Quantitative Design Decision Method: Performance-Based Design Utilizing A Risk Analysis Framework

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The model building and fire codes in Canada permit prescriptive-based design and performance-based design approaches. Within this regulatory framework, prescriptive-based designs are attributed objective and functional statements to qualify the level of fire protection and life safety required. Performance-based designs, or alternative solutions to prescriptive-based designs, must be demonstrated to achieve at least an equivalent level of performance as the prescriptive requirement based on evaluation of each associated objective and functional statement. Due to the qualitative performance descriptions available, the current system for developing and reviewing alternative solutions is vulnerable to the acceptance of over-designed or under-designed life safety and fire protection measures in buildings.

The objective of this thesis is to establish a method to compare the performance of alternative solutions with prescriptive design requirements on a quantitative basis. This thesis generates eight objectives for a fire risk analysis tool to address the challenges identified in the building regulatory industry. Based on review of existing techniques, a new fire risk analysis framework is developed. The Quantitative Design Decision (QDD) method, integrates risk analysis with quantitative decision assessment techniques to facilitate application-specific quantification of performance objectives and to aid evaluation of performance-based designs. The method utilizes an iterative three-stage structure.

To demonstrate the application of the QDD method, a case-study simulation has been conducted. The case-study provides an evaluation of alternative designs to the prescriptive requirements for explosion-relief ventilation in rooms housing flammable vapour producing operations. The case study supports the conclusion that QDD achieves the eight objectives set out in this thesis. For validation, the QDD method must be applied to a wider variety of practical design challenges and it is recommended that the results be considered in conjunction with live fire test data to verify key aspects of the performance decisions generated. Future work should include evaluation of Delphi technique application in the Design Decision Stage of the QDD method. It is proposed that the method developed can be extended for use as a general performance-based design tool.

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Nomenclature

Roman Symbols

$E_a(U,P)$ Expected utility of design a, 1 – performance-based design, 2 – prescriptive-based design

Max Maximum expected utility difference

Min Minimum expected utility difference

ML Most likely expected utility difference

P_i Probability of accident scenario outcome i

p_x Probability of successful component operation at pivot event x

U_i Utility of accident scenario outcome i

Abbreviations

AHJ   Authority Having Jurisdiction

FSCT   Fire Safety Concepts Tree

NBCC   National Building Code of Canada

NFCC   National Fire Code of Canada

NFPA   National Fire Protection Association

SFPE   Society of Fire Protection Engineers

SSDT   Super Soft Decision Theory

QDD   Quantitative Design Decision Method

UBC   Uniform Building Code

Chapter 1

INTRODUCTION

The Canadian objective-based building design regulatory system permits performance-based

alternative solutions to be proposed in lieu of solutions based solely on prescriptive design requirements.

A design challenge faced within the performance-based building industry is that the building and fire

codes, while allowing alternative solutions, do not specify methods of quantifying alternative design

performance and accounting for the uncertainty inherent in fire behaviour and in fire science prediction

methods. As such, the development and review of alternative solutions rely on the experience and

expertise of the designer and regulator to quantify performance within a building regulatory system

historically based in prescriptive design methods. This chapter describes the development of building

design standards, including prescriptive-based and performance-based building codes. Both

internationally recognized standards and codes developed within Canada are considered as frames of

reference for identifying challenges currently existing within the performance-based, alternative solution

design industry.

In addition, it is determined that fire risk analysis tools, among other fire science techniques

available, are used with increasing frequency within the design industry to establish the performance of an

alternative solution. Through this review, criteria are identified in this chapter with the objective of

selecting or generating a fire risk analysis tool to support the development of an alternative solution to a

prescriptive design challenge.

Following this chapter, Chapter 2 of this thesis provides a literature review of methods of developing alternative solutions using performance-based design. The chapter focuses on the three types of fire risk analysis methods available and evaluates which may suit the industry challenge established in Chapter 1. The new Quantitative Design Decision (QDD) fire risk analysis method developed in this thesis is then presented in Chapter 3 and a case study demonstrating the application of the method to a practical design challenge is described in Chapter 4. The design challenge considered in the case study involves explosion prevention and protection design approaches. Chapter 5 of this thesis provides an analysis of QDD to establish if the case study demonstrates that it can achieve the objectives developed in this thesis for a fire risk analysis method and its limitations. Future work to extend the potential applications of the method and to validate and verify design decision results are discussed in Chapter 6.

1.1 Building Design Standards

Design standards for the built environment identify the minimum requirements for fire protection and life safety in buildings. The first documented building standard dates back to the Babylonian King, Hammurabi, who decreed that if a building falls and kills its owner than the man who constructed the building should be killed [Rasbash 1984]. Modern building codes provide guidance for building designers and regulatory authorities and focus on design objectives, methods and performance criteria. Design standards can generally be classified as either prescriptive-based or performance-based codes.

Prescriptive-based codes provide specific design attributes that must be provided in a building; such as specifying the required rise and run dimensions for a stairway. In contrast, performance-based codes are developed to permit performance-based design which is defined as:

> "*an engineering approach to fire protection design based on (1) agreed upon fire safety goals and objectives, (2) deterministic and/or probabilistic analysis of fire scenarios, and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies and performance criteria*" [NFPA & SFPE 2007].

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The development of design standards in the previous century initially began with prescriptive requirements and has progressed towards performance-based codes in the past 40 years.

One of the first building codes recognized in North America was the 1927 Uniform Building Code (UBC). This standard was prescriptive and identified requirements for the fire-resistance of building construction based on building occupancy, height and area using the then recently developed fire testing endurance ratings in the American Society of Testing and Materials Standard C19 published in 1918 [Goode 2004]. The current edition of the original standard, ASTM E119, "Standard Test Methods for Fire Tests of Building Construction and Materials" is virtually unchanged [ASTM 2011]. The UBC's prescriptive concept for building fire-resistance was not numerically justified in the publication and has since been carried throughout modern prescriptive codes. It is considered that the rationale for the original prescriptive requirements may have been based on the findings of a survey conducted in 1913 by Woolson of fire chiefs from large cities around the United States [Fitzgerald 1991]. The UBC recognized the concept of an equivalency, which permitted designers to use alternative materials or construction that were considered to provide for equal or greater public safety or resistance to fire [Goode 2004]. This standard, uniquely, also incorporated a component of modern day performance-based requirements wherein it recognized that:

> "any system or method of construction to be used shall admit of a rational
> analysis in accordance with well established principles and mechanics"
> [ICBO 1927].

Notably, the first edition of the UBC did not specifically identify a suitable level of risk or mandate comprehensive fire analysis. The UBC's prescriptive framework has been maintained in current codes and standards that regulate fire safety, but do not mandate the engineering of fire safe designs [Fitzgerald 1991]. In this fashion, modern building codes differ from the traditional design approaches of other engineering disciplines, such as mechanical, structural and electrical. These other disciplines utilize standards that assume that qualified engineering professionals will take responsibility for their designs and calculations methods and, therefore, the standards identify performance requirements only. The

prescriptive building codes and fire codes, in contrast, are written in a fashion that does not necessarily require input from a fire safety professional or mandate a fire safety analysis.

The development and modification of prescriptive-based codes have frequently been triggered by catastrophic fire events or by the availability of new technologies. Changes are made in the codes to reflect shifting risk perception in society and to accommodate more rigorous social mandates [Wolski et al. 2000, Hall & Cote 1997]. Fischhoff and coworkers describe this trial and error approach to prescriptive code development as 'bootstrapping' [Fischhoff et al. 1981]. The prescriptive codes provide design criteria to maintain the minimum risk tolerated in society so as to provide a basis for evaluating the acceptability of new designs and new building criteria. As such, as new risks or technologies are recognized in society, adjustments are made in the prescriptive regulations [Wolski et al. 2000]. The 'bootstrapping' process however, has numerous disadvantages. This retrospective approach considers only those fires which have a low probability and high consequence (i.e. catastrophic) that occurred in the past and does not provide protection against fire events that could, but have not necessarily yet, occurred [Hurley & Rosenbaum 2008]. The prescriptive codes are also perceived to restrict or stifle innovation since the rapid development of modern architecture and materials moves more quickly than regular code revision cycles, which often take many years to recognize 'new' design approaches [Croce et al. 2008].

The movement towards the development and use of performance-based codes began in the 1970s and was conducted to overcome the shortcomings identified in the prescriptive-based code framework. Performance-based codes are inherently more flexible with respect to design options for non-traditional structures such as large stadiums, shopping centres and industrial processing facilities. The origins of performance-based design approaches are in the fields of fire science and fire protection engineering which differ significantly, in the context of developing a building design strategy, from the 'bootstrapping' approach common in prescriptive code development.

Performance-based codes have been developed around the world with the first editions published in the 1980s and 1990s in the United States, New Zealand, Australia, the United Kingdom and throughout the Nordic countries. In large part, these performance-based codes maintain the recognition of older

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prescriptive-based requirements as a guideline to achieve compliance with the new performance-based requirements or objectives [Bukowski & Babrauskas 1994]. This phasing-in framework is described by Fitzgerald as a means to permit the current design practice (i.e. prescriptive) to remain, while allowing performance-based systems to be developed by knowledgeable professionals so as to integrate new technologies and materials [Fitzgerald 1991]. Bukowski and Babruaskas provide detailed descriptions of the various performance-based codes adopted around the world [Bukowski & Babrauskas 1994]. In general, the objectives of performance-based codes focus on the prevention of losses, the safety of individuals and the prevention of social hurt and concern [Rasbash 1984]. These objectives are consistent throughout the performance-based codes adopted internationally and are intended to reduce the likelihood and consequence of fire events in all building types.

The advantage of performance-based codes is that new buildings can incorporate innovative design features and functions. As importantly, fire science and fire protection engineering principles are promoted in an industry that historically has not relied extensively on such knowledge [Hurley & Rosenbaum 2008]. The adoption of performance-based codes identifies the value of fire protection engineers in the building design process and provides a bridge between the academic study of fire and the practical application of fire safety principles in building design. The primary disadvantage associated with the application of performance-based codes is that a greater level of expertise is necessary both in the designer and in the Authority Having Jurisdiction (AHJ) – which differs significantly from that required in the prescriptive-based regulatory model [Croce et al. 2008]. In many countries, including Canada, the training programs and qualification systems for designers and for authorities is not commensurate with the expertise that is required to develop and evaluate complex performance-based designs. Additionally, performance-based designs are, by nature case-specific, which may complicate future opportunities to change the use or operation of a building developed utilizing this design technique.

1.2   Canadian Model Building and Fire Codes

The focus of this thesis is the National Model Codes in Canada, specifically the National Building Code of Canada (NBCC) [CCBFC 2010a] and the National Fire Code of Canada (NFCC) [CCBFC 2010b] as they pertain to building design requirements. As such, a brief summary of the development of these codes and their current composition is described. It should be recognized that the challenges identified in the Canadian building regulatory system are also present on an international scale where performance-based codes are utilized.

The NBCC and NFCC are classified as model codes. They are not legal regulations unless they have been adopted by a province or territory. The codes are therefore intended only to identify the minimum set of measures required to achieve the necessary level of life safety and fire protection in the built environment. In general, the NBCC applies to new construction, renovation or demolition of a building and the NFCC applies to maintenance and use of a building and to activities involving hazardous substances or operations. The first NBCC was published in Canada in 1941 and the first NFCC was published in 1963 by the National Research Council of Canada. Responsibility for development of the code was then, and remains the Canadian Commission on Building and Fire Codes. Subsequent editions of the NBCC were published in 1953, 1960, 1965, 1970, 1975, 1977, 1980, 1985, 1990, 1995, 2005 and 2010. Similarly, the subsequent editions of the NFCC were published in 1975, 1977, 1980, 1985, 1990, 1995, 2005 and 2010. The 10 year gap between the 1995 and 2005 editions of the codes was a result of the effort to develop the model code to recognize and permit performance-based designs [CCBFC 2010a, CCBFC 2010b]. The 2005 editions were the first objective-based building codes in Canada and this format is maintained in the recent 2010 publication.

The evolution the codes to an objective-based format integrates the first principle of performance-based design as defined in the SFPE Engineering Guide to Performance-Based Fire Protection: to identify agreed upon fire safety goals and objectives [NFPA & SFPE 2007]. The objectives of the NBCC include safety, health, accessibility and fire/structural protection [CCBFC 2010a] and the objectives of the NFCC

include safety, health and fire protection of buildings or facilities [CCBFC 2010b]. The codes have been developed such that for every acceptable solution (i.e. prescriptive requirement) there is a specific set of associated objectives and functional statements. Objectives identify the overall goals of a code requirement, while functional statements describe conditions required to satisfy the objectives. Both the objectives and functional statements identified in the model codes are qualitative and conceptual.

When designing a room or building utilizing the prescriptive requirements of the NBCC or NFCC, the design requirements are provided and the method of achieving the level of required fire protection and life safety is clearly identified. For example, NFCC Sentence 4.2.9.1.(1) prescribes a two hour fire-resistance rating for flammable liquids storage rooms containing more than 1,500 L of storage [CCBFC 2010b]. This is a prescriptive requirement since a fire separation is mandated its fire-resistance rating is specified. The design approach taken to achieve the prescriptive rating is at the discretion of the designer.

This prescriptive requirement is associated with the objective of limiting the probability that, as a result of the design related to the hazard associated with flammable liquid storage, neither persons within the building nor the building itself will be exposed to an unacceptable risk of injury or damage due to fire that is caused by fire or explosion impacting areas beyond the point of origin [CCBFC 2010b]. The functional statement for the requirement is F03 which is associated with the intent to retard the effects of fire on areas beyond its point of origin [CCBFC 2010b]. The detailed objectives and functional statements associated with NFCC Sentence 4.2.9.1.(1) are OS1.2-F03 and OP1.2-F03 as follows:

> "*OS1.2-F03 – An objective of this Code is to limit the probability that as a result of:*
> - *activities related to the construction, use or demolition of the building or facility,*
> - *the condition of specific elements of the building or facility*
> - *the design or construction of specific elements of the facility related to certain hazards, or*
> - *inadequate built-in protection measures for the current or intended use of the building,*
>
> *a person in or adjacent to the building or facility will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire addressed in this Code are those caused by fire or explosion impacting areas beyond its point of origin. The function of the prescriptive design is to retard the effects of fire on areas beyond its point or origin*" [CCBFC 2010b].

"*OP1.3-F02 – An objective of this Code is to limit the probability that as a result of*

- *activities related to the construction, use or demolition of the building or facility,*
- *the condition of specific elements of the building or facility*
- *the design or construction of specific elements of the facility related to certain hazards, or*
- *inadequate built-in protection measures for the current or intended use of the building,*

the building or facility will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by fire or explosion impacting areas beyond its point of origin. The function of the prescriptive design is to retard the effects of fire on areas beyond its point or origin" [CCBFC 2010b].

Therefore, the prescriptive requirement for a two hr fire separation in NFCC Sentence 4.2.9.1.(1) is intended to limit a fire originating within the room from spreading throughout the remainder of the building.

The Canadian model codes are developed within a framework similar to that of international codes. As described by Fitzgerald, this is because the historical prescriptive-based requirements remain available to designers and an additional option exists to conduct a performance-based design as an alternative [Fitzgerald 1991]. To achieve compliance with the NBCC or NFCC a design must comply with either the acceptable solutions (prescriptive requirements) identified or must use an alternative solution that is approved by the AHJ. Any alternative solution must achieve at least the minimum level of performance required by an acceptable solution, as defined by its associated objectives and functional statements.

1.3   Challenges in Performance-Based Designs and Alternative Solutions

As identified in the above description of prescriptive-based codes, there is often recognition within these regulations for design substitutions. Depending on the jurisdiction, such substitutions may be classified as a variance, equivalency or an alternative solution. Prior to the objective-based format of the NBCC and NFCC, designers could propose equivalencies to specific code requirements. Now such proposals are classified as alternative solutions. These regulatory devices permit designers to substitute a

performance-based design as a replacement for compliance with a prescriptive requirement. The following section describes alternative solution requirements and identifies the challenges faced by designers and authorities in quantifying design objectives, demonstrating design performance and accounting for uncertainty. The challenges identified are applicable to alternative designs within the prescriptive-based regulatory industry and are a factor in a comprehensive performance-based design process. The current methods used in industry to address the challenges are also identified.

It is first necessary to distinguish between performance-based codes and performance-based design. The codes provide a regulatory framework to design and accept building solutions while the methodology of rationalizing a life safety and fire protection system is considered performance-based design. While the codes are relatively recent, the practice of performance-based design has been permitted within the regulatory system in North America since the 1927 UBC, which recognized equivalencies. In Canada, alternative solutions are permitted if the alternative design can be demonstrated to achieve at least an equivalent level of life safety and fire protection as a prescriptive-based design requirement utilizing the associated objective and functional statements. Prior to the 2005 edition of the Canadian model codes, equivalencies were permitted pending AHJ review and approval. Often, alternative solutions will be used where a unique architectural feature or construction material is desired and is not recognized or permitted within the prescriptive requirements of the code. Similar practices exist in New Zealand, Japan, Australia and the United States, where the current fire risk in buildings as established by prescriptive designs are used as the basis for performance-based benchmarking [Bukowski & Babrauskas 1994]. This approach relies on the theory that society accepts the current level of risk associated with a building design, and that an alternative design must not create a greater risk than that already accepted [Bukowski 2006]. The method of benchmarking designs instead of providing specific quantitative risk objectives eliminates the reliance on individual judgements of fire risk and risk to society [Fixen 2003]. This provides a fairly routine mechanism, at least in principle, for the regulation of performance-based design approaches.

The existing framework for performance-based design approaches and alternative solutions, however, inherently faces a number of significant challenges. These challenges occur because the method

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of demonstrating alternative solution performance is not regulated; the performance objectives are qualitative; the origins of prescriptive and performance-based codes are in conflict: and, fire science and fire protection engineering are constantly evolving and naturally contain uncertainty.

The mechanism for alternative solutions is recognized in the existing codes; however, the means of demonstrating the required equivalent level of performance is not frequently specified. Typically, alternative solutions have been developed using logical arguments, industry precedence-setting examples or by using fire test data [Bukowski & Babrauskas 1994]. Such practices rely on the experience and expertise of the designers and the regulatory officials to determine the acceptability of the method utilized to demonstrate performance. As the complexity of building designs increase, the opportunities to use logical arguments and case-specific examples to justify a design performance, decrease. Furthermore, the performance of a specific design alternative is often difficult to establish through test data generated from scaled live fire testing, computational fire modeling or fire science literature. Such investigations may be time or cost prohibitive in the context of a single alterative solution project. The data available in the literature may also not be suited to the restrictions of the design case under consideration. Under such circumstances, fire risk analysis tools are used increasingly to demonstrate design performance since such tools are generally adaptable to specific design challenges and are relatively cost and time effective.

In addition to the challenge of determining an appropriate method to demonstrate the performance of a design, it is difficult to compare different design options since the objectives that must be achieved are typically qualitative in nature and vague in codes. Bukowski found that the level of detail given in performance objectives is often insufficient, in consideration of using available risk assessment methods to demonstrate performance [Bukowski 2006]. However, as described by Rasbash, the process of quantifying fire safety objectives is challenging and unique, since fire behaviour, the reliability of fire prevention and protection methods and the behaviour of people during fire events are difficult to describe [Rasbash 1984]. Currently, there is insufficient data available to effectively quantify fire protection and life safety performance objectives within a comprehensive performance-based code. Such an undertaking would be extensive since the codes are developed to regulate the entire built environment and it is

anticipated that such quantifications would vary based on building occupancy, size, location and use. The units of quantification would also require significant consideration and evaluation. Whereas many risk quantification systems rely on monetary units, the specification of the monetary value of human life is a contentious attribute for a model code to adopt. On this basis, the practice of benchmarking prescriptive designs for performance-based alternatives is the recognized means of achieving compliance for alternative solutions.

The third contributing factor that creates a challenge in performance-based alternative solution approaches is that the prescriptive-codes have been developed using an entirely different framework than performance-based tools. As described earlier, prescriptive codes are developed based on catastrophic events or technological innovation. These codes provide requirements for individual protection components but are not based on a systematic approach to fire safety that is driven by fire science principles, as performance-based tools are. The application of performance-based design within the prescriptive requirement framework is challenging because the requirements in each system are derived from vastly different backgrounds. While an alternative solution may be specific to a single fire protection component, such as sprinklers, for example, the performance-based approach to design must account for all protection and prevention systems and provide a holistic evaluation of hazard and risk for a room or an entire building. This type of evaluation may identify shortcomings in other prescriptive requirements applicable to the building, thereby generating a conflict for both designers and authorities in establishing the minimum requirement of design. The consideration of the approach to fire protection and life safety in a building as individual components versus interactive systems is a fundamental difference between performance-based and prescriptive design approaches.

The fourth significant challenge faced within alternative solutions and performance-based design is the randomness of fire events and the resulting uncertainty associated with approximations and models used to predict the effects of fire. Uncertainty is associated with qualitative design approaches and performance comparisons due to the subjective nature of qualitative analysis. Therefore, in demonstrating the performance of an alternative design solution this uncertainty must be evaluated and a measurement

assigned so that the robustness of the design decision (i.e. to approve or reject an alternative solution) is clear. The robustness of a design decision indicates how 'sure' the designer or AHJ is that the predicted performance is correct given the uncertainty associated with the design assumptions made.

1.4 Analysis

Based on the description of building design regulations, and alternative solutions in particular, the following analysis summarizes the challenges within the building regulatory system in Canada and internationally. The challenges identified pertain specifically to fire protection designs and the development of alternative solutions to prescriptive-based requirements. The major challenge identified is ensuring a uniform and consistent application of performance objectives and the subsequent impact on the quality of building designs.

The task of quantifying the objective and functional statements associated with prescriptive requirements so as to direct performance-based design is overwhelming. There is also insufficient data available to support such an endeavour with respect to providing meaningful accuracy with acceptable certainty. As such, designers and authorities are challenged to develop and evaluate performance-based designs based on qualitative objectives and benchmarked prescriptive designs. To further muddy the design waters, there is an abundance of fire risk analysis methods (see further discussion in Chapter 2), fire testing methods and computational modeling techniques available with every passing year; however, none are explicitly recognized in the Canadian codes as suitable means through which to demonstrate the performance of an alternative solution. The performance-based design framework is constructed in the codes, but the specification of methods and techniques required to utilize the framework is absent.

Due to the ambiguous nature of the performance-based design codes, engineers, architects and designers must rely on their experience and the experience of the regulatory authorities to establish and evaluate the suitability of design alternatives to prescriptive requirements of codes. This experience may be in traditional building design or in academic fire science; however, for such a system to function effectively both the designer and the authority must have the same knowledge base from which to draw.

A requirement that, in practice, is unlikely at this time. The alternative design must also be compared with a prescriptive design on an exclusively qualitative basis, since performance objectives are of a qualitative nature. The reliance on experience and qualitative comparisons is often inconsistent between different designers and different jurisdictions. Furthermore, while every design requiring an alternative solution is unique and developed to address specific hazards and conditions, there should be a reasonable level of approval consistency of an alternative solution to a specific prescriptive design requirement across various jurisdictions. Unfortunately, this may not be realised in practical design settings because of the reliance on individual experience and qualitative comparisons in assessing the various design options.

The disadvantages of inconsistent alternative solution designs and approvals is that the process generates a high potential for the over-design or under-design of life safety and fire protection measures in 'new' buildings utilizing modern architecture, materials or operations. When alternative solutions are accepted on a qualitative comparison basis instead of a quantitative comparison basis, the uncertainty inherent in fire development and propagation in a building can be significantly underestimated or overestimated. Since the codes provide a minimum standard of building design, alternative solutions, by definition, must only maintain that minimum.

The over-design of building systems results in high costs to an owner and sets an industry precedent that exceeds the minimum standard. Over-design is often implemented to account for the uncertainty associated with the performance of an alternative design approach, to provide a 'safety factor' without any performance-based reasoning or justification with the intent of ensuring that a design decision is robust. This practice can be costly for building owners and operators or can impose significant inspection, testing and maintenance obligations. While overachieving fire protection performance measures is considered by most to be beneficial, when such measures become cost-prohibitive it is imperative that the minimum requirement be clearly specified and understood. Unless desired by the owner for their own purposes (i.e. insurance stipulations), an alternative solution is not be required to exceed the standard minimum. In contrast, alternative solutions justified by overestimations of fire protection and life safety system performance are considered to be under-designed, in comparison with the prescriptive requirement

counterpart. Approvals of such alternative solutions are obviously undesirable, and by definition conflict with the intent of the codes.

1.5   Closure

The recent development of performance-based building design codes internationally is considered to foster innovation in the building industry, but also creates new challenges for designers and authorities. In Canada, and throughout the world, alternative solutions are a recognized mechanism by which engineered fire protection design can be utilized to replace a prescriptive-based code requirement. However, the methods to demonstrate and quantify alternative design performance and to account for the uncertainty inherent in fire behaviour at present are not specified in the codes. Current practices rely on designer and regulator experience and expertise which can result in over-design or under-design of new buildings and protection systems.

To address the challenges recognized in the performance-based regulatory system, specifically with alternative solution development, the objective of this thesis is to establish a method to quantify design performance, to address uncertainty associated with real fire events and to generate robust design decisions. In particular, a method or methods by which to quantitatively evaluate and compare the performance of a prescriptive design to a performance-based design must be identified or developed to replace the current reliance on subjective comparison of designs based on qualitative performance objectives found in building and fire codes.

In this thesis, fire risk analysis techniques will be investigated as the basis for the development of a method to address the challenge identified for performance-based designs in the alternative solution framework in Canada. Based on the foregoing discussion, any such method must adhere to the following four objectives:

- Utilize prescriptive-based design as a benchmark to develop alternative design options,
- Utilize prediction and evaluation techniques that are relatively simple to apply and understand, to bridge any gaps in the experience between authorities and the designers,

- Accommodate typical project timelines and resources by using fire risk and hazard analysis techniques that are not onerous in terms of time or monetary resources; and,

- Provide uncertainty analysis and robustness evaluation for each alternative solution.

These will form the foundation for development of the QDD method, a new fire risk analysis method that has been developed in this thesis.

Chapter 2

LITERATURE REVIEW

The purpose of this chapter is to establish fire risk analysis techniques that are best suited to estimating the performance of an alternative solution design in comparison to a prescriptive design requirement. Guidance tools available for selecting and evaluating performance-based designs utilizing risk analysis techniques, such as NFPA 551 and the SFPE Engineering Guide, are reviewed to identify critical components needed in a method to achieve the requirements of an alternative solution proposal. Methods of identifying appropriate data for use in fire risk analyses, focusing particularly on surveying methods, are described. The merits of qualitative, semi-quantitative and quantitative assessment methods are also evaluated. The literature review provides the basis for the development of a fire risk analysis method to address the design challenge and thesis objectives identified in Chapter 1.

2.1 Industry Guidelines

Fire risk analysis methods became increasingly utilized in the mid 1990s to develop fire and life safety solutions [NFPA 551 2010]. This practice was conducted without an acceptance framework within the regulatory environment or a set of rules by which to evaluate the application or results of a particular method. There exists a vast array of fire risk analysis methods available to fire protection engineers

including qualitative, semi-quantitative and quantitative techniques and a variety of means by which to collect and apply data. To assist both designers and AHJ in determining the best application of these methods, guidelines for the review of fire risk analyses have been developed by fire protection associations and government organizations. The guidelines have been developed to provide guidance to designers, practitioners and AHJ when applying and evaluating these methods within the building design industry.

