A RESEARCH PARADIGM FOR DEVELOPING A FIRE RISK ASSESSMENT MODEL FOR NEW CONSTRUCTION SITES IN HONG KONG

Daniel W.M. Chan*
Associate Professor, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

Yuming Hong
Research Assistant, Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

ABSTRACT

In Hong Kong, the construction industry is regarded as high-risk. Amongst all types of construction accidents, however, industrial practitioners tend to give less attention to those related to construction site fires, that is, fires which occur during new construction. Fire is perceived as a significant but common risk associated with construction projects which can lead to serious damage. Although construction site fires may not be frequent, the consequences are usually severe. This paper will present an overall research framework for developing a fire risk assessment model for new construction sites in Hong Kong. The research process mainly involves the identification of key fire risk factors and their associated sub factors contributing to fire risk for a construction site, and the development of a fuzzy fire risk assessment model based on the identified fire risk factors. The research methods to be adopted include desktop literature review, Delphi survey technique, empirical questionnaire survey and fuzzy set theory. The model can be used as an objective tool for measuring and comparing the overall fire risk levels existing at different construction sites. Therefore, high-risk areas could be identified and improved. The research findings from the developed fire risk assessment model will ultimately lead to the provision of remedial measures to reduce fire risk at new construction sites. Although the research study will primarily focus on the prevailing situation in Hong Kong, the research methodology will be applicable to many other parts of the world for facilitating international comparisons.

Keywords: *Assessment Model; Construction Site; Fire Risk; Hong Kong; Research Framework.*

1. INTRODUCTION

In Hong Kong, the construction industry is regarded as high-risk. It is evident that the construction industry still records the highest accident rate and number of fatalities amongst the various major industry sectors throughout the world (Choudhry *et al*., 2008; Labour Department, 2013). Amongst all types of construction accidents, however, industrial practitioners tend to give less attention to those related to construction site fires, that is, fires which occur during new construction.

Fire is perceived as a significant but common risk associated with construction projects which can lead to serious damage. Although construction site fires may not be frequent, the consequences are usually severe. Statistics from the Labour Department (2013) indicate that a construction site fire will not only delay the completion date of the project but can also result in serious monetary losses and even injuries and fatalities.

There are several reasons for the occurrence of fires on site, one of which is a lack of awareness of the nature of various fire risks and the other is a lack of a proper fire risk assessment mechanism (Yam *et al*., 2009). Fire risk assessment ought to be routine as a proactive and formal procedure in fire prevention. It should offer a structured and systematic assessment of fire safety management capabilities, fire protection capabilities, fire risks on site and emergency handling capabilities during a fire (Lo, 1999). It should also

*Corresponding Author: E-mail - daniel.w.m.chan@polyu.edu.hk

provide practical solutions and effective recommendations for fire risk mitigation. In fact, there exists a strong urgent need for an appropriate fire risk assessment mechanism for building construction sites.

In order to develop the fire risk assessment model for construction sites, it is essential to systematically examine the essential fire risk factors and their associated subfactors which affect both the likelihood of a fire arising and/or its level of severity to a construction project in terms of damage, life, time or cost if a fire does occur. Therefore, the proposed research study aims to develop a holistic fire risk assessment model for new construction sites in Hong Kong using the Delphi survey technique, empirical questionnaire survey and fuzzy set theory. It will be a multi-factor model where the essential fire risk factors are expressed both in broad terms and as finer, more detailed, subfactors. The model can be used as an objective tool for measuring and comparing the overall fire risk levels existing at different construction sites. Only new construction sites will be included in this investigation and not those building sites where substantial renovation with occupants inside is taking place. The developed model will be adjusted, validated and confirmed for use following face-to-face interviews with senior industrial practitioners and some real-life case studies.

2. BACKGROUND OF RESEARCH

In spite of Hong Kong government departments' efforts to mitigate fire risk through promulgating minimum fire safety requirements and measures (Yam *et al*., 2009), the situation of construction site fires has not been well improved as seen from the frequently reported cases of fires on construction site. In fact, serious construction site fires have occurred over recent years in Hong Kong. For example, there occurred a number 4 alarm fire at the site of the high-rise private residential building "One Silver Sea" in Tai Kok Tsui on 26 October 2005. Another number 4 alarm fire broke out on 1 December 2006 at the site of the Kowloon Bay Enterprise Square Phase V Mega Box Building, which is a private commercial development. About 2 weeks later, on 15 December 2006, two workers were seriously injured by a sudden gas explosion on a construction site in Shatin.

