A New Fire Protection Framework that Incorporates Fire Risk Indexing for Developing and Evaluating Alternative Solutions for Canadian Heritage Rehabilitation Projects

by

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Author's Declaration

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

Heritage buildings in Canada are a cultural resource that bear witness to Canada's defining moments and form a link to the past [1]. Several heritage buildings in Canada sit empty or underutilized and would benefit from rehabilitation so that they can be used for modern occupancies. From a fire protection standpoint, rehabilitation of heritage buildings in Canada is very challenging due to two major obstacles: 1) balancing heritage protection and fire protection requirements, and 2) evaluating alternative solutions for compliance. The first relates to the overlapping priorities of heritage protection and fire protection of the building. The fire protection codes and standards in Canada are rooted in prescriptive requirements that are generally written with new construction in mind and with the objectives and functional statements behind provisions provided. Heritage buildings cannot be unilaterally upgraded to meet requirements of the current fire protection codes and standards because often times, the required changes will alter the heritage character of the building. In order to develop alternative solutions that address both heritage and fire protection objectives during rehabilitation of a heritage building, alternative fire protection frameworks, tools, knowledge and experience have to be used. The second obstacle then becomes how these alternative solutions should be evaluated to assess whether the final design is code compliant or not. Development of a fire protection framework for managing heritage rehabilitation projects under federal jurisdiction in Canada that addresses these two issues forms the main focus of this research.

Prescriptive, objective and performance based codes were reviewed for their strengths and weaknesses for use in design of fire protection strategies for heritage rehabilitation projects. It was concluded that the objective-based framework that forms the basis of the current NBC and NFC provides an excellent platform on which to frame the approach to an alternative solution. Evaluation of fire risk assessment methods led to the conclusion that fire risk indices are the best way to evaluate alternative solutions. The final framework is tested through the use of three case studies. These case studies demonstrate that through application of fire risk indices, stakeholders can utilize fire science,

combined with their knowledge and experience, to compare relative fire risks of an alternative solution to those of a prescriptive solution, allowing for a structured way to argue for code compliance of an alternative design.

This thesis recommends the continued use of this framework in heritage rehabilitation projects for the design of fire protection strategies in order to refine the values for specific fire risk indices identified in this work, as well as to identify and document new fire risk indices that may be required, along with the science and rationale behind each. It is expected that centralizing the information obtained through sustained use of the framework developed here will benefit the fire protection community by sharing knowledge and experience garnered from working through these types of projects.

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Nomenclature

AHJ – Authority Having Jurisdiction

CLC – Canada Labour Code

CSA – Canadian Standards Association

FHBRO – Federal Heritage Buildings Review Office

FPE – Fire Protection Engineer

FRA – Fire Risk Assessment

FRI – Fire Risk Indexing

NBC – National Building Code of Canada

NFC – National Fire Code of Canada

NFPA – National Fire Protection Association

PBC – Performance Based Codes

SFPE – Society for Fire Protection Engineers

ULC – Underwriters Laboratory of Canada

1 Introduction

Canadian heritage buildings are a cultural resource that bears witness to defining moments in Canadian history and provide a link to the past [1]. The Government of Canada owns or leases 20,220 properties containing 36,715 buildings which make up over 27 million square meters of floor space [2]. As of 2009, these included 219 federally owned national historic sites and approximately 1,300 federal heritage buildings [3]. This number excludes heritage buildings that are not owned by the Government of Canada. It is important to preserve and maintain the historic sites and heritage buildings, as they are key resources and important tributes to the culture, history and social development of our country [1].

The overall significance of heritage buildings can be defined as "An historic building is one that gives us a sense of wonder and makes us want to know more about the people and culture that produced it. It has architectural, aesthetic, historic, documentary, archaeological, economic, social and even political and spiritual or symbolic value; but the first impact is always emotional, for it is a symbol of our cultural identity and continuity, a part of our heritage" [4].

