BILINGUAL PUBLISHING CO.
Pioneer of Global Academics Since 1984

Journal of Construction Research
https://ojs.bilpublishing.com/index.php/jcr-b

ARTICLE

Developing a Holistic Fire Risk Assessment Framework for Building Construction Sites in Hong Kong

John F. Y. Yeung[1*] Daniel W. M. Chan[2]

1. Division of Business, College of International Education, Hong Kong Baptist University, Hong Kong, China
2. Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China

ARTICLE INFO

Article history
Received: 14 October 2019
Accepted: 26 December 2019
Published: 31 December 2019

Keywords:
Fire risk assessment
Reliability interval method
Building construction sites
Hong Kong

ABSTRACT

Amongst all types of construction accidents, industrial practitioners tend to pay less attention to the prevention of fires at construction sites. Although fires may not occur frequently on construction sites, statistics show that when they do, the consequences are very serious; involving fatalities, injuries, serious project delays and financial loss. There are many reasons why fires occur on sites, but a simple lack of awareness of the risks of fire is a major contributor. Fire risk assessment is not commonly performed on sites. Hence, it is believed that an appropriate assessment method for evaluating potential fire risk is required in order to improve the awareness of fire risk on construction sites. This paper reports on the key findings of a research project which aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites based in Hong Kong. A comprehensive list of those factors (or conditions) which may constitute a fire risk was compiled using desktop research and structured face-to-face interviews with experienced site personnel. This list of factors was then used to develop a questionnaire survey form and the Reliability Interval Method (RIM) was used to analyse the survey results and determine the relative importance and rankings of the various fire risk factors at a broad level and risk sub-factors at a detailed level. It was found that the fire risk factor of "Fire Services Equipment and Installations" has the greatest impact on construction site fire safety, with "Means of Escape in Case of Fire" being the second, and "Attitude of Main Contractor towards Fire Safety" being the third. In fact, it is the main contractor who plays the pivotal role in maintaining construction site fire safety, which is in line with the high ranking given to the fire risk factor of "Attitude of Main Contractor towards Fire Safety". The proposed fire risk assessment framework can be used to develop a useful checklist for assessing the overall level of fire risk for a construction site, and to identify any areas needing improvement. Although the fire risk assessment framework was developed locally in Hong Kong, the research methodology could be replicated in other countries to produce similar frameworks for international comparison. Such an extension would aid the understanding of the management of fire risk on construction sites and help discover differences between countries.

**Corresponding Author:*
John F. Y. Yeung,
Division of Business, College of International Education, Hong Kong Baptist University, Hong Kong, China
Email: jfyyeung@hkbu.edu.hk

DOI: https://doi.org/10.30564/jcr.v1i1.1302

1. Introduction

Risk management is used to identify, evaluate, and prioritize risks, and it is followed by a coordinated and economical application of resources to minimize, manage, and control the likelihood and/or severity of ill-fated events or to maximize the realization of opportunities[1]. Risks can come from uncertainty in financial markets, project failures, legal liabilities, credit risks, accidents, natural causes and disasters as well as deliberate attacks from an adversary. Fire risk management is an important area of risk management in which risk assessment of building conditions usually includes economic risk, social risk, natural risk (including fire risk of buildings), construction risk, and operation risk. In fact, fire risk management in construction sites is an important research area that is lacking systematic investigation. To fill this research gap, this paper aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. The focus of the fire risk problem in this research study is on a combination of life safety risk due to fire, property loss risk due to fire, and business interruption risk due to fire. For example, the fire risk factor of "Means of Escape in Case of Fire" (reported later) has been identified to prevent life safety risk due to fire; and the fire risk factor of "Storage of Combustible Materials or Dangerous Goods" has been identified to minimize physical damage and business interruption.

The construction accident rate in Hong Kong is the highest amongst major industries despite a decreasing trend since 2001 as shown in Table 1. Although construction site fires may be infrequent, their consequences are usually severe. Recent statistics from the Hong Kong Labor Department show that when construction site fires occur (Figure. 1), damage is not only very serious in respect of fatalities and injuries, but also lead to serious project delay and financial loss. Two recent serious construction site fires in Hong Kong illustrate these significant risks[2][3]. There are many reasons why fire accidents occur on sites and one of the most important is the lack of awareness of the risks as evidenced by the fact that site supervisory teams usually do not conduct regular and formal fire risk assessments. This may be due to a lack of an appropriate fire risk assessment method for evaluating fire risk on site. To help overcome this deficiency, this paper reports the findings of a research project which aims to develop a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. The proposed framework with ranking of the associated fire risk factors assists safety officers and related construction personnel to objectively assess the overall fire risk level of an individual construction site and to prioritize improvements to reduce risk. Although the framework was developed locally in Hong Kong, the research method may be applicable to other countries, for the production of similar frameworks and subsequent international comparisons.

Table 1. Industrial Accidents in Major Industries of Hong Kong (2001 – 2018)[45]

Accident Rate/1,000 workers	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Construction Industry	114.6	85.2	68.1	60.3	59.9	64.3	60.6	61.4	54.6	52.1	49.7	44.3	40.8	41.9	39.1	34.5	32.9	31.7
Catering Industry	61.5	54.7	49.6	51.5	47.3	47.2	43.5	38.7	35.7	34.7	30.9	26.4	24.2	22.9	22.1	20.5	20.5	20.2
Manufacturing Industry	20.7	18.8	15.7	17.5	17.7	18.4	17.4	16.3	15.9	16.8	17.8	18.2	17.1	17.4	16.8	15.6	15.7	14.7

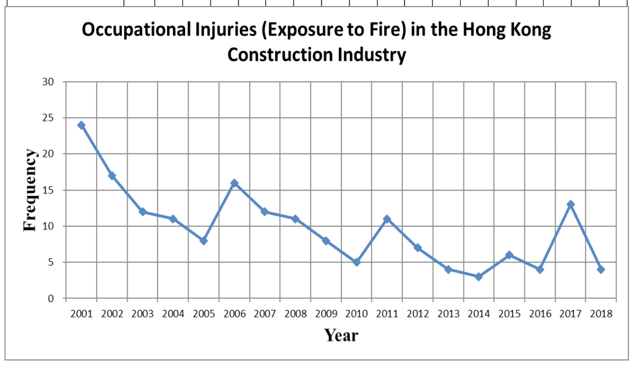


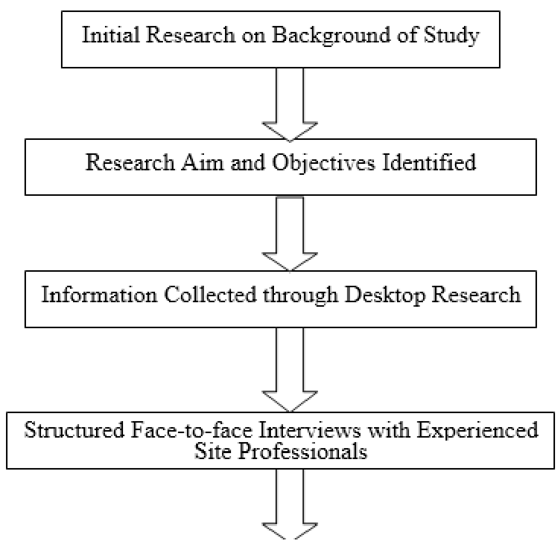
Figure 1. Numbers of Fire Accidents in the Hong Kong Construction Industry[46]

Note: The information is unavailable in year 2019.

2. Research Methodology

The research methods employed included: (1) desktop research; (2) structured face-to-face interviews with experienced site professionals; (3) questionnaire survey; and (4) weights assessment relating to the questionnaire survey results using the Reliability Interval Method (RIM).

Figure 2 shows the process of this research stage.



DOI: https://doi.org/10.30564/jcr.v1i1.1302

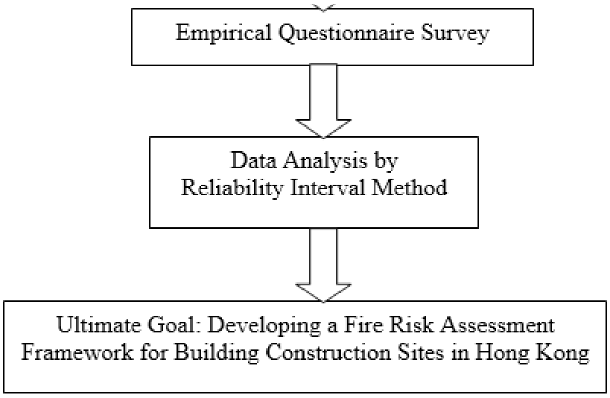


Figure 2. Research Process in this Study

2.1 Desktop Research

The desktop research covered: (1) a comprehensive literature review of fire risk assessment systems, assessment of weighting methods and site evacuation models; and (2) studies of legislation and current practices regarding fire safety in construction sites and of major past accidents. Through these studies, an initial checklist of fire risk factors and sub-factors was developed[4].

