 0.161, 0.081, 0.007)**

Table 3. The Membership Function of all Fire Risk Sub-Factors (Risk Severity)

No.	Fire Risk Sub-Factor	"Normalized" Weighting	Membership Function of Level 3	Membership Function of Level 2
C1	Inadequate provision of fire services equipment in areas with flammable liquids	0.209	(0.013, 0.114, 0.275, 0.436, 0.161)	**(0.026, 0.154, 0.326, 0.408, 0.086)**
C2	Fire services equipment and installations are in poor condition	0.204	(0.007, 0.148, 0.255, 0.483, 0.107)	
C3	Inadequate inspection of fire services equipment	0.200	(0.040, 0.141, 0.362, 0.396, 0.060)	
C4	Inadequate provision of fire alarms	0.194	(0.034, 0.235, 0.376, 0.309, 0.047)	
C5	Inadequate provision of fire hydrant risers	0.193	(0.040, 0.134, 0.369, 0.409, 0.047)	
C6	Inadequate provision of emergency lighting	0.551	(0.040, 0.168, 0.362, 0.349, 0.081)	**(0.034, 0.132, 0.329, 0.415, 0.090)**
C7	Inadequate width of means of escape	0.449	(0.027, 0.087, 0.289, 0.497, 0.101)	
C8	Low level of commitment for main contractor to establish and implement a fire safety system	0.354	(0.007, 0.121, 0.430, 0.322, 0.121)	**(0.009, 0.115, 0.406, 0.370, 0.102)**
C9	Low level of concern by main contractor about the probability of fire occurrence	0.329	(0.007, 0.128, 0.349, 0.403, 0.114)	
C10	Insufficient budget for construction site fire safety provisions	0.318	(0.013, 0.094, 0.436, 0.389, 0.067)	
C11	Improper use of earth leakage circuit breakers	1	(0.013, 0.262, 0.268, 0.409, 0.047)	**(0.013, 0.262, 0.268, 0.409, 0.047)**
C12	Inadequate enforcement of smoking prohibition for on-site personnel	0.517	(0.027, 0.141, 0.362, 0.329, 0.141)	**(0.024, 0.138, 0.339, 0.352, 0.147)**
C13	Improper use of hot work procedures for on-site personnel	0.483	(0.020, 0.134, 0.315, 0.376, 0.154)	
C14	Improper treatment of combustible materials after use	0.348	(0.000, 0.121, 0.295, 0.430, 0.154)	**(0.004, 0.102, 0.311, 0.436, 0.147)**
C15	Flammable liquids are not stored in metal container with self-closing lid	0.336	(0.013, 0.101, 0.349, 0.403, 0.134)	
C16	Excessive quantity of flammable liquids in working areas	0.316	(0.000, 0.081, 0.289, 0.477, 0.154)	
C17	Inadequate provision of firefighting and rescue staircases	1.00	(0.007, 0.121, 0.322, 0.443, 0.107)	**(0.007, 0.121, 0.322, 0.443, 0.107)**
C18	Designated staff are not provided to help evacuation in case of fire	0.469	(0.027, 0.201, 0.477, 0.248, 0.047)	**(0.023, 0.187, 0.445, 0.287, 0.058)**
C19	Inadequate provision of planned evacuation routes	0.531	(0.020, 0.174, 0.416, 0.322, 0.067)	
C20	Poor working relationship between various trade workers	1	(0.114, 0.275, 0.389, 0.174, 0.047)	**(0.114, 0.275, 0.389, 0.174, 0.047)**

Model 4: M (∧, +), $bj = \sum_{i=1}^{m}(wi \wedge rij) \qquad \forall bj \in B$

The symbol "⊕" in Model 3 means the summation of product of weighting and membership function. Model 3 is appropriate when numerous criteria are taken into account and it is not large for the difference in the weighting of each criterion. Nevertheless, it is unsuitable for single-item problems in which only the major criteria are considered while other minor criteria are ignored. Model 4 will miss some information with smaller weighting because it only considers major criteria. Thus, it yields similar results to those obtained from Models 1 and 2. To summarize, Model 3 is appropriate for the calculation of the OFRI/Fire Risk Index (FRI) of the building construction sites in Hong Kong because there are many fire risk factors and sub-factors involved in the calculations and the difference in the weighting of each fire risk factor and sub-factor is not great.