Fire occurrence always generates a risk on construction projects which may not only delay the completion date but also cause enormous financial losses and even causalities. There exist many causes of fire on construction sites, but key is the general lack of awareness of the nature of various fire risks. The undesirable situation of construction fires may be attributed to the lack of an appropriate fire risk assessment mechanism that could be employed to evaluate the potential fire risk levels. Therefore, the implementation of a proper fire risk assessment is regarded as good fire safety management practice for the prevention of fire. A structured and systematic assessment on site of fire safety management capabilities, fire protection capabilities, fire risks and emergency handling capabilities in fire can offer effective solutions and useful recommendations for mitigating the risk of a site fire (Lo, 1999). Systematic research is needed in order to understand how to build a model which will provide a single measure of fire risk on a particular site, a useful tool as part of a fire risk assessment system.

Several research studies have led to the development of effective fire risk assessment tools suitable for various scenarios and conditions (e.g. Marchant, 1982; Shields *et al*., 1986; Watts, 1997; Parks *et al*., 1998). A few recent studies have been undertaken, particularly in Hong Kong, to assist in the evaluation of fire safety levels of occupied premises. For instance, Chow *et al*. (1999) proposed a fire safety ranking system for dilapidated high-rise private buildings. Lo (1999) established a fire risk assessment system using the Delphi survey technique together with a fuzzy set theory approach to assess the overall fire risk levels in housing blocks. The assessment system allowed a prioritisation of various fire risk factors so that improvement works could be carried out at those areas with higher risks.

Chow and Liu (2001) generated a fire safety ranking system using a 20-point measurement scale. The study focused on karaoke entertainment establishments because of their box partition design and often crowded long corridors. Lo *et al*. (2001) introduced the reliability interval method to assess the fire risks for existing high-rise buildings. Lo *et al*. (2005) further adopted the reliability interval method and gray relational model for fire safety ranking of existing buildings. However, due to the fact that fires on construction sites are not as usually as life threatening as those within existing occupied premises, construction industry related fire safety/risk assessment systems have been developed for use in the latter context. There seem to be very few or even no assessment tools available for examining the fire risk levels on "new construction sites".

In view of the identified knowledge gap in fire risk assessment, the research team has carried out some preliminary groundwork to examine and assess fire risks on building construction sites in Hong Kong. An initial list of fire risk factors and subfactors were compiled and published in the study of Yam *et al*. (2009). Drawing upon previous studies on fire risk assessment tools and the list of fire risk factors and subfactors derived by the authors, the proposed study attempts to develop a fire risk assessment model for new construction sites.

3. RESEARCH AIMS AND OBJECTIVES

This research study aims to establish a comprehensive, objective, reliable, and practical fire risk assessment model for new construction sites in Hong Kong, and to identify any high-risk areas requiring remedial measures to reduce fire risk. An enhanced understanding of the key fire risk factors leads naturally to the study's another aim of generating an objective tool for measuring and comparing the overall fire risk levels at different construction sites in search of best practice recommendations for improvement. The following three research objectives were designed to achieve the aims of the proposed research study.

a) Objective 1: To identify a list of key fire risk factors and their associated subfactors which contribute to fire risk for a construction site.
b) Objective 2: To develop a fire risk assessment model for measuring and comparing the overall fire risk levels of different construction sites.
c) Objective 3: To provide the ability for users to identify high-risk areas where special attention is needed, and enable the provision of remedial measures to reduce fire risk.

4. RESEARCH METHODOLOGY

The overall research process of this study will comprise the following stages: (1) literature review; (2) face-to-face structured interviews; (3) a Delphi questionnaire survey; (4) an empirical questionnaire survey; (5) data collection; (6) data analysis; (7) development of a fire risk assessment model; and (8) validation of the developed model. The two questionnaire surveys will be different in nature. The Delphi method will be used for collecting and analysing the data collected from the Delphi questionnaire survey, while fuzzy set theory will be used for analysing the empirical questionnaire survey. The scope of the study is to be restricted only to new construction sites only in Hong Kong and therefore excludes existing buildings undergoing substantial renovation works with occupants inside. Figure 1 indicates the overall research framework for the proposed study for reference.

To achieve each of the three objectives as set before, corresponding research methods and process are designed as follows.

(a) Objective 1: To identify a list of key fire risk factors and their associated subfactors which contribute to fire risk for a construction site.