Indeed, several heritage buildings in the federal inventory are on national historic sites, preserved to bear continued witness to Canada's defining moments, illustrating our human creativity and cultural traditions [1]. In addition, many of the historic places are the most familiar landmarks in their community and since they form a link to the past, they evoke personal memories and feelings of pride. In a different vein, heritage places are important resources for education, through which Canadians and others learn about the history of our country. Such education can also be a potent driver for community action by increasing community values and promoting greater social inclusion through a shared understanding of the unique cultural identity that our heritage gives to a particular area [5]. In short, preservation of our heritage sites and buildings is of key import as they form an irreplaceable component of our collective history and identity [6]. Figure 1 shows a picture of Canada's Parliament Hill Centre Block, a historic building that is a symbol of Canada's nationhood [7].

Figure 1 - Parliament Hill Centre Block [8]

Heritage building designations are established when an authority having jurisdiction evaluates a building, or group of buildings, for its' historical associations, architecture and environment and formally recognizes its importance as a historic resource [9]. This recognition then protects a building from activities that will adversely affect the historic qualities of the building [4]. Therefore, many heritage buildings are used as parliaments, places of worship, historic sites, museums or for other monumental purposes [4]. There is a common myth that historic buildings need to be left as is in order to preserve their cultural importance. The reality is that these buildings need to be upgraded from time to time in order to remain operational. The key instead is to protect the character-defining elements of the original building when alterations, upgrades and repairs are made. As such, three different approaches can be followed toward long term utilization of a heritage building. These include conservation, restoration or rehabilitation of the building as defined below [10].

1. Conservation of a heritage building involves preservation of the building by continuing to use it, without changing the layout or original character of the structure and decoration. The surroundings should also be protected, so no transfer or removal of ornaments is permitted except under exceptional cases [10].
2. Restoration of a building or structure is undertaken only when necessary and does not involve reconstruction of the structure. Areas can be restored using either the traditional methods or, when

those prove inadequate, well tried modern restorative techniques are sometimes used [11]. Independent of method, the structure and authenticity of the original materials must be maintained, as should elements of value from any other period. In cases where new materials are required, the design should ensure these are clearly distinguishable from the restored areas [1].

3. In contrast to conservation and restoration, rehabilitation of historic places is more challenging. It involves the process of returning a property to a state of utility, through repairs and alterations, to ensure that the property can then be used for an efficient contemporary use and function. At the same time, the character defining elements, which are portions and features of the property which are significant to the historic, architectural, and cultural values of the original use must be carefully preserved [4].

Heritage preservation laws cover conservation, restoration and rehabilitation of heritage buildings. Such laws are broad and diverse. Internationally, several nations use principles established in the Venice Charter, which was written by the Second International Congress of Architects and Technicians of Historic Monuments in 1964 [10,11]. The primary purpose of the Venice Charter is to provide guidance on safeguarding of historic monuments. As such, it incorporates principles which can be applied by individual governments within the framework of their own culture and traditions. Most federal, provincial and local governments in Canada also have heritage legislation in place that defines how heritage buildings are to be identified and regulates actions that can affect the historic qualities of heritage buildings that fall under their jurisdiction [4].

In addition to any legislation surrounding preservation of heritage buildings, one of the major considerations with management of heritage buildings is related to managing fire risk through designs that effectively implement fire protection measures, since fire not only damages and destroys historic building components, it often destroys the irreplaceable collections they contain [12]. Jurisdictions manage fire risk by developing a legal framework using legislation or policies. The legislations or policies then adopt building codes and fire codes as the regulatory documents used to regulate fire protection in design, construction and maintenance of real property [13, 14, 15]. Canadian codes, such as the National Building Code of Canada (NBC) and National Fire Code of Canada (NFC), also make reference to other fire protection standards such as those published by National Fire Protection Association (NFPA), Canadian Standards Association (CSA), or Underwriters Laboratory of Canada (ULC) [14, 15]. Together such documents provide the fire safety stakeholders (designers, fire protection engineers, authority's having jurisdiction, and building owners) with tools by which to manage fire risk through the design of fire protection systems for a building under a variety of different possible fire scenarios.