Attention should be paid that there are three levels of membership function. Level 3 refers to each of 20 fire risk sub-factors (i.e. membership function of each fire risk sub-factor). Level 2 refers to each of the 9 fire risk factors (i.e. membership function of each fire risk factor) and Level 1 refers to the Overall Fire Risk Index (OFRI) (i.e. membership function of OFRI). Let *OFRI* denotes the Overall Fire Risk Index (OFRI) of building construction sites, W and R denote the weighting and member function of each fire risk factor.

The Membership Function of Overall Fire Risk Level (OFRI) (including Fire Services Equipment and Installations, Means of Escape, Attitude of Main Contractor, Electricity Management, Restrictions for On-Site Personnel, Storage of Flammable Liquids or Dangerous Goods, Means of Access for Firefighting & Rescue Purpose, Procedures Implemented in the Site, and Behavior of On-Site Staff) for risk probability and risk severity is shown in Table 4.

Table 4. The Results of Fuzzy Synthetic Evaluation for all Fire Risk Factors for Building Construction Sites in Hong Kong

Risk Probability (from Level 2 to Level 1)				
No.	**Fire Risk Factor**	**“Normalized” Weighting**	**Membership Function of Level 2**	**Membership Function of Level 1**
B1	Fire Services Equipment and Installations	0.117	(0.020, 0.108, 0.259, 0.282, 0.186, 0.098, 0.048)	**(0.022. 0.114. 0.237, 0.287, 0.201, 0.111, 0.029)**
B2	Means of Escape	0.116	(0.028, 0.103, 0.246, 0.295, 0.212, 0.083, 0.033)	
B3	Attitude of Main Contractor	0.116	(0.024, 0.118, 0.220, 0.248, 0.239, 0.141, 0.011)	
B4	Electricity Management	0.111	(0.007, 0.181, 0.289, 0.255, 0.188, 0.060, 0.020)	
B5	Restrictions for On-Site Personnel	0.111	(0.003, 0.061, 0.147, 0.231, 0.244, 0.229, 0.085)	
B6	Storage of Flammable Liquids or Dangerous Goods	0.109	(0.005, 0.071, 0.228, 0.225, 0.261, 0.188, 0.023)	
B7	Means of Access for Firefighting & Rescue Purpose	0.108	(0.040, 0.121, 0.248, 0.342, 0.174, 0.054, 0.020)	
B8	Procedures Implemented in the Site	0.108	(0.034, 0.140, 0.298, 0.322, 0.140, 0.060, 0.007)	
B9	Behavior of On-Site Staff	0.104	(0.034, 0.121, 0.201, 0.396, 0.161, 0.081, 0.007)	
Risk Severity (from Level 2 to Level 1)				
No.	**Fire Risk Factor**	**“Normalized” Weighting**	**Membership Function of Level 2**	**Membership Function of Level 1**
B1	Fire Services Equipment and Installations	0.117	(0.026, 0.154, 0.326, 0.408, 0.086)	**(0.028, 0.164, 0.348, 0.368, 0.093)**
B2	Means of Escape	0.116	(0.034, 0.132, 0.329, 0.415, 0.090)	
B3	Attitude of Main Contractor	0.116	(0.009, 0.115, 0.406, 0.370, 0.102)	
B4	Electricity Management	0.111	(0.013, 0.262, 0.268, 0.409, 0.047)	
B5	Restrictions for On-Site Personnel	0.111	(0.024, 0.138, 0.339, 0.352, 0.147)	
B6	Storage of Flammable Liquids or Dangerous Goods	0.109	(0.004, 0.102, 0.311, 0.436, 0.147)	
B7	Means of Access for Firefighting & Rescue Purpose	0.108	(0.007, 0.121, 0.322, 0.443, 0.107)	
B8	Procedures Implemented in the Site	0.108	(0.023, 0.187, 0.445, 0.287, 0.058)	
B9	Behavior of On-Site Staff	0.104	(0.114, 0.275, 0.389, 0.174, 0.047)	

Overall Risk Level =

$$\sqrt{(0.022\times1+0.114\times2+0.237\times3+0.287\times4+0.201\times5+0.111\times6+0.029\times7)\times(0.028\times1+0.164\times2+0.348\times3+0.368\times4+0.093\times5)}$$