Guidance documents for the development of performance-based designs utilizing fire risk analysis tools available to designers and AHJ include standards such as NFPA 551, the SFPE Engineering Guide: Fire Risk Assessment (SFPE Engineering Guide), British Standard Institute BS 7974 and the International Standard Organization's Technical Specification ISO-TS 16732: Fire Safety Engineering – Guidance on Fire Risk Assessment [Meacham et al. 2008]. The evaluation in this section focuses specifically on NFPA 551 and the SFPE Engineering Guide because the organizations developing those documents are widely recognized in North America and are therefore most likely to be recognized by Canadian building regulatory authorities. Since these guidelines are provided to assist in the application and evaluation of different design methods they provide criteria for the development of these tools and may be used to establish the requirements for an alternative solution submission. The standards are generally intended to guide the review process and do not specify which fire risk analysis techniques must be used for specific alternative solution proposals.

The guidance documents identify different types of methods available, both to direct designers in appropriate method selection and to assist AHJ in reviewing the application of a method to a fire protection engineering challenge. The guidance provided in NFPA 551, in particular, is distinctive from the approaches adopted in other guidelines, standards and handbooks, as well as from literature on fire risk method categorization and case studies prepared by, for example, Tixier and coworkers, Hall and Sekizawa and Kelly and Weckman [Tixier et al. 2002, Hall & Sekizawa 1991, Kelly & Weckman 1993]. NFPA 551 is unique within the available guidance documents because it identifies methods that the AHJ is expected to be familiar, but does not recommend or restrict the use of any one specific method in the

alternative design process. In that respect, NFPA 551 was developed specifically to provide guidance to AHJ for evaluating alternative solutions based on conclusions generated by fire risk assessment methods.

In addition to recognizing various fire risk analysis tools, current guidance documents identify specific criteria and submission components required for a complete evaluation of an alternative design solution. These items may not otherwise be mandatory components of a fire risk or hazard assessment or analysis technique. For instance, in an alternative solution prepared by a fire protection engineer, important attributes that must be addressed in the submission include acceptable documentation, evaluation of uncertainty and involvement of stakeholders, specifically the AHJ in the design and analysis process. The sources of data used in a fire risk analysis also must be justified as reliable, relevant and meaningful. These elements are discussed in the following sections since they are expected to be developed in a comprehensive alternative solution proposal to a prescriptive code requirement in combination with an appropriate fire risk analysis.

2.1.1   Documentation

NFPA 551 and the SFPE Engineering Guide direct fire protection engineers to prepare engineering design briefs or project reports to document the fire risk or hazard evaluation process conducted and the results of the exercise in the context of the design problem. The recommended document practices identified in both standards are largely similar with respect to report content. The objective of the documentation is to communicate the hazards and/or risks and the assessment process to the stakeholders, including the AHJ, as the basis for review and general comprehension [SFPE 2006]. The Canadian model codes provide requirements for alternative solution proposal documents in Division C; however, these requirements are prescriptive and do not provide the detail and rationale found in the guidance documents [SFPE 2006, NFPA 551 2010]. An alternative solution proposal report, describing the method and conclusions, must be developed in consideration of the requirements of the Canadian model code requirements. NFPA 551 specifically states that:

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> *"…the form of the documentation should meet the needs of the authority having jurisdiction within the context of applicable laws and regulations"*
> [NFPA 551 2010].

Generally, if fire risk analysis documents are prepared as described in the guidance standards then the alternative solution proposal report should achieve compliance with the requirements of the NBCC and NFCC for submission.

Based on the documentation submitted, the AHJ must consider the assumptions and limitations of the method and project when evaluating the suitability of the developed alternative solution. Furthermore, the specification of the assumptions and limitations of the method and of the analysis facilitates the management of change in the building subsequent to approval, with respect to the findings of the performance-based design approach conducted [SFPE 2006, NFPA 551 2010]. The specification of the acceptance criteria used in the fire risk analysis frames the evaluation conducted since these components form the basis for the acceptance of an alternative solution. The objectives attributed to prescriptive code requirements are often qualitative; whereas the performance criteria identified in alternative solution should be quantitative. As such, the assumptions made in quantifying the qualitative performance objectives must also be clearly described in the documentation prepared to support the fire risk analysis conducted.

To expedite design approval, the SFPE Engineering Guide identifies that it can be useful to develop a preliminary 'concept' report that describes the fire risk analysis framework and methodology as applicable to the design challenge to facilitate discussions with the AHJ at the onset of the project [SFPE 2006]. This document can be used to obtain an agreement in principle from the AHJ to support the proposed methodology. By approaching the AHJ during the early stages of the project with the documented approach, it reduces the likelihood that significant changes in the method or the design will be necessary later in the project [SFPE 2006].

2.1.2   Uncertainty Evaluation

As was identified in Chapter 1, an uncertainty evaluation is considered a necessary component of any alternative solution that is supported by a fire risk analysis. This conclusion is reflected in the key requirements outlined in the guidance documents under consideration [SFPE 2006, NFPA 551 2010]. Uncertainty, within the context of fire protection engineering is associated with the lack complete knowledge pertaining to the behaviour of fire and the performance of fire protection and prevention systems in the practical world. In terms of models and calculations, uncertainty is related to the reliability associated with predicting the performance attributed to fire scenarios. In terms of the practical world, it is related to randomness of events. Uncertainty may be categorized as either aleatory or epistemic. Aleatory uncertainty is associated with randomness of events, for example, how a fire event is initiated [Notarianni & Parry 2008]. Epistemic uncertainty is related to the approximations introduced in a model due to limitations in computational methods or background scientific knowledge. Generally, epistemic uncertainty can be quantified to some extent in the context of a fire risk assessment, but due to the unpredictable nature of real fire events, it is very challenging to quantify aleatory uncertainty.

In the field of fire protection engineering and design, it is not feasible to attempt to remove uncertainty from an evaluation entirely. The body of fire science knowledge is incomplete and fire behaviour is inherently random in practical settings. As such, designers are required to make design decisions when some level of uncertainty is involved. It is necessary to analyze the significance of the epistemic uncertainty inherent to the process since the appropriateness of the design decision is reflected in the reliability of the model and data utilized [Notarianni & Parry 2008]. In the analysis process, a means of evaluating and documenting uncertainty and rationalizing a design decision is required to confirm that the results of a fire risk analysis generate a robust conclusion that is reliable within measurable sensitivity.

The codes and fire risk analysis methods do not typically prescribe a means of determining design decision robustness or of quantifying the uncertainty associated with the conclusions generated. As such,

it is the responsibility of the designer to address the uncertainty inherent in a fire risk analysis and in the

data utilized to support the evaluation. NFPA 551 and the SFPE Engineering Guide each identify the

importance of describing and, if possible, quantifying the impact of uncertainty and variability on a fire

risk assessment conducted in support of design decisions [SFPE 2006, NFPA 551 2010]. The documents

identify that sensitivity analyses or uncertainty analyses must be conducted for complex assessments to

identify the potential impact and significance of uncertainty on the results [SFPE 2006, NFPA 551 2010].

The guidance documents require that the effects of the uncertainty in the method and the variability in the

assumptions and data utilized be analyzed in the calculation of risks and that this uncertainty be

documented. It is intended that the evaluation of uncertainties will substantiate the reliability and

robustness of the conclusions of a fire risk assessment. The outcome of a sensitivity or uncertainty

analysis may be the justification for use of safety factors or may better define the safety margins inherent

in the design [SFPE 2006]. By evaluating the uncertainty associated with each stage of a fire risk analysis,

the robustness of the output design decision can be determined.

2.1.3   Stakeholder Input

A significant component of a fire risk analysis is stakeholder involvement. A fire risk analysis for an

alternative solution should not be conducted in isolation. As defined by NFPA 551, stakeholders are any

individual, group or organization that might affect, be affected by, or perceive itself to be affected by, a

risk [NFPA 551 2010]. In the context of fire protection engineering and alternative solution development,

stakeholders usually include at least the designer, the owner and operators of a facility and the AHJ. Other

stakeholders may include: emergency responders, tenants, insurers, neighbours, local community groups,

investors and the construction team; having a financial, safety or regulatory interest in the scope of work

[NFPA 551 2010].

The reason that stakeholders must be involved in the fire risk analysis process is to ensure that design

decisions and assumptions are robust and defendable from a range of different perspectives. The inclusion

of stakeholders in the design process ensures that varied stakeholder values are considered such that a

design decision can be made to satisfy as many stakeholders as is possible. Typical stakeholder values may include protection of people such as building occupants, employees, public and emergency responders; protection of property, such as a building, equipment, building systems or components; protection of the environment from effects of fire or hazardous materials; and protection of an organization's mission such as business continuity, information assets, and reputation.

The role for the AHJ in the fire risk assessment process is particularly significant. The AHJ represents the authority that is responsible for enforcing the requirements of a code or standard. It is their responsibility to ensure that any approved alternative solutions have demonstrated a performance that is at least equivalent to the respective prescriptive requirement. They must also ensure that a rigorous and comprehensive evaluation of the fire risk has been conducted. This role does not, however, necessitate that the AHJ remain in isolation during an alternative design project.

NFPA 551 suggests that the AHJ participate in problem definition, selection of acceptance criteria, method of review selection, the detailed review process and the final approval of a design as an alternative solution to a prescriptive requirement [NFPA 551 2010]. When the AHJ is involved at the outset of an alternative solution design project, opportunities to reduce review time, benefit from their experience and engage in thoughtful discussion of code interpretations and challenges are available. A brief meeting of the owner and the designer with the AHJ at the onset of an alternative solution project permits the facility and design challenge to be introduced. By presenting the problem at the initial stages, the AHJ has time, well before the review of a solution formally begins, to consider the challenge; research industry approaches; and to raise questions to the design team, or to higher regulatory bodies, if necessary. Not only does this introduction encourage on-going communication throughout the project, it also should help to streamline the formal review. In the practical application of alternative solutions, time is always acting against the owners. Streamlining review time and conducting efficient design is critical. The practice of involving AHJ in fire risk analysis is at the discretion of both the designer to initiate meetings, and the AHJ to accept meeting requests. In the Canadian system, a meeting with the AHJ is not mandatory prior to alternative solution submission.

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Surveying techniques are frequently used to gather pertinent information from fire protection and life safety experts and stakeholders in fire risk analyses. This is one method of including stakeholders in the project. Various methods of surveying experts and stakeholders are recognized in industry including panels of experts in the form of committees and nominal groups [Donegan 2008]. Committees function with a chair and members, group debates and majority voting to establish risks associated with various fire events. The drawback of a committee format is that majority votes often do not reflect a group consensus in that strong personalities within the committee may dominate the debate process [Donegan 2008]. Nominal groups, in contrast, are formed by experts or stakeholders wherein member's positions are developed and circulated outside of the group setting with the various positions later pooled into a final consensus point of view.

The Delphi method of paneling experts is one type of nominal group survey technique that Linstone and Turoff described as:

> *"a method for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with a complex problem"* [Linstone & Turoff 1975].

In a traditional Delphi method, the members never meet and information is transmitted from and to a group controller. Each member has an opportunity to cast a vote or score. These scores are then compiled such that a group opinion is derived. In each subsequent round of voting, members are provided with feedback which includes the group's overall opinion score in comparison to their previous individual score to assist in re-voting. In this fashion the method promotes group consensus without permitting dominating personalities to direct individual opinions. Such a method may provide useful when applying fire risk analysis techniques where the input from multiple stakeholders having different priorities and values is desired.

Delphi methods are best suited to the development of subjective statements by a group and when it is necessary to avoid the pitfalls of group dynamics due to group size, group personalities or politics [Linstone & Turoff 1975]. A limitation of this method historically has been that it is time consuming to coordinate and that the role of the group controller is significant. With the advent of improved computer

technology and information networks, this drawback may be alleviated using a web-based program to survey and provide feedback to participants in real-time.

The Delphi method may also be limited in its application to fire risk analysis in that a group can achieve stability before it reaches consensus [Donegan 2008]. Consensus, in the context of stakeholder involvement, is critical when generating risk perceptions and opinions for use in a fire risk analysis. Since the AHJ stakeholders represent society at large and the owner of a facility represents individual priorities, consensus must be established to some extent if the objectives of a fire risk analysis are to be established and evaluated. While the use of subjective opinions of stakeholders or experts may be considered a 'step-backwards' from accurate risk quantification, data such as that which might be obtained from Delphi analysis is fairly simple to derive and may be extremely useful when ranking fire safety strategies [Zhao et al. 2004].

In summary, when applied in the context of alternative solution design, fire risk analysis must be supplemented by thorough documentation; must specifically evaluate methods and assumptions, as well as uncertainty in the techniques and data used; and must be conducted in cooperation with project stakeholders, specifically the AHJ to achieve consensus where possible. Utilizing the guidance available in NFPA 551 and the SFPE Engineering Guide, a designer is directed towards the suitable application of a fire risk assessment method and the development of a comprehensive alternative solution report. The guidance documents also assist AHJ in evaluating such applications.

2.2 Fire Hazard and Fire Risk Assessment and Analysis Techniques

Numerous fire hazard, and fire risk assessment, evaluation and analysis techniques are available to assist designers and AHJ in predicting and measuring the performance of fire protection and life safety designs. This section discusses the benefits, limitations and opportunities within this area of study, and focuses specifically on application of risk assessment within the alternative solution framework of prescriptive building and fire codes. Definitions of terms and types of tools available to designers and

AHJ which pertain to the development and evaluation of alternative solutions are described. Methods considered include qualitative, semi-quantitative and quantitative hazard and risk techniques.

The terms fire risk assessment, fire hazard analysis and combinations therein are used interchangeably throughout the building design industry. A generally accepted definition for the term 'hazard' is a "*chemical, physical condition or situation that has the potential for causing damage to people, property or the environment*" [Watts & Hall 2008]. In contrast, the term 'risk' is defined as:

> "*the probability distribution of events and associated consequences as the potential for the realization of unwanted, adverse consequences to human life, health, property or the environment*" [Watts & Hall 2008].

Essentially, a hazard represents the potential for an unwanted outcome, and a risk represents the product of the probability of occurrence of that unwanted event and its severity. The definition of each term is significant in the context of the evaluation of assessment and analysis tools for use in the support of the development of an alternative solution.

An assessment tool, as defined in the SFPE Handbook, is distinctive from an analysis, an evaluation or an identification tool. An assessment is "*the process of establishing information regarding acceptable levels of risk*" while an evaluation is "*the judgement of the significances and acceptability of risk*" and is considered one component of an assessment [Watts & Hall 2008]. Van Duijne and coworkers specify that a risk assessment should answer three questions: what can go wrong?, how likely is it to happen?, and if it does happen what are the consequences?; such that a risk assessment is comprised of three distinct phases (1) hazard/risk identification, (2) risk estimation and (3) risk evaluation [van Duijne et al. 2008]. The term 'analysis' is defined as an "*examination of negative consequences and the process of quantification of probabilities and expected outcomes*", and is considered to include assessments, evaluations and risk management approaches [Watts & Hall 2008]. The terms analysis, assessment and evaluation are also frequently used to refer to a thorough investigation of a topic. For the purposes of this investigation, the terminology proposed in the SFPE Handbook will be maintained and a comprehensive tool that quantifies the likelihood and consequence of each event will be described as a fire analysis.

A fire hazard analysis, as defined by Hall and Sekizawa, is a method to establish and describe a single fire situation while a fire risk analysis addresses all relevant fire situations [Hall & Sekizawa 1991]. Another distinction between risk analyses and hazard analyses is that risk analyses use probabilistic evaluations to determine consequences [Bukowski 2006]. The term fire risk assessment is used in NFPA 551 to refer to all fire risk analysis, fire hazard analysis, hazard analysis and fire hazard assessment methods which characterize risks associated with fires, their probability and potential consequences [NFPA 551 2010]. For the purposes of this investigation, risk and hazard techniques are distinguished by the use of probabilistic evaluation as described by Bukowski. Furthermore, a fire risk analysis is classified as a methodology by which multiple probabilistic fire event outcomes are considered.

The following provides a brief overview of some methods for hazard and risk assessment and analysis that are available within the fire protection industry. The following sections provide descriptions of qualitative, semi-quantitative and quantitative techniques.

2.2.1   Qualitative Tools

Tools used to identify and evaluate hazards associated with potential fire events that do not quantify either outcome - event likelihood or event consequence - are classified as qualitative methods. As identified in NFPA 551, Section 5.2, such methods are typically used in conjunction with other tools when conducting a fire hazard or risk analysis [NFPA 551 2010]. Common qualitative tools, include the What-If Analysis, hazard checklists and logic trees such as the Fire Safety Concepts Tree (FSCT) [NFPA 551 2010]. While these tools cannot be used exclusively to support the development of an alternative solution, they represent potentially valuable screening tools for designers.

The What-If Analysis method is an unstructured brainstorming technique which aims to identify the intended function and potential failure modes of a designed system using the phrase "what if 'X' happens". The results of such investigations may be a narrative; however, it will not include any ranking or quantification of hazards [NFPA 551 2010]. Checklists, in contrast, provide specific lists of questions or items to assist in the identification of known hazards or code deficiencies, i.e. door hardware is

installed to manufacturer's specifications [NFPA 551 2010]. Checklist tools should be used with caution, since by definition they are specific to a particular hazard or design system and have restricted application. These methods of qualitative fire hazard assessment assist in identifying potential hazards within a building or fire protection system but do not provide a means to numerically quantify performance. They are limited by the experience of the practitioner of a What-If-Analysis to generate appropriate questions or by the scope of the checklist system developed. These methods are not based on fire science principles and do not facilitate a comprehensive systems approach to the qualitative evaluation of hazards.

As an alternative to What-If-Analyses and checklists, the FSCT is a qualitative logic tree developed to identify strategies for achieving specific fire safety objectives. The logic tree illustrates the relationship between numerous components which contribute to overall fire safety to demonstrate how different design approaches may achieve the same fire safety objectives. The tree utilizes logic gates – AND or OR – to distinguish between fire safety objectives and design paths, as described by Rasbash and coauthors [Rasbash et al.2004a]. The FSCT is a recognized qualitative fire analysis tool to by which to evaluate various fire safety strategies [NFPA 551 2010], and in 1987 it was identified as the most frequently used fire safety system analysis method to address non-traditional fire safety design challenges and develop code equivalencies [Richardson 1987].

NFPA 550 specifies the structure, application and limitations of the FSCT [NFPA 550 2007]. This guide provides a detailed description of each component of the logic tree. The complete FSCT is provided in Appendix A for reference, where (●) represents an AND gate and (+) represents an OR gate. The FSCT was published originally in 1974 by the NFPA Committee on Systems Concepts for Fire Protection in Structures [NFPA 1974]; however, it was not until 1985 that the first edition of NFPA 550 was published by the NFPA technical Committee on Systems Concepts for Fire Protection in Structures [NFPA 550 1986]. The FSCT was unique within the fire protection industry since it was developed originally to assist with design decisions for high-rise structures [NFPA 550 1986]. The tree was distinctive from traditional fault trees available at the time, which also utilized logic gates, since the

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decision paths were constructed to lead to a fire objective success rather than failure. It does not, however, lend itself well to attributing specific likelihood probabilities to the various paths in the analysis. The current 2012 edition of the standard continues provide a success-based comprehensive fire safety framework.

The applications of the FSCT include the analysis of codes or standards and the development of performance-based designs [NFPA 550 2007, Richardson 1987]. The FSCT is recognized as a valuable design tool since it provides an overall framework under which common fire safety objectives can be systematically correlated to specific design components. The tool addresses building design components such as, construction, combustibility of contents, protection devices and occupant procedures [NFPA 551 2010]. The FSCT provides a comprehensive illustration of the interrelationships between fire safety strategies and a logical path for evaluating achievement of fire safety objectives.

This framework is useful to designers since the logic gate component of the FSCT identifies overall system redundancies and shortcomings. From a design perspective, for example, an OR logic gate in the FSCT implies that only one of many methods of prevention or protection are required to achieve a fire safety objective. This strength, however, also leads to a limitation of the FSCT in that an OR gate also implies that perfect achievement of any one method is sufficient to achieve the full fire safety objective. This approach is not realistic in practice; since no fire protection system is considered to achieve 100% reliability. Such limitations are easily overcome since multiple OR logic gate paths can be implemented in a final design to achieve the desired fire safety objectives.

One application of the FSCT methodology includes a qualitative assessment a fire safety design approach to determine where improvements are necessary [NFPA 550 2007]. However, Hall and Sekizawa identify that the FSCT may be utilized as a quantitative tool where probabilities for each event are estimated using laboratory results, historical data or expert opinion [Hall & Sekizawa 1991]. This method is described as a tool for use by architects, building managers or fire protection engineers to establish the probability of success of a fire protection system based on pre-defined objectives [Hall & Sekizawa 1991]. While the application of probabilities to establish the likelihood of success of meeting an

objective are recognized within the fire risk assessment industry, the method was not developed to be used in a quantitative format, as is clearly described in NFPA 550.

A major strength and unique attribute of the FSCT, within the category of qualitative tools, are its built in tutorial properties and its applicability as an equivalency guide to performance-based design [NFPA 550 2007]. The tree provides a simplistic means to communicate fire safety requirements that are incorporated into codes and standards – this tutorial function greatly assists designers in explaining design approaches to stakeholders. In addition, the FSCT is illustrative and easily expressed to persons who do not possess extensive fire protection or fire science knowledge. Furthermore, the FSCT has been developed specifically to assist in the design of equivalencies, such as those necessary to support alternative solutions; since OR gates effectively identify alternative means to achieve the same fire safety objective.

The FSCT is not without limitations, however [NFPA 550 2007]. In particular, the tool does not suit multi-objective design challenges and it does not address the lateral interactions between logic branches in complex fire protection systems [NFPA 550 2007]. Furthermore, the method cannot take into consideration the chronological sequence of fire scenarios and, as described in NFPA 550, it is only qualitative. Nonetheless, the FSCT holds much promise when applied as a screening tool in a larger fire analysis. Limitations in its ability to deal with multiple design objectives do not apply in the case of comparison of an alternative design to a single prescriptive code requirement where the requirement is related to simple fire safety objectives. When used only as a screening tool, limitations in its ability to address lateral design interactions are also less relevant since only design alternatives that represent equivalencies to the benchmarked prescriptive design are considered. Nonetheless, a comprehensive fire risk analysis method is required to provide a truly quantitative analysis which considers specific fire scenario events in terms of their likelihood and consequence. As such, a qualitative fire hazard assessment tool such as FSCT cannot be used exclusively to predict the performance of an alternative solution; on the other hand, the FSCT provides a systematic, logic-based evaluation of the design components required within an objective-based design framework.

2.2.2 Semi-Quantitative Tools

Semi-quantitative tools are those that describe either the likelihood or the consequence of a risk quantitatively. The other component is then generally described qualitatively. Deterministic enclosure models, actuarial and loss statistical models and network models such as event trees are common semi-quantitative methods [NFPA 551 2010]. Enclosure models are typically classified as semi-quantitative consequence methods, network models are classified as semi-quantitative likelihood methods and actuarial or loss models are represented in both categories depending on the nature of the data utilized to evaluate loss.

Enclosure models are used to quantify consequences of a fire scenario and are predominantly conducted using fire science correlations represented by computational fire models. The complexity of fire models has increased with the recent advances in computer technology such that numerous fire modeling software programs are readily available each having specific applications and limitations [Friedman 1992]. In 2003, Olenick and Carpenter surveyed the fire modeling programs available to fire protection engineers. This survey was an update to the efforts of Friedman, and catalogued 168 modeling programs related to fire and smoke phenomenon [Friedman 1992, Olenick & Carpenter 2003]. While fire modeling tools are useful when describing specific fire hazard events, this investigation focuses on identifying fire risk assessment methods that are resource efficient and transparent. Fire modeling techniques are often times complex, time consuming and costly to verify and validate when applied in the context of single case alternative solutions to complex building design challenges.

Actuarial and loss statistical models may be used to evaluate the probability or likelihood of single or multiple fire scenarios or may be used to predict the loss associated with a specific event outcome. These methods utilize statistical data based on historical losses. In the United States the FEMA/USFA National Fire Incident Reporting System (NFIRS), NFPA's Fire Incident Data Organization (FIDO) database and Survey of Fire Departments represent databases of documented losses to support statistical models [NFPA 551 2010]. These resources represent years of fire loss details; however, the data is not necessarily

consistently reported and is specific to each fire event. It must be applied with caution if supporting

performance-based design solutions.

Network models provide graphical representations of information. Depending on the nature of the

information under evaluation, the network will be shaped to connect associated nodes. A tree network is

one in which two nodes are only connected by a single path [NFPA 551 2010]. Event trees are tree

network models which quantify the likelihood of a fire scenario. Event trees sequentially quantify event

probabilities and utilize qualified consequences to describe risk. Event trees are described as "the simplest

and one of the most powerful probability models" [NFPA 551 2010]. A generic event tree is illustrated in

Figure 2.1, and its components are discussed in this section.
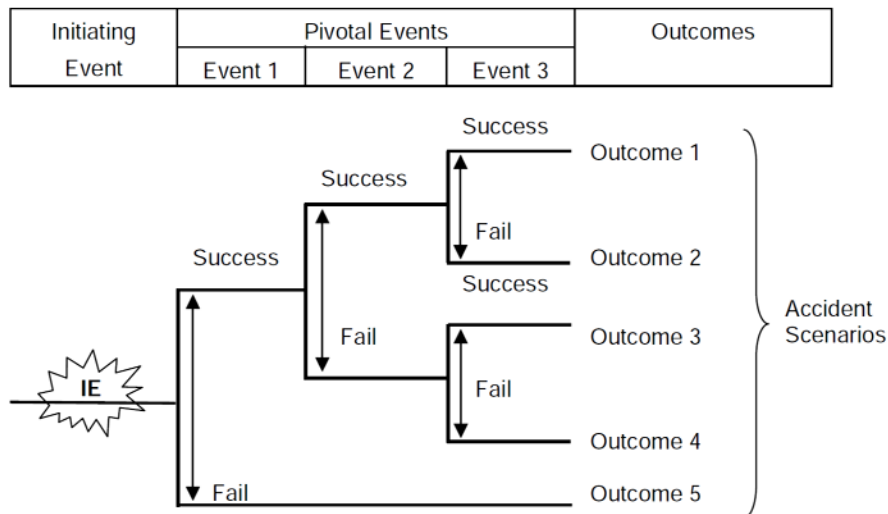
Figure 2.1 Illustration of an Event Tree [Ericson 2005]

Event trees are useful tools to identify and screen fire scenarios [Hadjisophocleous & Mehaffey

2008]. As described in Chapter 12 of the Hazard Analysis Techniques for System Safety, the purpose of

event tree analysis studies is to evaluate the consequences of every fire scenario outcome generated from

a single initiating event within a single design strategy [Ericson 2005]. It is believed that event trees were

originally developed in 1974 during the nuclear power plant safety study titled WASH-1400 [Ericson

2005]. These trees were generated to simplify the traditional fault tree analysis methods, which utilized

more complicated multi-branch event sequences instead of the binary decision format now adopted in

event trees [Ericson 2005]. Fault tree analysis techniques are illustrative network models and focus on establishing the cause of an event instead of the possible outcomes from an event. Fault tree analyses utilize logic gates, similar to the FSCT, and are a 'reverse thinking' tool to establish the cause of a fire event [Meacham et al. 2008]. In comparison to available network models, the event tree approach is considered to assist in generating fire scenario events in a simple and thorough fashion.