Building codes deal primarily with new construction; however, heritage buildings were built in the past under different rules and regulations. Application of building codes to these buildings becomes challenging, especially since some heritage buildings were even built when no official standard of safety was in existence. In the case of rehabilitation, the challenge becomes greater since the character defining aspects of a heritage building must be protected both during and after rehabilitation even when the final way a building is utilized may be quite different from how the building was originally built and used [16]. To meet the challenge of protecting heritage buildings and maintaining an effective fire protection regime, there are several different fire protection frameworks available for use by stakeholders. The stakeholders, who include building owners, property managers, authorities having jurisdiction (specifically fire and heritage), tenant representatives, design consultants, and general contractors, must agree on which framework to use in each individual situation. The applicable frameworks range from direct application of fire protection requirements contained in existing prescriptive building and fire codes, to application of more objective and functionally based requirements as are incorporated into objective based codes like the NBC, to full performance based (alternative) solutions as allowed by other codes. Fire protection and fire science knowledge, experience, codes and standards are available for use within a given framework to achieve project success.

When prescriptive code provisions cannot be applied because the resulting solution would damage the heritage value of a building, alternative solutions need to be designed and evaluated using an appropriate fire protection framework. This thesis will begin by reviewing the heritage and fire protection frameworks currently in place for federally owned buildings in Canada and discuss the status, strengths and weaknesses of each framework being examined. Additional fire protection frameworks that may be suitable for heritage rehabilitation projects in Canada will also be investigated and discussed. Finally one framework will be selected and its suitability demonstrated using case studies involving hypothetical Canadian rehabilitation projects that incorporate alternative fire protection solutions. Throughout the analysis, case studies will be used to determine gaps in the proposed framework. Identified gaps are also addressed via the studies in order to further refine and develop the selected framework as a more universal tool for fire risk management when implementing fire protection design principles in Canadian heritage buildings.

The objective of this thesis is to develop and propose a new fire protection framework that will aid with the development and evaluation of alternative solutions for projects where heritage buildings are being rehabilitated. Chapter 2 of this thesis will describe and discuss the present heritage framework and fire protection framework currently existing in Canada at the federal level. Additional fire protection frameworks that could be used to manage fire risk in heritage buildings will also be described in detail with the advantages and disadvantages of each framework also discussed. The best suited fire protection framework for this thesis is then proposed and known gaps in the proposed framework are studied and solutions proposed. The methodology of the framework will be proposed and further developed in Chapter 3. Chapter 4 will use case studies of existing federal heritage buildings and propose a hypothetical rehabilitation project in order to discuss and demonstrate the suitability of the proposed fire protection framework. Any additional gaps in the framework will be addressed and mitigated to further develop the final fire protection framework. Finally, Chapter 5 will provide conclusions and recommendations on how to continue to improve the fire protection framework proposed here for on-going use in fire safety decision making for Canadian heritage buildings.

2 Background Information

This chapter will discuss general background necessary to provide context for the thesis, including the current Canadian Heritage Protection Framework for federally owned buildings, the Fire Protection Regime that is applicable to federally owned buildings in Canada, and the fire protection framework currently being deployed in Canada. From this foundation, the challenges facing stakeholders who have to operate under the unique dual constraints of heritage protection and fire protection during rehabilitation of a building will also be explained. From this perspective, the importance of a flexible fire protection framework will be outlined and additional fire protection frameworks will also be explored. Finally, a potential solution will be proposed and its suitability for use within the Canadian context for heritage protection and fire protection context will be discussed.

2.1 Fire Protection and Fire Safety

Fire protection of a building involves protecting the environment, property and people from the dangers of fire [17]. Fire protection engineering applies science and engineering principles to protect people and their environment from fire and includes:

- analysis of fire hazards,
- mitigating risks of fire damage by using proper design, construction, arrangement and use of buildings, materials, structures, industrial processes and transportation systems, and
- the design, installation and maintenance of fire detection and suppression and communication systems [18].