The study will begin with an extensive review of the literature on fire risk assessment systems both for existing buildings and new construction sites from all available sources. All previous relevant studies will be summarised so as to condense existing knowledge and experience about prevailing practices, building regulations and fire codes on fire risk assessment, together with previous major fire accidents. The review exercise will help develop the overall research framework and help prepare appropriate templates for the in-depth structured interviews, and the Delphi and empirical questionnaire surveys.

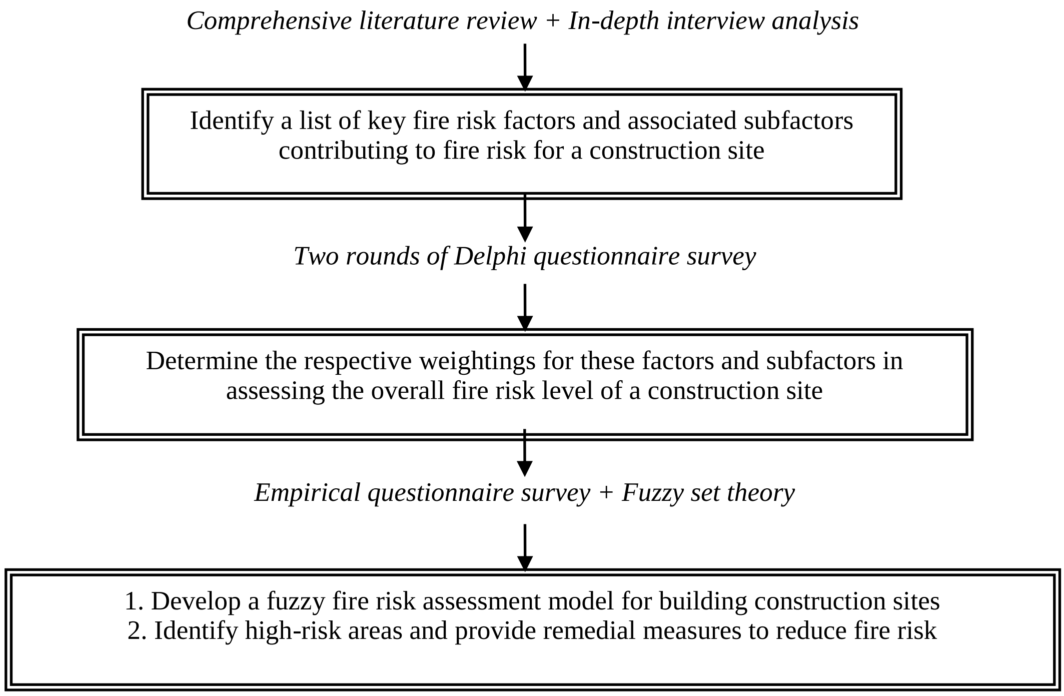

Figure 1: Flow of the Overall Research Framework

Typical core factors affecting the degree of fire risk may include: (1) Restrictions for on-site personnel; (2) Means of access for firefighting and rescue; (3) Means of escape in case of fire; (4) Storage of flammable liquids or dangerous goods; (5) Electricity management; (6) Fire services equipment and installation; (7) Attitude of main contractor towards fire safety; (8) Characteristics of construction site; (9) Safety procedures for evacuation on-site; (10) Site environment during fire; and (11) Safe behaviours of on-site staff (Yam *et al*., 2009). Each of these 11 fire risk factors will be further subdivided into some underlying subfactors which represent the detailed factors affecting that particular type of fire risk concerned, as outlined in Table 1. Through the literature review, an initial checklist of fire risk factors and their associated subfactors for a construction site will be placed within a systematic hierarchy of three levels: (1) the overall fire risk (at first level); (2) the fire risk factors (at second level); and (3) the fire risk subfactors (at third level) as portrayed in Figure 2. Then a series of face-to-face in-depth interviews with relevant senior industrial practitioners (e.g. government officers, project managers, safety managers, safety officers, fire safety engineers, etc) will be conducted to solicit their opinions and feedback on these key fire risk factors as captured from the literature based on their abundant hands-on experience with site fire safety. Finally, a full list of fire risk factors and subfactors will be produced.