The search engines "Scopus" and "Google Scholar" were used to conduct the literature search under the "Title/Abstract/Keyword" field. Search keywords included "Fire risk", "Fire risk assessment", "Fire safety", "Fire safety assessment", "Construction sites accidents" and "Construction site safety". Publications related to construction and fire safety from local government offices were also examined. The initial literature review demonstrated a lack of well-established fire risk assessment systems and the associated fire risk factors for construction sites. It should be noted that there are minimum safety and health requirements for construction sites issued by the EU Council (the EU Council Directive 92/57/EEC (of 24 June 1992) on the implementation of minimum safety and health requirements at temporary or mobile construction sites)[5]. The role of health and safety requirements in this context is that it is important to make sure that construction sites are maintained with adequate health and safety measures for combating potential fire risks. Some other organizations, such as the National Fire Protection Association (NFPA) in the US, the Fire Protection Association (FPA) in the UK, and the UK Health & Safety Executive, have also had guidelines on fire safety during building construction for several years. The National Fire Protection Association (NFPA) provided guidelines and standard for safeguarding construction, alternation, and demolition operations[6]. The UK Fire Protection Association (FPA) had similar guidelines in order to achieve similar interpretation in the European countries and to give examples of acceptable solutions, concepts and models[7]. The UK Health & Safety Executive provided guidelines for clients, designers, and those managing and carrying out construction work involving significant fire risks[8].

The significant fire risk factors identified from the desktop literature review included: (1) Law Enforcement and On-site Supervision; (2) Means of Access for Firefighting and Rescue Purpose; (3) Means of Escape in Case of Fire; (4) Storage of Combustible Materials and Dangerous Goods; (5) Electricity Management; (6) Characteristics of Construction Site; (7) Fire Services Equipment and Installations; (8) Safety Procedures for Evacuation; (9) Site Environment during Fire; and (10) Safety Behaviors of On-Site Staff. Since there is not much literature related to fire risk assessment on construction sites, the literature search was broadened to include fire risk assessment systems for existing buildings and building evacuation models. When fire risk is assessed on a construction site, Chan (2007) advised that it is not appropriate for practitioners to solely consider fulfilling the minimum fire services installations and equipment requirements stated in legislation[9]. The author suggested taking a wider view, adopting a fire risk assessment method comprising many relevant factors. This approach is in line with Watts'(1997) and Lo's (1999) research work which consists of a fire risk hierarchy comprising a number of risk factors for conducting a fire risk assessment for an existing building[10][11]. Watts stated that fire risk assessment is built by assigning values to fire risk attributes based on "professional judgment and past experience and then aggregated by some arithmetic function" to derive a safety index value[10]. In other words, fire risk assessment considers the multi-attribute characteristics of fire safety and could be developed into a standard tool for assessment. In fact, fire risk assessment systems for existing buildings and karaoke establishments in Hong Kong have been developed on the basis of fire risk ranking[11][12][13]. It should be noted that fire risk ranking systems are heuristic models of fire safety, and they originated with the insurance rating schedule[14]. For instance, a Fire Safety Evaluation System (FSES) has been developed based on fire risk ranking in the United States[10][15]. Gretener (1973, 1980) developed an arithmetical assessment of fire risk ranking and this approach constitutes different processes of analyzing and scoring hazard and other risk parameters to generate a rapid and simple estimate of relative fire safety level[16][17].

Lo (1999) developed a fire risk assessment system using a fuzzy set theory approach to assess the overall fire safety level of existing buildings[11]. The system allowed fire risk factors to be prioritized so that improvement works could be carried out at areas with higher risks. This system also forms a part of the "Building Safety Inspection Scheme (BSIS)". The BSIS sets out the mandatory safety assurance requirements enacted by the Hong Kong government in 1997. A trial application of this fire safety assessment system was conducted by the Hong Kong Housing Department. Figure 3 shows the systematic approach for the identification of fire safety factors proposed by Lo (1999)[11], and Chow & Lui[12] using a 20-point system. This application of the technique is quite different from those of Lo's (1999) research work[11]. The study focused on karaoke establishments because of their special risk features, including: (1) boxes-partitioning; and (2) often crowded long corridors. The objective of this ranking system was to identify where immediate action is needed for improvements in fire safety in karaoke establishments.

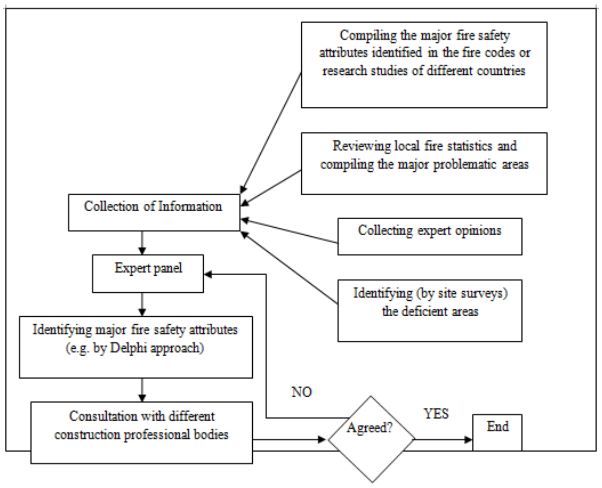


Figure 3. Simplified Approach for Identifying Fire Risk Sub-factors[11]

Lo (1999) considered research on fire safety to be complicated because of its multi-factor nature[11]. It was insufficient, therefore, to consider only legislation, current practices and major past fire incidents in the development of fire risk factors. Gwynne et al. (1999) considered that legislation and fire codes are not sensitive to human behavior and real fire situations[18]. Thus, evacuation models should be considered in the development of fire risk factors. However, evacuation models are often applied by fire engineers to check that adequate time is provided for evacuation of the occupants[19]. Such models are seldom used for assessing fire risk levels on construction sites. Hence, only that part of those evacuation models which is related to human behavior under an evacuation situation is considered. In fact, evacuation models are usually used together with fire models to establish the risk of occupants in fire. Thus, evacuation models are useful to develop the fire risk factor of "Means of Escape" together with its relevant fire risk sub-factors, such as "Adequate Number of Exits", "Free from Obstruction", and "Reasonable Travel Distance".

Lo (1999) suggested that major fire risk factors could be identified in the fire codes and regulations[11]. Based on this method, the following legislation was analyzed to identify an initial checklist of fire risk factors and sub-factors.

The Hong Kong Labor Department[20][21][22] issued the following documents:

1.The Construction Sites (Safety) Regulations[20]

2.A Guide to the Factories and Industrial Undertakings (Fire Precautions in Registrable Workplaces)[21]

3.A Guide to the Factories and Industrial Undertakings (Safety Supervisor)[22]

The Hong Kong Buildings Department[23][24][25] issued the following documents:

1.Code of Practice for Means of Access for Firefighting and Rescue[23]

2.Code of Practice for Fire Resisting Construction[24]

3.Code of Practice for Provision of Means of Escape in Case of Fire[25]

The Hong Kong Fire Services Department[26][27] issued the following documents:

1.Code of Practice for Minimum Fire Services Installation and Equipment[26]

2.Fire Safety (Building) Ordinance[27]

In addition, the Hong Kong Fire Services Department[28][29] provided some additional notices regarding some high-risk areas.

1.Fire Protection Notice No. 9 – Electrical Safety[28]

2.Fire Protection Notice No.13 – Fire Protection at Construction Site[29]

It should be noted that the Fire Protection Notice No.13 – Fire Protection at Construction Site issued by the Hong Kong Fire Services Department is in line with the EU Council Directive 92/57/EEC (of 24th June 1992) on the implementation of minimum safety and health requirements at temporary or mobile construction sites regarding emergency routes and exits, fire detection and fire-fighting[5]. Yam (2008) stated that legislation and current practice can provide a basic framework for fire protection on construction sites while major past fire incidents reflect the insufficiencies in existing practice and evacuation criteria[30].

After conducting a comprehensive literature review of the fire risk assessment systems, evacuation models; local legislations, current practices and major past fire incidents on construction sites, an initial checklist of fire risk factors

DOI: https://doi.org/10.30564/jcr.v1i1.1302

and sub-factors is developed (Table 2), which is reported in the subsequent section.