Other areas of study that are relevant to fire protection are fire sciences, fire dynamics, fire statistics, and occupant behaviour in fire situations. Fire protection engineers develop and integrate different strategies to create a balance of protection measures that reinforce one another and provide redundancy for critical facets of the system [4].

Fire Safety is the system that is intended to reduce the destruction caused by fire [19]. Building codes specify a minimum level of safety where provisions contained within are deemed appropriate for enforcement. Building codes regulate fire safety aspects that are enforceable through plan reviews and inspections. Fire codes deal more specifically with contents and the human activities that take place within the building [14, 15].

2.2 Current Canadian Heritage Protection Framework

Discussing fire safety solutions for heritage buildings in Canada necessitates some familiarity with how heritage buildings are designated and managed in Canada as outlined in this section. In Canada, the Treasury Board Policy on Management of Real Property governs how real property owned by the Government of Canada is to be managed in a sustainable and financially responsible manner in order to support the cost-effective and efficient delivery of government programs. The policy describes the role of the deputy head of each government department and how they are responsible for ensuring that their department complies with all the requirements contained within the policy on management of real property. For buildings that are over 40 years of age, the policy specifies Parks Canada Agency as the organization that evaluates these buildings for their heritage character [20]. Parks Canada's Federal Heritage Buildings Review Office (FHBRO) conducts heritage evaluations of federal buildings, reviews proposed interventions to classified federal heritage buildings, provides conservation advice regarding designated heritage buildings, and provides training on the heritage obligations under the Treasury Board Policy on Management of Real Property [21]. FHBRO consists of a committee made up of professionals from various disciplines and different federal departments who evaluate the heritage value of a building based on its historical, architectural, and environmental significance and recommend to the Minister responsible for Parks Canada what type of heritage designation a building receives. The Treasury Board Policy on Management of Real Property places protection of heritage character at the same level as other considerations related to real property management such as fire protection and financial stewardship of real properties [22].

FHBRO advises custodian departments on how to meet their heritage obligations under the Treasury Board Policy on the Management of Real Property. When it comes to heritage matters, the

Treasury Board Policy on Management of Real Property states that deputy heads of government departments are responsible to ensure that:

1. The heritage character of buildings are respected and conserved throughout the building's life cycle. Buildings that are 40 years of age or older, whether crown-owned and already under the administration of their minister or buildings they are planning to purchase, must be evaluated by Parks Canada for their heritage character.
2. Where the minister has administration of heritage buildings, conservation advice is sought and consultations with Parks Canada are undertaken before demolishing, dismantling or selling the recognized heritage building and before taking any action that could affect the heritage character of a classified building. In addition, best efforts are made to arrange for appropriate alternative uses of under-utilized or excess classified and recognized heritage buildings, first by users within the federal government and, failing that, by users outside the federal government [21].

FHBRO also develops policies, standards and guidelines in consultation with other departments. They provide criteria and a process for evaluating and designating heritage character, provide advice and recommendations to other departments, and maintain a register of federal heritage buildings. The minister responsible for Parks Canada is responsible for approving the heritage designations for federal buildings based on the recommendation of an interdepartmental advisory committee [21]. Under the policy on the management of real property, FHBRO develops a heritage character statement which includes basic general building information, along with a description of what is being designated for preservation and the heritage value in terms of historical (thematic, person/event, local development), architectural (aesthetic design, functional design, craftsmanship and materials) and environmental (site, settings, landmark) significance. The character-defining elements identify what the key elements or features of the building must be protected. This may include formal elements (volume, elements of its composition), materials, construction elements and craftsmanship, spatial configurations, finishes and ornamental details [23]. While this is a good approach for recognition and preservation of key attributes of heritage buildings, it stops short in addressing the full complexity of the situation since fire protection requirements for designated heritage buildings are not addressed in any of the associated documents in Canada.

