Quantitative Risk Assessment for Performance-Based Building Fire Regulation

Farid Wajdi Akashah a,*, Brit Anak Kayan b, Nor Haniza Ishak c

*a Centre for Construction, Building and Urban Studies (CeBUS), University of Malaya 50603 Kuala Lumpur, Malaysia
b Urban Conservation and Tropical Architecture (UCTA), University of Malaya 50603 Kuala Lumpur, Malaysia

Abstract

This paper provides a review of quantitative risk assessment (QRA) as a fire risk approach in performance-based fire regulation by presenting the shift to performance-based regulations from prescriptive-based regulations around the world for the past three decades. The adoption of performance-based regulations has helped QRA being an important fire risk approach to designers and Authority Having Jurisdictions (AHJs) involved in the built environment. This paper also explores the risk concepts in performance-based regulations and fire risk approaches focusing on QRA. This paper ends by stressing the needs to develop a novel methodology to improve the process of implementing QRA in line with the adoption rate of performance-based building fire regulations that keeps on increasing.

Keywords: building regulation; fire risk; performance; performance-based building; performance-based regulations; quantitative risk assessment

1. Introduction

The development of performance-based regulations and its widespread adoption by countries around the world has led to an increased interest in fire risk assessment. Under performance-based regulations, design objectives, which include the aspect of fire safety objectives, are clearly stated (Hadjisophocleous, Benichou, & Tamim, 1998). These objectives need to be fulfilled for any design to be approved as safe. However, in performance-based regulations, designers are given flexibility in providing fire safety solutions that can fulfill these requirements, as the detail on how specific requirements should be fulfilled is presented in the form of explicit statement of goals and objectives rather than an acceptable solution. From this, it is clear that the implementation of performance-based regulations gives the flexibility in building design, the room to innovate and the means to promote cost effectiveness. With the implementation of performance-based regulations, the need for a tool that is capable in helping both designers and Authorities Having Jurisdiction (AHJ) in assessing designs that fulfil performance statements in the regulations has become more important than ever.

2. Building fire regulations: prescriptive-based v performance-based

Traditionally, building fire regulations are of mostly prescriptive-based. Prescriptive-based regulations specifically state what its user should do in any given case in achieving safe design. This makes the implementation of prescriptive-based regulations a straightforward process (Frantzich, 1998a). The same can be said of the evaluation process of design under prescriptive-based regulations. The user will implement what the prescriptive regulations specify as requirements. If the requirements in the regulations are not fulfilled, the design is deemed unsatisfactory.

* Corresponding author. Tel.: +60 3 7967 6874; fax: +60 3 7967 5713.
E-mail address: faridakashah@um.edu.my
However, the requirements that were specified in the prescriptive-based regulations were presented without statement of objectives. This offers little flexibility for the user of prescriptive-based regulations to come up with different solutions to fulfill the requirements as it purports that there is only a certain way to provide the level of safety required (Blackmore, 2004). Alternative solutions that were not implemented or that were overlooked as a result of this inflexibility may be more effective in fulfilling the objectives as well as cost-effective. Therefore, it can be said that prescriptive-based regulations can lead to unnecessary spending on measures to make sure that the design produced is in accordance to prescribed regulations.

On top of that, the current development that sees large and complex buildings being built has made implementing prescriptive-based regulations even more difficult or impossible to implement. Both, engineers and AHJ, needs to use performance-based regulations in favour of prescriptive-based regulations to design and assess these large complex buildings.

### 2.1. International adoption of performance-based regulations

In the past three-decades, more and more countries have moved from prescriptive-based regulations to performance-based regulations. Countries like the United Kingdom introduced the Building Regulations of 1985 ("The Building Regulations," 1985), Japan with the introduction of their guidelines (Construction, 1989), Australia with the report by Beck and co-workers of the Warren Centre for Advanced Engineering (V. Beck, 1989a, 1989b) and Sweden with BBR94 (The Swedish Board of Housing, 1994) were among the first to adopt performance-based building fire regulations.

In performance-based regulations, design objectives are clearly defined without the mention of how these objectives need to be fulfilled. Designers will be given a choice to fulfill the design objectives by either one of the two methods: a deemed to satisfy method or design based on calculations (Notarianni, 2000).

The deemed to satisfy method has essentially the same provisions as the prescriptive-based regulations where the designer will implement simplified design method prescribed in the regulations when delivering fire safety solutions in their design. In the event that the design presented is within the boundary that allows the simplified method in the regulations to be implemented, the designer may just employ the deemed to satisfy method to deliver the design objectives demand by the regulations. The difference in performance-based regulations is the flexibility that the designer has in choosing engineering methods other than simplified design methods given in the provisions to fulfil the design objectives. In this method, the designer needs to demonstrate how the design objectives are fulfilled using acceptable engineering methods of their choice.