2.2. Structured Face-to-Face Interviews with Experienced Site Professionals

A panel of experts was invited for structured face-to-face interviews to help complement and refine the initial checklist of fire risk factors obtained from the literature review. The list of fire risk factors and sub-factors is formulated by comparing opinions of each expert. The structured interview, in which the interviewer asks predetermined questions with the same wording and order, is adopted because it provides uniform information[31]. Questions in the interview are based on the identified initial checklist of fire risk factors and sub-factors – legislation, current practices, major past accidents and evacuation issues with respect to fire safety in construction sites in Hong Kong. Finally, experts are also asked to identify fire risk factors and sub-factors that are not covered by the questions to ensure that a wide range of factors and sub-factors could be identified. Very importantly, each expert is asked for the extent their jobs relate to site fire safety at the beginning of the interview to ensure that they have adequate knowledge and experience. The interviewees included one fire safety engineer, one safety manager, one senior project manager (civil engineer), one senior structural engineer (who was involved in the drafting of the requirement of the site safety supervision plan issued by the Hong Kong Buildings Department), and two senior project building engineers. All the six interviewees had ten to twenty-five years of experience of construction site management and/or safety and they held vital roles in construction site management being responsible for monitoring the daily operations of construction sites and taking care of construction site safety (including construction site fire safety). They are believed to have adequate related knowledge and experience in assessing construction site fire risk and are well able to identify fire risk factors towards a comprehensive, objective, reliable, and practical fire risk assessment framework for building construction sites in Hong Kong. It should be noted that the use of expert judgment or expert elicitation has also been adopted for other fire risk engineering or infrastructure risk analysis related research studies[32][33][34][35][36][37]. As shown in Appendix 1, there were a total of twelve interview questions based on the initial checklist of fire risk factors developed from the desk research. The interview questions were divided into four parts: (1) background information; (2) views on the general construction sites situation; (3) views on evacuation issues; and (4) further supplementary information. Having conducted the structured face-to-face interviews, content analysis was adopted to identify the fire risk factors and sub-factors. Weber (1990) took a view that content analysis is able to assist in classifying textual material, so that more relevant and manageable bits of data can be grouped[38]. Fellows and Liu (2008) stated that the usage of content analysis is mainly to determine the main facets of a data set, by simply counting the number of occurrence of an activity or a topic[39]. The first step to conduct content analysis is to identify the materials to be analyzed. The second step is to decide the form of content analysis to be adopted, either qualitative or quantitative. The option depends on the nature of the research study. The choice of categories will also be dependent on the issues to be addressed in the study if they are known. The emphasis of qualitative content analysis is to determine the meaning of data (i.e. grouping data into categories) while the emphasis of quantitative content analysis is to extend the approach of the qualitative form to generate numerical values of the grouped data (frequency, ratings, ranking, etc.) which may be subject to statistical analyses[39]. During the process of content analysis in this study, the key points and main ideas of each interview verbatim transcript were first marked down. Then, similar main points were assembled and different fire risk factors and sub-factors were finally crystallized from the analyzed interview transcripts. Transcriptions of the interviews were returned to all interviewees for vetting and approval before further analysis. After the analysis of the results of the interviews, the final checklist of 11 fire risk factors and 48 sub-factors was developed (reported below), which then formed the basis for development of a subsequent questionnaire survey form.

2.3 Questionnaire Survey

This questionnaire survey form was developed based on the final checklist of fire risk factors developed from the results of the literature review and the structured interviews. The results of the survey were used to develop appropriate weightings for different fire risk factors and sub-factors. There were two major sections in the questionnaire, encompassing: (1) general conditions on construction sites; and (2) evacuation efficiency during fire on construction sites. These two parts were to be answered by survey respondents with interval grading so that the data analysis method, Reliability Interval Method (RIM), could be facilitated. The study population included all industrial practitioners who have acquired direct hands-on working experience at construction sites in general and site fire risk assessment in particular. The simple random sampling method was adopted in this study. A total of 111 blank questionnaires were dispatched

 DOI: https://doi.org/10.30564/jcr.v1i1.1302

by hand on the spot to those industrial practitioners who attended a continuing professional development (CPD) seminar on construction management in Hong Kong, and 46 completed questionnaires were returned, representing a very satisfactory response rate of 41.44%. In fact, the response rate is not considered to be low because a typical response rate of questionnaire survey in construction management in Hong Kong is around 30% to 50%[47]. The professional affiliation for the 46 survey respondents included 1 architect, 25 building engineers, 10 building services engineers, 3 fire engineers, 1 planning engineer, 4 safety engineers, and 2 structural engineers. Most of them worked for main contractors and some of them worked for client organizations, design consultants and trade subcontractors. They held important roles in construction site management, being responsible for monitoring the daily operations of construction sites and taking care of site safety (including site fire safety). Therefore, it is believed that they possessed adequate knowledge and experience to deal with site fire safety. In order to assess the weighting to be applied to each factor, a proper weighting assessment method is required, taking into account a good practice of using interval grading in fire study[29][30]. The following section presents two possible weighting assessment methods which can be used to develop the weightings for the factors and sub-factors.

2.4 Weighting Assessment Methods

It is important to choose the appropriate weighting assessment method since this directly affects the accuracy of the fire risk assessment[11]. Two weighting assessment methods were considered in this study. They are: (1) the Analytical Hierarchy Process (AHP) and (2) the Reliability Interval Method (RIM).

2.5 Analytical Hierarchy Process (AHP)

The AHP is a theory of measurement using pair-wise comparisons. It relies on the judgments of experts to derive priority scales. These scales measure the intangibles in relative terms and comparisons are made using a scale of absolute judgments that represents the extent to which one element dominates another with respect to a given attribute[40]. Saaty (1980) stated that AHP is widely used in prediction, prioritization, and probability judgments[41]. A hierarchy is constructed by analyzing real-life problems and investigating mutual dependence of the different criteria. A pair-wise comparison is incorporated in order to determine relative importance. The relationships are presented in matrix form. In our case, the impact of a fire risk factor on the fire risk is greater if the weighting is higher. Shields and Silcock (1986) felt that AHP was generally good at prioritizing the effect of uncertainty, but they experienced difficulties in conducting pair-wise comparisons when more than five criteria were under consideration at any one time[42]. Yiu et al. (2005) reported that there are two limitations of AHP[43]. Firstly, it is difficult to avoid inconsistency between pair-wise comparisons even if evaluators have comprehensive explanations of the factors and sub-factors. Secondly, evaluators may find it difficult to determine an exact weighting for some factors because they are vague in nature. In other words, fuzziness is difficult to incorporate with the use of AHP and evaluators may be unable to provide appropriate weightings when they find it difficult to weigh these vague criteria. These limitations make AHP difficult to apply to fire risk assessment.

2.6 Reliability Interval Method (RIM)

With reference to Moore's (1979) research work[44], Lo et al. (2001) developed RIM to assess fire risk for high-rise buildings[32]. RIM allows the expert to assign a grade range instead of a fixed integer score enabling flexibility in reflecting a fuzzy range of importance for each criterion as perceived by the expert[33][43]. RIM is different from another common weighting assessment method, i.e. direct point allocation (DIRECT)[43]. In the DIRECT method, the decision maker allocates numbers to describe the factor weights directly and then the factor weightings are obtained by normalization. However, it is questionable whether this is reliable since a fuzzy allocation of weightings is not allowed[43]. On the contrary, RIM is particularly useful in handling imprecise information. It requires evaluators to weigh a factor using a fuzzy range of numbers. For instance, evaluators can weigh a factor as a range of 2 to 4, [2, 4], instead of an exact value of [3]. The influence of a fire risk factor on fire safety is greater if the weighting is higher. As pair-wise comparisons are not needed in this assessment method, the problem of inconsistency arising from pair-wise comparison is eliminated. This method can also determine the degree of reliability based on center variance (CV) and interval variance (IV). According to Lo et al. (2005), the degree of reliability is the proportion of the ranges weighted by the evaluators which falls within the average range[33]. CV and IV indicate the consistency of opinions amongst survey respondents. When the values of CV and IV are small, it implies that the opinions of the survey respondents are consistent with one another as a whole. Yiu et al. (2005) used RIM to develop weightings for different decision criteria and their sub-criteria in evaluating cost estimator's performance[43]. Lo et al. (2005) stated that this method is particularly practical when the number of factors and sub-factors are large because the use of pair-wise comparisons

DOI: https://doi.org/10.30564/jcr.v1i1.1302

in AHP may lead to a lengthy questionnaire[43]. Based on the above discussion, RIM was chosen for this research as the most appropriate weighting assessment method for determining the weightings of each fire risk factor and sub-factor as they relate to the fire risk assessment of a construction site.

The mathematical principle of RIM is as follows[32][33][43]:

Let

J = Number of assessment criteria

M = Number of experts

N = Numbers of grades

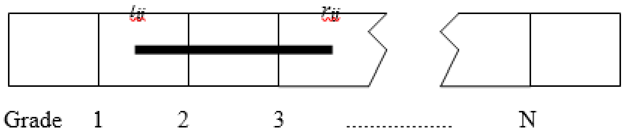


Figure 4. Illustration of Evaluating Fire Risk Factors

In Figure 4, let the i^{th} expert grades the j^{th} factor as belonging to the interval value $[l_{ij}, r_{ij}]$, where ,$0 \le l_{ij} \le r_{ij} \le N$, $i = 1, 2, \ldots, M$, $j = 1, 2, \ldots, J$.

Two assumptions are made for the development of RIM:

(1)The probability distribution function within the interval $[l_{ij}, r_{ij}]$ is linear;

(2)Equal weighting is given to the opinions of the different experts.