Ericson identifies specific terminology to describe event trees including the accident scenario, initiating event and pivot events, which are identified in Figure 2.1 [Ericson 2005]. The accident scenario represents one chain of events starting from the initiating event, and containing each pivot event through to generation of an accident outcome [Ericson 2005]. The initiating event is the first failure that starts the multiple accident scenarios. Rausand and Høyland emphasize that the initiating event should be the first significant deviation that could lead to the accident outcomes [Rausand & Høyland 2004]. Additional events may be associated with the initiating event, to better describe and capture all possible outcomes of the full accident scenario. For example, an additional event may relate to wind direction at the time of the initiating event, but may not necessarily reflect or relate to a specific design component [Rausand & Høyland2004]. Pivot events follow the initiating event and accident events, and represent design barriers that are evaluated to either successfully operate as intended or which fail to successfully operate as intended [Ericson 2005]. These barriers represent the design components intended to mitigate a fire or explosion event. Generally, pivot events are binary in character.

The quantification component of an event tree is in the assignment of probabilities to each pivot event and/or the accident scenario consequences. To quantify accident consequences, a decision making models may be required. If the consequences are described qualitatively, the descriptions will generally range between undesirable and desirable

As identified by Bukowski, hazard assessments conducted to demonstrate performance-based designs should represent the principal fire events threats, which frequently result from multiple failures [Bukowski 2006]. The event tree represents a simple model by which the multiple accident scenarios generated by an initiating event can be sequentially evaluated and considered. This tool is an illustrative

means to convey technical fire protection information pertaining to a proposed design and its possible modes of operation. The event tree is also a model that can be utilized early in the development stages of a design project since it relies largely on conceptual design information [Ericson 2005]. These attributes position event tree analysis well for application to alternative solution designs.

Limitations of event trees relate to the skill of the user, the restriction of outcomes to a single initiating event and the qualitative nature of outcome descriptions. As such, it is important that event trees be applied by a knowledgeable fire protection engineer who is familiar with both the prescriptive-based and performance-based design approaches under consideration, as well as event tree development and analysis techniques. Since event tree outcomes are associated with a single initiating event, the probability of similar outcomes occurring because of a different initiating event are not represented in outcome probabilities generated [Rasbash et al. 2004b]. This limitation reflects the importance of initiative event selection and evaluation by a knowledgeable designer. Additionally, since event trees are semi-quantitative, to compare the performance of design alternatives it is required that the consequences of the fire scenarios be evaluated on a quantitative basis. Quantitative consequence comparisons are necessary in a fire risk analysis method to assist the designers and the AHJ in making informed alternative solution design decisions. Event trees assist in describing the performance of fire safety designs; however, they do not direct the design process nor do they generate quantitative design decisions.

2.2.3 Quantitative Tools

Quantitative tools provide a numerical evaluation of both the likelihood and consequences related to a fire scenario or series of fire scenarios so as to assign quantitative values to the risk. Quantitative tools may include both subjectively derived and objectively derived risk values. A challenge inherent to quantitative tools is the identification of fire event likelihood and fire event consequence in numerical terms. Event likelihood is often more easily described using equipment failure rates or historical trends; however, the quantification of fire consequences is often difficult to ascertain with certainty without using complex and case-specific enclosure models such as those described in Section 2.2.2. Fire events and

their outcomes are uncertain with respect to the likely magnitude of damage caused to property and to human life. Fire risk analysis tools that generate quantitative results must therefore rely on decision making techniques for uncertain or risky conditions.

Risk-based decisions are those made using comparisons of statistically derived risk [Donegan 2008]. These decisions often utilize a single comparison parameter (i.e. total cost) and allow comparisons to be made between different alternatives under various conditions. For example, the cost of upgrading a sprinkler system and the losses expected based on statistical fire size would represent a risk-based decision. If the probability distribution for the fire size is not available or cannot be determined, the decision becomes uncertain and assumptions must be made to generate design decisions. Simple decision making methods will consider a single comparative parameter; however, in fire risk analysis objectives related to multiple outcomes must be considered. These can include economic, environmental, political, physiological and societal priorities. In this instance, multi-objective decision making tools utilizing utility principles and weighting factors are useful in evaluating the fire risks associated with various fire protection systems or life safety system designs. These types of tools are often integrated in quantitative fire risk analysis methods, both as objective or subjective tools.

Objective quantitative tools include statistical models developed using historical population and fire or explosion incident data. These tools are often extremely industry specific; for example, fire hazard and risk assessment tools were initially used in the 1960's in the nuclear industry, chemical processing industry and in structural building design [Rasbash 1984]. These early methods were based on frequency and consequence distributions created from historical data specific to each industry and used to benchmark acceptable risks to individuals and to society in consideration of the hazards of that specific industry. For example, within the chemical processing industry, correlations between manmade fatality hazards and natural disaster fatality statistics have been used to define an acceptable level of risk or the permitted annual fatality distribution associated with a chemical plant within a population. These types of investigations rely on population data and have been shown to indicate that higher fatality risks are generally better accepted in rural areas versus urban areas [Rasbash 1984].

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Within the context of building design, such tools have been utilized historically to establish load bearing building component failure rates and their necessary safety factors. Industry specific quantitative methods which rely on statistical loss data and population details continue to be developed. For example, methods have recently been developed to analyze risk in such specific applications as oil and gas floating production storage offloading facilities [Suardin et al. 2009] and the transportation of dangerous goods through urban environments [Fabiano et al. 2002]. Due to the specific nature of these types of tools and the reliance on current statistical data, such objective quantitative risk analysis methods are limited in application to specific industries and regional populations. Similarly, evacuation models developed specifically for building design evaluations of exiting and movement are valuable in specific application but cannot generally be applied across all types of performance-based design analyses.

As an alternative to objective quantitative models, subjective risk valuation tools include the application of risk indices and risk matrix tools, fuzzy logic or economic theories to fire science, wherein numerical values are utilized to quantify risks. These methods are developed to assist in making decisions under uncertainty. The quantification of risk derived using these methods is subjective in nature and cannot be compared directly with risk results calculated using alternative methods. Van Duijne and coworkers identify that methods such as ordinal ranking used to describe risk are a suitable approach if the estimation of risk is described and an unambiguous system for ranking likelihood and consequence is provided [van Duijne et al. 2008]. The evaluation of event consequences required in quantitative fire risk analysis tools relies on consideration of the affect of economic, environmental, political, physiological and societal values in assessing the consequences associated with an event outcome [Suddle 2008].

Risk indices and matrices are identified as qualitative tools in NFPA 551; however, the tools are classified as quantitative tools in the SFPE Handbook. In brief, the tools utilize scoring systems or graphical representations to evaluate hazards. The scoring systems are compared with a base 'acceptable' risk level while graphical representations in the form of a risk decision matrix can be used to compare the risk associated with the performance of different designs. The tools are quantitative to the extent that numerical values are calculated to represent the risk associated with a design or event. Tools available to

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assist in the ranking of risks or weighting of risk perceptions include safety factors and risk adjustment factors [Wolski 2000] and the analytical hierarchy process [Zhao et al. 2004].

The principles of risk matrices and risk ranking or indexing form the basis for many quantitative risk evaluation techniques when used in conjunction with fuzzy logic algorithms and safety factors. The use of linguistic variables to describe complex or ill-defined systems, such as fire development and human behaviour, can be translated into mathematical relationships which may then be manipulated to represent risk [Zadeh 1973]. These principles are utilized in set-pair analysis and fuzzy logic theory [Zhou 2010] and in computational programs such as Progrid [Bowman 2005]. These methods also utilize risk matrices to represent and subjectively evaluate the risk associated with complex systems. Using fuzzy logic factors, uncertainty in a complex system may be integrated into risk estimations. In Progrid, language ladders are developed to convert physical observations to numerical equivalents and to quantify risk and performance [Bowman 2005]. In general, such methods use language indicators to assign quantitative equivalents to risk in order to provide a means of ranking, weighing and comparing attributes of complex systems within a contrived scale to value or measure the perceived risk associated with a fire event [Bowman 2005]. When applied appropriately, these methods are fairly flexible in analyzing generic situations and can effectively identify and account for uncertainty in those analyses.

Economic principles are also frequently utilized in the quantification of consequences and loss due to fire. These include the application of cost-benefit analysis, decision analysis and utility theory, described in detail by Ramachandran [Ramachandran 1998]. The assignment of monetary equivalents to quantify the non-monetary costs and consequences of accident scenarios, such as injury or death, is frequently relied on in the insurance industry and within the legal system in cost-benefit analyses. This practice includes assigning a monetary value to a human life based on various factors such as gross output, life insurance policies, previous court awards and 'willingness to pay' theories [Ramachandran & Hall 2008]. The practice of assigning a cost to human fatality or injury, while it may be computationally effective within the context of a fire risk analysis method, is controversial and difficult to defend such that all stakeholders are satisfied.

Utility theory offers an alternative to monetary equivalents by using decision-making rules to account for the uncertainty associated with outcomes of fire events. Based in economics, this theory considers the preferences of people when making decisions under uncertainty as well as their aversion to risk [Ramachandran 1998]. The utility theory is based on the principle of maximizing expected utility as the basis for a decision. This approach describes the consequences of an event in terms of the preference for an outcome and its probability. Utility represents the preference for uncertain outcomes in relation to each other, in other words, how good or bad they are perceived to be [Johansson 2003]. This method allows the consequences from fire events to be compared directly to one another. Expected utility represents the expected value of a function of event probability and outcome utility and can be used to consider non-linear aspects of event consequences such as risk aversion [Hall & Sekizawa 1991]. In isolation, the utility theory does not represent a fire risk analysis technique; however, if combined with other risk assessment techniques then applications in fire risk analysis are available, as is represented by the Super Soft Decision Theory (SSDT).

The SSDT methodology has been developed to address fire protection engineering problems that have high epistemic uncertainty by utilizing the principles of maximization of expected utility, Bayesian decision theory and extended decision analysis [Johansson & Malmñas 2004]. SSDT utilizes probabilistic evaluations that are derived from event trees, a semi-quantitative fire risk assessment technique as described in the previous section. Utilizing extended decision analysis, SSDT forms user-described probability distributions to evaluate design options instead of precise event likelihood values. The SSDT method relies on maximum, minimum and most likely expected utility values to compare design performance. The combination of these components in SSDT permits the robustness of design decisions to be considered since a range of expected performance is attributed to each design alternative. The influence on the estimated design performance of a change in event likelihood and consequence utility can also be measured.

The user-described probability distributions derived are based on relatively vague assessments of event likelihood and consequence utility [Johansson & Malmñas 2004]. To conduct SSDT, a decision

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frame must be established to assign event likelihood and consequence utility values to convert qualitative

statements into their respective quantitative values [Johansson & Malmñas 2004]. A specific

methodology for this process is not prescribed for SSDT applications; and, numerous methods of

developing a decision frame are available to designers, including simplistic group consensus surveying

tools through complex mathematical relations based in economic theory. A limitation of the SSDT

method is that the decision frame development process may be time consuming and complicated, and that

it may be difficult to obtain group consensus in practical design scenarios depending on the type of

method used. However, since SSDT relies on a range of probabilities associated with specific events there

is an opportunity to represent multiple values proposed by different stakeholders for a single variable

which facilitates group consensus.

The SSDT method does not quantify how much better or worse the performance of a design

alternative is in comparison to another; instead it identifies that one is likely better or that one is likely

worse. Within the fire protection engineering industry, however, it would be considered extremely

difficult to quantify with great certainty the performance of a design solution under all possible fire

scenarios. As such, SSDT reduces an alternative solution design challenge to manageable and meaningful

design performance comparisons.

In the context of the fire protection design industry, the SSDT method is limited to quantifying the

expected performance of a pre-conceived design for direct comparison. The method directs users to a

decision regarding the most preferable design option and facilitates sensitivity and robustness evaluation.

The method does not direct the fire protection system design development process nor does it describe the

performance of a design approach.

2.3   Analysis

The investigation described in Section 2.2 identifies numerous qualitative, semi-quantitative and

quantitative fire risk and hazard assessment tools available to designers for rationalizing, developing and

evaluating alternative solution designs. Each method, and type of method, has inherent weaknesses and

strengths. In general, qualitative methods, such as the FSCT, are useful in describing and identifying the types of hazards which could occur. Semi-quantitative methods, such as event trees, can be used to describe the risk associated with proposed designs in terms of sequential quantified events and their qualitative outcomes. Quantitative tools available in industry include both objective and subjective tools, the latter being considered the more flexible in terms of application across a range of performance-based design challenges. These tools assist designers in ascribing quantitative values to evaluate risks and provide methods for making decisions under uncertainty, such as SSDT.

The evaluation conducted has demonstrated that a one-size-fits-all fire risk analysis technique is not available for alternative solution designs and performance-based design comparisons; however, numerous valuable tools are available to assist designers in each of the three stages of the fire risk analysis process. As described by van Duijne and coworkers, a comprehensive fire risk analysis tool is comprised of three distinct phases: hazard/risk identification, risk estimation and risk evaluation [van Duijne et al. 2008]. Utilizing the investigation of qualitative, semi-quantitative and quantitative tools available, a fire risk analysis methodology may be developed to support performance-based alternative solutions by incorporating components of each of the three types of tools. Such a method would combine existing techniques of fire risk and hazard assessment to capitalize on the strengths of the individual techniques while compensating for weaknesses.

It is proposed in this thesis to combine existing methods of fire risk and hazard assessment into a quantitative design decision methodology for fire risk analysis that will aid both designers and authorities in developing and evaluating alternative solutions to prescriptive code requirements. To be classified as a fire risk analysis method, the new tool must provide a quantitative evaluation of both fire scenario likelihood and consequence and must consider all significant fire events when evaluating overall risk. Based on the evaluation in Section 2.2 and the three-phase criteria described by van Duijne and coworkers, the new quantitative design decision methodology should combine qualitative, semi-quantitative and quantitative tools to capitalize on the strengths and to compensate for the weaknesses inherent to each technique [van Duijne et al. 2008]. Furthermore, as specified in the guidance documents

described in Section 2.1, stakeholder input, effective documentation and uncertainty evaluations must be represented in the method [SFPE 2006, NFPA 551 2010].

2.4   Conclusions

A single fire risk analysis method is not available that can address the breadth of performance-based design challenges identified in Chapter 1 and that can provide a quantitative design comparison between alternative solutions and prescriptive-based designs. Therefore, in this thesis, it is proposed that a new fire risk analysis method be developed to achieve the following criteria:

- Represent performance of comparison designs in a manner which addresses the contributions of all significant fire events to overall fire risks.
- Provide quantitative evaluation of consequence and likelihood associated with design performance.
- Account for uncertainty associated with design outputs in relation to input parameters and assumptions to evaluate the robustness of design decisions.
- Involve stakeholders (owners and AHJ) and to achieve consensus regarding design priorities and risks throughout the design process.
- Combine qualitative, semi-quantitative and quantitative fire assessment methods.

The method must also consider the documentation requirements identified in Section 2.1 of this chapter. Furthermore, the method developed must also incorporate the objectives described in Chapter 1 as follows:

- Utilize prescriptive-based design as a benchmark to develop alternative design options.
- Utilize prediction and evaluation techniques that are relatively simple to apply and understand, to bridge any gaps in the experience between authorities and the designers.
- Accommodate typical project timelines and resources by using fire risk and hazard analysis techniques that are not onerous in terms of time or monetary resources.
- Provide uncertainty analysis and robustness evaluation for each alternative solution.

The above method criteria form the basis for the development of a new fire risk analysis method. Considering that the objectives pertaining to uncertainty and design decision robustness may be combined as 'Account for uncertainty associated with design outputs in relation to input parameters and

assumptions to evaluate the robustness of design decisions'; then a list of eight objectives for the new method has been established.

2.5   Summary

Fire risk analysis methods pertaining to the development of performance-based alternative solutions are numerous and diverse. The evaluation conducted in this chapter has determined that no one method is best-suited to address the design challenge identified in Chapter 1 of this thesis. Utilizing guidance documents and, in consideration of a review of qualitative, semi-quantitative and quantitative techniques, the components of a fire risk analysis method have been identified. Utilizing the conclusions of Chapter 1 and the findings described herein, eight objectives have been defined to guide the development of a new quantitative design decision methodology. It is intended that the new tool incorporate available risk and hazard evaluation and assessment techniques to build a comprehensive fire risk analysis method.

Chapter 3

QUANTITATIVE DESIGN DECISION METHOD

This chapter provides a description of the Quantitative Design Decision (QDD) method, a new fire risk analysis method that has been developed in this research work. The intended application and limitations of the method, when utilized to evaluate alternative solutions to designs specified via prescriptive code requirements, is described in this chapter. The QDD method consists of three stages: Design Stage, Fire Scenario Stage and Decision Evaluation Stage. Each stage is first described, then the function and operation of each stage are outlined, and finally the application of the new QDD method within a performance-based design context is discussed. The design process stages in which the method is to be utilized and the team of stakeholders required to conduct the method are also defined. A case study is provided in Chapter 4 to demonstrate the applicability of the new QDD method to a typical design challenge.

3.1 Application of Method

The QDD method has been developed utilizing the evaluation of fire risk and hazard assessment and analysis techniques and guidance documents considered in Chapter 2, as well as taking into consideration

the challenges recognized within the performance-based building regulatory system in Canada outlined in

Chapter 1. The eight objectives established to direct the development of the method, as summarized at the

end of Chapter 2, are:

1. Utilize prescriptive-based design as a benchmark to develop alternative design options.
2. Utilize prediction and evaluation techniques that are relatively simple to apply and understand, to bridge any gaps in the experience between authorities and the designers.
3. Accommodate typical project timelines and resources by using fire risk and hazard analysis techniques that are not onerous in terms of time or monetary resources.
4. Represent performance of comparison designs in a manner which addresses the contributions of all significant fire events to overall fire risks.
5. Provide quantitative evaluation of consequence and likelihood associated with design performance.
6. Account for uncertainty associated with design outputs in relation to input parameters and assumptions to evaluate the robustness of design decisions.
7. Involve stakeholders (owners and AHJ) and to achieve consensus regarding design priorities and risks throughout the design process.
8. Combine qualitative, semi-quantitative and quantitative fire assessment methods.

The purpose of the new method is to demonstrate quantitatively and with reliability indices the

performance of an alternative solution through comparisons with a prescriptive-based design and the use

of fire science principles in combination with stakeholder input. As such, the method is intended to

supplement the development of an alternative solution by a fire protection engineer and to assist in the

selection of quantitative and rationalized performance-based design decisions.

The QDD method is intended for use by fire protection engineers (designers) who are familiar with

fire science principles, risk assessment methods and the alternative solution approvals framework of the

region in which the building is, or will be, located. As such, the method must be applied by persons that

understand the intended operation of the subject space and its associated life safety or fire hazards. An

understanding of fire science is required to categorize protection and prevention approaches with

accuracy and to identify realistic fire scenarios and events. It is expected that the techniques utilized in the

method will be familiar to the designer. For example, it is expected that the designer is familiar with

common risk evaluation and analysis techniques and fire protection principles, such as event trees for

example. It is expected that the designer will understand the intended use and pitfalls of such methods and apply them in a thoughtful and thorough manner. Therefore, the focus of this thesis is not on teaching designers how to use the underlying fire protection design methods, but is instead focused on directing professionals with respect to how to use certain tools to achieve a desired outcome in the context of a performance-based design.

While the primary user of the QDD method is intended to be the designer, a team of stakeholders must be assembled to apply each stage of the process. The primary stakeholders include: the owner(s) and/or operator(s) (owner) of the building or facility requiring an alternative solution and the AHJ who have responsibility for approval or rejection of the alternative solution. Additional stakeholders may include the insurer of a facility, staff of a facility, public interest groups, system manufacturers or designers, mechanical or electrical specialists, etc. These must be determined as the scope and breadth of the design dictates. For effective use of the method, all stakeholders must be educated in the function and intent of the fire risk analysis process and the QDD method to the extent necessary to ensure that their input and contributions are relevant and the decision outputs are understood. In addition, the stakeholders must be present throughout the application of the method to the development of the alternative solution.

In summary, the QDD method has been developed as a method by which to compare design alternatives having uncertain performance within commonly accepted fire scenarios. The method can be utilized to guide development of alternative solutions that necessitate quantitative performance comparisons to prescriptive code requirements. The method is intended to be applied by a team, led by a design engineer and involving a group of stakeholders, including at least the owner and the AHJ.

3.2   QDD Method Description

The QDD method is an organized decision-making process by which alternative building or system designs may be compared and evaluated. It involves of a series of fire hazard and risk assessment and analysis techniques that are applied in consideration of the fire protection and life safety objectives established by the stakeholders and the prescriptive code, as depicted in Figure 3.1 below. The QDD

method utilizes an iterative three-stage structure: Design Stage, Fire Scenario Stage and Decision Evaluation Stage. Following Figure 3.1, a brief overview of the method is provided, and each stage is described in detail in the subsequent subsections.
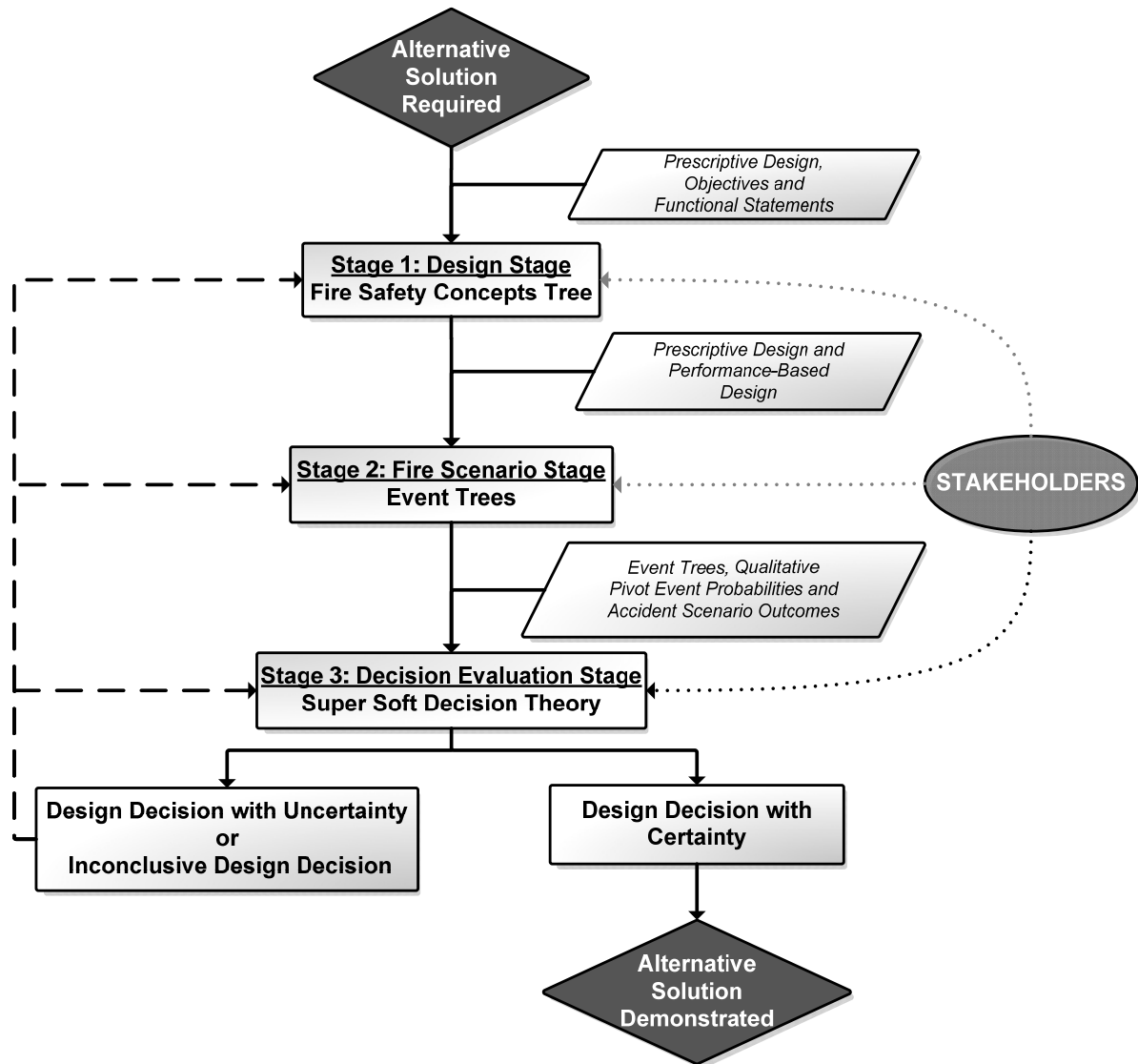
Figure 3.1 Quantitative Design Decision (QDD) Method Outlines

The Design Stage utilizes the Fire Safety Concepts Tree (FSCT) framework to illustrate qualitatively the prescriptive design requirements, including the related objectives and functional statements, applicable to a building or room. This process enables design shortcomings or incompatibilities to be identified and various approaches to alternative designs to be established. The NFPA 550 FSCT

framework facilitates systematic and comprehensive fire protection and prevention design. This first stage of QDD assists stakeholders in identifying design components that can be developed into performance-based alternative solutions; that are otherwise not easily compared, quantified or interchanged within the context of prescriptive design practice. The performance-based design generated from this stage requires further evaluation to assign quantitative performance measures with confidence.

The second stage of QDD is the Fire Scenario Stage. An event tree framework is used to establish the performance of the prescriptive-based design and the performance-based design alternative identified in Stage 1. Event trees provide a means to illustrate the sequence of events that could develop once an event that could initiate a fire or explosion takes place. The development of the event trees includes the selection of a common initiating event, the identification of qualitative system pivot event probability variables and the description of the accident scenario outcomes variables. The event trees are then utilized in Stage 3 to calculate the risks associated with the performance of each design under consideration.

Stage 3 of the QDD method is the Decision Evaluation Stage. This stage of the method applies Super Soft Decision Theory (SSDT) to the event trees developed in Stage 2 to compare quantitatively the established risk and uncertainty associated with each proposed design. Important components of this stage are the identification of uncertainty associated with the probability of pivot events and establishing the utility of each accident scenario outcome. Stage 3 relies on coordinated and systematic input from numerous stakeholders, including at a minimum, the designer, the owner and the AHJ. It is proposed that surveying methods such as a Delphi technique be applied to establish unknown variables with input from stakeholders.

The application of QDD method addresses the uncertainty typically encountered when quantifying performance of fire protection or prevention systems. In Stage 3, the application of SSDT enables the robustness of the decision to be evaluated. At the end of this stage, an alternative design is either justified through quantitative comparison with the prescriptive solution performance criteria (design decision with certainty) or is rejected (design decision with uncertainty or inconclusive design decision). Upon rejection, the iterative design process framework is adopted the variables established in Stage 3 are

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revisited and if necessary, Stage 1 or Stage 2, or both, are revisited to refine the performance-based design or to identify alternative design approaches.