2.3 Current Fire Protection Framework at the Federal Level in Canada

The current fire protection framework in place for the Government of Canada, and thus applicable to federal heritage buildings, is also regulated under the Treasury Board Policy on Management of Real Property and further expanded on under the Treasury Board Fire Protection Standard. In the context of federally owned heritage buildings, the Fire Protection Standard names federal custodians and tenants, and local fire services as stakeholders in fire protection of federally owned heritage buildings. Collectively, these stakeholders help the Government of Canada avert interruption of government services as a result of fire in the federal physical infrastructure. The objective of the standard is to have sound fire protection practices in place so that

1. the public is protected from fire-related injury on federal property;
2. damage from or destruction by fire of federal real property assets is averted;
3. fire-related interruption of federal program delivery is prevented; and
4. federal legal liability and costs to the Crown for loss due to fire are limited.

The standard recognizes that fire protection is a continuous risk management process in which fire risks to real property and to the public are identified and reduced, and the costs and consequences of harmful or damaging incidents arising from fire are minimized and contained. The accepted fire protection strategy involves the application of building, fire and occupational health and safety codes to each heritage structure. The standard also establishes the role of a Departmental Fire Protection Coordinator who is responsible for many fire protection tasks including ensuring that:

1. Real property administered by the department complies with the following:
    a. the fire protection requirements of the National Fire Code of Canada (NFC), the National Building Code of Canada (NBC), and the National Farm Building Code of Canada (NFBC) or

of applicable local codes when there is a change in use of the real property, when real property is acquired or new structures are constructed, or when existing real property is altered, and

b. the NFC or applicable local fire codes throughout the life cycle of the property.

2. Fire protection equipment and systems under a department's control or installed to meet a tenant department's operational needs, are compatible with a building's existing fire protection system and are inspected, tested and maintained in accordance with the NFC and applicable local codes [24].

It is clear from the above, then, that fire protection for federal heritage buildings inherently must adhere to clauses outlined in the NBC and NFC, which are the second iteration of the Objective-Based National Model Codes. These are developed as complimentary and coordinated documents and each contain provisions that deal with safety of persons in buildings in the event of a fire and protection of buildings from the effects of fire. Furthermore, every NBC and NFC requirement must address at least one of the Code's four stated objectives: safety, health, accessibility for persons with disabilities, and fire and structural protection of buildings [14, 15].

The application of these codes when rehabilitating heritage buildings presents some interesting challenges. The NBC governs how buildings are to be designed and constructed and is thus most often applied at the time of construction and/or sufficient reconstruction of a building. Division A defines the scope of the codes and contains the objectives, the functional statements and conditions necessary to achieve compliance. Division B contains acceptable building design solutions (which were referred to as "technical requirements" in editions before adoption of Objective-Based Model Codes) deemed to satisfy the objectives and functional statements listed in Division A. Division C contains administrative provisions relating to the application of the Code [14]. On the other hand, the NFC applies to the operation and maintenance of the fire-related features of the building in use. There will inevitably be some overlap between the NBC and NFC, however these instances are reduced through the use of cross references between the two codes [15]. Since these codes are updated in a continuous 5-year cycle, cases can arise where there are significant changes in code requirements between when, and for what purpose, a heritage building was constructed and the code requirements for its present use.