Hence, the interval grade for the j^{th} factor is defined as:

$$[a_j, b_j] = \frac{1}{M}\sum_{i=1}^{M}[l_{ij}, r_{ij}] \quad (1)$$

and the grade eigenvalue of the j^{th} factor is defined as:

$$\zeta_j = \frac{1}{2}(a_j + b_j) = \frac{1}{M}\sum_{i=1}^{M}\frac{l_{ij}+r_{ij}}{2} \quad (2)$$

Then, by normalization, the weighting of the j^{th} factor (η_j) is obtained:

$$\eta_j = \frac{\zeta_j}{\sum_{i=1}^{J}\zeta_i} \quad (3)$$

The weighting of the j^{th} factor (that is η_j) equals the grade eigenvalue (that is ζ_j) of the j^{th} factor divided by the sum of grade eigenvalues of J factors.

To allow statistical analysis of the results, RIM provides three parameters with the fuzzy assessment of weightings, namely, reliability, center variance (CV) and interval variance (IV).

For the definition of reliability, two parameters are introduced:

$$\delta\zeta_j = \{x \,|\, |x - \zeta_j| \le 0.5\} \quad (4)$$

$$I_j = \{i \,|\, [l_{ij}, r_{ij}] \cap \delta\zeta_j \ne \phi\} \quad (5)$$

$\delta\zeta_j$ corresponds to a range where x has a value such that $|x-\zeta_j| \le 0.5$, which means that $-0.5 \le x - \zeta_j \le 0.5$. Therefore, the range $\delta\zeta_j$ is $[\zeta_j - 0.5, \zeta_j + 0.5]$.

I_j corresponds to a set that i has a value such that $[l_{ij}, r_{ij}]$ and $\delta\zeta_j$ contain elements in common (under the situation that they have elements in common, denoted: ≠f), which is the intersection of the two sets as shown in Fig. 5.

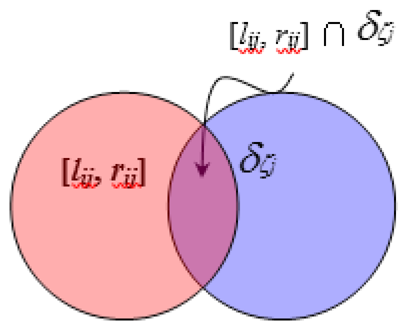


Figure 5. Intersection of $[l_{ij}, r_{ij}]$ and $\delta\zeta_j$

So, the reliability of the j^{th} factor attaining η_j grade is $|I_j|/M$, where $|I_j|$ is the number of set I_j. As mentioned above, the reliability illustrates the proportion of the ranges weighted by the experts that falls within the average range.

Center variance (CV_j) and interval variance (IV_j) for the j^{th} factor are defined as:

$$CV_j = \frac{1}{M}\sum_{i=1}^{M}\left(\zeta_j - \frac{l_{ij}+r_{ij}}{2}\right)^2 \quad (6)$$

$$IV_j = \frac{1}{M}\sum_{i=1}^{M}\left(\max\{|\zeta_j - l_{ij}|, |\zeta_j - r_{ij}|\}\right)^2 \quad (7)$$

The value of CV reflects the difference between the grade eigenvalue (ζ_j) and the average of interval grades (l_{ij} and r_{ij}) for a particular factor.

The value of IV reflects the difference between the grade eigenvalue (ζ_j) and the interval value l_{ij} or r_{ij} (which has a larger difference with the grade eigenvalue).

As mentioned, consistency of opinions among experts can be reflected with the use of these two variances. The smaller the values of center variance (CV) and interval variance (IV) are, the more consistent are the opinions of the respondents.[32][33][43]

3. Research Findings and Discussion

Based on the comprehensive literature review of fire risk assessment systems, evacuation models, local legislation, current practices and the major past fire accidents in construction sites, an initial checklist of 10 fire risk factors and 52 fire risk sub-factors was developed (Table 2). It should be noted that only the 10 fire risk factors identified in the initial checklist were used to set questions for the subsequent interviews with experienced site experts. The panel of experts was expected to identify the fire risk sub-factors during the interviews without any prior knowledge of the results of the desk research conducted in the study. By doing so, the consistency of the fire risk factors and sub-factors identified by the desk research can be compared with the fire risk factors and sub-factors proposed by the site experts during the interviews.

Table 2. An Initial Checklist of Fire Risk Factors and Sub-factors[4]

Ultimate Goal: Developing a Fire Risk Assessment System for Building Construction Sites	
Fire Risk Factors	Fire Risk Sub-factors
Law Enforcement and On-site Supervision	Enforcement of smoking prohibition
	Gas welding and flame cutting works done by competent workers
Means of Access for Firefighting and Rescue Purpose	Emergency vehicle access
	Free from obstruction
	Provision of firefighting and rescue staircase
	Smoke vent
	Substantial staircases erected
	Ventilated lobby
Means of Escape in Case of Fire	Adequate emergency lighting
	Adequate width of means of escape
	Adequate number of exits
	Free from obstruction
	Provision of exit signs
	Reasonable travel distance
	Under good condition
Storage of Combustible Materials and Dangerous Goods	Clearance of rubbish
	Flammable liquids in spraying area stored in metal container with self-closing lid
	Flammable liquids stored in closed containers that kept in cupboard or bin
	Provision of water type fire extinguisher near doorway of dangerous goods store
	Reasonable quantity of flammable liquids in spraying area
	Removal or disposal of combustible materials after use
	Smoking prohibition
	The use of dangerous goods store
Electricity Management	Overheating of excavator
	Overheating of generator
	Overheating of roller
	Properly insulate and protect electric wiring
	Use of earth leakage circuit breakers
Characteristics of Construction Site	Fire resistance period of elements of construction
	Size of compartment
Fire Services Equipment and Installations	Audio/visual advisory systems
	Fire alarm
	Fire blankets
	Fire hydrant riser
	Fixed fire pump with electricity supply
	Hose reel
	Periodical Inspection
	Portable fire extinguishers at each floor and site office
	Portable fire extinguishers at open flame workplace
	Provision in area of spraying flammable liquids
	Sprinkler system
	Under good condition
Safety Procedures for Evacuation	Evacuation training for on-site staff
	Location of emergency signage
	Configuration knowledge of occupants
Site Environment during Fire	Low hazards of heat
	Low hazards of irritant gases
	Low hazards of smoke
	Low hazards of toxic gases
Safety Behaviors of On-Site Staff	Achievable travel rate
	Peer relationship of individuals
	Willingness of on-site staff for evacuation in fire situation

After developing the initial checklist of fire risk factors and sub-factors, five structured face-to-face interviews with experienced site experts were conducted to verify and validate the comprehensiveness of the initial checklist. Then, the opinions of the panel of experts were consolidated and a total of 11 fire risk factors and 48 fire risk sub-factors were identified (Table 3). It should be highlighted that most of the fire risk factors and sub-factors identified during the interviews were in line with those fire risk factors and sub-factors identified by the desk research. Therefore, it was deemed valid and logical to use these 11 fire risk factors and 48 fire risk sub-factors in the development of the next questionnaire survey form.

Table 3. Average Interval Grades for the Final Checklist of 11 Fire Risk Factors and 48 Fire Risk Sub-factors Developed from Structured Face-to-Face Interviews with Experienced Site Professionals

Goal: Fire Safety of Construction Sites		
	Fire Risk Factors and Sub-factors	Average Interval Grades
1	**Law Enforcement and On-site Supervision**	**[2.978, 4.402]**
1.1	Enforcement of smoking prohibition	[3.228, 4.370]
1.2	Gas welding and flame cutting work done by competent workers	[2.815, 4.141]
1.3	Supervision by site supervisors or foremen	[2.793, 4.228]
1.4	System of rewards and punishment	[2.359, 3.663]
1.5	Use of hot work procedures	[2.891, 4.207]