=3.6427

After obtaining the membership function of Level 1, the Overall Fire Risk Index (OFRI) can be calculated using Equation 4:

$$OFRI=\sum_{k=1}^{5}(W\times R_k)\times L \qquad \text{(Equation 4)}$$

Where $OFRI$ is the Overall Fire Risk Index;

W is the weighting of each fire risk sub-factor;

R is the degree of membership function of each fire risk sub-factor (for both risk probability and risk severity);

L is the linguistic variable where 1 = very very low; 2 = very low; 3 = low; 4 = medium; 5 = high; 6 = very high; and 7 = very very high (for risk probability) and 1 = very low; 2 = low; 3 = medium; 4 = high; and 5 = very high (for risk severity)

Therefore, the Overall Fire Risk Index (OFRI) is:

$$\sqrt{(0.022\times1+0.114\times2+0.237\times3+0.287\times4+0.201\times5+0.111\times6+0.029\times7)\times(0.028\times1+0.164\times2+0.348\times3+0.368\times4+0.093\times5)}=3.6427$$

In order to have a deeper analysis, the Fire Risk Index (FRI) of a particular fire risk factor can also be calculated using the same method. The results are shown in Table 5.

Table 5. Fire Risk Index (FRI) of a Particular Fire Risk Factor and the Overall Fire Risk Index (OFRI) of Building Construction Sites in Hong Kong

No.	Fire Risk Factor	Risk Probability	Risk Severity	Risk Index
B1	Fire Services Equipment and Installations	3.9905	3.3713	**3.6678**
B2	Means of Escape	3.9396	3.3968	**3.6581**
B3	Attitude of Main Contractor	4.0313	3.4450	**3.7267**
B4	Electricity Management	3.6960	3.2120	**3.4455**
B5	Restrictions for On-Site Personnel	4.6815	3.4600	**4.0246**
B6	Storage of Flammable Liquids or Dangerous Goods	4.3271	3.6209	**3.9583**
B7	Means of Access for Firefighting & Rescue Purpose	3.7280	3.5220	**3.6235**
B8	Procedures Implemented in the Site	3.6050	3.1677	**3.3793**
B9	Behavior of On-Site Staff	3.8030	2.7620	**3.2410**
A	Overall Fire Risk Level	3.9806	3.3336	**3.6427**

The empirical research findings (Table 5) indicated that the Overall Fire Risk Index (OFRI) of building construction sites in Hong Kong as assessed by the industrial practitioners was 3.6427, which can be regarded as "moderate risk". In addition, the survey respondents perceived that the top-3 vial fire risk factors were 1. "Restrictions for On-Site Personnel", with the value of Fire Risk Index equal to 4.0246; 2. "Storage of Flammable Liquids or Dangerous Goods", with the value of Fire Risk Index equal to 3.9583; and 3. "Attitude of Main Contractor", with the value of Fire Risk Index equal to 3.7267. This study has developed an objective, reliable, comprehensive, and practical fuzzy fire risk evaluation model for evaluating the fire risk level of building construction sites using Reliability Interval Method and a fuzzy synthetic evaluation approach. It can be used to evaluate the overall fire risk level for a building construction site, and to identify improvement areas needed. The proposed model provides an objective basis for evaluating the level of fire risk for building construction sites. It not only enhances the understanding of clients, consultants and contractors in managing a safe construction site, but it also forms a solid foundation for industry practitioners to assess and improve the current performance of fire safety in their construction sites. An automated system for the fuzzy fire risk evaluation model for building construction sites can be developed in the near future. A practical risk evaluation tool for building construction sites could be thus used for benchmarking purposes.

An Instance to Demonstrate the Applicability of Fuzzy Fire Risk Evaluation Model for Building Construction Sites

The newly established model, though obtained from all survey respondents, could be further adapted to evaluate the fire risk level of a particular construction site. The adapted model will compose of two weighted components. The first component handles the generic situations, and the second one to evaluate the site-specific situations. The rationale of having two components is to objectify the evaluation, in that the assessment process will not be only governed by the survey respondents or the end-user.