After the literature review and interviews, two rounds of Delphi questionnaire survey will be launched as adopted by Lo (1999) in order to evaluate the relative importance (weightings) of the respective fire risk factors and subfactors. The Delphi method is a highly formalised method of communication that is designed to extract the maximum amount of unbiased information from a panel of experts (Chan *et al*., 2001; Yeung *et al*., 2007; Chan and Chan, 2012). It is generally conducted in several rounds interspersed with group opinions and information feedback in the form of relevant statistical data. The desired outcome is that, by using an iterative forecasting procedure, on reaching the final round, the experts will have achieved unanimity on the issues put before them (Manoliadis *et al*., 2006). The selected panel of Delphi experts will be either industrial practitioners equipped with extensive hands-on working experience in fire risk assessment or prominent academics with demonstrated research experience in fire safety. The Delphi experts will include government officers, safety managers, safety officers, fire safety managers, fire safety engineers, project managers, building engineers, building services engineers, academics and other allied construction professionals.

Table 1: List of Fire Risk Factors and their Associated Subfactors for a Construction Site

1	**Restrictions for On-site Personnel**
1.1	Enforcement of smoking prohibition
1.2	Gas welding and flame cutting work done by competent workers
1.3	Supervision by site supervisors or foremen
1.4	System of rewards and punishment
1.5	Use of hot work procedures
2	**Means of Access for Firefighting and Rescue**
2.1	Free from obstruction
2.2	Emergency vehicle access
2.3	Provision of firefighting and rescue staircases
3	**Means of Escape in Case of Fire**
3.1	Adequate emergency lighting
3.2	Adequate width of means of escape
3.3	Free from obstruction
3.4	Provision of exit signs
3.5	Under good condition
4	**Storage of Flammable Liquids or Dangerous Goods**
4.1	Clearance of rubbish
4.2	Flammable liquids in spraying area stored in metal container with self-closing lid
4.3	Flammable liquids stored in closed containers that are kept in cupboard or bin
4.4	Reasonable quantity of flammable liquids in spraying area
4.5	Removal or disposal of combustible materials after use
4.6	Smoking prohibition
4.7	Use of dangerous goods store
5	**Electricity Management**
5.1	Adequate electricity supply
5.2	Proper insulation and protection of electricity wiring
5.3	Use of earth leakage circuit breakers
6	**Fire Services Equipment and Installation**
6.1	Fire alarm
6.2	Fire blanket
6.3	Fire hydrant riser
6.4	Fixed fire pump with electricity supply
6.5	Hose reel
6.6	Periodical inspection
6.7	Portable fire extinguishers at each floor and site office
6.8	Portable fire extinguishers at open flame workplace
6.9	Provision in area of spraying flammable liquids
6.10	Under good condition
7	**Attitude of Main Contractor towards Fire Safety**
7.1	High level of commitment to fire safety system
7.2	High level of concerns over the probability of starting fire
7.3	Reasonable budget spent on construction site fire safety
8	**Characteristics of Construction Site**
8.1	Choice of less combustible materials
8.2	Good level of ventilation
8.3	Types of work that induce the number of fire sources (e.g. welding work, open flame)
9	**Safety Procedures for Evacuation On-site**
9.1	Designated staff (e.g. wardens) help with evacuation in fire situation
9.2	Evacuation training for on-site staff
9.3	Location of emergency signage
9.4	Planned evacuation route

10	**Site Environment during Fire**
10.1	Low hazard of smoke
10.2	Low hazard of irritant gases
10.3	Low hazard of toxic gases
11	**Safe Behaviours of On-site Staff**
11.1	Peer relationship of individuals
11.2	Willingness of on-site staff for evacuation in fire situation

Source: Yam *et al*. (2009)

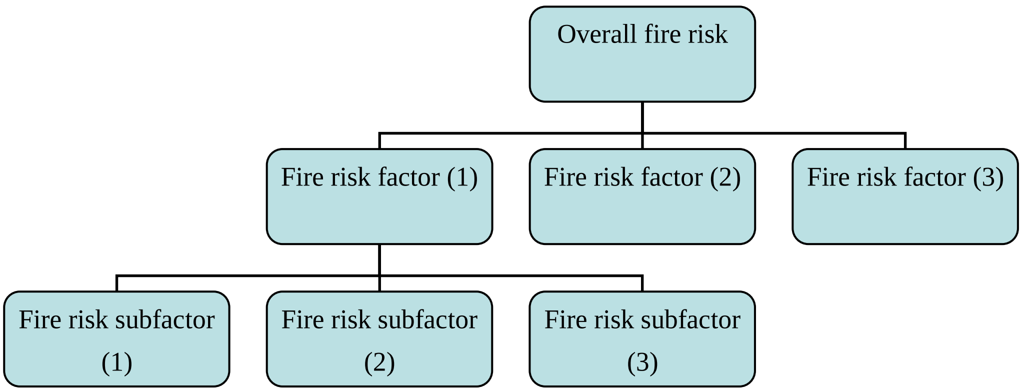

Figure 2: A Systematic Hierarchy of Fire Risk Factors and their Associated Subfactors for a Construction Site