### 2.2. Risk concept in performance-based regulations

The transition from prescriptive-based regulations to performance-based regulations was described as the transition from selecting strict design standards to more functional design standards that provide the least detail about what need to be fulfilled. This transition has been driven by significant improvement of knowledge on the subject of fire science and fire safety engineering. This factor has certainly helped designers and AHJ in the transitional situation from prescriptive-based regulations to performance-based regulations within the built environment industry. In implementing the performance-based regulations, more complex and difficult decisions are to be made compared to decision making under prescriptive-based regulations. Although the best way to evaluate the performance of a building is by having a full-scale building built and burned it under different probable scenarios (Brannigan & Smidts, 1998), this is something that is unfeasible to implement because of the cost it will incur. Even if the design team or AHJ has the means to foot the bill, at any one time, the building can only be subjected to just one specific scenario (Notarianni, 2000).

In order to help people within the current situation of performance-based regulations, engineering methods are used to satisfy these regulations. These engineering methods are implicitly based on risk. The level of safety associated with a design is measured by the level of risk the design holds against the level of acceptable risk. The design team needs to demonstrate their design is safe for public use by delivering the design objectives stated in the regulations. Risk assessment methods need to be conducted in order to show that a design under review is safe.
namely that the design objectives have been fulfilled by means of completely avoiding hazardous conditions or reducing the impact of hazardous conditions by introducing special measures (Phillips, 1994).

2.2.1. Level of risk acceptance in performance-based regulations

The society accept the fact that for whatever we do in life, there will be a certain number of chance that things will go wrong and affect us in a negative way. However, there is a difference between how one person/society or the other viewed risk. For an instance, a person who love outdoor activities and a person who hate outdoor activities may have different view towards risk of doing extreme sports like bungee jumping or skydiving.

In the event of fire, unwanted consequence of death, injuries and interruptions to business can be represented by multiplication of numerical values of probability and consequence of possible fire. This is a way of representing risk quantitatively. However, loss of building of social importance is an example of unwanted consequence that is somewhat difficult to express, as different building can be perceived of having different social importance to different people. This may affect how the decision maker (a person or an entity) decides on the acceptable level of risk. For example, a director working in the Investment Department of an oil and gas company will have different view on level of risk he/she is willing to take compare to his/her counterpart in the Health and Safety Department on an issue of exploring new oilrig in Middle Eastern countries. The decision will be based on the willingness of decision maker i.e. board of directors to endure risk e.g. political instability and terrorist threats to the operation against the advantages i.e. profit that their organisation will be making out of the operation. The willingness of the board to take the risk will result in the readiness to accept a little higher risk that comes with continuing the operation.

From this example and probability, it is clear that the level of risk acceptance is the degree of unwanted consequence a society or an individual deemed acceptable. Level of risk acceptance is about a value judgment of a person or a society on risk (Bottelberghs, 2000).

The definition above highlights the fact that there is no situation as absolute risk-free. It is the level of risk acceptance that makes the difference (Rasbash, 1985). As mentioned earlier in this section, the level of risk acceptance is about value judgement. This level of acceptance varies based on confidence on the scale and method used to measure risk. An individual or a society that have confidence on the method used by the authority to measure risk would be more willing to accept higher threshold value of risk compare with the situation where the public confidence is lot less. The level of risk acceptance may differ based on whose values, between an individual or a society, will be used to obtain the level of risk acceptability (Watts & Hall, 2008). Other than these two factors above, the level of risk acceptance are influenced by the type of industry, the level of loss and the economic and social factors surrounding individual, society, property and the environment (Bottelberghs, 2000).

The process of evaluating level of risk acceptance is done when the risk assessment process is completed. These days where performance based regulations are practised, the local authority will have the jurisdiction to perform this task of evaluating risk. In order for local authority to approve any given designs, the level of risk that is associated with the design presented must be below the acceptable level of risk. Health and Safety Executive (HSE) in the United Kingdom has published a document (HSE, 1992) containing a framework from which decision-making in risk assessment, where societal risks are concern, is based (refer Error! Not a valid bookmark self-reference, illustrates if risk is at or above unacceptable region, immediate action shall be taken to reduce risk or terminate the activity altogether at any cost. If the level of risk is at or below broadly acceptable region, no further measures required in reducing the level of risk. However, it is necessary to maintain the risk within this region. The middle region, called As Low As Reasonably Practicable (ALARP) region, is where risk reduction measures need to be made to keep the risk at a level where the cost of risk reduction exceed the improvements gained.
Error! Not a valid bookmark self-reference. illustrates if risk is at or above unacceptable region, immediate action shall be taken to reduce risk or terminate the activity altogether at any cost. If the level of risk is at or below broadly acceptable region, no further measures required in reducing the level of risk. However, it is necessary to maintain the risk within this region. The middle region, called As Low As Reasonably Practicable (ALARP) region, is where risk reduction measures need to be made to keep the risk at a level where the cost of risk reduction exceed the improvements gained.