In order to demonstrate its applicability, project data of a construction site A is inputted for demonstration purposes. The fuzzy membership functions obtained by the survey respondents for the generic situations are indicated in Tables 2 and 3. Those obtained for site-specific situations are indicated in Figures 3 and 4 (for risk probability and risk severity) and the corresponding fuzzy sets are indicated in Tables 6, 7, 8, and 9. Previous research studies [18,22] viewed that the most commonly adopted fuzzy membership functions are the one with triangular shapes. In addition, it is viewed as one of the easiest ways for establishing the fuzzy membership functions. Triangular fuzzy membership functions are thus adapted for construction site-specific situations.

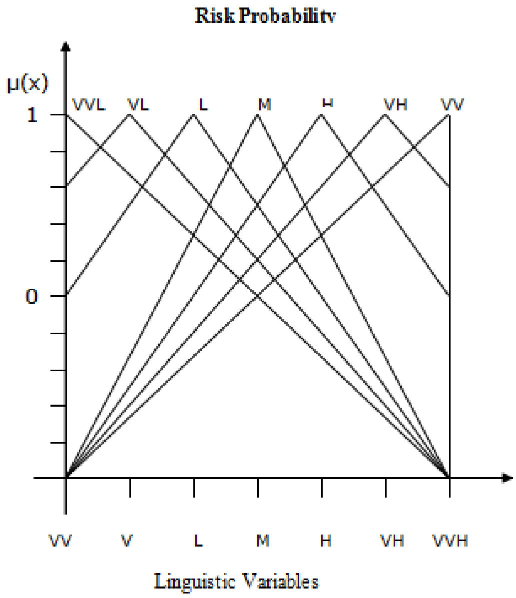

Figure 3. Membership Functions of Risk Probability

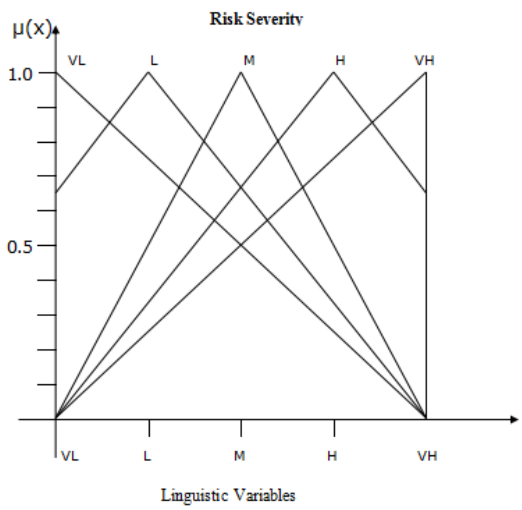

Figure 4. Membership Functions of Risk Severity

Table 6. The Membership Function (for Project-Specific Situations) of all Fire Risk Sub-Factors for Building Construction Sites in Hong Kong (Risk Probability)

Risk Probability	Degree of Membership
Very Very Low	= (1, 5/6, 2/3, 0.5, 1/3, 1/6, 0)
Very Low	= (0.8, 1, 0.8, 0.6, 0.4, 0.2, 0)
Low	= (0.5, 0.75, 1, 0.75, 0.5, 0.25, 0)
Medium	= (0, 1/3, 2/3, 1, 2/3, 1/3, 0)
High	= (0, 0.25, 0.5, 0.75, 1, 0.75, 0.5)
Very High	= (0, 0.2, 0.4, 0.6, 0.8, 1, 0.8)
Very Very High	(0, 1/6, 1/3, 0.5, 2/3, 5/6, 1)

Table 7. The Membership Function (for Project-Specific Situations) of all Fire Risk Sub-Factors for Building Construction Sites in Hong Kong (Risk Severity)

Risk Severity	Degree of Membership
Very Low	= (1, 0.75, 0.5, 0.25, 0)
Low	= (2/3, 1, 2/3, 1/3, 0)
Medium	= (0, 0.5, 1, 0.5, 0)
High	= (0, 1/3, 2/3, 1, 2/3)
Very High	= (0, 0.25, 0.5, 0.75, 1)

Table 8. The Normalized Membership Function (for Project-Specific Situations) of all Fire Risk Sub-Factors for Building Construction Sites in Hong Kong (Risk Probability)

Risk Probability	Degree of Membership
Very Very Low	= (0.286, 0.238, 0.190, 0.143, 0.095, 0.048, 0)
Very Low	= (0.211, 0.263, 0.211, 0.158, 0.105, 0.053, 0)
Low	= (0.133, 0.2, 0.267, 0.2, 0.133, 0.067, 0)
Medium	= (0, 0.111, 0.222, 0.334, 0.222, 0.111, 0)
High	= (0, 0.067, 0.133, 0.2, 0.267, 0.2, 0.133)
Very High	= (0, 0.053, 0.105, 0.158, 0.211, 0.263, 0.211)
Very Very High	= (0, 0.048, 0.095, 0.143, 0.190, 0.238, 0.286)