The first round of the Delphi questionnaire survey will be based on the already identified list of various fire risk factors and subfactors. The target respondents will be invited to provide "importance" ratings to each of the fire risk factors and subfactors elicited based on a five-point Likert scale. A statistical analysis will be performed on all survey questionnaires received in which the mean ratings for all the fire risk factors and subfactors will be computed. Hence, a series of fire risk factors and subfactors with their respective weightings will be derived based on the mean ratings advocated by the Delphi group of panel experts. The weighting for each fire risk factor or subfactor will be calculated as their individual mean ratings divided by the total mean ratings of all the factors or subfactors under consideration as computed by using the following equation (Chow, 2005; Ng *et al*., 2005; Yeung *et al*., 2007; Eom and Paek, 2009; Chan *et al*., 2011; Chan and Chan, 2012):

$$W_{FRF_a / FRS_a} = \frac{M_{FRF_a / FRS_a}}{\sum_k M_{FRF_k / FRS_k}} \qquad \text{for a = 1} \qquad \text{(Eq: 01)}$$

Where,

W_{FRF_a / FRS_a} represents the weighting of a particular fire risk factor (FRF)/fire risk subfactor (FRS)

M_{FRF_a / FRS_a} represents the mean ratings of a particular FRF/FRS

$\sum_g M_{FRF_k / FRS_k}$ represents the summation of mean ratings of all the FRF/FRS

In Round 2 of the Delphi questionnaire survey, the participating Delphi experts will be given the consolidated results obtained from Round 1. The average ratings of the Delphi experts for each fire risk factor and subfactor, together with the Delphi expert's own ratings suggested in Round 1 will be provided. The Delphi experts will then be requested to reconsider their ratings to see if they would like to adjust their original option in the light of the mean scores by all the Delphi experts. By doing so, the series of most important weighted fire risk factors and subfactors will be found out.

(b) Objective 2: To develop a fire risk assessment model for measuring and comparing the overall fire risk levels of different construction sites.

Having determined the respective weightings for those key fire risk factors and subfactors from the two rounds of Delphi questionnaire survey, an empirical questionnaire survey will be undertaken to develop a comprehensive, objective, reliable, and practical fire risk assessment model. Since many fire risk factors and their associated subfactors are descriptive (linguistic) and "fuzzy" in nature and only vague or imprecise information is often available for the assessment, the value judgments of assessors are essential during evaluation. Consequently, it is desirable to generate a multi-criteria evaluation model for fire risk assessment by adopting a fuzzy set theory approach (Watts, 1997). Fuzzy synthetic evaluation (FSE), which enables multi-criteria evaluation, can be applied to offer a synthetic evaluation of one object relative to another objective in a fuzzy decision environment with many factors or criteria (Hsu and Yang, 1997).

Fuzzy synthetic evaluation, building upon fuzzy set theory, has been used within many disciplines. Sadiq and Rodriguez (2004) also employed this method to determine the health risks inherent with disinfection by-products. Zhao *et al*. (1997) proposed a fuzzy integrative evaluation method for assessing the risk factors of any project in general. Hsu and Yang (1997) developed a fuzzy synthetic evaluation model for selecting the most suitable candidate in a recruitment process for university academic staff. Chan *et al*. (2011) generated a fuzzy risk assessment model for guaranteed maximum price and target cost contracts in the construction industry of Hong Kong. It can be observed from their research that fuzzy synthetic evaluation is good at dealing with complicated evaluations where multi-attributes at multi-levels are involved.

This proposed research study will follow a similar approach to fire risk assessment analysis by considering both the likelihood of occurrence and the level of severity to the construction site of various fire risk factors and subfactors based on the abundant hands-on experience of target survey respondents. The target respondents will include government officers, safety managers, safety officers, fire safety managers, fire safety engineers, project managers, building engineers, building services engineers and other allied construction professionals. They will be invited to rate both the likelihood of occurrence and the level of severity of each fire risk factor and subfactor on a five-point Likert scale (1 = very low; 2 = low; 3 = medium; 4 = high and 5 = very high). A score representing the average total overall fire risk level for all the construction sites as a whole based on the personal non-project-specific perceptions of the survey respondents will be computed using fuzzy set theory and may serve as a benchmark score for reference within the industry. The calculation of this overall score is based on the assessment for each weighted fire risk factor and subfactor identified. The assessed values of these fire risk factors and subfactors will be used to derive their corresponding fuzzy membership functions.