DOI: https://doi.org/10.30564/jcr.v1i1.1302

2	**Means of Access for Firefighting and Rescue Purpose**	**[2.891, 4.304]**
2.1	Free from obstruction	[3.000, 4.380]
2.2	Emergency vehicle access	[2.457, 3.859]
2.3	Provision of firefighting & rescue staircase	[2.837, 4.304]
3	**Means of Escape in Case of Fire**	**[3.185, 4.554]**
3.1	Adequate emergency lighting	[3.261, 4.543]
3.2	Adequate width of means of escape	[2.511, 3.848]
3.3	Free from obstruction	[2.978, 4.326]
3.4	Provision of exit signs	[2.533, 3.935]
3.5	Under good condition	[2.565, 3.946]
4	**Storage of Flammable Liquids and Dangerous Goods**	**[2.880, 4.391]**
4.1	Cleared of rubbish	[2.859, 4.163]
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid	[2.750, 3.957]
4.3	Flammable liquids stored in closed containers that kept in cupboard or bin	[2.543, 3.804]
4.4	Reasonable quantity of flammable liquids in spraying area	[2.554, 3.761]
4.5	Removal or disposal of combustible materials after use	[2.815, 4.152]
4.6	Smoking prohibition	[3.185, 4.554]
4.7	The use of Dangerous Goods Store	[2.598, 3.978]
5	**Electricity Management**	**[3.011, 4.380]**
5.1	Enough supply of electricity	[2.478, 3.685]
5.2	Properly insulate and protect electricity wiring	[2.717, 4.087]
5.3	Use of earth leakage circuit breakers	[2.946, 4.446]
6	**Fire Services Equipment and Installations**	**[3.217, 4.609]**
6.1	Fire alarm	[2.543, 3.913]
6.2	Fire blankets	[1.967, 3.500]
6.3	Fire hydrant riser	[2.478, 3.957]
6.4	Fixed fire pump with electricity supply	[2.652, 4.087]
6.5	Hose reel	[2.641, 4.054]
6.6	Periodical Inspection	[2.663, 4.000]
6.7	Portable fire extinguishers at each floor and site office	[3.054, 4.500]
6.8	Portable fire extinguisher at open flame workplace	[2.957, 4.402]
6.9	Provision in area of spraying flammable liquids	[2.761, 4.207]
6.10	Under good condition	[2.707, 4.087]
7	**Attitude of Main Contractor towards Fire Safety**	**[3.043, 4.652]**
7.1	High level of commitment to fire safety system	[2.967, 4.467]
7.2	High level of concerns of probability of starting fire	[2.728, 4.185]
7.3	Reasonable budget spent on site fire safety	[2.652, 4.033]
8	**Characteristics of Construction Site**	**[2.554, 3.859]**
8.1	Choices of less combustible materials	[2.272, 3.576]
8.2	Good level of ventilation	[2.228, 3.663]
8.3	Types of works that induce numbers of fire sources (e.g. welding works, open flame)	[2.130, 3.511]
9	**Safety Procedures for Evacuation**	**[2.848, 4.337]**
9.1	Designated staff (e.g. wardens) help evacuation in fire situation	[2.576, 3.848]
9.2	Evacuation training for on-site staff	[2.587, 3.870]
9.3	Location of emergency signage	[2.478, 3.815]
9.4	Planned evacuation route	[2.870, 4.402]
10	**Site Environment during Fire**	**[2.402, 3.837]**
10.1	Low hazards of smoke	[2.522, 3.793]
10.2	Low hazards of irritant gases	[2.196, 3.478]
10.3	Low hazards of toxic gases	[2.272, 3.609]
11	**Safety Behaviors of On-Site Staff**	**[2.728, 4.207]**
11.1	Peer relationship of individuals	[2.435, 3.859]
11.2	Willingness of on-site staff for evacuation in fire situation	[2.152, 3.663]

Table 3 shows the results of the average interval grades for each fire risk factor and sub-factor obtained from the 46 completed and valid questionnaires. A "valid" questionnaire here refers to a questionnaire that is wholly completed. In fact, there were five questionnaires that were only partly completed and they were regarded as "invalid" questionnaires and therefore, they were excluded from the data analysis. Table 4 shows the survey results of the respondents' weightings of each fire risk factor and sub-factor. Since RIM has only been recently applied to fire related safety, the following principles should be noted. Lo et al. (2001) stated that when the weightings of two factors are nearly the same, the one with the higher reliability and vice versa is more reliable[32]. They also stated that a low value of variance indicates that a higher level of consistency exists amongst respondents, and vice versa. Yiu et al. (2005) conducted questionnaires on performance evaluation for cost estimators and suggested that when adopting the RIM, a level of 65% reliability could be regarded as reasonably good[43]. The authors also took the view that only minor inconsistencies in opinions exist amongst clients if the values of average center and interval variances are lower than 0.65 and 2.10 respectively. Accordingly, cut-off values of 0.65, 0.65 and 2.20 for reliability, center variance (CV) and interval variance (IV) respectively were used in establishing the fire risk assessment framework. It should be noted that the cut-off value of 2.10 for IV was too strict so a slightly modified value 2.20 was chosen. Any fire risk factor or sub-factor beyond these values was deemed worth eliminating. In total, 9 fire risk factors and 20 fire risk sub-factors met those requirements and they were selected for the development of the fire risk assessment framework of this study (Table 5).

Table 4. Results of Reliability Interval Method (RIM)

Fire Risk Factors and Sub-factors		First level weighting	Second level weighting	Reliability	Center variance	Interval variance
1	Law Enforcement and On-site Supervision	0.09310	--	0.93478	0.63909	1.97817
1.1	Enforcement of smoking prohibition	--	0.02374	0.89130	0.64571	1.83580
1.2	Gas welding and flame cutting work done by competent workers	--	0.02174	0.65217	0.78485	2.27009
1.3	Supervision by site supervisors or foremen	--	0.02194	0.80435	0.66564	2.20711
1.4	System of rewards and punishment	--	0.01882	0.82609	0.68195	2.03462
1.5	Use of hot work procedures	--	0.02218	0.89130	0.60494	2.04977
2	Means of Access for Firefighting and Rescue Purpose	0.09077	--	0.95652	0.25402	1.39473
2.1	Free from obstruction	--	0.02307	0.86957	0.75050	2.50133
2.2	Emergency vehicle access	--	0.01974	0.80435	0.68304	2.17016
2.3	Provision of firefighting & rescue staircase	--	0.02232	0.93478	0.47191	1.99637
3	Means of Escape in Case of Fire	0.09763	--	1.00000	0.21940	1.31971
3.1	Adequate emergency lighting	--	0.02439	0.95652	0.46869	1.77942
3.2	Adequate width of means of escape	--	0.01987	0.93478	0.55615	2.04741
3.3	Free from obstruction	--	0.02283	0.84783	0.75402	2.25780
3.4	Provision of exit signs	--	0.02021	0.86957	0.60707	2.23172
3.5	Under good condition	--	0.02035	0.86957	0.63992	2.21565
4	Storage of Flammable Liquids and Dangerous Goods	0.09173	--	0.84783	0.33888	1.68824
4.1	Cleared of rubbish	--	0.02194	0.86957	0.65749	1.99634
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid	--	0.02096	0.89130	0.35483	1.39441
4.3	Flammable liquids stored in closed containers that kept in cupboard or bin	--	0.01984	0.69565	0.87465	2.37902
4.4	Reasonable quantity of flammable liquids in spraying area	--	0.01974	0.89130	0.43576	1.49341
4.5	Removal or disposal of combustible materials after use	--	0.02177	0.78261	0.44403	1.65374
4.6	Smoking prohibition	--	0.02419	0.86957	0.66233	2.33648
4.7	The use of Dangerous Goods Store	--	0.02055	0.67391	1.10317	2.59325
5	Electricity Management	0.09324	--	0.89130	0.54868	1.89036
5.1	Enough supply of electricity	--	0.01926	0.73913	1.18221	2.57978
5.2	Properly insulate and protect electricity wiring	--	0.02127	0.82609	0.67250	2.17781
5.3	Use of earth leakage circuit breakers	--	0.02310	0.86957	0.61933	2.15430
6	Fire Services Equipment and Installations	0.09872	--	0.93478	0.37287	1.60539
6.1	Fire alarm	--	0.02018	0.97826	0.46692	1.85456
6.2	Fire blankets	--	0.01709	0.82609	0.72935	2.41768
6.3	Fire hydrant riser	--	0.02011	0.89130	0.48807	1.92888
6.4	Fixed fire pump with electricity supply	--	0.02106	0.76087	0.65147	2.25118
6.5	Hose reel	--	0.02093	0.80435	0.68065	2.17557
6.6	Periodical Inspection	--	0.02082	0.82609	0.58982	1.92831
6.7	Portable fire extinguishers at each floor and site office	--	0.02361	0.84783	0.65823	2.20100
6.8	Portable fire extinguisher at open flame workplace	--	0.02300	0.80435	0.74365	2.47758
6.9	Provision in area of spraying flammable liquids	--	0.02177	0.84783	0.43044	1.69722
6.10	Under good condition	--	0.02123	0.78261	0.55591	1.96778
7	Attitude of Main Contractor towards Fire Safety	0.09708	--	1.00000	0.21326	1.53592
7.1	High level of commitment to fire safety system	--	0.02324	0.91304	0.29785	1.54608
7.2	High level of concerns of probability of starting fire	--	0.02160	0.78261	0.64213	2.17628
7.3	Reasonable budget spent on site fire safety	--	0.02089	0.78261	0.49826	1.80213
8	Characteristics of Construction Site	0.08090	--	0.84783	0.66659	2.04360
8.1	Choices of less combustible materials	--	0.01828	0.78261	0.73334	2.19624
8.2	Good level of ventilation	--	0.01841	0.84783	0.73346	2.31534
8.3	Types of works that induce numbers of fire sources (e.g. welding works, open flame)	--	0.01763	0.86957	0.73278	2.20135
9	Safety Procedures for Evacuation	0.09063	--	0.95652	0.35152	1.69958
9.1	Designated staff (e.g. wardens) help evacuation in fire situation	--	0.02008	0.89130	0.41839	1.47120
9.2	Evacuation training for on-site staff	--	0.02018	0.78261	0.65170	1.99634
9.3	Location of emergency signage	--	0.01967	0.78261	0.83037	2.47498
9.4	Planned evacuation route	--	0.02273	0.89130	0.48562	1.93859
10	Site Environment during Fire	0.07871	--	0.84783	0.84440	2.37914
10.1	Low hazards of smoke	--	0.01974	0.76087	0.96293	2.35565
10.2	Low hazards of irritant gases	--	0.01773	0.80435	0.78592	2.09983
10.3	Low hazards of toxic gases	--	0.01838	0.78261	0.94072	2.39393
11	Safety Behaviors of On-Site Staff	0.08748	--	0.80435	0.52339	1.94293