Table 9. The Normalized Membership Function (for Project-Specific Situations) of all Fire Risk Sub-Factors for Building Construction Sites in Hong Kong (Risk Severity)

Risk Severity	Degree of Membership
Very Low	= (0.4, 0.3, 0.2, 0.1, 0)
Low	= (0.25, 0.375, 0.25, 0.125, 0)
Medium	= (0, 0.25, 0.5, 0.25, 0)
High	= (0, 0.125, 0.25, 0.375, 0.25)
Very High	= (0, 0.1, 0.2, 0.3, 0.4)

Various weightings are assigned to both the generic situations and the site-specific situations so as to evaluate the fire risk level of Construction Site A. The weightings assigned are flexible in a sense that it is highly possible for various construction site end-users to have various perceptions towards the relative importance between generic and site-specific situations. It is the end-user to determine the weightings to be adopted. Therefore, if the end-user is less confident on his/her own assessment, then it can assign a higher weighting of "the generic situation", which makes the generic situation more decisive in the assessment process. In this demonstration example, equal weightings on both generic situation and site-specific situation are assigned (e.g. 0.5 and 0.5 respectively).

It is further assumed that the construction site end-user evaluates the risk probability and risk severity of the fire risk sub-factors of Construction Site A as per Table 10.

The risk level of Construction Site A can be calculated by incorporating two weightings together with the fuzzy membership functions as indicated in Table 11. The results are summarized in Tables 12 and 13.

Table 10. The Risk Probability and Risk Severity of all Fire Risk Sub-Factor for Construction Site A

No.	Fire Risk Sub-Factor	Risk Probability	Risk Severity
C1	Inadequate provision of fire services equipment in areas with flammable liquids	Low	Medium
C2	Fire services equipment and installations are in poor condition	Medium	Medium
C3	Inadequate inspection of fire services equipment	Medium	Medium
C4	Inadequate provision of fire alarms	Very High	Low
C5	Inadequate provision of fire hydrant risers	Very Very High	Very Low
C6	Inadequate provision of emergency lighting	Medium	Medium
C7	Inadequate width of means of escape	High	Medium
C8	Low level of commitment for main contractor to establish and implement a fire safety system	Medium	High
C9	Low level of concern by main contractor about the probability of fire occurrence	High	High
C10	Insufficient budget for construction site fire safety provisions	Medium	Medium
C11	Improper use of earth leakage circuit breakers	Medium	Low
C12	Inadequate enforcement of smoking prohibition for on-site personnel	High	High
C13	Improper use of hot work procedures for on-site personnel	High	High
C14	Improper treatment of combustible materials after use	High	Low
C15	Flammable liquids are not stored in metal container with self-closing lid	High	Medium
C16	Excessive quantity of flammable liquids in working areas	Medium	Medium
C17	Inadequate provision of firefighting and rescue staircases	Medium	Medium
C18	Designated staff are not provided to help evacuation in case of fire	Medium	Low
C19	Inadequate provision of planned evacuation routes	Medium	Medium
C20	Poor working relationship between various trade workers	High	Low

Table 11. The Membership Functions of all Fire Risk Sub-Factors for Construction Site A (Risk Probability and Risk Severity)