2.4 Challenges of Working with Heritage Buildings

A major challenge facing fire protection engineers, designers, authorities having jurisdiction (AHJs), building owners and occupants from a fire protection and heritage protection point of view is how a heritage building can be redesigned for contemporary use while protecting the heritage value of the building, managing fire risk properly and implementing fire protection measures smartly. Building owners face multiple challenges when managing fire risks in a heritage building. They have to balance current code requirements, utilize the building, maintain the building, and make investments in the building for sustained and future uses. Yet, there is a lack of guidance in the existing codes on how to proceed. For example, a building left vacant may be prone to illegal occupancy and vandalism. On the other hand, if a heritage building is under renovation, it may have minimal, sometimes non-operational, or inadequately serviced security or fire detection systems, which, in the event of a fire, can allow significant fire growth and spread prior to the fire being observed and acted upon. Some buildings may not have safe access for fire fighters during an emergency, thus affecting occupants, adjacent structures and fire fighting personnel in the event of a fire [4]. After renovation of a building, a proper maintenance regimen for the building, whether occupied or vacant, is critical. On-going activities including removal of hazards such as accumulation of combustible materials and servicing of antiquated equipment are critical steps that can greatly reduce the fire risk to a heritage building but are generally not addressed specifically in the context of fire safety concerns within the applicable codes.

The challenge of balancing fire protection and heritage protection considerations often results in the standard approaches to fire protection running counter to preserving the heritage features of a building as identified under the heritage protection regulations. The balance achieved in the final design is extremely important as it impacts the property value of the building in complex ways while at the same time the legal costs incurred while navigating through the regulations, codes and standards are fully borne by the owner [26]. With such inherent added costs of ownership and operation of a heritage building, it becomes critical that an owner have the flexibility to rehabilitate a heritage building so that it supports a viable economic use, such that the owner is able to make a reasonable return on their investment and generate sufficient income to cover the long term maintenance of the building fabric and associated space around it [27].

On the other hand, fire protection codes and standards are written to use one or more of three common design frameworks to demonstrate code compliance with intent to achieve flexibility in obtaining code-based design solutions. These codes can be prescriptive-based, objective-based and performance-based design. In reality, however, most modern building and fire codes focus on new construction and some may provide little information relating to upgrades and rehabilitation of heritage buildings. In addition, modern codes often present the inherent presumption that modern construction is safer than construction which used the traditional materials found in heritage buildings.

Under the present codes, there are no clear guidelines for dealing with heritage buildings. A fire protection engineer can decide to approach heritage building rehabilitation projects by complying with either the prescriptive provisions of the codes, by developing alternative solutions to comply with the objective-based requirements, or by utilizing performance-based fire protection codes and standards. Despite these choices, however, existing legislation, codes and standards are written in a way that may actually limit this flexibility since it permits an authority having jurisdiction (AHJ) room for interpretation as to which is the most acceptable method for any given case [24, 28]. This environment makes it difficult, if not impossible, to achieve code compliance in heritage buildings when there is no clear line for when retroactive upgrades to existing fire safety systems or installation of new systems are required to achieve a particular level of fire protection [4]. Therefore, despite recent advancements in knowledge, tools and expertise in fire science and fire safety engineering, limitations of our present system often make it difficult to implement what could otherwise be very exciting, new uses for our important heritage buildings [27]. As a result, there is a need for a flexible, robust and consistent framework through which fire protection engineers can develop fire safety solutions in heritage rehabilitation projects. Towards this end, a range of possible methods that can be employed in designing fire safety solutions are outlined in the following section and some of the strengths and tradeoffs in their use are also discussed.

2.5 The Different Fire Protection Frameworks and Choosing an Appropriate Framework for Heritage Rehabilitation Projects

Heritage buildings are assumed, for the purposes of this thesis, to be built in accordance with the governing building and fire codes of the day. When these buildings are rehabilitated for modern use, the occupancy type may change and improvements to the building are often needed to comply with current codes. Some examples include the rehabilitation of residential buildings for use as public buildings, office buildings, or museums that house one-of-a-kind artifacts. For these situations, a variety of fire hazards may exist that require a fire risk management strategy to mitigate them [27], such as electrical wiring in the building may need to be upgraded to satisfy the electrical code and the needs of the new occupancy, a sprinkler system may need to be installed to protect the building and assets inside, and it may be necessary to construct a fire separation to separate one occupancy from another. In order to protect the heritage character and value of the building during such a rehabilitation project, a flexible fire protection framework must be deployed to manage fire risk for the building during the entire course of the project from the design phase through to the occupancy phase. Whether it is best for the framework to utilize prescriptive-based, objective-based or performance-based frameworks for analysis will be investigated in the sections below with advantages/disadvantages to their use discussed.