3.2.1   Stage 1: Design Stage

The first stage of the QDD method is the Design Stage. This stage represents the first of the three phases of risk assessment proposed by van Duijne and coworkers by providing a comprehensive fire hazard identification or an inventory to describe what could go wrong in a building that could lead to the requirement to mitigate or control a fire [van Duijne et al. 2008]. In this stage, the objective is to identify potential design paths that are expected to achieve the same fire safety objectives as the benchmark defined by any existing prescriptive requirement(s) using a qualitative fire hazard assessment technique. Once identified, design alternatives can be evaluated to assist in the development of an alternative solution. This stage, therefore, must first provide a method through which the prescriptive design approach is described within a logical and systematic performance-based framework. From this framework, alternative design approaches which could best suit stakeholder values and achieve the objectives and functional requirements of the alternative solution must be identified. This first stage is used to identify design paths to be followed for the development of an alternative solution. This alternative solution will then be evaluated quantitatively using the subsequent stages in QDD.

When designing a complex room or space, a number of prescriptive requirements may be provided in a code or standard. They may specify a range of specific construction components such as wall assembly materials, fire detection systems, automatic suppression systems and allowed distances to protected exits, for example. The development of a design using the prescriptive code solution comes about from achieving compliance for each design component independently, rather than through a comprehensive analysis of the contribution of various design components in relation to the progression of fire risks (as described in Chapter 1). In this fashion, the prescriptive design approach does not often direct designers to alternative design options. In order to address the fact that prescriptive-based requirements are developed utilizing a different rationale from performance-based codes, while still

allowing prescriptive code solutions to form benchmarks for new designs, a flexible objective-based and comparative framework must be utilized.

The NFPA 550 FSCT framework is one such framework. It facilitates systematic and comprehensive comparisons of fire protection and prevention designs and can be used to illustrate a prescriptive design approach. In particular, the application of the FSCT, as described in NFPA 550 and provided in Appendix A, assists the designer in identifying alternative design options that achieve the same fire safety objectives as a given prescriptive design. The FSCT provides a logical, systems-based approach to achieving fire safety objectives in contrast to solely meeting prescriptive requirements as described in NFPA 550:

> "… *rather than considering each feature of fire safety separately, the FSCT examines all of them and demonstrates how they influence the achievement of fire safety goals and objectives*" [NFPA 550 2007].

In addition, since the objective and functional statements associated with prescriptive designs in the NBCC often parallel the FSCT fire safety objectives, prescriptive design approaches can be described and illustrated using the FSCT.

The FSCT is a logic tree developed to identify strategies for achieving fire safety objectives. As previously described in Section 2.2.1, this tree utilizes logic gates – AND and OR – to distinguish between design paths that accomplish particular fire safety objectives. When a prescriptive design is described using the FSCT, shortcomings are identified as situations where AND paths or OR paths are not sufficiently addressed. This is represented either by exclusion of a necessary path or by incomplete consideration of all requirements of an AND gate. Redundancies are identified where numerous OR paths are represented in the design. Multiple OR paths are frequently used to account for the fact that 100% reliability or 100% success of any one prevention or protection approach is often unrealistic in practice. Permitting a single OR path in a design presents a vulnerability in the approach, since if any feature of the system on that path fails, the entire path fails. As such, redundancies are often perceived to benefit a design. The extent to which redundancies are necessary and/or valuable to a group of stakeholders depends on the stakeholders' values as well as their perception of the cost versus performance relationship.

The following provides an example of fitting a prescriptive-based design requirement within the FSCT framework. As described in Chapter 1, NFCC Sentence 4.2.9.1.(1) specifies a two hr fire-resistance rating for fire separations between flammable liquids storage rooms and the remainder of a building [CCBFC 2010b]. The objectives and functional statements attributed to this sentence relate to limiting the spread of a fire originating within the room throughout the remainder of the building. In the FSCT, this prescriptive requirement would be represented on the '*Manage Fire Impact*' - '*Manage Fire*' - '*Control Fire by Construction*' branch which mandates that the movement of fire be controlled and that the structural stability of the construction be maintained via an AND gate, as identified in bold in the simplified FSCT in Figure 3.2 below, where (●) represents an AND gate and (+) represents an OR gate.

To control the movement of fire either containment or venting is permitted via an OR gate. The fire separation, by definition in the NBCC which is referenced by the NFCC, is an assembly constructed to prevent the passage of fire (i.e. contain the fire) [CCBFC 2010a]. In accordance with the NBCC, the fire-resistance rating of the assembly must be determined in accordance with CAN/ULC-S101, "Fire Endurance Tests of Building Construction and Materials", and its supporting construction generally must have an equivalent fire-resistance rating. As such, a fire separation defined by the NBCC achieves the '*Control Fire by Construction*' branch of the FSCT shown in Figure 3.2.

Alternatives to achieving compliance with the '*Control Fire by Construction*' branch of the FSCT include the redundant '*Suppress Fire*' and '*Control Combustion Process*' branches of the '*Manage Fire*' OR gate. Fire suppression may be achieved by manual or automatic suppression and the combustion reaction may be controlled by controlling the environment or the fuel. These redundant OR paths may be utilized to develop alternative solutions to the prescriptive requirement of NFCC Sentence 4.2.9.1.(1). Furthermore, the '*Manage Fire*' OR gate, is located within the '*Manage Fire Impact*' branch and is redundant to the '*Manage Exposed*' OR gate. In theory, alternative designs may also be derived from the '*Mange Exposed*' path to achieve the same fire safety objectives as would be satisfied by the prescriptive requirement. The branches of the '*Manage Exposed*' path have not been identified in Figure 3.2, for simplicity.
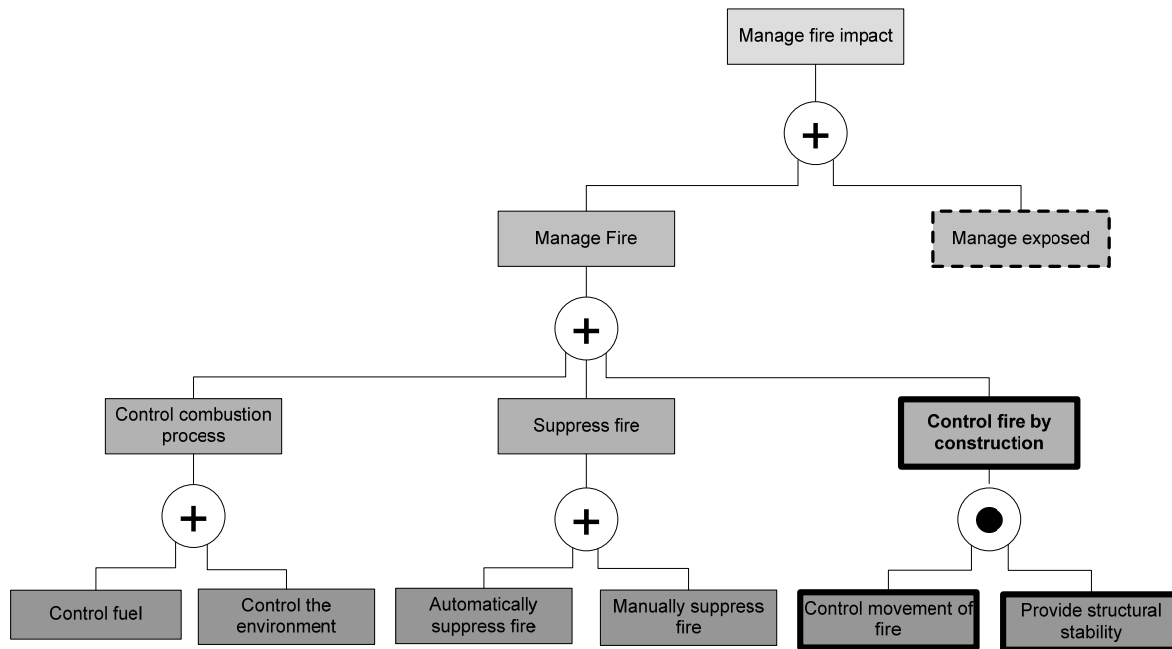
Figure 3.2 Simplified FSCT Demonstration of NFCC Sentence 4.2.9.1.(1)

As demonstrated above, once a prescriptive code solution is cast in the FSCT logic framework, a series of potential alternative design paths can be identified where a prescriptive requirement is located on an OR path and where an alternative OR path designs represents a feasible solution. At this point, the available alternative design paths to achieving a set of fire safety objectives associated with the prescriptive design are identified through the integration of the prescriptive design in the FSCT.

In the first stage of the QDD method, a designer can develop a performance-based design alternative based on the paths identified within the FSCT framework. QDD provides a means to identify how to select a design path, but is not intended to replace engineering methods of designing a solution. The methods used to develop and assess design path options identified in the FSCT framework are numerous and may include consideration of other recognized standards, results provided in fire testing or fire science literature, or the application of other design precedents recognized by the AHJ. The best design and analysis approaches will vary from case to case and must be evaluated by the stakeholders to assess the feasibility and relative effectiveness of implementation. For example, additional criteria such as

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physical restrictions, cost restrictions or liability acceptance might be considered in determining the final set of acceptable alternative design solutions.

It is important to acknowledge that there may be design alternatives in a particular path in the FSCT which cannot be achieved using current technology. For example, from the FSCT framework established above for NFCC Sentence 4.2.9.1.(1), the alternative of controlling the environment to achieve compliance within the '*Control Combustion Process*' branch, which is redundant to the '*Control Fire by Construction*' prescriptive-based branch, may not be practical in an occupied building. To achieve compliance with this branch, it would be necessary to modify the occupied environment such that combustion could not be sustained should a fire be ignited. Such an approach might be achieved through reducing the oxygen concentration of the environment. This condition represents not only a serious design challenge, but also a safety challenge for occupants. In these circumstances, either a different alternative design path must be specified using an OR gate, or the technology or method required to achieve the required fire safety design must be developed.

Alternative design paths, those which may be considered for alternative solution development, are identified at the conclusion of Stage 1 when all of the AND gates and all of the OR gates, as deemed necessary by the stakeholders, have been selected to achieve the same fire safety objectives as the prescriptive requirement. At this point, the fire safety design developed from these alternative design paths is qualitatively demonstrated to meet all necessary fire safety objectives via the FSCT framework. The QDD method may be concluded at this stage if a solution is readily available for immediate consideration and is already deemed acceptable to the AHJ. Such a solution would not require further demonstration of its performance and the design process would not indicate that that solution required the development of new technology. For all other cases the performance of the alternative solutions(s) developed from the alternative design paths identified in Stage 1 should be evaluated quantitatively. For this purpose, Stage 2 and Stage 3 of QDD are applied, as is described in the following sections.

3.2.2   Stage 2: Fire Scenario Stage

The second stage of the QDD method is the Fire Scenario Stage. This stage provides a framework

that can be used to evaluate the performance of a selected alternative design generated in Stage 1 by

considering all potential fire events with respect to their likelihood and consequences. To demonstrate the

performance of an alternative solution, the design alternative must be compared with the benchmark

prescriptive-based design. As such, an illustrative comparison of the performance of each design must be

developed such that the event probability and event consequence are identified. In Stage 2 of the QDD

method, a semi-quantitative fire hazard assessment framework is developed to assist in the quantification

of design performance through the representation of all significant fire events.

As a first step event trees having common initiating events are created to describe the performance of

the prescriptive-based design and the alternative designs generated in Stage 1 of QDD. The focus is on

generating significant fire events beginning with an initiating event and associated with each design under

comparison. These event trees then form the basis for quantitative analysis of the various alternative

design options in Stage 3. As described in Section 2.2.2, an event tree establishes a binary decision tree to

identify all possible outcomes resulting from an initiating event [Ericson 2005]. This stage is largely

executed by the designer who is familiar with the operation of the intended design, fire science principles

and fire protection engineering concepts.

The initiating event is an event that could result in a fire or explosion if unmitigated. It is, by

definition, the first significant deviation that could occur [Rausand & Høyland 2004]. From the initiating

event, the accident scenario includes the sequential failure or success of each barrier to fire that is

incorporated into the prescriptive-based or performance-based design. Fire barriers are identified within

the tree based on the sequence in which they would be activated and can include active fire protection

systems such as detection or suppression systems and passive fire protection systems such as fire

separations. Each accident scenario represents a specific sequence of barrier operations, with each

operation classified as either a success (operates as intended in design conception) or as a failure (does

not operate as intended in design conception). The operation of each barrier is identified as a pivotal event in the event tree. The probability of each sequential pivotal event determines the overall probability of the outcome for each accident scenario. Figure 2.1 in Chapter 2 illustrates a generic event tree.

The development of event trees related to the designs under consideration establishes the possible accident scenarios which may occur given a common initiating event. The initiating event must be selected to represent the type of conditions that the design is intending to mitigate. For example, if the design is developed to mitigate a fire or explosion resulting from an accumulation of flammable gas in a cylinder storage room, an initiating event would be the unintended release of flammable gas from the container(s). The initiating event is not the cause of the accident; instead it is a consequence of an accident that was anticipated in the design. It is associated with the first significant accident that could occur and lead to the fire or explosion that is to be mitigated. Whether the initiating event of flammable gas leaking from a container is a result of human error or improper maintenance, the sequential pivotal events in the event tree that are defined to represent the response of the designed system to that event are not necessarily altered. Thus the selection of the proper initiating event(s) will ensure that the prescriptive and alternative design event trees are representative of the system's intended operation and effective performance.

While the initiating event is associated with a single accident, common knowledge dictates that the type of accident will affect the scale of the consequences of that accident. As such, additional events that follow the initiating event and that precede the pivotal events related to any design barriers should also be incorporated into an event tree. These additional events qualify the accident and would include the size of the gas leak and whether the gas ignited in the above described scenario. These additional events function as pivotal events in that they have binary components in the event tree. However, rather than relating to the alternative design, these events describe the nature of the accident and ensure that the principal threats are considered. This is important when comparing design alternatives, since it is not the best-case scenario that is generally of greatest comparative value. Most often, it is the consequences of the worst

case scenarios that have the greatest impact on design decisions; therefore, such components must be incorporated into the event trees developed.

It is also important to identify all barriers specific to each design option when developing the event trees. The number of barriers or obstacles integrated into a design to mitigate fire determines the complexity and size of an event tree, and effectively, the number of pivotal events represented. The pivotal events developed for the alternative design event tree and the prescriptive design event tree will be different and should represent all the barrier components incorporated into each design, including both passive and active systems. Each barrier must be described by a negative statement (it does not operate as intended) and a positive statement (it does operate as intended). These barriers should not include human involvement or intervention, or fire department response, unless such components are specific to the designed system. Generally, fire department response to a fire event should be considered to be the same when comparing alternative design approaches and the prescriptive design, unless the inclusion of fire department response is critical to the control of a fire event in the prescriptive requirement.

The outcome of an accident scenario is reached when all of the barriers representing the design are exhausted. The accident scenario outcomes are described in terms of the desired fire safety objectives as identified in the FSCT and the performance-based requirements associated with a prescriptive design. For example, the outcomes of the above gas leak scenario would be related to a fire occurring or not occurring or an explosion occurring or not occurring. They should also represent the range, in terms of the order of magnitude, of this outcome (i.e. an uncontrolled explosion through to a controlled fire). If the initiating events have been correctly identified, the outcomes of the prescriptive design event tree and the alternative design event tree should be the same (i.e. fire and explosion); however, the magnitude of the outcomes will likely vary to some extent. Any outcomes should also reflect the shared objectives of the designs under consideration.

The focus of the event trees developed in this stage is on the generation of fire scenarios to describe the performance of the designed systems and is not on quantification of that design performance. In Stage 2, through the creation of the event trees, the pivot events (including additional events) and the accident

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scenario outcomes are identified and described qualitatively with respect to their common performance objectives. The quantification of event likelihood and consequence is conducted in Stage 3 utilizing stakeholder input.

3.2.3   Stage 3: Decision Evaluation Stage

The final stage of QDD is the Decision Evaluation Stage. In this stage, it is necessary to quantify the event scenarios established in Stage 2 to allow direct quantitative comparison of the performance of the prescriptive-based and performance-based designs. This stage engages the stakeholders to quantify each event probability and accident scenario outcome (consequence) subjectively in order to take into consideration their different values, such as an allowable extent of equipment damage, potential for loss of life or impact of business interruption. This may be accomplished using surveying techniques, but in the end the results must facilitate a decision to accept or reject the alternative solution design based on quantified performance comparison with the required prescriptive design. For this reason, this stage must also provide a means to measure and account for uncertainty in the design and design decision.

The QDD method, as presented here, incorporates a simplified Delphi technique as a means to survey stakeholders and uses SSDT as a means to quantify design performance and provide a reliable decision frame that accounts for performance uncertainty. SSDT is proposed as the basis for this analysis as it is considered well suited to problems in which decisions have a high degree of epistemic uncertainty, such as found in fire protection system design challenges [Johansson & Malmnäs 2006]. Using this theory with stakeholder input, the objective is to generate a robust design decision, with a level of certainty that suits all stakeholders, as to whether the alternative design solution will perform to provide at least an equivalent level of fire protection and life safety as the comparative prescriptive design solution.

To apply the SSDT methodology to the design challenge, particular information must be obtained from the stakeholders to generate the data necessary to compare the performance of each design option. The following provides guidance for the collection of data and the analysis required to apply the SSDT methodology in the framework of the proposed QDD method.

The development of the event trees in Stage 2 provides a qualitative description of the pivot events for each accident scenario, as well as the scenario outcomes. To compare design performance quantitatively, probability and consequence of each accident scenario must be established. The determination of the probability of pivot events represents a significant challenge within the fire protection industry since it is often difficult to establish event probabilities with a certainty sufficient to support a design decision. In this stage of QDD, the principles of SSDT are used to account for the uncertainty associated with the probability of successful component performance, or component reliability. Stakeholders establish three probability values for each pivot event in the event trees: maximum, minimum and most likely probability. The maximum probability and minimum probability associated with a pivot event are self-explanatory. The most likely probability is not necessarily the average probability, but is the probability expected to occur under most circumstances. This value is often best established based on the performance history of a component as identified through reliability data or via the manufacturer's specifications. The most likely probability is a variation on the average considered by Johansson and Malmnäs and by Chu and Sun [Johansson & Malmnäs 2006, Chu & Sun 2008]. These values are then utilized in SSDT to evaluate the maximum expected performance; the minimum expected performance; and, the most likely expected performance of each design under consideration.

With respect to pivot event probability, input from stakeholders having experience with the intended operation of a particular component and the field-performance of the component in practical installations is necessary. Data from fire safety literature, fire incident reports and other sources may be available to assist in the selection of values for the probability of operation for certain mechanical components; however, consideration of additional factors such as system maintenance or normal-down-time is also necessary. Additionally, while the owner may not have specific knowledge relating to the performance of a particular system component such as a sprinkler head, it is critical that the owner understand the impact that regular maintenance and inspection will have on its reliability, and therefore on the overall performance of the system. During this stage of the design process then, if values of probability are used that take into account regular maintenance and inspection routines, the owner must commit to a system of

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maintenance, testing and inspection for each design component. This will assist in the establishment of more realistic values for performance probability and system reliability.

In Stage 3, the stakeholders must also establish estimates for the consequences associated with each outcome using comparative evaluations of the perceived effects of an accident scenario ranked according to stakeholder values and priorities. The method of determining event consequence is challenging. The parameter may be based on specific fire performance data, as in the case study presented by Chu and Sun in which a calculation of the number of people at risk in each accident scenario is used to assign a utility value to that scenario [Chu & Sun 2008]. This approach requires that detailed fire scenario analysis be conducted and also prioritizes 'risk to people' as of primary value to the stakeholder. Alternatively, in their work, Johansson and Malmnäs consider the consequences based on anticipated monetary losses instead of the 'risk to people' [Johansson & Malmnäs 2004]. From these two examples, it is clear that the consequences established for each accident scenario, and their relative ranking in terms of magnitude, must consider all stakeholder priorities and concerns. Stakeholder principles that should be considered in establishing consequences include, but may not be limited to: injury/loss of life, cost of damage to equipment or property, cost of damage to public, cost of business interruption or downtime, time and cost associated with repair/replacement, impact on the environment and impact on corporate image. Stakeholders may choose to utilize a single principle or a weighted combination of principles to quantify the consequences of each outcome in a manner that best represents their interests.

The probabilities assigned to each pivot event and the level of consequence assigned to each outcome in the above analysis impacts the calculated values of expected utility, representing the expected value of risk associated with the design and in turn, the results of any design decisions. The identification of pivot event probability values and accident scenario utility relies on coordinated and systematic input from numerous stakeholders including the designer, the owner of the facility, the AHJ and perhaps the installers and/or manufacturer's of the designed components. The inclusion or exclusion of other stakeholders such as insurance representatives will be at the discretion of the designer and will be case-specific. If the basis for design decisions established during this stage of QDD cannot be validated by

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industry consensus, the resulting decisions cannot be justified. Consequently, the assignment of variables must be conducted in a systematic, rigorous and transparent manner to ensure that results are meaningful and valuable.

In Stage 3 a Delphi technique is proposed to survey stakeholders regarding event probability and consequence determination. As described in Section 2.1.3, the Delphi technique is a group survey and consensus seeking method that allows numerous experts or stakeholders to anonymously refine a group opinion. The value of the Delphi technique in the current context is that the survey method is iterative and utilizes controlled feedback from experts. The application of the technique within the QDD method would involve an expert panel (i.e. stakeholders). The QDD method promotes iterative re-evaluation to determine if modification of the design or changes to operational practices by the owner should be applied to achieve greater certainty in the final risk estimate.

In applying SSDT to the event trees generated in Stage 2, the probability and consequence values determined by the stakeholders are evaluated using the following equations and variable parameters. The expected value of risk or the expected utility, E(U,P), associated with a design is calculated as shown in Equation 3.1 as the summation of all of the possible risks attributed to a design event tree , where P_i is the probability of outcome i occurring, and U_i is the utility associated with the occurrence of outcome i. The utility attributed to an accident scenario outcome is considered independently of the probability of the pivot events and is different from expected utility which is associated with the overall value of risk associated with the design approach.

$$E(U, P) = \sum_{i=1}^{n}(P_i \cdot U_i) \tag{3.1}$$

The frequency of an accident scenario is established through the identification of pivot event probability by the stakeholders and often correlates to the reliability of a specific design component. The probability of successful component operation at each pivot event is represented by variable (p_x), and the probability of operational failure of the component is represented by the relationship (1-p_x), where 'x' represents each pivot event. P_i represents the product of pivot event probabilities associated with a single outcome.

In the QDD method, outcome utility values are assigned to a given outcome according to the following scale. A value of -1 represents the worst-case consequence and a value of 0 represents the best case outcome. Intermediate values are assigned through case specific analysis and stakeholder values. This approach is largely consistent with the case studies presented by Johansson and Malmnäs and by Chu and Sun [Johansson & Malmnäs 2006, Chu & Sun 2008]. In taking this approach to utility values, a design is considered more desirable as the expected value of risk decreases in magnitude. When evaluating the expected utility difference, described below, a positive result will demonstrate a preference for the alternative solution design.

The application of SSDT in QDD utilizes the evaluation of maximum, minimum and most likely pivot probabilities and outcome utility in order to establish expected overall utility differences between the prescriptive design and the alternative solution design. The values of the differences are then used to determine if the alternative design is at least as good as, if not better than, the prescriptive design. Expected overall utility difference in this application is associated with the difference in the expected value of risk attributed to each design. The difference in maximum, minimum and most likely expected overall utility are described in Equations 3.2, 3.3, and 3.4, where '1' represents the alternative design and '2' represents the prescriptive design variables.

$$Min = Min\left(E_1(U,P)\right) - Min\left(E_2(U,P)\right) \tag{3.2}$$

$$Max = Max\left(E_1(U,P)\right) - Max\left(E_2(U,P)\right) \tag{3.3}$$

$$ML = ML\left(E_1(U,P)\right) - ML\left(E_2(U,P)\right) \tag{3.4}$$

To calculate *Min*, in Equation 3.2 above the minimum probability values established are used to calculated the expected risk associated with each design approach. Similarly, the maximum probability value and most likely probability value are used to calculate *Max* and *ML*, respectively using Equations 3.5, 3.6 and 3.7.

$$Min\left(E(U,P)\right) = Min_{P,U}\left(\sum_{i=1}^{n}(P_i \cdot U_i)\right) \tag{3.5}$$

$$Max\left(E(U,P)\right) = Max_{P,U}\left(\sum_{i=1}^{n}(P_i \cdot U_i)\right) \tag{3.6}$$

$$ML\ (E(U,P) = ML_{P,U}\ (\textstyle\sum_{i=1}^{n}(P_i \cdot U_i)) \tag{3.7}$$

Therefore, in Stage 3 of QDD, the expected utility difference between the design alternatives and the

maximum, minimum and most likely expected utility values are calculated to quantify the risk associated

with the prescriptive-based and performance-based designs. These values are subjectively established by

the stakeholders, but directly attributed to the pivot event probabilities and the accident scenario

consequences.

3.2.4   Results and Analysis

The decision resulting from the application of SSDT in Stage 3 of the QDD method is either that the

alternative solution is suitable or that the design, and/or the estimated performance of its components,

requires re-evaluation based on a comparison of the predicted performance of the prescriptive-based and

the performance-based design solutions. As indicated in Section 3.2.3, the results of the expected utility

differences are determined using Equations 3.2 through 3.4 and values of maximum, minimum and most

likely expected risk values are determined using Equations 3.5 through 3.7. This section outlines how the

results of these calculations are applied in SSDT to establish if the alternative design under consideration

is at least as good as, if not better than, the corresponding prescriptive design.

In this stage of SSDT analysis, the above calculated results are reviewed considering two criteria:

their sign, either positive or negative; and, any overlap in their values. Depending on the results, one of

three decisions will be generated: (1) decision with certainty, (2) decision with uncertainty; or, (3)

inconclusive decision. Note that the terminology 'decision with certainty' is intended to reflect scenarios

in which the design decision in clear; however, it is not intended to infer that the performance of the

selected design has been demonstrated with 100% certainty. These three possibilities are illustrated

schematically in Figures 3.2, 3.3 and 3.4, respectively, with each illustration representing (a) a preference

for the alternative design, or (b) a preference for the prescriptive design, where possible. The symbols in

the figures represent the values of maximum and minimum values of expected risk value, with

magnitudes as given on the x-axis, for the alternative solution (squares) and the prescriptive design

(diamonds) respectively, while the line between them indicates the range. In these plots all values are negative. Only maximum and minimum expected utility are represented for general demonstration purposes.