Figure 1. Levels of risk and ALARP (Lo & Cheng, 2003)
2.3. Fire risk assessment approaches

In the previous sections, the authors mentioned about how the designer has the options to achieve design objectives set by performance-based regulations: the deemed to satisfy method or the design based on calculations. The design based on calculations is called performance-based engineering.

Performance-based engineering is an engineering approach used to deliver a safe design based on fire safety objectives agreed by the stakeholders e.g. AHJ, design team, clients. The methods of performing performance-based include subjecting the design to deterministic and/or probabilistic evaluation of different fire phenomena to assess the physical and chemical properties of fire products and the effectiveness of the design under review against the objectives laid down earlier (Meacham & Custer, 1995).

From this definition, it is clear that in performance-based engineering, risk assessment plays a large part in the process of decision making in the implementation of performance based regulations. Risk assessment is a process of decision-making based on the estimate of probability of an incident by engineering evaluation and mathematical techniques (Arendt & Lorenzo, 2000). Risk assessment methods can be of qualitative, quantitative or combination of both (Charters, 2013): sub-methods include checklists (CPQRA, 2000), risk ranking (Charters, 2013), reliability index \( \beta \) method (Magnusson, Frantzich, Karlsson, & Särdqvist, 1994) and QRA (Frantzich, 1998a).

Qualitative methods are methods used to identify factors that affect safety objectives. An example of qualitative methods is HAZOP (CPQRA, 2000). In practice, the factors that are identified to be affecting risk are listed. Next, these factors are assessed against a set of safety objectives. The design team will use their engineering judgement to assess these factors by using the word such as more, less and as well as (BSI, 2001) to describe on how these factors may contribute to the design to deviate from its safety objectives. The causes and effects of these factors are then analysed after which the design will undergo modification to improve its safety.

Semi-quantitative methods or ranking methods such as the Gretener method (Fontana, 1998) and NFPA 101M fire safety evaluation system (Frantzich, 1998b) use the combination of qualitative methods of identifying factors that affect the safety objectives of a design with a scoring system. By associating hazards identified with numerical values provided by the scoring system, risk associated with factors identified earlier can be presented in numerical terms. Next, the resulting scores of the factors that were identified to affect safety objectives are compared to the benchmark score of the safety objectives of the design under question.

Quantitative methods are the most extensive among the three in terms of risk quantification. It is the most time consuming and labour intensive (Frantzich, 1998a; Salisbury, Johnson, Yii, & Hui, 2007). QRA is driven by three main questions: what can go wrong; how often will it happen; what are the consequences if it happens (CPQRA, 2000; Frantzich, 1998a). The process of implementing QRA consists of the following steps: hazard identification; accident frequency estimation; consequence calculation; risk evaluation and risk reduction (CPQRA, 2000; Fontana, 1998). The fire risk assessment approaches were compared and contrasted in Table 1.

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<td>Complexity</td>
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According to Table 1, in terms of degree of resolution, QRA is the most extensive method compared to semi-quantitative and qualitative risk assessment. However, it is also the most labour intensive and time consuming among the three (Charters, 2013; Hui & Salisbury, 2006). On the other hand, qualitative risk assessment is the least extensive and least complex. In terms of extensiveness and complexity, semi-quantitative method lies between the two. The ideal situation would be to have a level of extensiveness of a QRA with the complexity of qualitative risk assessment. The next sections will present the steps of implementing QRA.

3. Quantitative risk assessment (QRA) and performance-based regulations

Quantitative Risk Assessment (QRA) is the process of quantifying risk estimates based on engineering methods and mathematical techniques for the basis of decision making process (Arendt & Lorenzo, 2000). QRA has been
used as a decision making tools in nuclear industry (Beckjord, Cunningham, & Murphy, 1993; Commission, 1975), chemical industry (CPQRA, 2000), and petro-chemical industry (Paté-Cornell, 1993). In the built environment, generic approach to QRA is presented in PD 7974-7:2011 (BSI, 2003) as shown in Figure 2.