2.5.1 Prescriptive-Based Code Framework

Prescriptive based codes are used in most countries to specify fire protection requirements in buildings. They become law when they are adopted as part of legislation. During the architectural design process, the designer utilizes the code and designs a building that complies with the code's prescriptive requirements on building size, use, design, and materials [4]. The prescriptive requirements for construction characteristics, limiting dimensions of key attributes, such as travel distances and clearances, to within certain values or requiring specific types of fire protection systems form the basis of an acceptable level of performance [29]. The codes have evolved over several decades, with new requirements being adopted over existing requirements through various code change cycles.

The NBC and NFC originated as prescriptive based codes and as they evolved into an objective based format, the prescriptive requirements remained in Division B of the codes. Compliance with the code provisions in Division B is generally recognized as achieving the minimum level of performance that satisfies the objectives of the code provisions. As such, conformance to these requirements will be acceptable to the authority who adopts the NBC and NFC into law or regulation [14]. Outside the intended application of a prescriptive requirement; however, it is difficult to determine how a given requirement, or set of requirements, might be applied to achieve a certain fire protection goal. The main objective of a code written in this form is to preserve life by regulating the provision for safe and adequate emergency exits for occupants of a building in case of a fire and also for protecting neighbouring buildings from the spread of fire. The code provisions generally do not deal directly with property protection within the building, which can clearly be a limitation when dealing with irreplaceable heritage buildings and collections [12]. The primary assumption behind prescriptive-based code provisions is that there is one single fire source. Historically, this assumption has proven appropriate and led to fire safety solutions that met society's expectations [30].

Prescriptive codes are advantageous because the process of determining whether or not a requirement is met is very straightforward [31]. The disadvantages are that the codes specify requirements without stating any objectives behind those requirements, what objectives are being achieved nor the outcomes of implementing the prescribed solution [32]. As such, they provide very little flexibility for innovative solutions and unusual situations such as those that may be encountered in fire protection designs in heritage buildings. Further, they presume there is only one solution to providing a minimum level of safety, though the actual level of safety that should be achieved is not specifically stated. As a result, it is difficult to directly apply the provisions of prescriptive-based codes in design of fire safety solutions for unusual buildings [13].

2.5.2 **Objective-Based Code (OBC) Framework**

The code development committee for the NBC and NFC recognized that the acceptable (prescriptive) solutions could not cover all possible valid design and construction options. Therefore, the codes were recast into Objective-Based National Model Codes that are currently in their third cycle of revision. Such objective-based codes and standards work by linking a fire safety intent, application(s), objective and functional statement to each prescriptive code provision. Intent statements provide the basic thinking behind a code provision and are expressed in terms of fire risk avoidance and expected performance. Application statements serve an explanatory purpose and provide guidance on when a code provision is applicable [15]. Objective statements describe, in broad terms, the overall fire safety goals that the prescriptive code provisions are intended to achieve. They define the boundaries of the subject areas. Functional statements are more detailed and describe conditions necessary in the building that will help satisfy the chosen fire safety objectives. Objective and functional statements are qualitative in nature and are not intended to be used on their own in determining compliance. Instead the minimum technical level of performance required in the areas defined by the objective and functional statements is prescribed through requirements provided by the prescriptive clauses in Division B [25]. Compliance with an objective-based code is achieved by complying with the applicable acceptable (prescriptive) solutions, or by using well-justified alternative solutions that can be demonstrated to achieve at least the minimum level of fire safety performance necessary for compliance with those acceptable (prescriptive) solutions in the areas defined by the objectives and functional statements attributed to the applicable acceptable solution [15].