(a)   (b)
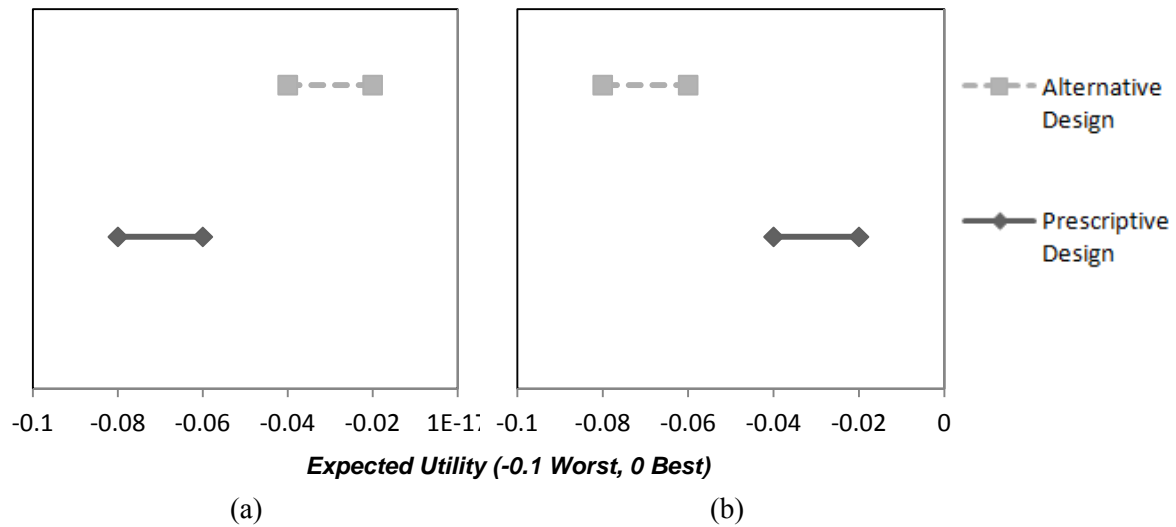
Figure 3.3 Generic Illustrations of Results: Design Decision with Certainty

(a)   (b)
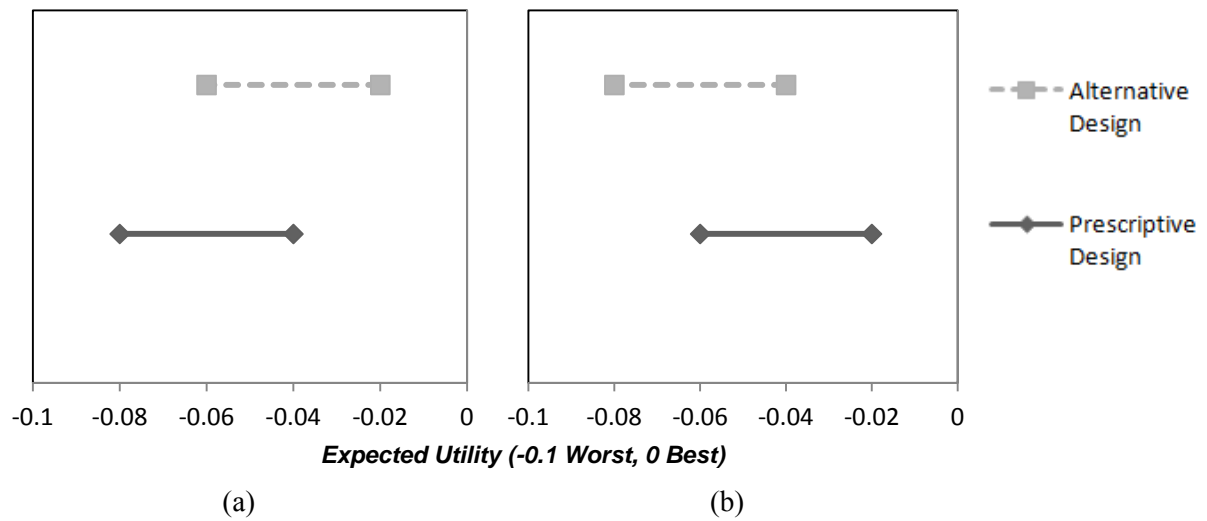
Figure 3.4 Generic Illustrations of Results: Design Decision with Uncertainty
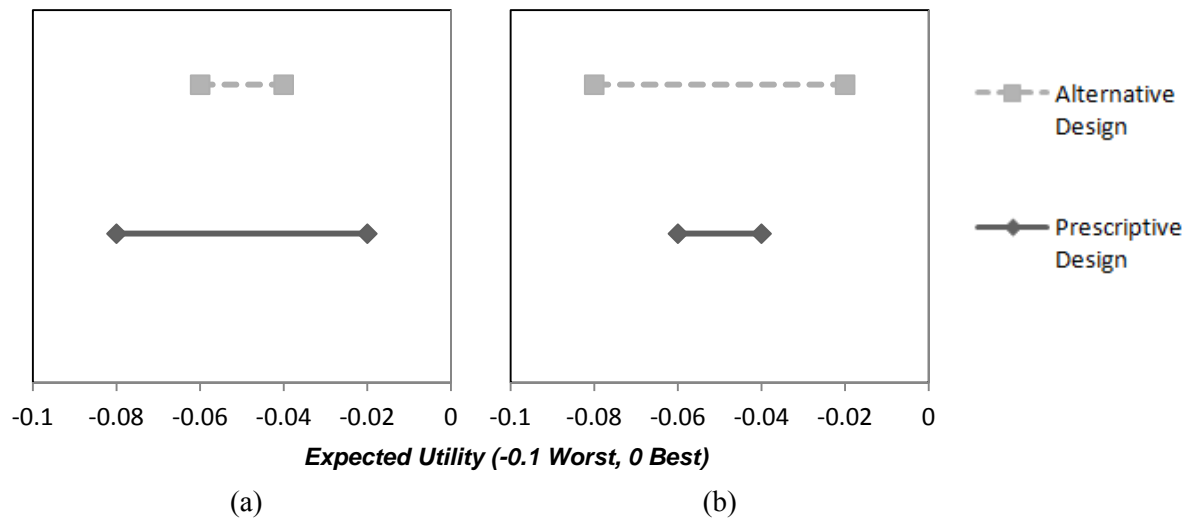
Figure 3.5 Generic Illustrations of Results: Inconclusive Design Decision

In conducting the analysis, the first step is to establish if a design decision can be made based on the results of Equations 3.2 through 3.4. The second step is to evaluate the robustness, or certainty, of the design decision. A design decision is established if all of the results of Equations 3.2 through 3.4 have the same sign (positive or negative). As a result of the approach taken to assigning utility, a design is considered more desirable as the magnitude of its expected risk value decreases. Therefore, if the all of the results of Equations 3.2 through 3.4 are negative, then the alternative solution is determined to be undesirable (Figures 3.3(b) and 3.4(b)). If the results are all positive, then the performance of the alternative solution is considered better than that of the prescriptive design (Figure 3.3.(a) and 3.4.(a)). Both circumstances described above generate a design decision; however, the robustness of the decision requires evaluation. The design decision is considered robust when there is no overlap in the range of values between the minimum and maximum expected risk value for the compared designs (Equations 3.5 through 3.7), as would be the case in Figures 3.3(a) and 3.3(b). The robustness of the decision is not certain if there is overlap, as depicted in Figures 3.4(a) and 3.4(b), since if both designs performed between their best and worst predicted risk, the best design solution is not immediately clear.

If the results of Equations 3.2 through 3.4 have different signs, the design decision is considered inconclusive, as depicted in Figures 3.5(a) and 3.5(b).Such results imply that there is not sufficient

sensitivity in the analysis to determine which design solution will perform better. In this respect, it is similar to the results of a decision with uncertainty (Figures 3.4(a) and 3.4(b)). In the event of an inconclusive or uncertain design decision, the designer can return to the values of the pivot event variables identified in Stage 3 to determine whether improvements in equipment inspection, testing and maintenance procedures or to different device selections will improve the performance of the alternative solution design approach. The sensitivity of the expected risk value to a specific pivot event probability assists in focusing on issues such as the cost-benefit of certain protection systems, system efficiency, system maintenance or other stakeholder values including overall cost or business interruption. By refining values of the maximum, minimum and most likely pivot event probabilities, the alternative solution performance may become comparable to that of the prescriptive design, generating a decision with certainty. In the event that the design decision remains inconclusive upon repeated iterations of Stage 3, the design may select to revisit and modify the design details established for the alternative solution in Stage 1 and Stage 2 of the QDD method.

It is not anticipated that outcome utility values determined by the stakeholders will be modified in progressive rounds of evaluation of the competing design solutions. The comfort of the stakeholders with the overall consequences of an accident scenario should not be affected by revising pivot event probabilities associated with the performance of design components. It is important that the Delphi technique, or a similar surveying method, be utilized in the re-evaluation rounds to ensure that consensus is reached in a reliable and informed manner. Detailed documentation of variables using qualitative statements and a clear description of the logic used in selection of their values during the first round of iterations of the method is critical as it assists in later evaluation of, and possible modifications to, any parameter values.

Through the above-described iterative process, QDD allows for the re-evaluation of pivot event probabilities and the overall design approach developed for the alternative solution when the robustness of the design decision is established to be inadequate or when the design decision established in the first assessment is uncertain. For the next, and any subsequent iterations of the process, the maximum,

minimum and most likely pivot event probabilities can be refined, the design approach can be modified and the decisions re-evaluated. On this basis, it is suggested that conservative values for pivot event probability and outcome utility be chosen for both designs in the first round of Stage 3. If necessary, these ranges can be reduced using stakeholder input in following evaluation rounds. This must be done, however, maintaining the principles and methods of justification used in the first iteration of the evaluations. As an example, an increase in a p_x value for an active system design component of the alternative solution may be justified by improving its inspection, monitoring, testing and maintenance program. If this approach is adopted, the owner must commit to the necessary improved practices, including self-regulation and maintenance of fire protection systems. In other situations, the same improvement might be derived when device components are replaced with alternatives that have better reliability or performance statistics. Understanding of the sensitivity of the expected risk value on the probability of a specific pivot event assists in focusing the design discussion on issues such as the cost-benefit of certain protection systems, system efficiency, system maintenance or other stakeholder values such as overall cost or business interruption.

The analysis described in this subsection is repeated until a design decision can be made with certainty or until it is apparent that a design decision cannot be made with certainty. In the event that the design decision remains inconclusive upon repeated iterations, one of two outcomes is possible. Either the sensitivity of the analysis will be considered insufficient for a justified conclusion to be drawn or the performance of the designs will be considered equivalent. It will be the responsibility of the AHJ to determine if the alternative solution may be considered equivalent in performance to that of the prescriptive requirements based on the results of the SSDT calculations. Under the codes, the performance of the alterative solution is only required to be demonstrated as equivalent to the prescriptive-based design. It is feasible that the outcome of QDD will demonstrate equivalent performance without establishing with confidence that the performance-based design is better than the prescriptive-based design.

It is noted that the above iterative process can also be conducted in the opposite fashion. If it is established that the alternative solution design exceeds the performance of the prescriptive-based design as depicted in Figure 3.3(a), the iterative analysis can be conducted to bring the design performance of the alternative closer to that of the prescriptive design. In this way, QDD can identify if design approaches exceed the minimum code requirements and to what extent, with respect to expected performance.

In summary, the results from Stage 3 of the proposed QDD method provide a framework under which to conduct an iterative and systematic evaluation of the expected performance of an alternative design versus a prescriptive design using SSDT. It is suggested that a Delphi technique be utilized to establish critical performance indicators including pivot event probability and outcome utility. The QDD method accounts for the uncertainty associated with the selection of variables by considering maximum, minimum and most likely pivot event probability and evaluating expected utility difference based on SSDT. The results of the analysis can be utilized to demonstrate whether an alternative design achieves at least an equivalent level of performance as the prescriptive design and also allows for iterative re-evaluation of the design criteria and analysis of the results, should that be necessary.

3.3   Summary

The QDD method has been developed in consideration of the eight objectives established in Chapter 2 of this thesis. Utilizing the FSCT, event trees and SSDT this method provides means of quantifying and comparing the performance of a prescriptive design and a performance-based design by way of three distinct stages: Design Stage, Fire Scenario Stage and Decision Evaluation Stage. The method also provides means to measure the uncertainty in various design parameters and to evaluate the robustness of the final design decision. The three-stage fire risk analysis method is demonstrated in Chapter 4 and an analysis of the method, with respect to the achievement of the eight objectives established, is provided in Chapter 5 of this thesis.

Chapter 4

CASE STUDY

DEMONSTRATION

This chapter provides a case study in which the QDD method, as described in Chapter 3, is applied

to a typical design challenge. The aim is to apply the method to identify potential approaches to an

alternative design solution and, once a design is selected, to quantify the uncertainty associated with the

performance of that design decision. The case study is a theoretical demonstration of the method, applied

to a design challenge in an existing industrial facility. Since the owner cannot achieve the prescriptive

requirements of the NFCC, an alternative solution must be developed and justified. Therefore, the

objective of this case study is to demonstrate the application of QDD to a typical compliance challenge as

well as to facilitate use of the QDD method by a variety of end users for future case studies and designs.

4.1   Case Study Details

The case study outlined in this Chapter is intended to demonstrate the application of QDD to a

practical design challenge. It is based on the development of an alternative solution for a hypothetical

non-compliance scenario such as one that might be encountered in the industrial sector. The case study

and its evaluation are not intended to reflect a specific facility, owner or the opinions of any referenced

stakeholders. However, as described, the case study is considered representative of a typical design challenge that the QDD method has been developed to address.

Based on a typical situation encountered in the industrial sector, the case study considers a facility in which Class IB flammable liquids (those having a flash point of less than 22.8ºC and a boiling point greater than 37.8 ºC as defined in the NFCC [CCBFC 2010b]) are dispensed in a room. The facility under evaluation, Industrial Facility ABC, is an existing establishment that has been operating in Canada for approximately 15 years and is regulated by the NFCC. The facility conducts manufacturing processes which rely on the use of Class IB flammable liquids. A component of the facility operations includes an existing flammable liquids dispensing room in which Class IB flammable liquids are manually blended and mixed in open containers. The room is located centrally within the building, adjacent to the manufacturing floor area. It is not located on the building perimeter. The dispensing room is located within a high-ceilinged (6 m) portion of the large production building, but is constructed to have a ceiling height that is approximately 2.5 m.

Industrial Facility ABC has recently been audited by the local fire department (AHJ). It was determined that the existing dispensing room does not comply with the requirements of the NFCC. Specifically the room does not comply with NFCC Sentence 4.2.9.5.(1). In accordance with this sentence, where Class IB flammable liquids are dispensed or are handled in open containers within a storage room, the room is required to be designed to prevent critical structural and mechanical damage in the event of an internal explosion [CCBFC 2010b]. The codes specify compliance with NFPA 68, "Standard on Explosion Protection by Deflagration Venting" (NFPA 68) [NFPA 68 2007], to prevent critical structural and mechanical damage [CCBFC 2010a].

Generally, compliance with NFPA 68 mandates that explosion relief panels be provided to release the pressure wave and fire ball created during a deflagration event and that the room be constructed of damage-limiting construction to withstand the pressure generated during the deflagration [NFPA 68 2007]. Explosion relief panels are required to release a deflagration outside of the building, and are generally intended to be located on an exterior wall. The existing dispensing room is not provided with

damage limiting construction or explosion relief panels, and therefore does not comply with NFPA 68 or NFCC Sentence 4.2.9.5.(1). Furthermore, installation of explosion panels is not practical in the dispensing room given that it is not located on an exterior wall.

The facility owner has been advised that the dispensing room must be brought into compliance (i.e. dispensing operations ceased) or that an engineer must be engaged to develop a compliance approach within 4 months time. If in 4 months time compliance has not been achieved or an engineer has not been engaged to develop a compliance approach, the owner will be subject to criminal charges under the Fire Protection and Prevention Act of Ontario [CCBFC 2010b].

The owner has evaluated methods of achieving compliance with the prescriptive requirements of the NFCC. Compliance methods considered included moving the dispensing operations within the building to a new room renovated to achieve compliance with the code, moving the dispensing operations to a new dedicated building designed to achieve compliance with the code, changing the operations to remove the dispensing component or replacing the materials dispensed with non-flammable liquids. The first two methods of compliance were determined to be cost-prohibitive and all would result in significant business interruption or reductions in product quality. The owner has established that achieving compliance with the prescriptive requirement of the NFCC, as described above, is not feasible. Therefore, the owner has chosen to engage an engineer (designer) to investigate alternative solution options to achieve compliance with the requirements of the NFCC. The investigation will establish if an alternative design can be developed that is suitable to meet business objectives, can be implemented within the physical restrictions of the existing facility and can achieve an equivalent performance to the prescriptive requirement of NFCC Sentence 4.2.9.5.(1).

4.2   Application of QDD Method

The QDD method is applied to the case study scenario to evaluate alternative design approaches to achieving compliance with NFCC Sentence 4.2.9.5.(1). This section provides a detailed description of the application of Stages 1 through 3 of QDD with respect to development of an alternative solution for the

owner of Industrial Facility ABC. The case study represents a feasibility investigation to establish if an

alternative solution can be developed to suit the owner's objectives and if its performance can be

demonstrated as achieving at least an equivalent level of fire protection and life safety performance as the

prescriptive design defined under NFCC. The prescriptive requirement of the NFCC is clearly

distinguished and the associated objectives and functional statements can be utilized. Further, the

prescriptive requirement relates to a single fire protection objective – explosion protection. As such, the

use of the FSCT in Stage 1 of the QDD method is well suited to this design challenge. The components of

a compliant prescriptive design are simple and limited in number (i.e. explosion relief panel and damage-

limiting construction) so are well suited to the Event Tree development in Stage 2 of QDD. Since non-

compliance was identified through an audit process, the AHJ is already involved in the project and their

involvement in the design process, specifically in the identification of variables in Stage 3 of the QDD

method, is feasible. For the purposes of the case study, as defined, the theoretical stakeholders include the

designer (engineer), the owner and the AHJ. The present investigation does not consider input from other

stakeholders, such as the insurers of Industrial Facility ABC. Such concerns were considered to fall

outside the scope of the present work, but could certainly be included in any expanded applications of the

QDD method to real fire safety design challenges.

4.2.1   Design Stage

Stage 1 of the QDD method involves using the FSCT to identify alternative design paths that can

potentially achieve the fire safety objectives of the prescriptive solution. This stage requires that the

objectives and functional statements of the prescriptive requirement be evaluated and that the prescriptive

design be defined within the FSCT framework. Upon integration of the design within the FSCT, possible

alternative design paths are identified and considered for development as an alternative solution(s).

The case, as outlined above, identifies that compliance with NFCC Sentence 4.2.9.5.(1) cannot be

achieved. For this reason, an alternative design approach is desired. NFCC Sentence 4.2.9.5.(1) mandates

compliance with NFPA 68 to prevent critical structural and mechanical damage resulting from an internal

explosion [CCBFC 2010b]. T he detailed objectives and functional statements associated with NFCC

Sentence 4.2.9.5.(1) are OS1.3-F02, OP1.3-F02 and OP3.1-F02 as follows:

"OS1.3-F02 – An objective of this Code is to limit the probability that as a result of:

- *activities related to the construction, use or demolition of the building or facility,*
- *the condition of specific elements of the building or facility*
- *the design or construction of specific elements of the facility related to certain hazards, or*
- *inadequate built-in protection measures for the current or intended use of the building,*

a person in or adjacent to the building or facility will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire addressed in this Code are those caused by the collapse of physical elements due to a fire or explosion. The function of the prescriptive design is to limit the severity and effects of a fire or explosion" [CCBFC 2010b].

"OP1.3-F02 – An objective of this Code is to limit the probability that as a result of

- *activities related to the construction, use or demolition of the building or facility,*
- *the condition of specific elements of the building or facility*
- *the design or construction of specific elements of the facility related to certain hazards, or*
- *inadequate built-in protection measures for the current or intended use of the building,*

the building or facility will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by the collapse of physical elements due to a fire or explosion. The function of the prescriptive design is to limit the severity and effects of a fire or explosion" [CCBFC 2010b].

"OP3.1-F02 – An objective of this Code is to limit the probability that as a result of

- *activities related to the construction, use or demolition of the building or facility,*
- *the condition of specific elements of the building or facility*
- *the design or construction of specific elements of the facility related to certain hazards, or*
- *inadequate built-in protection measures for the current or intended use of the building,*

adjacent buildings or facilities will be exposed to an unacceptable risk of damage due to fire. The risks of damage due to fire addressed in this Code are those caused by fire or explosion impacting areas beyond the building or facility of origin. The function of the prescriptive design is to limit the severity and effects of a fire or explosion" [CCBFC 2010b].

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It can be seen from these statements that the OS objectives are related to protecting people from risk of injury while the OP objectives are related to protection of the building and adjacent areas from risk of damage due to fire [CCBFC 2010b]. Functional statement F02 is related to limiting the severity and the effects of a fire or explosion [CCBFC 2010b].

Based on the objectives and functional statements associated with this prescriptive requirement, the design approach is integrated into the framework of the FSCT. While the focus of the investigation is on a specific requirement applicable to the dispensing operations (i.e. explosion protection), it is necessary that the entire design for the room be considered during application of the FSCT to ensure that design deficiencies, redundancies and/or opportunities for alternative design development are identified and considered in the evaluation. As such, all design requirements necessary to achieve compliance with NFCC Subsection 4.2.9. for storage and dispensing rooms are considered in this stage of the analysis. Integration of the design requirements into the FSCT framework should be conducted by the designer, who is familiar with the facility, the various design components, the NFCC and FSCT principles. The completed illustration of FSCT to the present case is provided in Figure 4.1 and discussed further in the following paragraphs. Figure 4.1 is simplified to identify only those branches pertaining to the evaluation of the prescriptive design. The prescriptive requirement requiring an alternative solution is identified in bold bordered branches. The entire FSCT is provided in Appendix A for reference.
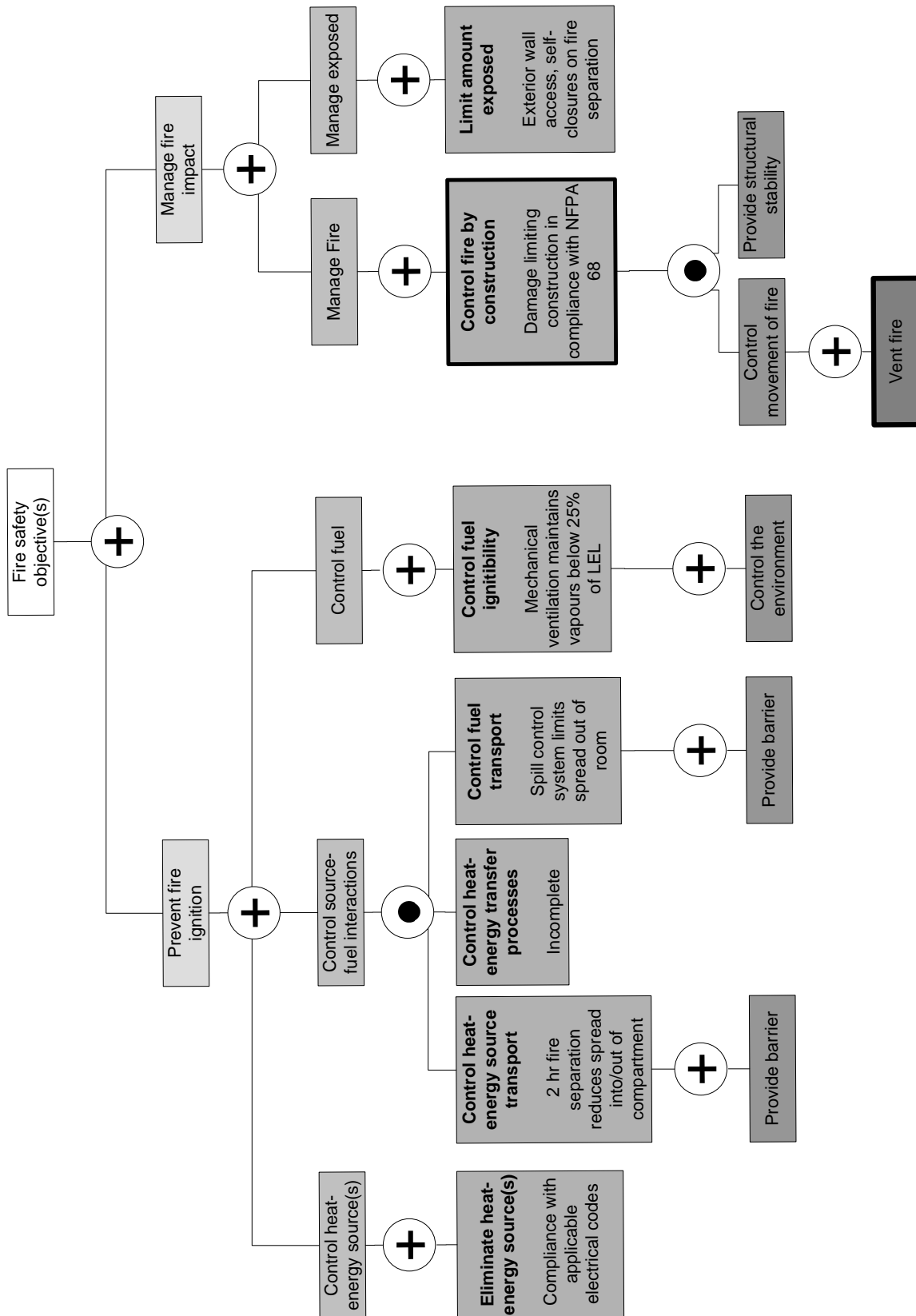
Figure 4.1 Fire Safety Concepts Tree Simplified for NFCC Subsection 4.2.9. Prescriptive Design

The design path in which the code-compliant explosion protection system fits within the FSCT framework is the '*Manage Fire Impact*' - '*Manage Fire*' - '*Control Fire by Construction*' branch. The damage-limiting construction and the explosion relief vents used in the compliant design achieve the objectives of this design path. The design path is consistent with the objectives and functional statements associated with the prescriptive requirements with respect to limiting the impact of a fire or explosion on the building occupants, structure and adjacencies, in particular impacts that could result from a collapse of physical building elements or from explosions impacting beyond their point of origin. Location of the compliant design solution within the '*Manage Fire*' branch of the FSCT implies that a fire or explosion does occur, but that measures are provided to protect the occupants and the building (and/or adjacent buildings) from the impacts of that fire or explosion. One important attribute of the prescribed explosion protection system is that staff located within the dispensing room at the time of an explosion will likely be injured or fatally wounded. This component of the performance of the explosion protection system is not considered consistent with OS1.3-F02 associated with the prescriptive requirement relating to the protection of persons. However, as identified in the '*Manage Fire Impact*' - '*Manage Exposed*' - '*Limit Amount Exposed*' branch of the FSCT, the explosion protection approach does provide protection for the majority of the building occupants and since few staff are required in a dispensing room it must be assumed that the probability of risk is considered suitable within the context of the NFCC.

Upon integration of the prescriptive design into the FSCT framework, alternative design paths are identified and evaluated for development of the final alternative solution. A systematic evaluation of each branch of the FSCT, starting at the prescriptive design branch location, considers different methods to achieve the desired objectives. In the present analysis, the direct alternatives (i.e. OR gate alternatives) within the '*Manage Fire*' branch include '*Control Combustion Process*' and '*Suppress Fire*' (Figure A.3 in Appendix A). It is not feasible to modify the properties of the fuel or the oxygen content within the dispensing room to comply with the '*Control Combustion Process*' branch. The operations in the dispensing room involve manual blending of flammable liquids. As such, the fuel cannot be removed and a low oxygen environment would not be appropriate for the personnel. Similarly, implementation of an

explosion suppression system that would comply with the '*Suppress Fire*' branch is not feasible. Due to the volume of the room and the time necessary for the system to respond to and suppress an explosion, such systems would be extremely costly and could involve greater demands on water supply than is available to the facility. While neither of the two options within the '*Manage Fire*' branch is desirable with respect to protection of staff within the dispensing room, they do not necessarily represent a different level of performance from the explosion vents mandated in the prescriptive design with respect to safety of personnel, as discussed above.