No.	Fire Risk Sub-Factor	"Normalized" Weighting	Membership Function (Risk Probability)	"Normalized" Weighting	Membership Function (Risk Severity)
C1a	Inadequate provision of fire services equipment in areas with flammable liquids (generic situation)	0.209	(0.020, 0.101, 0.275, 0.221, 0.201, 0.087, 0.094)	0.209	(0.013, 0.114, 0.275, 0.436, 0.161)
C1b	Inadequate provision of fire services equipment in areas with flammable liquids (project-specific situation)		(0.133, 0.200, 0.267, 0.200, 0.133, 0.067, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C2a	Fire services equipment and installations are in poor condition (generic situation)	0.204	(0.007, 0.161, 0.262, 0.255, 0.188, 0.094, 0.034)	0.204	(0.007, 0.148, 0.255, 0.483, 0.107)
C2b	Fire services equipment and installations are in poor condition (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C3a	Inadequate inspection of fire services equipment (generic situation)	0.200	(0.013, 0.094, 0.188, 0.362, 0.195, 0.121, 0.027)	0.200	(0.040, 0.141, 0.362, 0.396, 0.060)
C3b	Inadequate inspection of fire services equipment (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C4a	Inadequate provision of fire alarms (generic situation)	0.194	(0.013, 0.060, 0.262, 0.349, 0.181, 0.107, 0.027)	0.194	(0.034, 0.235, 0.376, 0.309, 0.047)
C4b	Inadequate provision of fire alarms (project-specific situation)		(0.000, 0.053, 0.105, 0.158, 0.211, 0.263, 0.211)		(0.250, 0.375, 0.250, 0.125, 0.000)
C5a	Inadequate provision of fire hydrant risers (generic situation)	0.193	(0.047, 0.121, 0.309, 0.228, 0.161, 0.081, 0.054)	0.193	(0.040, 0.134, 0.369, 0.409, 0.047)
C5b	Inadequate provision of fire hydrant risers (project-specific situation)		(0.000, 0.048, 0.095, 0.143, 0.190, 0.238, 0.286)		(0.400, 0.300, 0.200, 0.100, 0.000)
C6a	Inadequate provision of emergency lighting (generic situation)	0.551	(0.034, 0.094, 0.255, 0.295, 0.221, 0.074, 0.027)	0.551	(0.040, 0.168, 0.362, 0.349, 0.081)
C6b	Inadequate provision of emergency lighting (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C7a	Inadequate width of means of escape (generic situation)	0.449	(0.020, 0.114, 0.235, 0.295, 0.201, 0.094, 0.040)	0.449	(0.027, 0.087, 0.289, 0.497, 0.101)

C7b	Inadequate width of means of escape (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.000, 0.250, 0.500, 0.250, 0.000)
C8a	Low level of commitment for main contractor to establish and implement a fire safety system (generic situation)	0.354	(0.013, 0.168, 0.215, 0.242, 0.228, 0.128, 0.007)	0.354	(0.007, 0.121, 0.430, 0.322, 0.121)
C8b	Low level of commitment for main contractor to establish and implement a fire safety system (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.125, 0.250, 0.375, 0.250)
C9a	Low level of concern by main contractor about the probability of fire occurrence (generic situation)	0.329	(0.034, 0.081, 0.255, 0.228, 0.242, 0.148, 0.013)	0.329	(0.007, 0.128, 0.349, 0.403, 0.114)
C9b	Low level of concern by main contractor about the probability of fire occurrence (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.000, 0.125, 0.250, 0.375, 0.250)
C10a	Insufficient budget for construction site fire safety provisions (generic situation)	0.318	(0.027, 0.101, 0.188, 0.275, 0.248, 0.148, 0.013)	0.318	(0.013, 0.094, 0.436, 0.389, 0.067)
C10b	Insufficient budget for construction site fire safety provisions (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C11a	Improper use of earth leakage circuit breakers (generic situation)	1	(0.007, 0.181, 0.289, 0.255, 0.188, 0.060, 0.020)	1	(0.013, 0.262, 0.268, 0.409, 0.047)
C11b	Improper use of earth leakage circuit breakers (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.250, 0.375, 0.250, 0.125, 0.000)
C12a	Inadequate enforcement of smoking prohibition for on-site personnel (generic situation)	0.517	(0.000, 0.067, 0.128, 0.208, 0.215, 0.255, 0.128)	0.517	(0.027, 0.141, 0.362, 0.329, 0.141)
C12b	Inadequate enforcement of smoking prohibition for on-site personnel (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.000, 0.125, 0.250, 0.375, 0.250)
C13a	Improper use of hot work procedures for on-site personnel (generic situation)	0.483	(0.007, 0.054, 0.168, 0.255, 0.275, 0.201, 0.040)	0.483	(0.020, 0.134, 0.315, 0.376, 0.154)
C13b	Improper use of hot work procedures for on-site personnel (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.000, 0.125, 0.250, 0.375, 0.250)
C14a	Improper treatment of combustible materials after use (generic situation)	0.348	(0.000, 0.047, 0.201, 0.282, 0.215, 0.228, 0.027)	0.348	(0.000, 0.121, 0.295, 0.430, 0.154)
C14b	Improper treatment of combustible materials after use (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.250, 0.375, 0.250, 0.125, 0.000)
C15a	Flammable liquids are not stored in metal container with self-closing lid (generic situation)	0.336	(0.007, 0.054, 0.262, 0.215, 0.282, 0.148, 0.034)	0.336	(0.013, 0.101, 0.349, 0.403, 0.134)
C15b	Flammable liquids are not stored in metal container with self-closing lid (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.000, 0.250, 0.500, 0.250, 0.000)
C16a	Excessive quantity of flammable liquids in working areas (generic situation)	0.316	(0.007, 0.114, 0.221, 0.174, 0.289, 0.188, 0.007)	0.316	(0.000, 0.081, 0.289, 0.477, 0.154)
C16b	Excessive quantity of flammable liquids in working areas (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C17a	Inadequate provision of firefighting and rescue staircases (generic situation)	1.00	(0.040, 0.121, 0.248, 0.342, 0.174, 0.054, 0.020)	1.00	(0.007, 0.121, 0.322, 0.443, 0.107)
C17b	Inadequate provision of firefighting and rescue staircases (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C18a	Designated staff are not provided to help evacuation in case of fire (generic situation)	0.469	(0.034, 0.094, 0.262, 0.376, 0.161, 0.067, 0.007)	0.469	(0.027, 0.201, 0.477, 0.248, 0.047)
C18b	Designated staff are not provided to help evacuation in case of fire (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.250, 0.375, 0.250, 0.125, 0.000)