![Figure 2. Generic approach to Quantitative Risk Assessment (QRA) from PD 7974-7:2011 (BSI, 2003)](image)

The King’s Cross Disaster (Fennell, 1988) has helped uncover the potential that QRA might bring in terms of evaluating risk within the built environment in the UK. The work by Charters (Charters, 1996), Frantzich (Frantzich, 1998b), Yung (D. Yung, Hadjisophocleous, & Proulx, 1999), Beck (V. R. Beck, 1998), Fraser Mitchell (Fraser-Mitchell, 1999), and Jonsson and Lundin (Jönsson & Lundin, 2000) are examples of how quantified risk-based approach is being adopted for the purpose of evaluating risk and fire safety problems within the built environment.

The decision by designer to choose between available risk assessments methods available is based on the complexity of the problem at hand and the budget available (both monetary and time). For these reasons, QRA with its rigorous procedure (Atallah, Gupta, de la Garza, & Tappi, 1999), and its perceived complexity has not been preferred by practitioners in the built environment as a method of choice in assessing risk despite being the most extensive (Hui & Salisbury, 2006; Salisbury et al., 2007).

In the built environment, Charters (Charters, 1996), Frantzich (Frantzich, 1998b), Yung (David Yung, 2008) Beck (V.R. Beck, 1991), and Fraser-Mitchell (Fraser-Mitchell, 1996), are just some of those who have undertaken a quantified risk-based approach for the evaluation of building fire safety problems. However, QRA is not used as much compared to other risk assessment techniques (Salisbury et al., 2007).

### 3.1.1. Components of Quantitative Risk Assessment (QRA)

Quantitative risk assessment (QRA) includes the use of fault tree, event tree and consequence analysis. QRA is also often used to provide risk curves, which are internationally recognized standard for presentation of risk (Paté-Cornell, 1996). Matthews et al (Mathews, Karydas, & Delichatsios, 1997) has proposed the methodology for QRA as shown in Figure 3.

![Figure 3. Components of Quantitative Risk Assessment (QRA)](image)
Fault tree is a method of risk assessment that considers an event from an initial failure condition (Watts & Hall, 2008). The preceding scenarios that lead to the failure condition are studied. The order in which this analysis is being carried out is from top-to-bottom. On the other hand, event tree analysis is carried out from bottom-to-top. An initial event is the starting point of an analysis. This event will escalate and corresponds to probability of both success and failure of any given system.

The other component of QRA, consequence analysis, is an analysis that looks into an outcome of a scenario being considered earlier in fault tree and event tree respectively. These outcomes can be calculated in terms of monies, business interruption or life safety. For this study, only life risk and property risk are taken into consideration. Risk curves are used to illustrate the probability to have a certain scenario (the consequence) greater than a certain value.

4. Moving forward with quantitative risk assessment (QRA) and performance-based regulations

Quantitative risk assessment (QRA) involves examining multiple scenarios to determine which design is better than the other. It is different from the traditional way of focusing the assessment to just a worst-case scenario. In order to do that, a method is needed to assess the many outcomes associated with QRA. Event tree, the graphical logic model used within QRA, is one of the most common methods in QRA for identifying and quantifying possible outcomes following an initial event. Event tree if constructed manually is a time consuming task. As with any manual approach, human errors may appear due to its invariably complex nature of constructing manual event tree. Therefore, attempts have been made to automate event tree generation, as it is faster and easier to construct compared to manually constructed event tree.

At present, a method that is capable of generating event trees automatically in quantitative fire risk assessment does not exist. A methodology develop need to provide flexibility. It also needs to be highly customizable to assess different aspect of issues within fire safety engineering concerning design that will definitely include different models with varying complexity. Another are that the methodology need to be able to achieve is addressing uncertainty in order to add credibility to the data. For that reason the methodology must incorporate uncertainty analysis. The methodology needs to present the result in the form of risk curves, a comprehensive standard for presentation of risk. A method that is rigorous and comprehensible is needed.

5. Final remarks

The main aim of this paper is to critically review QRA as a fire risk approach, in assessing risk in performance-based building fire regulation. This paper highlights the need to develop a novel methodology to improve the process of implementing QRA in line with the increased adoption rate of performance-based building fire regulations around the world. The current method of implementing QRA is perceived to be complex. There is a need to improve the way of implementing QRA as this perceived complexity has made QRA not widely used method in performing risk assessment. This is despite the advantage QRA holds in comparison to other risk assessment method in which it offers more holistic view of a design as the assessment made is not limited to just the worst case or the credible worst case scenario.

Acknowledgements

The authors would like to thank support extended by the University of Malaya through UMRG (Project No.: BK024-2011B ).
References