DOI: https://doi.org/10.30564/jcr.v1i1.1302

Table 5. Selected Fire Risk Factors and Sub-factors after Considering the Values of Reliability, CV and IV

Fire Risk Factors and Sub-factors (Cont'd)		First level weighting	Second level weighting	Reliability	Center variance	Interval variance
6	Fire Services Equipment and Installations	0.09872	--	0.93478	0.37287	1.60539
6.1	Fire alarm	--	0.02018	0.97826	0.46692	1.85456
6.3	Fire hydrant riser	--	0.02011	0.89130	0.48807	1.92888
6.6	Periodical Inspection	--	0.02082	0.82609	0.58982	1.92831
6.9	Provision in area of spraying flammable liquids	--	0.02177	0.84783	0.43044	1.69722
6.10	Under good condition	--	0.02123	0.78261	0.55591	1.96778
3	Means of Escape in Case of Fire	0.09763	--	1.00000	0.21940	1.31971
3.1	Adequate emergency lighting	--	0.02439	0.95652	0.46869	1.77942
3.2	Adequate width of means of escape	--	0.01987	0.93478	0.55615	2.04741
7	Attitude of Main Contractor towards Fire Safety	0.09708	--	1.00000	0.21326	1.53592
7.1	High level of commitment to fire safety system	--	0.02324	0.91304	0.29785	1.54608
7.2	High level of concern for main contractor about the probability of fire occurrence	--	0.02160	0.78261	0.64213	2.17628
7.3	Reasonable budget spent on site fire safety	--	0.02089	0.78261	0.49826	1.80213
5	Electricity Management	0.09324	--	0.89130	0.54868	**1.89036**
5.1	Use of earth leakage circuit breakers	--	0.02310	0.86957	0.61933	2.15430
1	Law Enforcement and On-site Supervision	0.09310	--	0.93478	0.63909	1.97817
1.1	Enforcement of smoking prohibition	--	0.02374	0.89130	0.64571	1.83580
1.5	Use of hot work procedures	--	0.02218	0.89130	0.60494	2.04977
4	Storage of Flammable Liquids and Dangerous Goods	0.09173	--	0.84783	0.33888	1.68824
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid	--	0.02096	0.89130	0.35483	1.39441
4.4	Reasonable quantity of flammable liquids in spraying area	--	0.01974	0.89130	0.43576	1.49341
4.5	Removal or disposal of combustible materials after use	--	0.02177	0.78261	0.44403	1.65374
2	Means of Access for Firefighting and Rescue Purpose	0.09077	--	0.95652	0.25402	1.39473
2.3	Provision of firefighting & rescue staircase	--	0.02232	0.93478	0.47191	1.99637
9	Safety Procedures for Evacuation	0.09063	--	0.95652	0.35152	1.69958
9.1	Designated staff (e.g. wardens) help evacuation in fire situation	--	0.02008	0.89130	0.41839	1.47120
9.4	Planned evacuation route	--	0.02273	0.89130	0.48562	1.93859
11	Safety Behaviours of On-Site Staff	0.08748	--	0.80435	0.52339	1.94293
11.1	Peer relationship of individuals	--	0.01967	0.84783	0.63472	2.09006

Figure 6 shows the results of rankings and weightings of the 9 selected fire risk factors in descending order. The results show that "Fire Services Equipment and Installations" is the most important fire risk factor. Referring to Table 4, its reliability nearly reaches 94%, which is very satisfactory. The center variance (CV) and interval variance (IV) of this fire risk factor are small (0.37287 and 1.60539 respectively) and this implies that the opinions of the survey respondents are consistent. Due to the high reliability and small variances, it is appropriate to rank this fire risk factor as the most important one. The second and the third most important fire risk factors are "Means of Escape in Case of Fire" and "Attitude of Main Contractor towards Fire Safety", with weightings of 0.09763 and 0.09708 respectively. These two factors both achieved a reliability of 100% and their

CV (0.21940 and 0.21326, respectively) and IV (1.31971 and 1.53592, respectively) are also small, which show that the opinions of survey respondents are consistent. It should be noted that the fire risk factor "Attitude of Main Contractor towards Fire Safety" was formulated through structured interviews. The high ranking of this fire risk factor reflects the fact that respondents believe that to only consider fire services equipment and installations is not enough to achieve a good site fire safety level. Attention needs to be paid to human factors as well.

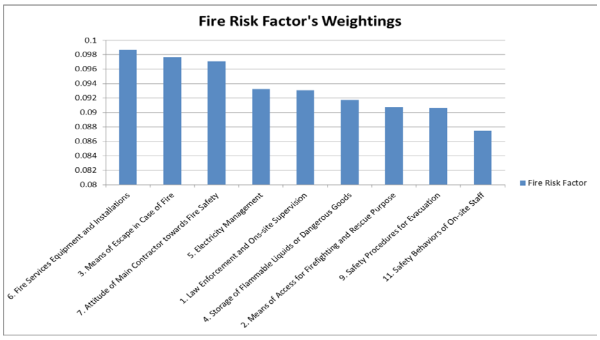


Figure 6. Fire Risk Factors' Weightings

Figure 7 indicates the rankings and weightings of the 20 selected fire risk sub-factors in descending order. The results show that "Adequate Emergency Lighting" is the most important fire risk sub-factor, with a weighting of 0.02439. Referring to Table 4, its reliability nearly reaches 96%, which is a very satisfactory result. The center variance (CV) and interval variance (IV) of this fire risk sub-factor are small (0.46869 and 1.77942, respectively) implying that the opinions of respondents are consistent. With the high reliability and small variances, it is appropriate to rank this fire risk sub-factor as the most important. In addition, its high ranking is in line with the high ranking of its corresponding fire risk factor. The second and the third most important fire risk sub-factors are "Enforcement of Smoking Prohibition" and "High Level of Commitment to Fire Safety System", with weightings of 0.02374 and 0.02324, respectively. These two fire risk sub-factors both achieved a reliability of 89.13% and 91.30% and their CV (0.64571 and 0.29785, respectively) and IV (1.83580 and 1.54608, respectively) are also small, which show that the opinions of survey respondents are quite consistent. It should be noted that these are main-contractor related fire risk sub-factors, indicating that main contractors play a vital role in securing construction site fire safety. In other words, it is important for main contractors to monitor and maintain fire safety standards and practices. This analysis also fits the high ranking of the fire risk factor "Attitude of Main Contractor towards Fire Safety", which was ranked as the third most important factor.

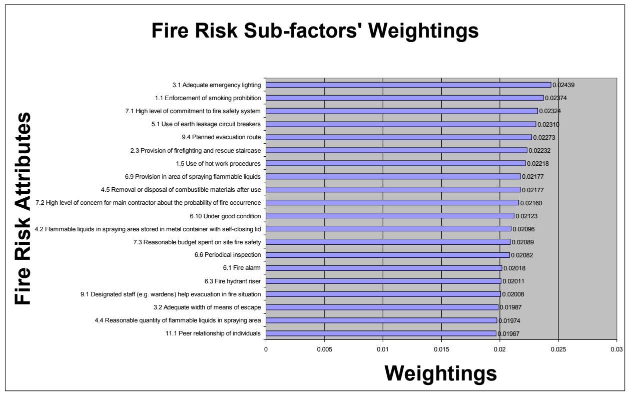


Figure 7. Fire Risk Sub-factors' Weightings

4. Application of the Developed Fire Risk Assessment Framework

The fire risk assessment framework which has been developed allows the assessment of site fire risks and their prioritization so that improvement can be affected as necessary for areas with higher risks. In this section, application of the fire risk assessment framework is illustrated using a hypothetical simplified example.

4.1 Application Procedures

The following application procedures for the fire risk assessment system represent a departure from the inspection approach for existing buildings as suggested by Lo et al. (2005)[33]. First, when the level of fire risk is assessed for a construction site, a checklist of fire risk factors should be established. Second, a site inspection should be carried out and information collected relating to the checklist factors. Finally, a fire risk assessment can be conducted and improvement work prioritized, and scheduled.

4.2 A Hypothetical Simplified Example of Applying the Proposed Fire Risk Assessment Framework for a Building Construction Site

To ensure a better understanding of the use of the checklist of fire risk factors and sub-factors, a hypothetical simplified example is presented here, which is based on the 3 selected fire risk factors: (1) "Means of Escape in Case of Fire"; (2) "Electricity Management"; and (3) "Attitude of Main Contractor towards Fire Safety". Their corresponding fire risk sub-factors are also included in the checklist in order to assess the fire risk level (construction site A).