C19a	Inadequate provision of planned evacuation routes (generic situation)	0.531	(0.034, 0.181, 0.329, 0.275, 0.121, 0.054, 0.007)	0.531	(0.020, 0.174, 0.416, 0.322, 0.067)
C19b	Inadequate provision of planned evacuation routes (project-specific situation)		(0.000, 0.111, 0.222, 0.334, 0.222, 0.111, 0.000)		(0.000, 0.250, 0.500, 0.250, 0.000)
C20a	Poor working relationship between various trade workers (generic situation)	1	(0.034, 0.121, 0.201, 0.396, 0.161, 0.081, 0.007)	1	(0.114, 0.275, 0.389, 0.174, 0.047)
C20b	Poor working relationship between various trade workers (project-specific situation)		(0.000, 0.067, 0.133, 0.200, 0.267, 0.200, 0.133)		(0.250, 0.375, 0.250, 0.125, 0.000)

Table 12. The Results of Fuzzy Synthetic Evaluation for all Fire Risk Factors for Construction Site A

Risk Probability (from Level 2 to Level 1)				
No.	**Fire Risk Factor**	**"Normalized" Weighting**	**Membership Function of Level 2**	**Membership Function of Level 1**
B1	Fire Services Equipment and Installations	0.117	(0.024, 0.107, 0.222, 0.259, 0.190, 0.127, 0.072)	**(0.012. 0.104. 0.211, 0.279, 0.218, 0.131, 0.045)**
B2	Means of Escape	0.116	(0.014, 0.097, 0.214, 0.284, 0.227, 0.117, 0.046)	
B3	Attitude of Main Contractor	0.116	(0.012, 0.107, 0.206, 0.269, 0.238, 0.141, 0.027)	
B4	Electricity Management	0.111	(0.004, 0.146, 0.256, 0.295, 0.205, 0.086, 0.010)	
B5	Restrictions for On-Site Personnel	0.111	(0.002, 0.064, 0.140, 0.215, 0.255, 0.214, 0.109)	
B6	Storage of Flammable Liquids or Dangerous Goods	0.109	(0.002, 0.076, 0.194, 0.234, 0.257, 0.180, 0.057)	
B7	Means of Access for Firefighting & Rescue Purpose	0.108	(0.020, 0.116, 0.235, 0.338, 0.198, 0.083, 0.010)	
B8	Procedures Implemented in the Site	0.108	(0.017, 0.126, 0.260, 0.328, 0.181, 0.086, 0.004)	
B9	Behavior of On-Site Staff	0.104	(0.017, 0.094, 0.167, 0.298, 0.214, 0.141, 0.070)	
Risk Severity (from Level 2 to Level 1)				
No.	**Fire Risk Factor**	**"Normalized" Weighting**	**Membership Function of Level 2**	**Membership Function of Level 1**
B1	Fire Services Equipment and Installations	0.117	(0.076, 0.219, 0.360, 0.302, 0.043)	**(0.040, 0.182, 0.323, 0.283, 0.068)**
B2	Means of Escape	0.116	(0.017, 0.191, 0.415, 0.333, 0.045)	
B3	Attitude of Main Contractor	0.116	(0.004, 0.140, 0.368, 0.353, 0.136)	
B4	Electricity Management	0.111	(0.132, 0.319, 0.259, 0.267, 0.024)	
B5	Restrictions for On-Site Personnel	0.111	(0.012, 0.131, 0.295, 0.363, 0.199)	
B6	Storage of Flammable Liquids or Dangerous Goods	0.109	(0.046, 0.198, 0.362, 0.321, 0.074)	
B7	Means of Access for Firefighting & Rescue Purpose	0.108	(0.004, 0.186, 0.411, 0.347, 0.054)	
B8	Procedures Implemented in the Site	0.108	(0.070, 0.248, 0.414, 0.239, 0.029)	
B9	Behavior of On-Site Staff	0.104	(0.182, 0.325, 0.320, 0.150, 0.000)	