Having assessed the '*Manage Fire*' alternatives, the analysis proceeds to alternative options under the '*Manage Fire Impact*' branch (Figure A.1 in Appendix A). One alternative involves application of the '*Manage Exposed*' branch which is presented as an OR gate alternative to '*Mange Fire*'. Since significantly limiting or safeguarding exposures is not considered to be reasonable as a direct alternative to explosion protection, none of the alternatives within the '*Mange Fire Impact*' branch of the FSCT is considered an appropriate path to follow in development of the alternative design solution.

At this stage in the discussion, it should be noted that the FSCT identifies both prevention and protection approaches to achieving fire safety objectives. These are included through the use of an OR gate directly stemming from the fire safety objectives, though in reality most design approaches would provide both protection and prevention systems to varying degrees. Nonetheless, given that no direct alternative solution is found via the '*Manage Fire*' branch, alternatives within the '*Prevent Fire Ignition*' branch are next evaluated to determine possible alternative design paths and solutions.

Within the '*Prevent Fire Ignition*' branches of the FSCT, each of the OR/AND gate options of '*Control Heat-Energy Source(s)*', '*Control Source-Fuel Interactions*' or '*Control Fuel*' can be evaluated (Figure A.2 in Appendix A). Evaluation of the '*Control Heat-Energy Source(s)*'option suggests that even if all electrical devices were removed from the dispensing room, so as to remove potential ignition sources; a transient ignition source (e.g. cigarette) could still be introduced to the room by human error. As such, this branch is not considered completely reliable from a performance perspective. Provision of both a fire separation and spill containment within the dispensing room, are requirements under NFCC

Section 4.2.9. These design requirements already implemented in the dispensing room address two of the three AND gate branches of '*Control Source-Fuel Interactions'*. The fire separation satisfies '*Control Heat-Energy Source Transport*' by reducing the likelihood of fire propagation into the compartment, which might result in ignition of the flammable liquids. The spill containment system satisfies '*Control Fuel* Transport' by decreasing the possibility for a fluid spill to migrate out of the compartment and ignite via an unprotected ignition source. Since these design components are already required and cannot be significantly improved upon, they do not represent an alternative solution to the prescriptive code requirement. The '*Control Heat-Energy Transfer Process*' component of the '*Control Source-Fuel Interactions*' branch is not considered here, as it is not a common, nor viable, strategy for use in dispensing rooms [NFPA 550 2007].

The final design path available within the '*Prevent Fire Ignition*' branch is the '*Control Fuel*' branch. This involves either elimination of fuel, which is not feasible in the present situation, or control of fuel ignitability. Fuel ignitability may be controlled either through tailoring the fuel properties or controlling the environment. The flammable properties of the fuel (Class IB liquid) cannot be altered without changing the liquid in use. The owner has already identified that this is not a desirable option. Environmental control can be accomplished by reduction of the oxygen content in the room, an option already considered and discarded due to its impact on the personnel in the dispensing room. Alternately, the environment can be controlled through provision of continuous mechanical ventilation. The ventilation system would need to be designed to provide continuous supply and exhaust so as to capture and remove any flammable vapours released into the room during dispensing operations. It must be noted that the continuous mechanical ventilation system required under the NFCC prescriptive design is not designed to provide a level of protection equivalent to that necessary for an explosion prevention system. However, modifications and additions to the existing ventilation system that currently complies with the NFCC may create an explosion prevention system as an alternative design solution to the prescriptive-based explosion protection system.

To proceed with analysis of this alternative, the designer must consult existing guidelines for the design of explosion prevention systems. These are found in NFPA 69, "Standard on Explosion Prevention Systems" (NFPA 69) [NFPA 69 2008]. The life safety objectives of an explosion prevention system are to: prevent structural failure of the enclosure; to minimize injury to personnel in adjacent areas outside of the enclosure; and, to avoid injury to personnel [NFPA 69 2008]. The property protection objectives of NFPA 69 are: to limit damage of the protected enclosure; and, to avoid ignition of, or damage to, adjacent property [NFPA 69 2008]. These objectives are all well aligned with those under consideration in the present situation. NFPA 69 permits the use of either performance-based design or prescriptive-based design approaches and recognizes numerous means to prevent deflagration events. The design approach best suited to Industrial Facility ABC is to undertake a prescriptive design to reduce the concentration of fuel to below its flammability limit, as described in NFPA 69 Chapter 8 [NFPA 69 2008]. Such an explosion prevention system relies on maintaining the concentration of flammable vapours in the room at a level below 25% of the lowest Lower Explosive Limit (LEL) using a mechanical ventilation system to dilute the environment in the room through addition of fresh air. In this way, the prevention system continuously removes any flammable vapours that might accumulate within the room such that an explosive concentration is not developed and ignited. Such systems are typically designed utilizing combustible gas detector(s) interlocked with dedicated ventilation systems having high exhaust rates.

This explosion prevention approach, should it be adopted, inherently provides a level of protection to the occupants of the room since, when operating as designed, it is intended to prevent the occurrence of the explosion rather than to provide protection against the impacts of an explosion. Qualitatively at least, this approach provides life safety benefits to the owner even in comparison with the prescriptive-based design. It is also consistent with the owner's objectives, since the implementation of a detection and ventilation system is considerably less costly than any reconfiguration of the facility, equipment and/or operations and does not require that existing processes or practices be altered significantly.

Finally, the objectives of an explosion prevention system, as described in NFPA 69, are consistent with the objectives and functional statements associated with NFCC Sentence 4.2.9.5.(1) and the

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framework of the FSCT. As such, an explosion prevention system, designed according to NFPA 69, is proposed for further development and quantitative performance evaluation in Stages 2 and 3 of the QDD method. This alternative approach will be assessed in comparison to the NFCC prescriptive requirement for explosion venting designed in conformance with NFPA 68.

4.2.2   Fire Scenario Stage

Stage 2 of the QDD method involves the development of event trees to describe the performance of the prescriptive design requirement(s) for comparison with the performance of the alternative design path(s) generated in Stage 1. The event trees summarize the potential accident scenarios which could result from a common initiating event. In this stage, the components of each proposed design are identified and a common initiating event is selected. The aim is to develop event trees that are representative of all possible significant accident scenarios for each design. After identification of the scenarios, the pivot events and accident consequences are qualified for later quantification in Stage 3 of the QDD method. The outcome of Stage 2 is comprehensive and comparable event trees for the prescriptive design and any alternative design paths.

To develop the event trees both initiating event(s) and pivot event(s) must be identified for each design approach. To do so, it is also necessary to develop and evaluate the intended function of each system based on detailed design concepts. Event trees will be developed for the explosion protection design specified by NFCC Sentence 4.2.9.5.(1) and developed in accordance with NFPA 68, as well as for the proposed alternative explosion prevention design based on NFPA 69. The outcomes associated with each accident scenario are also qualified to establish a context in which to assess the anticipated performance. The final illustrated event trees for both of these design options are provided in Figure 4.2 later in this section and their development is discussed in more detail in the following paragraphs.

The prescriptive design is based on the provision of damage-limiting construction to contain a deflagration within the dispensing room and explosion-relief vents to control the release of any pressure wave and fire ball that could be generated in the event of an explosion in the dispensing room. These two

principle components of the designed system must operate properly to mitigate an explosion event. In contrast, the alternative solution design is based on an explosion prevention approach and relies on two different principle components from the prescriptive design. These are the provision of combustible gas detection to monitor the enclosure environment and to identify hazardous accumulations of flammable vapours and an interlocked mechanical ventilation system to remove the vapours from the enclosure before an explosive concentration develops. While not considered performance components of the alternative solution design, upon detection of hazardous accumulations of vapours in the dispensing room, the fire alarm system in the building will go into evacuation mode and visual and audible alarms will be activated in the dispensing room to alert occupants to the developing hazard. Each of the two design components associated with the prescriptive-based design and the alternative solution design are represented by separate pivot events in each respective design event tree shown in Figure 4.2 later in this section.

It is important that the designer consider the attributes of each proposed design approach and qualitatively compare the required function of each component of each design before the development of event trees, and throughout all stages of the design process. For example, the prescriptive design relies on passive fire protection systems while the alternative design relies entirely on active fire protection systems. Generally, passive systems are more reliable than active systems during normal upset conditions such as a power outage since the systems do not rely on electrical power to maintain their performance. As such, the designer would have to include a specification that emergency power be supplied to the components of the explosion prevention system to improve the overall system reliability in the event that power is lost, so as to be qualitatively comparable in performance to the prescriptive-based passive protection system. Since the provision of emergency power is an integral aspect of the design which directly influences the reliability of the design components, it is not identified as a pivot event. Instead consideration of the reliability of design components will be incorporated into the evaluation of variable values conducted in Stage3.

The initiating event selected for the event trees is a spill of flammable liquids within the dispensing room. Container sizes located in the dispensing room are considered to be small (under 25 L) or large (up to 170 L). Therefore, an additional pivot event is defined to identify the relative size of the spill as being either small or large. Addition of these types of components to an event tree assists in establishing the qualitative nature of each accident scenario and its possible outcome(s).

The event trees developed assume that if liquid is spilled in the dispensing room that an ignition source is available. Under this assumption, an explosion is considered to occur 100% of the time, unless flammable vapours are detected and removed before an explosive concentration is generated (i.e. performance-based design approach operating as intended). This approach considers that the explosion protection and prevention systems are designed to address the risk of an explosion instead of the risk associated with a flammable liquid pool fire. As such, only explosion outcomes are evaluated. Since the likelihood of a transient ignition source in the room is independent of the design approach adopted, the inclusion of this probability in the event tree analysis is considered redundant. Additionally, outcomes with 0% probability (i.e. no ignition) have been excluded for simplicity.

The event tree considers that if an explosion occurs, the explosion event must first be contained within the room (e.g. no open doors) and that the explosion venting system must then operate properly to vent the pressure wave and fireball. It is assumed that the dispensing room fire separations are maintained in accordance with the NFCC and that the explosion venting has been sized correctly, in accordance with NFPA 68, to safely release an explosion from the building.

The event tree developed for the alternative design solution assumes that if the mechanical ventilation system operates as intended, then it is sized sufficiently to remove a developing hazard before an explosive concentration can accumulate and encounter a transient ignition source. This assumption is practical since the ventilation system will be sized to address the largest reasonable spill generated from the largest container in the room, assuming that no liquid is drained or has leaked from the enclosure during the spill, and since the system will be served by emergency power.

The pivot events for the event trees associated with both designs are summarized in Table 4.1. The probability variables associated with each pivot event represent the operation of each system component. A statement is provided in the Table to describe each of the probability variables qualitatively.

Table 4.1 Pivot Event Probability Variables and Descriptions

p_x	Description
$p_{(Large)}$	Probability that a large container is involved in the flammable liquids spill.
$p_{(Enclosure)}$	Probability that the damage-limiting enclosure contains the deflagration within the enclosure.
$p_{(Relief)}$	Probability that explosion relief vents operate to release pressure wave and fire ball as designed.
$p_{(Detect)}$	Probability that combustible gas detection detects a developing accumulation of vapours as designed.
$p_{(Vent)}$	Probability that emergency ventilation system removes flammable vapours before an explosive concentration is generated.

Once the design approaches are represented as event trees, the outcome of each accident scenario should be evaluated and qualitatively described. The utility value for each outcome is assigned in Stage 3 of the QDD method. Through qualitatively describing each accident scenario outcome at this Stage in the method, the designer confirms that the identified outcomes are representative of those expected as they relate to the fire/explosion hazard associated with each design approach. The designer also confirms that each design approach functions to achieve the objectives and functional statements defined for the prescriptive requirement and that the performances are comparable. Qualitative descriptions of the accident scenario outcomes established for this design are listed in Table 4.2 below.

Table 4.2 Qualitative Descriptions of Accident Scenario Outcomes

Outcome Classification	Description
1	Uncontrolled explosion impacts beyond compartment
2	Uncontrolled explosion and early warning is provided to occupants
3	Uncontrolled explosion contained in compartment
4	Controlled explosion
5	No explosion

In Table 4.2, outcome classifications distinguish between explosion events where early warning is provided to occupants. Early warning reflects an explosion event occurring in the alternative solution design wherein the explosion prevention system has failed to exhaust flammable vapours and an explosion occurs; however, the activation of combustible gas detection has initiated audible and visual alarms and the building fire alarm system to evacuate occupants. Early warning systems are intended to limit the number of building occupants involved or injured in the event of an explosion. Outcome classifications also distinguish between explosions that impact beyond the compartment and those that are contained within the compartment. These conditions reflect the inherent safety of the damage limiting construction of the explosion protection design, which in the event of a minor failure (i.e. open door) will still provide much more protection to building occupants than a normal fire separation which is provided in the alternative solution design for the dispensing room.

It is noted that the subsequent consequences of the event tree outcomes in terms of potential spread of fire in the building or additional explosions are not considered in this evaluation. The prediction of subsequent fire or explosion events is complex and does not necessarily reflect directly on the performance of each designed system in terms of its objectives and functionality in the context of the codes.

Figure 4.2 below identifies the event trees for the prescriptive-based design and the alternative solution design as described in this section. The event trees identify the initiating event, the additional event that describes the accident scenario (i.e. spill size) and the pivot events for each design approach. The outcomes are listed using the qualitative outcome classifications identified in Table 4.2.
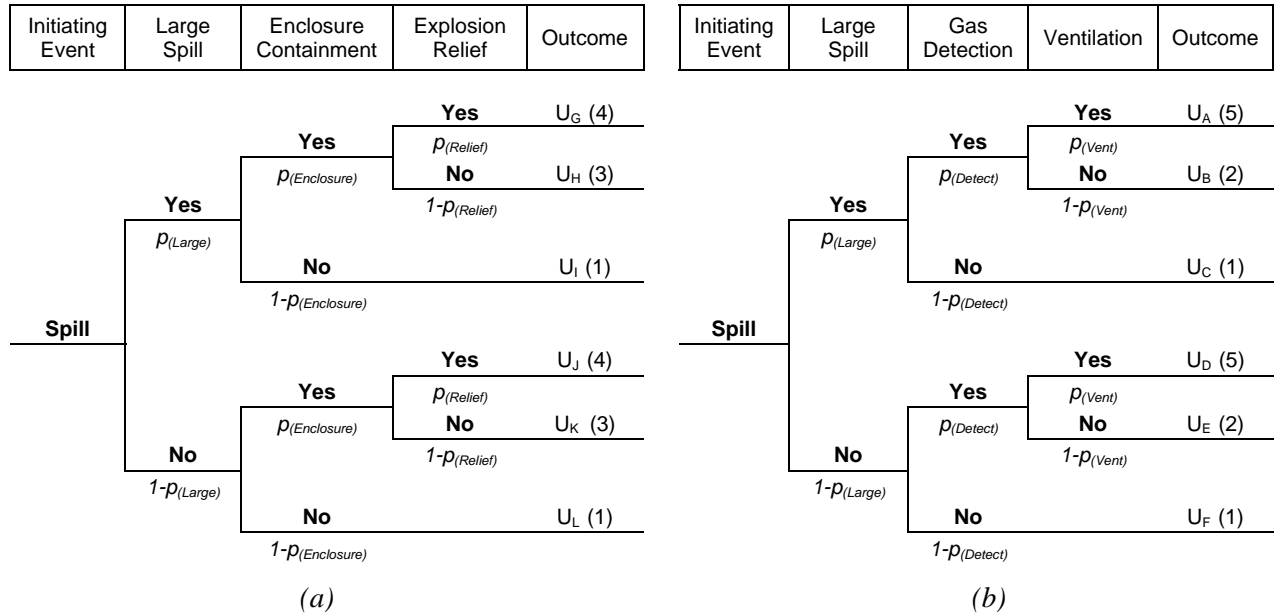
Figure 4.2 Event Trees for Prescriptive Design (a) and Alternative Solution Design (b)

The product of Stage 2 of the QDD method is the generation of the event trees (Figure 4.2), the identification of pivot event probability variables (Table 4.1) and the qualification of accident scenario outcomes (Table 4.2). These outputs form the basis for further development and quantification of the overall fire safety system design in Stage 3 of the analysis. The summary tables provide context for the event trees developed and, when properly formulated, outline the assumptions made in Stage 2 of the QDD method.

4.2.3   Decision Evaluation Stage

The third stage of the QDD method involves applying SSDT to the event trees generated in Stage 2 and comparing the expected utility associated with each proposed design to that found for the prescriptive design solution. The minimum, maximum and most likely pivot event probability variables and the outcome utility variables are quantified by the stakeholders as input for the application of SSDT. The outcome of Stage 3 is comparable expected risk value ranges for the prescriptive design and any alternative design(s). The robustness of the analysis is also considered when making a final design

decision as another metric by which to establish if the alternative design achieves a performance level at least equivalent to that of the prescriptive design or if the alternative design requires modification in order to meet the required level of performance.

To conduct SSDT, the maximum, minimum and most likely values of the variable p_x and U_i must be determined by a group of stakeholders. This process, spearheaded by the design engineer, involves coordinating the stakeholder group to ensure that all members understand the function of the QDD method and the intended operation and failure modes of each component of the design approaches under review. The stakeholders typically include the designer, owner and the AHJ. While it is recommended in Chapter 3 that a low bias, consensus seeking technique such as the Delphi technique be used; since the case study is limited to a theoretical demonstration of the application of QDD to an alternative design challenge, the Delphi technique was not applied.

At this point also, it should be emphasized that both the choice of variables to represent a design and their determined values are unique to the particular design scenario under evaluation. Therefore, the set of variables and values used here should not to be used in applications of the QDD method to other situations. In this respect, each application of the method will generate different probability and utility values based on the intended function of a proposed design and its application within a practical fire safety context. The selection of values for each variable is also dependent on the stakeholder group involved in a particular design analysis and their values in terms of life safety, property loss and business interruption. As such, results from one application of QDD cannot be directly compared to results from a different case study. On the other hand, the values determined within a given case study and therefore the results of SSDT as applied to that particular case are comparable since the context of variable selection, assignment of values and stakeholder input are consistent across all the design options considered in a single application of the QDD method.

The variables identified in the case study are listed in Table 4.1 and Table 4.2 and are illustrated in Figure 4.2 above. Values for pivot event probability and outcome utility variables, are discussed in the remainder of this section and are summarized in Tables 4.3 and 4.4, respectively.

Table 4.3 Pivot Event Probabilities Selected

Pivot Event Probability Variable	Description	Min	Most Likely	Max	Comments
$p_{(Large)}$	Probability that a large container is involved in the flammable liquids spill	0.30	0.30	0.30	Containers in the room are 30% large and 70% small.
$1 - p_{(Large)}$	Probability that a small container is involved in the flammable liquids spill	0.70	0.70	0.70	
$p_{(Detect)}$	Probability that a combustible gas detector detects a developing accumulation of vapours as designed.	0.70	0.89	0.95	The design includes an audible alarm to sound if detection device fails, system is served by emergency power and is inspected every 3 months.
$1 - p_{(Detect)}$	Probability that a combustible gas detector does not detect a developing accumulation of vapours as designed.	0.30	0.11	0.05	
$p_{(Vent)}$	Probability that emergency ventilation system removes flammable vapours before an explosive concentration is generated.	0.55	0.95	0.99	The design includes an audible alarm to sound if detection device fails, system is served by emergency power and is inspected every 3 months.
$1-p_{(Vent)}$	Probability that emergency ventilation system does not remove flammable vapours before an explosive concentration is generated.	0.45	0.05	0.01	
$p_{(Enclosure)}$	Probability that the damage-limiting enclosure contains the deflagration within the enclosure.	0.75	0.81	0.90	Annual inspection of fire separations in accordance with NFCC. Client notes habit of holding door open during use for convenience.
$1-p_{(Enclosure)}$	Probability that the damage-limiting enclosure does not contain the deflagration within the enclosure.	0.25	0.19	0.10	
$p_{(Relief)}$	Probability that explosion relief vents operate to release pressure wave and fire ball as designed.	0.50	0.95	0.99	Annual inspections of explosion vents and calibration in accordance with NFPA 68.
$1-p_{(Relief)}$	Probability that explosion relief vents do not operate to release pressure wave and fire ball as designed.	0.50	0.05	0.01	

To establish $p_{(Large)}$, a survey of the containers used in the dispensing room was considered. This survey indicated that 30% of the containers holding flammable materials are large, while 70% of them are small. Based on the assumptions that there was equal chance of a large or a small container being involved in an accident scenario, that the spilled container was full and that all of the liquid spilled, the maximum, minimum and most likely probabilities of a large container being involved in a flammable liquid spill was taken as equal to the percentage of large containers in the room (i.e. 30%). The probabilities of a small container being involved is therefore assigned the value of $(1 - 0.3)$ or 70% for each of these cases.

To establish the remaining pivot event probabilities, the reliability data for sprinkler, smoke and fire separations published by Bukowski and coworkers [Bukowski et al. 1999] was used as a starting. Due to limitations in the scope of literature data available, assumptions were made to apply the data within the context of the case study designs as described in this section. Where inspection, monitoring or regular practices were perceived to improve the reliability of benchmark industry components the minimum probability was increased by 5%. Conversely, where practices were perceived to reduce system performance, minimum probability was decreased by 5%.

To establish $p_{(Detect)}$, the design components of the alternative solution and industry reliability data was considered. Since data for specific types of fire safety system components was not readily available in literature, generic component reliability was utilized. Smoke detector data was substituted for combustible gas detection reliability since these systems each rely on environment monitoring of chemicals/particulate. As described by Bukowski and coworkers, smoke detectors have a maximum, most likely and minimum reliability of 95%, 89% and 65% respectively [Bukowski et al. 1999].

In accordance with NFPA 69, an audible alarm is required to sound if a combustible gas detector is not in operation (through electrical contact monitoring) [NFPA 69 2008]. This monitoring component of the system provides factor of certainty that detector will be in good working order during normal conditions. The combustible gas detectors are also served by emergency power as part of the design of the alternative solution, improving the overall reliability of the devices in the event of power loss. In

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accordance with NFPA 69, inspections of the detectors are required to be conducted at 3 month intervals [NFPA 69 2008]. These components improve the maximum reliability which may be attributed to the combustible gas detectors and exceeds the measures typically provided for smoke detectors. These factors, in combination with industry reliability data for smoke detectors, directed the selection of the minimum, maximum and most likely successful probability for the combustible gas detectors identified in Table 4.3.

To establish $p_{(Vent)}$, the design components of the alternative solution and industry reliability data was considered. Since data was not readily available to describe performance reliability of mechanical exhaust, generic sprinkler protection system data was used to guide the selection of $p_{(Vent)}$. Sprinkler systems were identified as having maximum, most likely and minimum reliability of 95%, 90% and 80% respectively [Bukowski et al. 1999]. Based on good practice, and as described in NFPA 69 and the NFCC, an audible alarm will sound if the emergency ventilation system components, such as a fan, are not in operation (through electrical contact monitoring). This monitoring component of the alternative solution provides greater certainty that the system will be in good working order during normal operating conditions. Additionally, the ventilation system is served by emergency power as part of the design of the alternative solution, improving the overall reliability of the devices in the event of power loss. In accordance with NFPA 69, inspections of the explosion prevention ventilation system are required to be conducted at 3 month intervals [NFPA 69 2008]. These components improve the maximum reliability which may be attributed to the ventilation system and exceeds the measures typically provided for sprinkler systems. These factors, in combination with industry reliability data for sprinkler systems, directed the selection of the minimum, maximum and most likely successful probability for the ventilation systems identified in Table 4.3.

To establish $p_{(Enclosure)}$, the design components of the prescriptive-design and industry reliability data was considered. Masonry construction reliability data was used to guide selection of enclosure reliability probability since damage limiting construction is typically reinforced concrete. Masonry construction, as described by Bukowski and coworkers, has a maximum and minimum reliability of 90% and 80%

respectively [Bukowski et al. 1999]. In conformance with the NFCC, fire separations including the damage limiting construction enclosure of the dispensing room, are required to be inspected and doors tested to ensure that self-closing devices and latches are operating correctly annually [CCBFC 2010b]. These inspections should identify if deficiencies in the enclosure exist that could compromise its performance in the event of an explosion. The owner identified a practice of propping doors open in the dispensing room to facilitate staff movement in the building despite the fact that this practice is prohibited by the NFCC. This practice, in addition to the annual inspection frequency and industry reliability data for masonry construction, directed the selection of the minimum, maximum and most likely successful probability for the damage limiting construction enclosure indentified in Table 4.3.

To establish $p_{(Relief)}$, the design components of the prescriptive-design and industry reliability data was considered. Since data was not readily available to describe performance reliability explosion venting systems, generic sprinkler protection system data was used to guide the selection of variables. Sprinkler systems were identified as having maximum, most likely and minimum reliability of 95%, 90% and 80% respectively [Bukowski et al. 1999]. In conformance with the NFPA 68, explosion relief vents are required to be inspected and calibrated annually to ensure that release latches are operating correctly [NFPA 68 2007]. These inspections should identify if deficiencies in the installation and maintenance of the explosion relief vent which could compromise the venting performance in the event of an explosion. Consideration of performance reliability also included examining the effect of one explosion vent panel failing to operate correctly, while the remaining panels operate to relieve an explosion. Generally, under such conditions an explosion would be vented; however, under less control. This, in combination with the inspection requirements of NFPA and industry reliability data for sprinkler systems, directed the selection of the minimum, maximum and most likely successful probability for the damage limiting construction enclosure identified in Table 4.3.

To establish utility values, the outcome classifications identified in Table 4.2 and in Figure 4.2 were considered. The best outcome (explosion successfully prevented) is assigned a utility value of 0 and the worst outcome (uncontrolled explosion occurs) is assigned a utility value of -1. The remaining outcomes

are assigned utility values based on the aversion to risk, as described in Table 4.4. Early warning of an explosion was prioritized above moderate control of an explosion event. While damage to the building would be greater in the event of an explosion prevention system failure, since damage limiting construction is not provided, the early warning to staff was seen as having a greater value than building protection since it would to reduce injuries or fatalities to building occupants. As such, an explosion occurring, regardless of the success of the protection system, was considered less desirable than an explosion being successfully prevented since an explosion would inevitably cause damage to the dispensing rooms, could injury staff and could lead to business interruption. A lower aversion to the risk associated with an explosion resulting from the spill of a small container was identified versus a large container, since it was considered that a smaller spill would produce less vapours and consequently, would result in a less powerful explosion event.