Table 6 shows the weightings of these fire risk factors and sub-factors, obtained from Table 4. Rating means the "score" obtained from the assessed construction site (that is construction site A) during site inspection. The rating system in this instance is based on a 5-point Likert scale, in which 1 represents "very unsatisfactory", 2 represents

  DOI: https://doi.org/10.30564/jcr.v1i1.1302

"unsatisfactory", 3 represents "neutral", 4 represents "satisfactory", and 5 represents "very satisfactory".

After multiplying the weighting and rating for each fire risk sub-factor, the overall grading for the construction site can be calculated as follows:

The overall grading for the construction site, R:

$$R = \sum_{i=1}^{m} (\text{Weighting})_i \text{ x } (\text{Rating})_i \quad (8)$$

where R = overall grading for the construction site
m = total number of fire risk sub-factors

Table 6. A Hypothetical Simplified Example of Application of the Developed Fire Risk Assessment Framework

Fire Risk Factors and Sub-factors	Weight-ings	Rating for the Con-struction Site A 1 – very unsatisfactory 2 – unsatisfactory 3 – neutral 4 – satisfactory 5 – very satisfactory	Weights x Rating	Overall Grading
Means of Escape in Case of Fire	0.0976	4	0.3904	0.3904
Adequate emergency lighting	0.0244	5	0.1220	
Adequate width of means of escape	0.0199	3	0.0597	
Free from obstruction	0.0228	4.5	0.1026	0.4669
Provision of exit signs	0.0202	5	0.1010	
Under good condition	0.0204	4	0.0816	
Electricity Management	0.0932	2	0.1864	0.1864
Enough supply of electricity	0.0193	1	0.0193	
Properly insulate and protect electricity wiring	0.0213	2.5	0.0533	0.1188
Use of earth leakage circuit breakers	0.0231	2	0.0462	
Attitude of Main Contractor towards Fire Safety	0.0971	3	0.2913	0.2913
High level of commitment to fire safety system	0.0232	5	0.1160	
High level of concerns of probability of starting fire	0.0216	4	0.0864	0.2233
Reasonable budget spent on site fire safety	0.0209	1	0.0209	

The calculation regarding the total number of 11 fire risk sub-factors is as follows:

$$\begin{aligned} R &= R_{\text{Means of Escape in Case of Fire}} + R_{\text{Electricity Management}} + R_{\text{Attitude of Main Contractor towards Fire Safety}} \\ &= (0.0244 \text{ x } 5 + 0.0199 \text{ x } 3 + 0.0228 \text{ x } 4.5 + 0.0202 \text{ x } 5 + 0.0204 \text{ x } 4) \\ &\quad + (0.0193 \text{ x } 1 + 0.0213 \text{ x } 2.5 + 0.0231 \text{ x } 2) \\ &\quad + (0.0232 \text{ x } 5 + 0.0216 \text{ x } 4 + 0.0209 \text{ x } 1) \\ &= 0.4669 + 0.1188 + 0.2233 \\ &= 0.809 \end{aligned}$$

The overall grading for the construction site, "R", could be used as an indicator for internal benchmarking (i.e. to compare the fire risk levels between the construction sites of a specific construction company). It should be noted that when the overall grading is high, the level of fire risk is low, and vice versa. Based on the above example, when comparing the overall grading of the 3 fire risk factors, it was found that "Electricity Management" should be set as the first priority when conducting improvement work because its overall grading is the lowest (0.1188) in relation to the other two factors. Hence, the proposed fire risk assessment framework can help prioritize improvement work.

5. Significance and Limitations of the Research Study

The developed fire risk assessment framework should be very useful and relevant to those construction personnel responsible for assessing fire risk levels on construction sites and prioritizing improvement work. These construction personnel are not necessarily the safety committee members of the main contractor. They could be project managers, safety managers, building engineers, and building services engineers. The research validity is limited by the number of interviewees. If more respondents with a full range of types of site experiences were sought, the validity of the fire risk assessment framework could be further improved. It should be noted that other fire risk factors, such as underground structures, temporary structures on sites, scaffolding, roofing, planning and phasing, are also important for fire risk assessment for construction sites. However, it is observed that they are of less importance in the local context when compared with the 11 fire risk factors identified in this research study (also verified and validated by the six interviewees). However, these fire risk factors may be significant in construction sites of other countries. Therefore, it is suggested that these other fire risk factors could be included for developing similar comprehensive, objective, reliable, and practical fire risk frameworks for construction sites in other countries. Since the fire risk assessment framework developed in this research study is mainly used for generic situation, this study has not considered the "Planning and Phasing" factor into the framework in order to make the model simpler and easier. By doing so, the industrial practitioners working for client organizations, main contractors, design consultants and trade subcontractors may find the model use-friendly and this could enhance the effectiveness and efficiency of the model.

6. Summary and Conclusion

Major construction site fire risk factors and their sub-factors were successfully identified following the use of (1) review of the literature, legislation, current practices, major past accident records and evacuation issues related to fire safety on construction sites; and (2) structured face-to-face interviews with experienced site personnel using questions developed from the desktop research. On the basis of the identified fire risk factors and their sub-factors, an empirical questionnaire survey was launched to determine the levels of influence of each fire risk factor and sub-factor. Subsequently, the weighting assessment method, Reliability Interval Method (RIM), was used to develop the weightings for the fire risk factors and sub-factors. RIM is considered the most appropriate method because it is suitable for analyzing a large number of fuzzy factors and sub-factors and allows the use of fuzzy ranges in the weighting assessments. In addition, statistical analysis of weightings using RIM, allows the determination of reliability, center variance (CV) and interval variance (IV). The RIM analysis found the reliability of the questionnaire results attained in this study to be reasonably high and the opinions of the survey respondents to be consistent with one another as a whole.

Based on the analytical results, it was found that the top three fire risk factors are: (1) "Fire Services Equipment and Installations", "Means of Escape in Case of Fire" and "Attitude of Main Contractor towards Fire Safety". The high ranking of "Attitude of Main Contractor towards Fire Safety" implies that to solely rely on fire services installations and the provision of equipment are inadequate if a good site fire safety level is to be attained. Attention should also be paid to human factor aspects. The rankings of fire risk sub-factors show that a number of main-contractor related sub-factors ranked highly, reflecting the fact that it is the main contractor who plays the essential role in maintaining site fire safety. This observation also agrees with the high ranking of the fire risk factor "Attitude of Main Contractor towards Fire Safety".

Based on the weighted fire risk factors and sub-factors, the overall fire risk level of an individual construction site can be objectively assessed and given a score. Moreover, the fire risk assessment framework can be used to identify those factors needing attention to enhance site fire safety. The established assessment framework should be useful to those construction personnel responsible for assuring fire safety levels on construction sites and for prioritizing improvement work. It should be stressed that since this is a generic assessment framework, it can be applied to all types of construction sites, including large, medium or small scale.

References

[1] Hubbard D. (2009). *The Failure of Risk Management: Why Its Broken and How to Fix It*. John Wiley & Sons.

[2] Anonymous. (2005, October 26). Fire in One Silver Sea. *Ming Pao Daily News.*

[3] Anonymous. (2006, December 2). Fire in Mega Box. *Sing Tao Daily News.*

[4] Yam, M. C. H., Yeung, J. F. Y., Chan, R. K. W., Wong, F. K. W., Chan, A. P. C., & Chan, D. W. M. (2009, July 7 – July 10). Identification of Fire Risk Criteria and Attributes for Building Construction Sites in Hong Kong. *Proceedings of the AUBEA Conference 2009 on "Managing Change: Challenges in Education and Construction for the 21st Century."*, University of South Australia, Adelaide, Australia.

[5] European Council. (1992, June 24). *EU Council Directive 92/57/EEC of 24 June 1992 on the Implementation of Minimum Safety and Health Requirements at Temporary or Mobile Construction Sites*, UK.

[6] National Fire Protection Association (NFPA). (2009). *NFPA 241 (2009 edition) on Standard for Safeguarding Construction, Alteration, and Demolition Operations*, US.

[7] UK Fire Protection Association (FPA). (2009). *European Guideline: Fire Prevention on Construction Sites*.

[8] UK Health and Safety Executive. (2010). HSG 168 – Fire Safety in Construction – Guidance for Clients, Designers, and those Managing and Carrying out Construction Work Involving Significant Fire Risks.

[9] Chan, R. K. W. (2007). A Fire Safety Assessment System for Construction Sites in Hong Kong. *Unpublished Undergraduate Dissertation*, Department of Building and Real Estate, The Hong Kong Polytechnic University.

[10] Watts, J. M. (1997). Analysis of the NFPA fire safety evaluation system for business occupancies. *Fire Technology*, 33(3):276-282.

[11] Lo, S. M. (1999). A fire safety assessment system for existing buildings. Fire Technology, 35(2):131-152.