Overall Risk Level =

$$\sqrt{(0.012\times1+0.104\times2+0.211\times3+0.279\times4+0.218\times5+0.131\times6+0.045\times7)\times(0.040\times1+0.182\times2+0.323\times3+0.283\times4+0.068\times5)}$$

=3.4412

Table 13. Fire Risk Index of a Particular Fire Risk Factor and the Overall Fire Risk Index (OFRI) of Construction Site A

No.	Fire Risk Factor	Risk Probability	Risk Severity	Risk Index
B1	Fire Services Equipment and Installations	4.1532	3.0164	**3.5394**
B2	Means of Escape	4.1492	3.1984	**3.6429**
B3	Attitude of Main Contractor	4.1491	3.4801	**3.7999**
B4	Electricity Management	3.8480	2.7310	**3.2417**
B5	Restrictions for On-Site Personnel	4.7402	3.6050	**4.1338**
B6	Storage of Flammable Liquids or Dangerous Goods	4.4368	3.1800	**3.7562**
B7	Means of Access for Firefighting & Rescue Purpose	3.8640	3.2610	**3.5497**
B8	Procedures Implemented in the Site	3.8025	2.9080	**3.3253**
B9	Behavior of On-Site Staff	4.3010	2.5060	**3.2830**
A	Overall Fire Risk Level	4.1613	2.8457	**3.4412**

The research findings (Tables 12 and 13) indicated that the Overall Fire Risk Index (OFRI) of this construction site (Construction Site A) was 3.4412, which can be interpreted as "moderate risk". Therefore, the risk level for Construction Site A can be viewed as "moderate". Also, the research findings indicated that the top-2 fire risk factors are "Restrictions for On-Site Personnel" and "Attitude of Main Contractor". The bottom-2 fire risk factors are "Behavior of On-Site Staff" and "Electricity Management". In order to successfully manage this construction site, the industrial practitioner should pay special attention to the behavior of on-site personnel and attitude of main contractors, which may pose a great barrier for this construction site to be safely managed for construction site fire.

4. Conclusions

This study has used a new approach to develop a practical fire risk evaluation model for building construction sites on the basis of the data derived from Hong Kong. The research findings indicated that the top three fire risk factors were: (1) Restrictions for On-Site Personnel; (2) Storage of Flammable Liquids or Dangerous Goods; and (3) Attitude of Main Contractor. The research methodology can be used as an assessment tool to evaluate the fire risk level of a construction site, and then to identify improvement areas. An objective, reliable, comprehensive, and practical fire risk evaluation model for building construction sites was developed. By adopting the fuzzy fire risk evaluation model for building construction sites, the most vital fire risk factor for building construction sites can be identified and both precautionary and remedial actions can be taken as early as possible. Both the clients and main contractors can use this model to evaluate the fire risk level of their construction sites. And the results can be used to compare the fire risk levels with their counterparts for benchmarking purposes. Though the fire risk evaluation model was developed in Hong Kong, the same method can be reproduced in other nations for benchmarking purposes. This comparison can help a deeper understanding of managing construction sites across various geographical places.

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