Table 4.4 Outcome Utility Selected

Outcome Variable	Description	Utility Value
U_A	Best scenario – explosion prevented.	0.00
U_B	Early warning of explosion permits occupants to exit prior to explosion. Explosion damage is significant to building and occupants since a large volume of vapour is released in spill. No enclosure protection provided.	-0.75
U_C	Worst scenario – explosion not prevented.	-1.00
U_D	Best scenario – explosion prevented.	0.00
U_E	Early warning of explosion hazard permits occupants to exit prior to explosion. Explosion damage is moderate to building and occupants since a small volume of vapour is released in spill. No enclosure protection provided.	-0.50
U_F	Worst scenario - explosion not prevented.	-1.00
U_G	Best scenario – explosion event is controlled. Outcome is less desirable than explosion prevention success since an explosion has occurred. Explosion damage is limited to the dispensing room.	-0.10
U_H	Explosion occurs – explosion vents fail to release explosion in a controlled fashion but enclosure provides a measure of explosion containment. Explosion damage is moderate to building and occupants. Explosion damage is moderate since a large volume of vapour is released in spill.	-0.90
U_I	Explosion occurs – enclosure fails to contain explosion. Explosion damage is significant to building and occupants.	-1.00
U_J	Best scenario – explosion event is controlled. Outcome is less desirable than explosion prevention success since an explosion has occurred. Explosion damage is limited to the dispensing room.	-0.10
U_K	Explosion occurs – explosion vents fail to release explosion in a controlled fashion but enclosure provides a measure of explosion containment. Explosion damage is minimal to building and occupants. Explosion damage is minimal since a small volume of vapour is released in spill.	-0.85
U_L	Explosion occurs – enclosure fails to contain explosion. Explosion damage is moderate to building and occupants.	-0.90

Tables 4.3 and 4.4 developed in Stage 3 of the QDD method form the basis for the application of SSDT. The summary tables quantify the variables for the event trees developed in Stage 2. The assumptions made in assigning quantitative parameters are justified utilizing industry reliability data, specific design monitoring and inspection requirements and stakeholder values.

4.2.4   Results and Analysis

Utilizing Equations 3.2 through 3.7, defined in Section 3.2.3, the pivot event probabilities and outcome utilities listed in Tables 4.3 and 4.4 are used to establish the expected maximum, minimum and most likely expected risk value for each design approach. From this, the maximum, minimum and most likely expected utility differences can also be established. The of the expected utility for each design approach are represented in Figure 4.3 and the respective values for the utility differences (Max, ML and Min) are listed in Table 4.5.
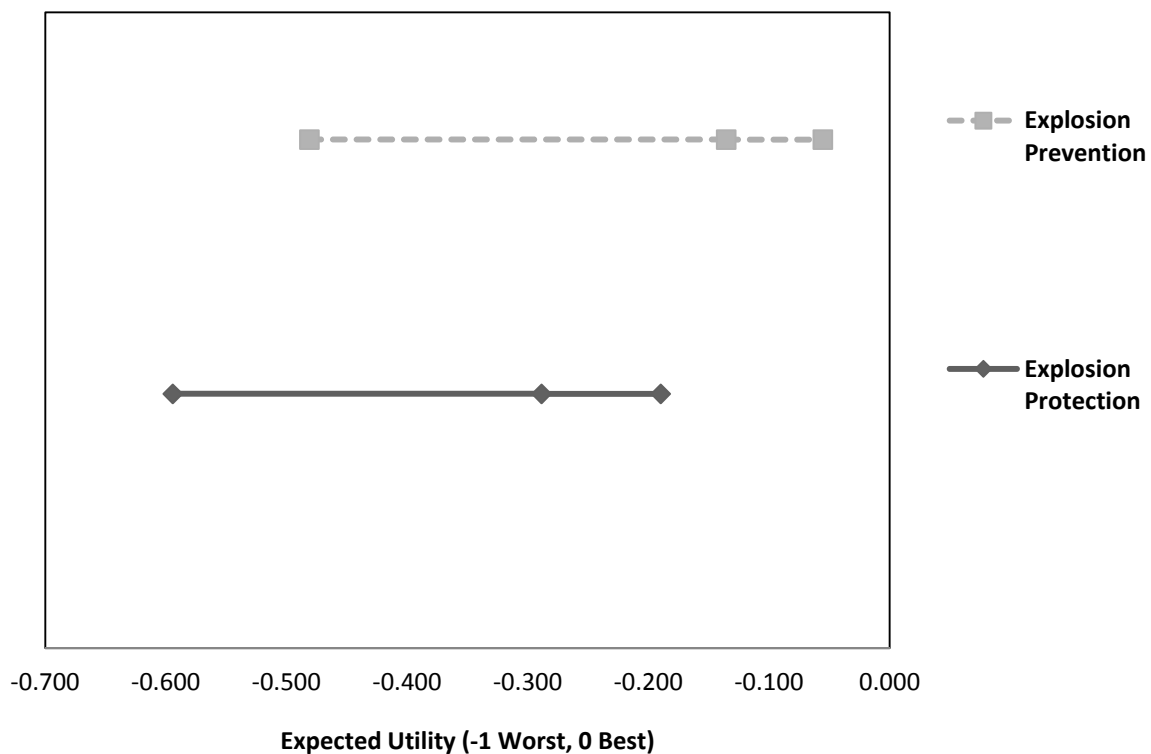
Figure 4.3 Expected Utility for Explosion Prevention Design and Explosion Protection Design Approaches

Table 4.5 Expected Utility Difference, (1) Explosion Prevention System (alternative solution), (2) Explosion Protection Design (prescriptive requirement)

Expected Utility Difference	
$Min(E_1(U,P))-Min(E_2(U,P))$	0.113
$ML(E_1(U,P))-ML(E_2(U,P))$	0.153
$Max(E_1(U,P))-Max(E_2(U,P))$	0.134

The application of SSDT to the alternative dispensing room fire safety system designs indicates that a design decision can be made, but with a degree of uncertainty. The values of the expected utility differences are all positive, indicating that the alternative design solution is generally considered to perform better than the prescriptive design, as identified in Table 4.5. However, uncertainty is associated with the results because of the overlap between the values of the expected utilities of the two designs, as illustrated in Figure 4.3. The results show that most of the time the alternative solution design is likely to perform at least as well as, or better than, the prescriptive design; however, there is a possibility that the prescriptive-based design operating at its best could out-perform the performance-based design operating at its worst.

At this stage in application of the QDD method to a real design situation, the stakeholders would again be brought together to evaluate the results. It would be acknowledged that there is uncertainty associated with the design decision and then a decision made as to whether further analysis or refinement of the design would be needed. In this case, a key discussion would focus around whether the performance of the alternative solution design was sufficiently demonstrated to achieve or exceed the performance of the prescriptive design solution. Since the most likely anticipated performance of the alternative design ($ML(E_1(U,P))$) exceeds the best performance of the prescriptive-based design ($Max(E_2(U,P))$), it might be considered that the alternative design was at least equivalent in achieving the objectives and functional statements associated with NFCC Sentence 4.2.9.5.(1) and that further design analysis was not necessary. At this stage, the alternative solution could be documented and submitted to the AHJ for review and would include an account of the data collected, summaries of stakeholder input

and the analysis process conducted. On the other hand, if the stakeholders concluded that the uncertainty inherent in making the design decision was too great, modifications to the pivot event probability variables and/or outcome utility would be necessary. In a practical application of the method, many avenues to resolve the uncertainty, for instance opportunities to increase scheduled maintenance practices, could be investigated. Furthermore, the data utilized to guide pivot event probability selection could be expanded.

4.3   Conclusions of Case Study

The application of QDD to the compliance challenge presented at Industrial Facility ABC resulted in the demonstration that the alternative solution, consisting of an explosion prevention system designed in compliance with NFPA 69 could be shown, with some uncertainty, to achieve at least an equivalent level of performance as the benchmark explosion protection solution designed in compliance with NFPA 68 as required in NFCC Sentence 4.2.9.5.(1). In Stage 1, the QDD method established that both design approaches achieved the same objective and functional statements as those established in the NFCC for the prescriptive requirement. In Stage 2, the performance of each design was illustrated using comparable event trees to identify the fire hazard(s) associated with a spill of flammable liquids and to qualify the possible significant outcome events. The performance of the design approaches were quantified and compared in Stage 3 using the principles of SSDT to establish the desired design solution. The robustness of the design decision was evaluated and could be deemed to satisfy the performance priorities described.

4.4   Summary

The case study considered the requirements for explosion protection in a flammable liquid dispensing room in Canada as regulated by the NFCC. The case study demonstrates the three-stage application of the QDD method developed in Chapter 3 as applied to a theoretical industry-based case study. The case study developed an alternative solution to NFCC Sentence 4.2.9.5.(1) utilizing NFPA 69 as the basis for an explosion prevention system. The alternative solution design and its performance were

quantitatively compared to the prescriptive design utilizing QDD which incorporates the FSCT, event trees and SSDT. The conclusion of the case study was that the alternative design was demonstrated to perform at least as well as the prescriptive design within a range of uncertainty. In closure, it should be re-iterated that the results of this case study, as presented, cannot be applied to similar cases due to the theoretical and demonstrative nature of the investigation described and the subjective stakeholder values represented in the above discussion.

Chapter 5

QDD Method Analysis

The QDD method, a new fire risk analysis method that has been developed in this research work, is outlined and described in Chapter 3 and a demonstrative case study is presented in Chapter 4 of this thesis. This chapter includes a discussion of the QDD method in consideration of the eight objectives established in Chapter 2 with the purpose of discerning its valuable attributes and its inherent limitations as a tool for use in assessing performance-based alternative designs. Through describing the limitations of the QDD method and identifying opportunities for its modification, applicability of this approach to practical design challenges is established.

5.1   Evaluation of QDD Method

In Chapter 2, eight objectives are established that formed the basis for the development of the QDD method as follows:

1. Utilize prescriptive-based design as a benchmark to develop alternative design options.
2. Utilize prediction and evaluation techniques that are relatively simple to apply and understand, to bridge any gaps in the experience between authorities and the designers.
3. Accommodate typical project timelines and resources by using fire risk and hazard analysis techniques that are not onerous in terms of time or monetary resources.
4. Represent performance of comparison designs in a manner which addresses the contributions of all significant fire events to overall fire risks.

5. Provide quantitative evaluation of consequence and likelihood associated with design performance.

6. Account for uncertainty associated with design outputs in relation to input parameters and assumptions to evaluate the robustness of design decisions.

7. Involve stakeholders (owners and AHJ) and to achieve consensus regarding design priorities and risks throughout the design process.

8. Combine qualitative, semi-quantitative and quantitative fire assessment methods.

To evaluate the success of the QDD method in achieving the above objectives, a simulated case study is described in Chapter 4. Utilizing observations and results from the case study, the performance of each stage of the QDD method and the method's overall performance as a comprehensive fire risk analysis technique is evaluated in this section. In addition to the eight objectives, the QDD method is also evaluated in consideration of the documentation requirements identified in Chapter 2.

5.1.1 Objective 1

The FSCT used in Stage 1 is recognized in NFPA 551 as a means to qualitatively analyze overall fire protection design and to identify gaps and areas of design redundancy. In the QDD method, this tool is utilized to assist in directing the development of the alternative solution to the prescriptive-based design benchmark. The FSCT proves to be a flexible tool by which to establish suitable design alternatives that will achieve the fire safety objectives of the prescriptive-design under consideration. The use of the FSCT in the QDD method achieves objective 1, to utilize prescriptive-based design as a benchmark to develop alternative design options.

Through application of the FSCT, alternative OR gate design paths that may be developed into alternative solutions are identified. In the Industrial Facility ABC case study, the objective and functional statements associated with the prescriptive design requirement for NFCC Sentence 4.2.9.5.(1) were established and the appropriate branch of the FSCT identified to represent the performance objectives of the code. A systematic evaluation of design alternatives was conducted; to identify which 'redundant' design alternatives on the FSCT could be developed for analysis in Stages 2 and 3 of the QDD method. It should be noted that, as was the situation in the case study, some of the alternative design options

available to the owner might be filtered before the FSCT is applied. For example in the case discussed, the option of relocating or removing the dispensing operations was considered prior to considering the pursuit of an alternative solution.

Certain stakeholder values, such as business continuity in the event of fire, are not often recognized in building codes or fire code performance objectives or functional statements. Instead the code statements have a primary focus on preserving life safety. QDD is vulnerable to similar limitation as there is no formal basis for the inclusion of these other objectives until Stage 3 of the method. This limitation of the codes supports the inclusion of the owner in Stage 1 of QDD to voice values or design priorities that may exceed the qualitative objectives and functional statements provided in the codes.

5.1.2 Objectives 2 and 3

Each stage of QDD has an illustrative component to simplify communication of the complex and technical fire safety challenges to all stakeholders. The methods used have been selected based on their function, but also in consideration of objectives 2 and 3 above – to utilize simple and easy-to understand, illustrative techniques that are not onerously demanding of time or money. The FSCT, event tree and SSDT methods utilized are technically valuable and provide relatively simplistic illustrations of complex fire safety objectives, possible design performance scenarios and quantitative performance comparisons. The case study demonstrates the integration of complex prescriptive requirements in the FSCT's comprehensive objective-based framework (see Figure 4.3). The sequential nature of event trees generated in the case study aligns with the sequential operation of both the explosion prevention and explosion protection designs being assessed. While not designed or intended for use as an illustrative tool, the results of SSDT are easily depicted in a graphical format which facilitates effective comparison of the performance-based and prescriptive-based designs.

The techniques utilized in QDD are all relatively cost and time effective. Application of the QDD method does not rely on extensive data generation or analysis, on fire modeling or on fire testing, all of which can be costly and time consuming approaches depending on the nature of the design challenge

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under consideration. The case study demonstrates an application of QDD within the time-frame expected for development and evaluation of a standard alternative design solution, which usually does not exceed one month for the design concept development portion. It is of note that the case study did not demonstrate the application of the Delphi technique for surveying of stakeholders in Stage 3, as such the time necessary to conduct such surveying methods has not been evaluated in detail.

5.1.3   Objective 4

The fourth objective, to represent performance of comparison designs to address the risk contribution of all significant fire events, is achieved in Stage 2 of the QDD method. The event trees generated in this stage describe the performance of each design under consideration in terms of accident scenarios and outcomes. Each event tree includes specific design components such as active and passive fire protection systems. The event tree model represents the significant fire events that could reasonably occur, given a selected initiating event. If the initiating events are appropriately selected, then during the performance analysis those event trees will facilitate consideration of the risk of all significant fires associated with the design. This method again provides a very flexible framework since it allows consideration of a diverse range of outcomes – significant consequences and minor consequences – to represent all potential performance sequences.

In the case study, event trees were generated to represent the prescriptive design approach, utilizing an NFPA 68 explosion protection design, and the alternative performance-based explosion prevention design based on NFPA 69. To develop the event trees the designer needed familiarity with each of the NFPA design standards and the intended function of each component of the designed systems. Through this knowledge, the event trees were generated by systematically representing component failure or success. The sequential contribution of the failure or success of each design component allowed all possible fire events, as generated from the selected initiating event, to be integrated into the analysis process.

5.1.4 Objectives 5 and 6

Stage 3 of the QDD method utilizes SSDT to achieve objectives 5 and 6 which relate to quantitative evaluation of consequence and likelihood, uncertainty analysis, and evaluation of design decision robustness. SSDT is applied to establish the expected utility for each design approach. The results of SSDT are evaluated to establish if a design decision can be made and furthermore to determine the uncertainty associated with the quantification of the performance of each design under study. In the QDD method simulated through the case study, quantitative pivot event probability and event utilities are established. The reliance on utility values instead of quantitative definition of particular consequences, such as monetary losses, allows for subjective quantification of accident scenario outcomes that are meaningful to everyone in the stakeholder group. Further, it avoids the challenges associated with objective quantification of likelihood and consequence of fire events that are described in Section 2.2.3. The QDD approach, then, provides an adaptable framework through which to addresses objective 5 above.

SSDT allows for the expected utility of each design approach to be compared within a range of maximum and minimum expected risk values, while also considering the most likely perceived risk level. This approach enables the uncertainty associated with selected values for each of the variables to be quantified and compared directly. With the information available from the SSDT results, a design decision may be determined either with certainty or with uncertainty. Through application of SSDT in Stage 3 of the case study, the alternative explosion prevention design solution was determined to perform at least as well as the explosion protection approach prescribed in the NFCC; however, there was uncertainty associated with the design decision due to the overlap in the expected utility calculated. It was described in the case study how this uncertainty could either lead to a second iteration of the QDD method or alternately to the conclusion that the performance of the explosion prevention alternative solution was sufficiently demonstrated to achieve or exceed the fire safety objectives associated with the prescriptive design.

5.1.5 Objective 7

The QDD method as currently outlined identifies the owner and AHJ as primary stakeholders and relies on their contributions throughout the application of the method. Input from these and other stakeholders is also specifically required in Stage 3. For this it is proposed to engage a surveying technique, such as the Delphi method, to obtain stakeholders input when establishing the critical variables and values of those variables required to conduct the comparison of quantitative performance of two competing design solutions. These functions directly address objective 7, to involve stakeholders (owners and AHJ) and to achieve consensus regarding design priorities and risks throughout the design process.

While inclusion of the AHJ is considered a necessity to achieve the objectives of the QDD method, there is also a need to maintain the roll of the AHJ as the independent reviewer of the alternative solution proposed. In preliminary discussions with the AHJ at the onset of a design project where the QDD method was to be applied, the limits of their involvement in, and influence on, the conclusions generated will need to be explicitly defined and documented. An alternative to inclusion of AHJ personnel in the survey component of the QDD method, if it is deemed necessary to restrict AHJ input in the design development of the alternative solution, would be to meet with the AHJ to present the variables and their values as chosen by the remaining stakeholders and to ask for AHJ consideration of these as the primary variables on which a design decision should be based. By presenting the variables for AHJ comment during the design process, the AHJ have an opportunity to see the QDD method at work and to understand the assessment methods utilized without directly influencing the design. This inclusion in the process will also allow the AHJ an opportunity to voice concerns and to develop a level of comfort with the process while maintaining the integrity of their role within the regulatory framework.

In Stage 3 of the QDD method, the stakeholders are involved in the design process to quantify measures of utility for each type of accident scenario, taking into consideration their values such as the allowable extent of equipment damage, potential for loss of life or impact of business interruption. Stakeholder input is used to define quantitatively the maximum, minimum and most likely values of pivot

event likelihood. In its full application to a practical design situation, it is proposed that the a surveying method such as the Delphi technique be utilized to establish both the pivot event probabilities and utility values for each outcome. The identification of pivot event probability values and accident scenario utility relies on coordinated and systematic input from numerous stakeholders including the designer, the owner of the facility, the AHJ and the installers and/or manufacturers of the various components used in the design. The anonymous nature the Delphi technique reduces the influence of individuals on the group and the repetitious convergence approach promotes group consensus. The inclusion or exclusion of other stakeholders, such as insurance representatives, will be at the discretion of the designer and the owner and will have to be determined on a case-specific basis.

The application of QDD is intended to involve of both the owner and AHJ in the fire risk analysis process. This approach ensures that both parties are familiar with the design approach, its performance and its likely failure methods. Furthermore, it promotes a rigorous design decision developed through consensus based variable selections. However, the case study did not employ the suggested group of stakeholders to gather input since this was not practical in the context of a theoretical demonstration of the overall methodology. While the case study is representative of the application of the method by an individual, this is not the intended QDD process. The assignment of variables in Stage 3 must be conducted in a systematic, rigorous and transparent manner to ensure that results of QDD are meaningful and valuable. If the basis for design decisions established cannot be validated by industry and stakeholder consensus, the resulting decisions cannot be justified.

5.1.6   Objective 8

The three-stage QDD approach integrates recognized fire science, risk evaluation and critical decision making techniques including qualitative, semi-quantitative and quantitative methods to achieve objective 8 above. The iterative design improvement component of the method further allows the designer to evaluate the performance of the design alternative and to modify it repetitiously until a design is

excluded or a final design having the desired performance is achieved. In this way, the method also promotes systematic and quantifiable decision making within the performance-based design context.

The sequence of the QDD method optimizes the strength of each of the hazard and risk assessment techniques used by taking valuable information generated from each stage as the necessary input for the following stage. The limits of the FSCT, for example, are that the method is non-sequential and qualitative while the strength of the technique is the generation of a rationalized design path. This output is valuable when applied in development of the event tree, a method which does not provide for any design rationalization and instead is utilized to sequentially represent a series of fire scenarios for a pre-selected design. By using the same initiating event for the event trees developed for both the prescriptive-based design and the alternative design, the performance of each design may be directly compared in Stage 3. In this final stage, the data generated through development of the event trees is then subjectively quantified and cast in a better format for informed decision-making using SSDT. Since the prescriptive design and the alternative design are conceptually developed in Stage 1 to achieve the same fire safety objectives through their input into the FSCT, the consequences of the accident scenarios and/or design failures are comparable in this final stage of the analysis.

5.1.7   Documentation

While not identified as an objective of the QDD method, the need for thorough documentation of the development of an alternative design solution and of any subsequent fire risk analysis process employed to evaluate its performance was outlined in Chapter 2. Such documentation of assumptions, methodology and results is a critical component of a successful fire risk analysis and alternative solution, as described in NFPA 551, the SFPE Engineering Guide and the requirements of the NBCC and NFCC [NFPA 551 2010, SFPE 2006, NBCC 2010 & NFCC 2010]. For this, all assumptions made during the application of the QDD method must be documented, each variable must be qualitatively described and any decisions made regarding selection of pivot event probability and outcome utilities must be rigorously documented and justified. In consideration of the subjective nature of the quantitative fire risk analysis methodology

utilized in the QDD method, it is also necessary to describe and rationalize any assumptions in order to communicate effectively the basis for the final design decision. Furthermore, a well executed documentation of the method permits, as necessary, peer review of both the process and the final alternative design solution.

5.1.8   Closure

Based on an analysis of the case study, QDD is considered to achieve the eight objectives established in this thesis, in addition to supporting the requirements for documentation identified in Chapter 2, and is also well suited to undertake the design challenge posed in the dispensing room scenario. In the case study the prescriptive requirements could be integrated into the FSCT and alternative design approaches that were suitable to the owner could be developed using recognized standards and known technology. The event trees generated comparable fire scenario outcomes which were then quantified using SSDT and could be evaluated by a group of stakeholders to establish a final design decision.

5.2   Limitations of QDD Method

Application of the initial version of the QDD method to the case study presented here has several limitations and allows identification of areas which require additional attention, either to facilitate the use QDD or to improve its reliability. The case study described in Chapter 4 does not attempt to demonstrate application of an iterative re-evaluation that could be conducted in Stage 3 if the uncertainty of the design decision is considerable. This process is documented in Section 3.2.4 but how it would be applied in a real situation should be assessed further in support of future and more complex applications of the QDD method.

Stakeholder input was not actually obtained in Stage 3 of the QDD method since the case study developed in this investigation was a theoretical demonstration of the method. It is proposed that a surveying method be used to achieve consensus when selecting critical variables to describe the risk and uncertainty associated with the expected utility. The Delphi technique has been suggested; however, this

has not been demonstrated or tested in a field application of QDD. A full-scale case study application of the QDD method was not conducted as resources for such an undertaking were beyond the scope of the thesis; however, the theoretical case study provides a basis to support further examination, optimization and application of the method in practical design challenges. To demonstrate the robustness and reliability of the QDD method for practical applications, field case studies must be conducted and documented for evaluation and comparison with current industry practice and/or use of other design and evaluation methods. The impact of human dynamics and group behaviour within the design process, and specifically when trying to achieve group consensus on variable values to input into SSDT, requires additional research and investigation.

The case study demonstrates the type of data that is necessary to conduct QDD, specifically the need for pivot event probabilities and outcome utility values. The selection of utility and probability variables for input into Stage 3 is subject to the limitations of the specific design challenge under study. The resources available to the owners and the designer, as well as the nature of the probability values required will dictate the level of detail required to establish component reliability, for example. At a minimum, the variable and value selection process should take into consideration the input from numerous experts and establish consensus; however, it is understood that many, if not most, design projects will not have access to multiple experts for each design component or that resources in terms of time and money may not be sufficient to conduct a complete evaluation of each probability range and outcome utility. It is expected that the process of establishing variable values in Stage 3 would be significantly simplified if a collection of reliable performance probabilities were available for consideration. A table of standardized 'expert-generated' values for basic fire safety system design components would facilitate the selection process. If data were readily available for the maximum, minimum and most-likely probability categories, then these values could be discussed with the stakeholders as a starting point during consensus surveys. This data may be tabulated for sprinklers or detection systems through industry sources or based on historical loss data. It is expected that the maximum and most-likely probabilities might be relatively consistent between various design applications and that minimum probabilities would be generated based on the level and

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programs of maintenance defined by the owner. Of course, caution would be required when utilizing

standardized probability tables to ensure that the values selected are meaningful to the design under

consideration. In all cases, it would still be necessary for them to be verified by stakeholders as part of the

QDD application process.

5.3   Conclusions

The case study presented in Chapter 4 demonstrates the intended application of the Quantitative

Design Decision (QDD) method, a new fire risk analysis method that has been developed in this research

work. This application has been evaluated to confirm that the eight objectives determined in Chapter 2

have been achieved in the development of the method, with some limitations in the case study conducted.

The findings of this evaluation, in relation to the objectives developed, are as follows:

1. The Fire Safety Concepts Tree (FSCT) in Stage 1 of the QDD method is an effective hazard

   assessment framework by which to direct the development and selection of alternative design

   approaches to prescriptive-based design benchmarks. Using the AND and OR logic gates in the

   FSCT, alternative design approaches are qualitatively demonstrated to achieve the objectives and

   functional statements of the codes.

2. The FSCT and event tree techniques utilized in the QDD method and the graphical representation

   of results of the Super Soft Decision Theory (SSDT) proposed all provide means of illustrating

   complex fire science principles and mathematical relationships in formats that are easily

   communicated to stakeholders. The ease-of-understanding attribute of these illustrative formats

   promote user understanding and effective documentation for Authority Having Jurisdiction (AHJ)

   review.

3. The techniques utilized in the QDD method are not demanding of either monetary or temporal

   resources, in comparison to traditional fire safety design investigations using computational or

field modeling of fire events. The case study demonstrates the application of the method within the restrictions of typical project timelines and resources.

4. The event trees generated in Stage 2 of the QDD method identify the contributions of all significant fire events resulting from a shared initiating event for both the prescriptive-based and performance-based design approaches. The evaluation of all significant fire events necessary to classify QDD as a fire risk analysis method.

5. Stakeholder input is used in Stage 3 of the QDD method to quantify pivot event probability and outcome utility variables generated in the Stage 2 event trees for the prescriptive-based and performance-based designs. Using Super Soft Decision Theory (SSDT) and applying expected utility criteria, the risk of fire associated with each design option is calculated. Quantitative evaluations of both fire scenario likelihood and consequence is required to classify QDD as a fire risk analysis method.

6. SSDT provides a method of quantifying the uncertainty associated with the calculated expected utility so as to establish if the design decision generated is robust. Stakeholders establish minimum, most likely and maximum pivot event probability variables to calculate the range of expected risk associated with each design. The iterative application of Stage 3 of the QDD method permits input variables to be re-evaluated and modified such that the sensitivity of the fire risk analysis to individual parameters can be established.