[12] Chow, W. K., & Lui, C. H. (2001). A fire safety ranking system for karaoke establishments in Hong Kong. *Journal of Fire Sciences*, 19(2):106-120.

  DOI: https://doi.org/10.30564/jcr.v1i1.1302

[13] Chow, W. K., Wong, L. T., & Kwan, C. Y. (1999). A proposed fire safety ranking system for old high-rise buildings in the Hong Kong Special Administrative Region. *Fire Materials*, 23(1):27-31.

[14] Zhao, C. M., Lo, S. M., Lu, J. A., & Fang, Z. (2004) A simulation approach for ranking of fire safety attributes of existing buildings. *Fire Safety Journal*, 39(7):557-579.

[15] National Fire Protection Association 101A. (1995). Guide on Alternative Approaches to Life Safety. Quincy, MA: National Fire Protection Association.

[16] Gretener, M. (1973). Evaluation of Fire Hazard, Determining Protective Measures. Zurich: Association of Cantonal Institutions for Fire Insurance and Fire Prevention Service for Industry and Trade.

[17] Gretener, M. Fire Risk Evaluation. (1980). *Zurich: Association of Cantonal Institutions for Fire Insurance, Society of Engineers and Architects and Fire Prevention Service for Industry and Trade*.

[18] Gwynne, S., Gelea, E. R., Owen, M., Lawrence, P. J., & Filippids, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. *Building and Environment*, 34(6):741-749.

[19] Ko, S., Spearpoint, M., & Teo, A. (2007). Trial evacuation of an industrial premises and evacuation model comparison. *Fire Safety Journal*, 42(2):91-105.

[20] Hong Kong Labour Department. (1978). The Construction Sites (Safety) Regulations. H*ong Kong Special Administrative Region: Government Printer*.

[21] Hong Kong Labour Department. (1981). A Guide to the Factories and Industrial Undertakings (Fire Precautions in Registrable Workplaces). *Hong Kong Special Administrative Region: Government Printer*.

[22] Hong Kong Labour Department. (1997). A Guide to the Factories and Industrial Undertakings (Safety Supervisor). *Hong Kong Special Administrative Region: Government Printer*.

[23] Hong Kong Buildings Department. (1995). Code of Practice for Means of Access for Firefighting and Rescue. *Hong Kong Special Administrative Region: Government Printer*.

[24] Hong Kong Buildings Department. (1996a). Code of Practice for Fire Resisting Construction. *Hong Kong Special Administrative Region: Government Printer*.

[25] Hong Kong Buildings Department. (1996b). Code of Practice for Provision of Means of Escape in Case of Fire. *Hong Kong Special Administrative Region: Government Printer*.

[26] Hong Kong Fire Services Department. (1993). Code of Practice for Minimum Fire Services Installation and Equipment. *Hong Kong Special Administrative Region: Government Printer*.

[27] Hong Kong Fire Services Department. (2002). Fire Safety (Building) Ordinance. *Hong Kong Special Administrative Region: Government Printer*.

[28] Hong Kong Fire Services Department. (2007a). Fire Protection Notice No.9 – Electricity Safety. *Hong Kong Special Administrative Region: Government Printer*.

[29] Hong Kong Fire Services Department. (2007b). Fire Protection Notice No. 13 – Fire Protection at Construction Sites. *Hong Kong Special Administrative Region: Government Printer*.

[30] Yam, B. L. P. (2008). A Study of the Construction Site Fire Safety in Hong Kong. *Unpublished Undergraduate Dissertation*, Department of Building and Real Estate, The Hong Kong Polytechnic University.

[31] Kumar, R. (2005). Research Methodology: A Step-by-Step Guide for Beginners. London: SAGE Publications, 2005.

[32] Lo, S. M., Lu, J. A., Hu, Y. Q., & Fang, Z. (2001). Incorporating reliability and variance into weighting function of fire risk assessment for high-rise buildings. *China Safety Science Journal*, 11(5):11-13. (Chinese)

[33] Lo, S. M., Hu, B. Q., Liu, M., & Yuen, K. K. (2005). On the use of reliability interval method and grey relational model for fire safety ranking of existing buildings. *Fire Technology*, 41(4):255-270.

[34] Ezell B. C., Farr, J. V., & Wiese, I. (2000). Infrastructure risk analysis of municipal water distribution system. *Journal of Infrastructure Systems*, 6(3):118-122.

[35] Grimsey, D., & Lewis, M. (2002). Evaluating the risks of public private partnerships for infrastructure projects. International Journal of Project Management, 20(2):107-118.

[36] Xu, Y. L., Chan, A. P. C., & Yeung, J. F. Y. (2010). Developing a fuzzy risk allocation model for PPP projects in China. Journal of Construction Engineering and Management, ASCE, 136(8):894-903.

[37] Xu, Y. L., Yeung, J. F. Y., Chan, A. P. C., Chan, D. W. M., Wang, S. Q., & Ke, Y. J. (2010). Developing a risk assessment model for PPP projects in China: A fuzzy synthetic evaluation approach. Automation in Construction, 19(7):929-943.

[38] Weber, R. P. (1990). Basic content analysis (2nd edition). Sage Publication.

[39] Fellows, R., & Liu, A. (2008). *Research methods*

for construction (3rd Edition). Blackwell Science, Oxford, United Kingdom.

[40] Saaty, T. L. (2008). Decision making with the analytic hierarchy process. International Journal of Services Sciences, 1(1):83-98.

[41] Saaty, T. L. (1980). *The Analytic Hierarchy Process*. New York: McGraw Hill, 1980.

[42] Shields, J., & Silcock, G. (1986). An application of the hierarchical approach to fire safety. *Fire Safety Journal*, 1986; 11(3):235-242.

[43] Yiu, C. Y., Ho, H. K., Lo, S. M., & Hu, B. Q. (2005). Performance evaluation for cost estimators by reliability interval method. *Journal of Construction Engineering and Management*, ASCE, 131(1):108-116.

[44] Moore, R. E. (1979). *Methods and Applications of Interval Analysis*. Philadelphia: SIAM.

[45] Hong Kong Labour Department. (2019). Occupational Safety and Health Statistics Bulletin Issue No. 19, 2019. *Hong Kong Special Administrative Region: Government Printer*. Retrieved on 14 October 2019 from: https://www.labour.gov.hk/eng/osh/pdf/Bulletin2018_issue19_eng.pdf

[46] Hong Kong Labour Department. (2019). Occupational Safety and Health Statistics 2013. *Hong Kong Special Administrative Region: Government Printer*. Retrieved on 14 October 2019 from: http://www.labour.gov.hk/eng/osh/pdf/OSH_Statistics_2019.pdf

[47] Yeung, J. F. Y., Chan, A. P. C., Chan, D. W. M., & Li, L. K. (2007). Development of a Partnering Performance Index (PPI) for construction projects in Hong Kong: a Delphi study. *Construction Management and Economics*, 25(12):1219-1237.

Appendix 1: Interview Questions Based on the Initial Checklist of Fire Risk Factors Developed From the Desk Research

Part 1: Background Information

Q1. To what extent does your job deal with fire safety in construction sites?

Part 2: Views on General Situation on Construction Sites

Q2. Do you think appropriate restrictions for on-site personnel, such as smoking prohibition, gas welding and flame cutting work carried out by competent workers, could affect fire safety on site? If yes, could you identify major sub-factors of appropriate restrictions for on-site personnel?

Q3. Do you think provision of means of access for firefighting and rescue purposes could affect fire safety on sites? If yes, could you identify major sub-factors of provision of means of access for firefighting and rescue purposes?

Q4. Do you think provision of means of escape could affect fire safety on sites? If yes, could you identify major sub-factors of provision of means of escape?

Q5. Do you think storage of flammable liquids or dangerous goods could affect fire safety on sites? If yes, could you identify major sub-factors of storage of flammable liquids or dangerous goods?

Q6. Do you think proper electricity wiring management such as insulating electric wiring properly could affect fire safety on sites? If yes, could you identify major sub-factors of proper electricity wiring management?

Q7. Do you think appropriate design of construction sites, such as compartment, could affect fire safety on sites? If yes, could you identify major sub-factors of appropriate design characteristics of construction sites?

Q8. Do you think provision of fire services equipment and installations could affect fire safety on sites? If yes, could you identify major sub-factors of provision of fire services equipment and installations?

Part 3: Views on Evacuation Issue

Q9. Do you think procedures implemented within the site, such as provision of staff evacuation training and prior knowledge of location signage, could affect fire safety on sites? If yes, could you identify major sub-factors of the procedural influences?

Q10. Do you think environment within the site during fire, such as hazards of heat, smoke and toxic and irritant gases, could affect fire safety on sites?

Q11. Do you think behaviour of site staff, such as initial response to fire alarm and travel rate, could affect fire safety on sites?

Part 4: Further Information

Q12. Can you suggest any other factors that could affect fire safety on sites? If yes, could you identify major sub-factors of this factor?

DOI: https://doi.org/10.30564/jcr.v1i1.1302