For each fire risk subfactor identified, the membership function can be found by the personal evaluation of the survey respondents. For example, if the survey results on the first fire risk subfactor "1.1 - Enforcement of smoking prohibition" indicated that 2% of the respondents opined the level of severity of this risk to the project as very low, 17% as low; 33% as medium; 30% as high and 18% as very high, then the membership function of this risk would be set as:

$$C1 = \frac{0.02}{\text{very low}} + \frac{0.17}{\text{low}} + \frac{0.33}{\text{medium}} + \frac{0.30}{\text{high}} + \frac{0.18}{\text{very high}}$$

$$C1 = \frac{0.02}{1} + \frac{0.17}{2} + \frac{0.33}{3} + \frac{0.30}{4} + \frac{0.18}{5}$$

The membership function can also be expressed as (0.02, 0.17, 0.33, 0.30, 0.18). Similarly, the membership functions of other fire risk subfactors and the corresponding fire risk factors for both severity and likelihood can be computed using the same method. The derived fuzzy membership functions together with the weightings obtained from the two rounds of Delphi questionnaire survey will enable the development of the fuzzy fire risk assessment model (Yam *et al*., 2009). The proposed fire risk assessment model could also be modified to suit places other than Hong Kong by altering as appropriate the set of fire risk factors and subfactors, adjusting the membership functions of the input variables, and changing the fuzzy inference rules.

(c) Objective 3: To provide the ability for users to identify high-risk areas where special attention is needed, and enable the provision of remedial measures to reduce fire risk.

After inputting the scores of the respective essential factors and associated subfactors included in the fire risk assessment model for a particular single project-specific construction site, any high-risk areas will be captured, and the opinions of various target survey respondents on appropriate risk mitigation measures to reduce fire risk will be solicited. By using a fuzzy set theory approach, various assessment scores will be found on each of the fire risk factors and subfactors for a particular construction site so that immediate improvement strategies and remedial measures can be prioritised according to the magnitude of the respective scores. If a certain fire risk factor or subfactor has a high score, then it should be given a higher priority for improvement works. The risk assessment scoring system serves as a decision support tool for the prioritisation of fire risk remedial measures.

5. VALIDATION OF RESEARCH FINDINGS

Triangulation from multiple sources will be employed to reinforce the credibility of the findings obtained from the research data and subsequent analyses. Results derived from the empirical questionnaire survey and in-depth interviews will be cross-referenced to the published literature as well as with each other whenever appropriate. Appropriate workshop discussions with prominent industrial practitioners who have acquired extensive hands-on experience in dealing with various fire risk factors on new construction sites will be organised to generate relevant information and to supplement and/or confirm the outcomes of the analyses, and a set of possible recommendations for improving the developed fire risk assessment model based in Hong Kong. A meeting will be scheduled via discussions and moderations to validate the research findings and explanations with practitioners involved in the study.

6. CONCLUSIONS AND SIGNIFICANCE OF RESEARCH

The prospective results of the proposed research study are mainly three folds: (1) Deriving a list of key fire risk factors and their associated subfactors for new construction sites; (2) Developing a fire risk assessment model for measuring and comparing the overall fire risk levels of different construction sites; and (3) Providing a useful tool for users to identify high-risk areas and adopt remedial measures to reduce fire risk in new construction sites.

Successful development of the fire risk assessment model can enable its use for the setting up of a useful tool for easily and promptly measuring and comparing the overall fire risk levels of various construction sites within an organisation, between organisations and within the construction industry as a whole leading to an improved fire safety culture. A composite overall fire risk score, which is representative of all essential fire risk factors and subfactors on a construction site, will be derived by the model to provide a single measure of fire risk. The overall fire risk score can be monitored throughout the entire construction period for any one site. By adopting the developed fire risk assessment model, project managers, safety managers, safety officers, fire safety engineers and other related construction personnel could objectively assess the overall fire risk levels of their individual construction sites and prioritise improvement measures for the high-risk areas.

Although the proposed research study will primarily focus on the prevailing situation in Hong Kong, the research methodology may be replicated in other parts of the world, and may lead to international comparisons of the fire safety culture from place to place. It will also begin to expand the current body of knowledge about the relationship between fire safety culture and fire events and how these compare internationally.

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