7. The QDD method involves stakeholders, primarily the owners and the AHJ throughout the fire risk analysis process. A surveying method to collect expert and stakeholder opinions for inclusion in the method has not been demonstrated. However, a group surveying and consensus seeking method that allows numerous stakeholders to contribute to the decision process, such as the Delphi technique, is recommended. Consensus is necessary to establish in the QDD method to ensure that its results are meaningful, valuable and representative of good engineering practice.

8. The combination of the qualitative FSCT, semi-quantitative event trees and quantitative SSDT in the QDD method is demonstrated to promote the strength of each individual tool. In combination, these tools generate a comprehensive fire risk analysis technique that is tailored for assessment of performance-based design challenges.

The evaluation found that the documentation requirements for alternative solutions relying on fire risk analysis techniques could be generated from the information necessary for conducting the QDD method.

The limitations of the case study centred on the fact that it was a theoretical demonstration of the method and therefore the Delphi or other surveying technique were not employed to obtain stakeholder input during Stage 3 of the design evaluation. To demonstrate the robustness and reliability of the QDD method in practical applications, field case studies must be conducted and documented for evaluation and comparison. The impact of human dynamics and group behaviour within the design process, and specifically when achieving group consensus on SSDT variables, requires greater investigation.

Evaluation of the case study identified that the application of the QDD method, specifically the quantification of probability and consequence variables, is restricted by the resources available to the design project. It is proposed that these limitations may be overcome by the development and use of standardized probability tables for design system components. While such tables are available for certain parts, such as sprinklers, a consistent, reliable and industry-wide accepted source of performance data for numerous fire protection system components would be valuable for application of QDD or other similar methods.

Based on the analysis conducted, the QDD method is considered well suited to the design challenges identified in Chapter 1; however, it is still necessary that designers carefully consider their particular challenge to determine the best fire risk analysis methodology to apply in a given situation. This thesis concludes that the QDD method will be a valuable asset to designers developing alternative solutions to prescriptive code requirements in the objective-based format for building design utilized in Canada.

Chapter 6

FUTURE WORK

The QDD method was designed to develop alternative designs by using a prescriptive-based design as a benchmark. There are, however, broad applications for QDD in the performance-based design industry which have not been demonstrated in this thesis. Such applications include FSCT directed designs and extending the application of the method beyond a single design feature or prescriptive requirement. The investigation of alternative applications and the verification and validation of the QDD method applied as designed are suggested for future work.

The FSCT in Stage 1 is used to fit prescriptive designs into an objective-based framework. Instead of a prescriptive design, the initial application of QDD could be related to a single fire safety objective. For example, in the '*Manage Fire Impact*' - '*Manage Fire*' branch of the FSCT there are three distinct redundant approaches which could be developed to achieve the same fire safety objectives. This branch can be used as a starting point to direct the design of three alternative approaches to achieving the same performance objective which could then be carried forward through the QDD method for quantitative comparison in the same type of fire risk analysis and critical decision making framework.

This approach to using the FSCT to direct the design process, theoretically, could be administered to all fire performance objectives to develop a comprehensive design for a room, floor area or building instead of limiting the application to a single prescriptive requirement. The design approaches developed using the FSCT could be compared to various prescriptive designs mandated by codes. The subsequent

application of Stage 2 and 3 of the QDD method would quantify the difference in the performance of the comprehensive designs. Such application would generate extensive and complex event trees in Stage 2; however, theoretically the QDD method could certainly be utilized for such performance comparisons. The application and potentially further development of the QDD method as a comprehensive performance-based design fire risk analysis methodology garners future consideration.

Applications of QDD to practical design challenges will provide the data required to validate the fire risk analysis methodology. To evaluate the sensitivity of the method to subjective influence, case studies should be conducted and documented where different design teams develop alternative solutions using the QDD method for the same prescriptive code requirement. Future investigations should also apply the Delphi technique in gathering stakeholder input as suggested in Stage 3. Consideration of alternative surveying methods and their impact on design decision robustness may also prove necessary. Such investigations should consider the simplicity of the surveying method and the relative resource demands to ensure that the QDD method maintains the intended performance objectives.

An interesting opportunity through which to verify the results of the QDD method would be through a comparison with live fire test data generated for the respective prescriptive and performance-based designs. Such an investigation could be used to determine if the results of a fire risk analysis that concludes that one design is at least as good as, or better than, another would be substantiated by performance demonstrated under actual fire conditions.

References

ASTM E119, *Standard Test Methods for Fire Tests of Building Construction and Materials*, developed by the ASTM Technical Committee E.05.11 on Fire Resistance, ASTM International, 11a edition, Pennsylvania, 2011.

Bukowski, R. and Babrauskas, V., "Developing Rational, Performance-based Fire Safety Requirements in Model Building Codes", Fire and Materials, Vol. 18, 173-191, 1994.

Bukowski, R., "An Overview of Fire Hazard and Fire Risk Assessment in Regulation", CH-06-3-2, ASHRAE Transactions: Symposia, Vol. 112, No. 1, 387-393, 2006.

Bukowski, R., Budnick, E. and Scheme1, C., "Estimates of the Operational Reliability of Fire Protection Systems", Third International Conference on Fire Research and Engineering, 4-8, 1999 and Proceedings in Society of Fire Protection Engineers, National Institute of Standards and Technology and International Association of Fire Safety Science, 87-98, 1999.

Canadian Commission on Building and Fire Codes, "National Building Code of Canada", National Research Council of Canada, Ottawa, 2010a.

Canadian Commission on Building and Fire Codes, "National Fire Code of Canada", National Research Council of Canada, Ottawa, 2010b.

Chu, G. and Sun, J., "Decision Analysis on Fire Safety Design Based on Evaluating Building Fire Risk to Life", Safety Science, Vol. 46, 1125-1136, 2008.

Croce, P., Grosshandler, W., Bukowski, R. and Gritzo, L., "The International FORUM of Fire Research Directors, A Position Paper on Performance-Based Design for Fire Code Applications", Fire Safety Journal, Vol. 43, 234-236, 2008.

Donegan, H., Decision Analysis, Section 5, Chapter 2, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 9-24, 2008.

Ericson, C., Event Tree Analysis, Chapter 12, *Hazard Analysis Techniques for System Safety*, John Wiley & Sons Inc., 223-234, 2005.

Fischhoff, B., Lichtenstein, S., Slovic, P., Derby, S. and Keeney, R., *Acceptable Risk*, Cambridge University Press, Cambridge UK, 1981.

Fitzgerald, R., "Integration of Fire Sciences into Building Requirements", Fire Safety Journal, Vol. 17, 159-163, 1991.

Fixen, E., "A Statistical Benchmarking Framework for Developing Stakeholder Consensus", Fire Protection Engineering, Penton Media Inc, 1st Quarter, 2003.

Friedman, R., "An International Survey of Computer Models for Fire and Smoke", Journal of Fire Protection Engineering, Vol. 4, 81-92, 1992.

Goode, M., Ed., "Fire Protection of Structural Steel in High-Rise Buildings", Civil Engineering Research Foundation, NIST GCR 04-872, Maryland, 2004.

Hadjisophocleous, G. and Mehaffey, J., Fire Scenarios, Section 5, Chapter 11, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 186-205, 2008.

Hall, J. and Sekizawa, A., "FRA: General Conceptual Framework for Describing Models", Fire Technology, Vol. 27, No. 1, 33-53, 1991.

Hall, J. and Cote, A., "America's Fire Problem and Fire Protection", *Fire Protection Handbook*, 18th Edition, National Fire Protection Association, Massachusetts, 1997.

Hurley, M. and Rosenbaum E., Performance-Based Design, Section 3, Chapter 16, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 440-455, 2008.

International Council of Building Officials, Uniform Building Code, 1st Edition, 1927.

Johansson, H. and Malmnäs, P., "Application of Super Soft Decision Theory in Fire Risk Assessment", Journal of Fire Protection Engineering, Vol. 14, 55-84, 2004.

Johansson, H., "Decision Analysis in Fire Safety Engineering – Analysing Investments in Fire Safety", Report 1027, Lund University, 2003.

Kelly, B. and Weckman, E., "Practical Risk Assessment for the Process Industries", First Biennial Canadian Conference on Process Safety and Loss Management, Edmonton, April, 1993.

Linstone H. and Turoff M., Eds, *The Delphi Method: Techniques and Applications*, Addison-Wesley, Reading, Massachusetts, 1-12, 1975.

Meacham, B., Charters, D., Johnson, P. and Salisbury, M., Building Fire Risk Analysis, Section 5, Chapter 12, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 206-236, 2008.

NFPA, Decision Tree, NFPA Committee on Systems Concepts for Fire Protection in Structures, National Fire Protection Association, Boston, Massachusetts, 1974.

NFPA 550, *Firesafety Concepts Tree,* developed by the NFPA Technical Committee on Systems Concepts for Fire Protection in Structures, National Fire Protection Association, Quincy, Massachusetts, 1984.

NFPA 550, *Guide to the Fire Safety Concepts Tree,* developed by the NFPA Technical Committee on Fire Risk Assessment Methods, National Fire Protection Association, Quincy, Massachusetts, 2007.

NFPA 551, *Guide to the Evaluation of Fire Risk Assessments,* developed by the NFPA Technical Committee on Fire Risk Assessment Methods, National Fire Protection Association, Quincy, Massachusetts, 2010.

NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, developed by the NFPA Technical Committee on Explosion Protection Systems, National Fire Protection Association, Quincy, Massachusetts, 2007.

NFPA 69, *Standard on Explosion Prevention Systems*, developed by the NFPA Technical Committee on Explosion Protection Systems, National Fire Protection Association, Quincy, Massachusetts, 2008.

Notarianni, K. and Parry, G., Uncertainty, Section 5, Chapter 4, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 69-1002008.

Olenick, S. and Carpenter J., "An Updated International Survey of Computer Models for Fire and Smoke", Journal of Fire Protection Engineering, Vol. 13, 87-110, 2003.

Ramachandran, G. and Hall, J., Measuring Consequences in Economic Terms, Section 5, Chapter 6, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 116-128, 2008.

Ramachandran, G., *The Economics of Fire Protection*, Routledge, 1998.

Rasbash, D., "Criteria for Acceptability for Use with Quantitative Approaches to Fire Safety", Fire Safety Journal, Vol. 8, 141-158, 1984/85.

Rasbash, D., Ramachandran G., Kandola, B., Watts, J. and Law, M., Fire Safety Concepts Tree and Derivative Approaches, Chapter 16, *Evaluation of Fire Safety*, John Wiley & Sons Ltd., 421-450, 2004a.

Rasbash, D., Ramachandran G., Kandola, B., Watts, J. and Law, M., Logic Trees, Chapter 14, *Evaluation of Fire Safety*, John Wiley & Sons Ltd., 391-398, 2004b.

Rausand, M. and Høyland, A., Qualitative System Analysis, Chapter 3, *System Reliability Theory, Models, Statistical Methods, and Applications*, 2nd Ed, Wiley, 2004.

Richardson, J., "Fire Loss Statistics Regulatory Framework", Proceedings of Building Science Insight '87, Institute for Research in Construction, National Research Council Canada, Ottawa, 1987.

SFPE, *Engineering Guide to Fire Risk Assessment*, Society of Fire Protection Engineers, Maryland, 2006.

Suddle, S., "The Weighted Risk Analysis", Safety Science, Vol. 47, 668-679, 2009.

Tixier, J., Dusserre, G. and Gaston, D., "Review of 62 Risk Analysis Methodologies of Industrial Plants", Journal of Loss Prevention in the Process Industries, Vol. 15, 291-303, 2002.

van Duijne, F., van Aken, D. and Schouten, E., "Considerations in Developing Complete and Quantified Methods for Risk Assessment", Safety Science, Vol. 46, 245-254, 2008.

Watts J. and Hall J., Introduction to Fire Risk Analysis, Section 5, Chapter 1, *SFPE Handbook of Fire Protection Engineering*, DiNenno, P.J (Editor-in-Chief), Society of Fire Protection Engineers, National Fire Protection Association, Massachusetts, 1-8, 2008.

Wolski, A., Dembsey, N. and Meacham, B., "Accommodating Perceptions of Risk in Performance-Based Building Fire Safety Code Development", Fire Safety Journal, Vol. 34, 297-309, 2000.

Zadeh, L., "Outline of a New Approach to the Analysis of Complex Systems and Decision Processes", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-3, No. 1, 28-44, 1973.

Zhao C., Lo, S., Lu, J. and Fang, Z., "A Simulation Approach for Ranking of Fire Safety Attributes of Existing Buildings", Fire Safety Journal, Vol. 39, 55-579, 2004.

Zhou, J., "SPA-fuzzy method based real-time risk assessment for major hazard installations storing flammable gas", Safety Science, Vol. 48, 819-822, 2010.

Appendix A

Fire Safety Concepts Tree

NFPA 550 specifies the structure, application and limitations of the Fire Safety Concepts Tree (FSCT) [NFPA 550 2007]. This guide provides a detailed description of each component of the logic tree. The following four figures are provided in, or are based on , those figures available in NFPA 550 and represent the entire FSCT [NFPA 550 2007]. The logic decision paths in the FSCT are constructed to lead to a fire objective *success* rather than failure. The FSCT provides a comprehensive illustration of the interrelationships between fire safety strategies and a logical path for evaluating achievement of fire safety objectives. The symbol (●) represents an AND gate and the symbol (+) represents an OR gate.
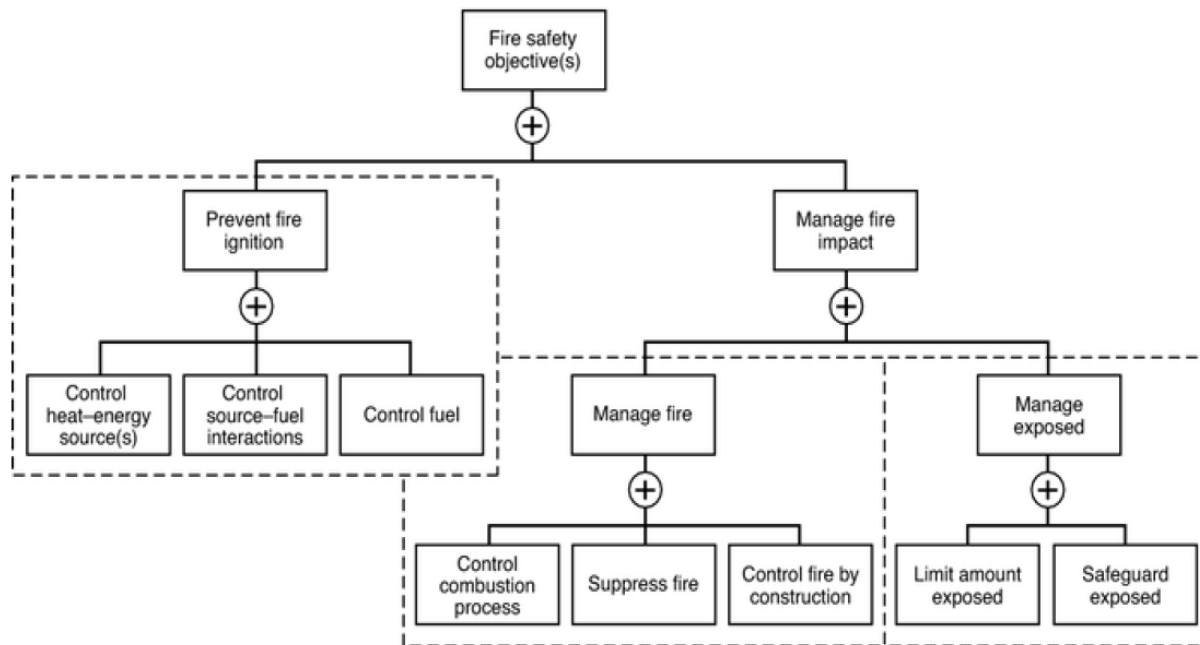

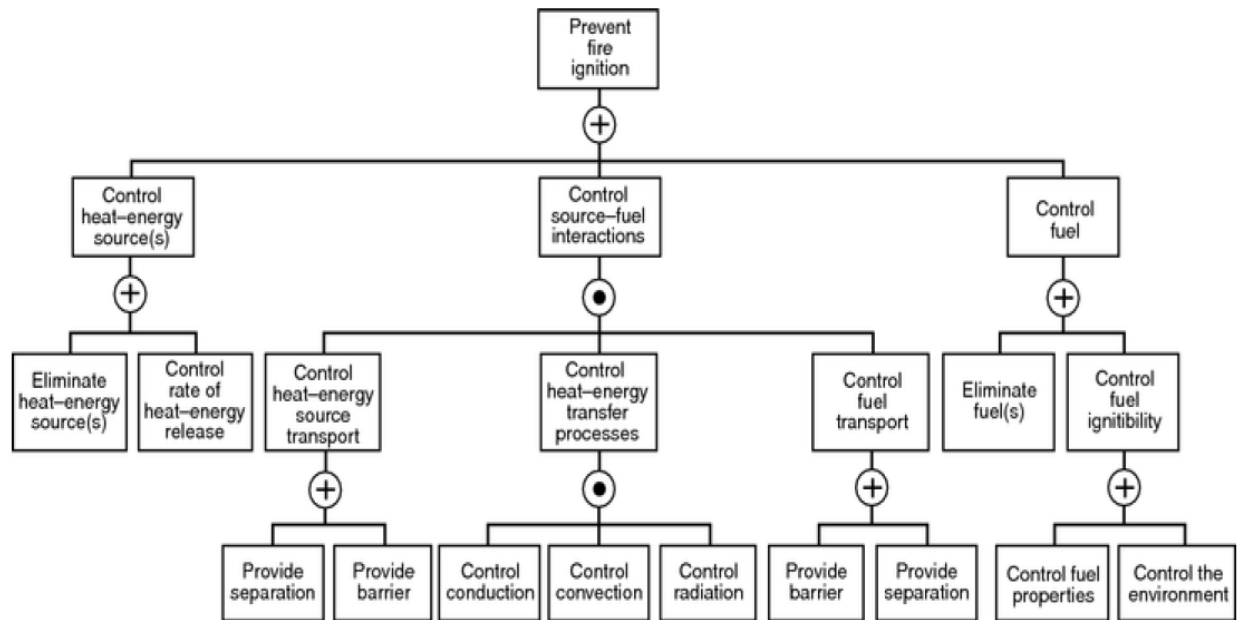*Figure A.1 Top Gates of Fire Safety Concepts Tree [NFPA 550 2007]*

Figure A.2 (Prevent Fire Ignition)

```
                                    Prevent
                                      fire
                                    ignition
                                      (+)
        ┌────────────────────────────────┼────────────────────────────────┐
    Control                           Control                           Control
  heat–energy                      source–fuel                          fuel
   source(s)                       interactions
      (+)                               (●)                               (+)
   ┌────┴────┐              ┌────────────┼────────────┐              ┌────┴────┐
Eliminate   Control      Control      Control       Control       Eliminate  Control
heat–energy rate of    heat–energy  heat–energy     fuel          fuel(s)    fuel
source(s)   heat–energy  source      transfer       transport                ignitibility
            release      transport   processes
                            (+)        (●)                            (+)         (+)
                         ┌───┴───┐  ┌────┼────┐                   ┌───┴───┐   ┌───┴───┐
                      Provide Provide Control Control Control  Provide Provide Control Control
                     separation barrier conduction convection radiation barrier separation fuel the
                                                                                  properties environment
```

Figure A.2 "Prevent Fire Ignition" Branch of Fire Safety Concepts Tree [NFPA 550 2007]

Figure A.3 (Manage Fire)

```
                                   Manage Fire
                                       (+)
        ┌──────────────────────────────┼──────────────────────────────┐
  Control combustion                Suppress fire                 Control fire by
      process                                                      construction
        (+)                              (+)                            (●)
    ┌────┴────┐                     ┌──────┴──────┐                 ┌────┴────┐
 Control    Control            Automatically   Manually        Control      Provide
  fuel     the                  suppress fire  suppress        movement of  structural
           environment                         fire            fire         stability
   (+)        (+)                    (●)          (●)              (+)
    │          │                      │            │               │
Control     Control              Detect fire   Detect fire      Vent fire
fuel        physical
properties  properties of
            environment
Limit fuel  Control chemical     Apply        Communicate      Confine/contain
quantity    composition of       sufficient   signal           fire
            environment          suppressant
Control                                        Decide action
fuel
distribution
                                               Respond to site

                                               Apply sufficient
                                               suppression
```
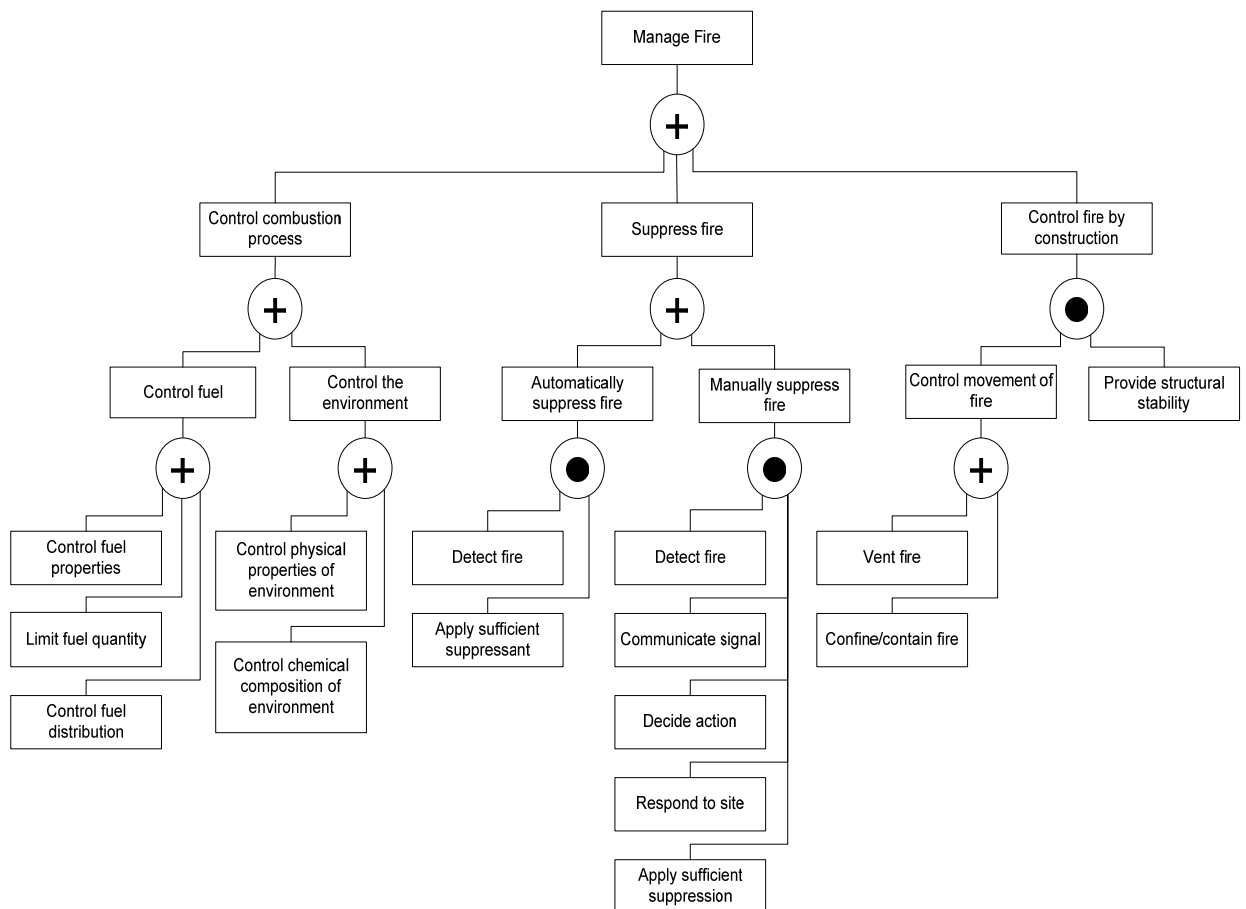
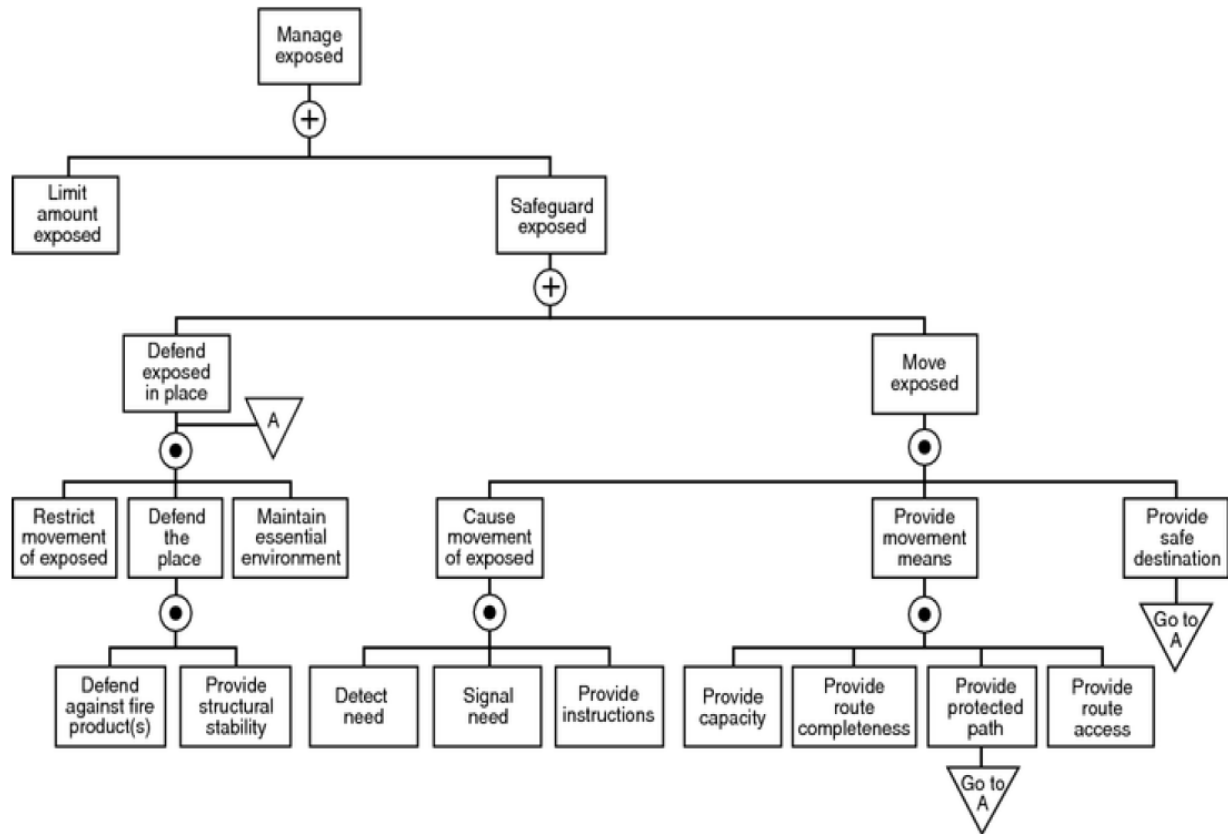*Figure A.3 "Manage Fire" Branch of Fire Safety Concepts Tree [NFPA 550 2007]*

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Figure A.4 "Manage Exposed" Branch of Fire Safety Concepts Tree [NFPA 550 2007]