Objective-based codes are advantageous for code users and authorities having jurisdiction as the objective, functional, application and intent statements provide:

- Clarity of intent: Rationale behind a code provision is explained which will facilitate understanding of what must be done to satisfy that requirement.
- Clarity of Application: Applicability of a code provision can be clarified.
- Flexibility: A person may propose a new method or material not described in the code and use the information provided to understand the expected level of performance that their alternative solution must achieve to satisfy the Code [15].

The disadvantage behind objective-based codes is that they do not provide specific guidance on how to evaluate whether an alternative fire safety solution, such as is often required in heritage buildings, satisfies the minimum requirements of the code [31].

Due to the layered use of objective statements, functional statements and associated technical requirements, as well as the many cross references between the NBC and NFC, determination of the equivalency of a proposed design solution with an acceptable solution will often involve very careful analysis of the objective and functional statements behind the code requirements of interest [25]. Unfortunately, the code itself does not address the question of who is responsible for doing this; nor does it provide a framework within which consistent assessments of conformity to the requirements can be carried out [15]. To some degree, this is done by legislation or policy that adopts the codes into force; however, often times these do not provide clear guidance as to how to assess compliance either. As a result, the preference, particularly amongst many AHJ's, for designs to comply with Part B of the NBC and NFC continues. There are sporadic uses of alternative solutions across Canada but that depends on expertise and established practices that are present within the fire safety engineering industry in a particular jurisdiction [34].

The Canadian Commission on Building and Fire Codes adopted the objective-based code format to provide guidance to the building community on how to assess alternative solutions and to permit more flexibility in design. The intent was that provisions would be easier to apply to renovation and other unique applications, as well as being more responsive to innovative design solutions [35].

The reality, however, is that there are jurisdictions in which it is not common practice to consider fire safety design solutions outside those prescribed in Part B of the code. This undermines the advancements that were intended by the new objective-based format and poses significant challenges in the design of fire safety solutions during rehabilitation of Canadian heritage buildings [34].

2.5.3 **Performance-based Code Framework**

Performance-based codes (PBC) specifically state fire protection goals, desired level of safety and reference sets of approved methods that can be used to demonstrate a design's ability to meet the stated goals [36]. The clearly stated goals are an attempt to provide better guidance when dealing with increasingly complex designs and fire risks [37]. In practice, performance-based codes can be described as a framework under which fire protection goals and performance objectives can be identified and developed while uncertainties related to fire protection engineering, such as analysis and design methods used, can be managed [38]. Under this type of framework, any and all solutions that demonstrate compliance with stated goals are acceptable design solutions. Such a framework, then, allows the stakeholders in building design projects the flexibility to design new and innovative structures while maintaining a specified level of safety [36]. The fire safety objectives of performance-based fire protection codes are:

- To prevent structural damage;
- To prevent loss of life in room of fire origin;
- To separate occupants from the effects for a "specified period of time;" and
- To contain the fire to the room of origin [36].

The advantages of performance-based fire protection codes and standards are that they

- establish clear fire safety goals and leave the means of achieving those goals to the designer;
- permit innovative design solutions that meet the established performance requirements;
- permit the use of new knowledge as it becomes available;
- allow cost-effectiveness and flexibility in design;

- enable the prompt introduction of new technologies into design;
- eliminate the complexity of the existing prescriptive regulations; and
- eliminate technical barriers to trade and allow international harmonization of regulation systems [13].

Even though PBC allows the designer more freedom to design a space, there are several disadvantages when working within a performance-based framework. One disadvantage is that these codes use general guidance documents which may result in important fire performance concerns being missed, which becomes more pronounced when they are applied by inexperienced personnel. Further, it is the FPE who defines, uses and quantifies performance and acceptance criteria on a project specific basis, while these criteria should be determined by third party policy and decision makers (AHJs) since they establish minimum targets for public safety. In addition, the selection of the design fire scenarios tend to focus on the evaluation of fire protection system performance, often in isolation, rather than being specified in a way that tests the building holistically for fire safety performance. Another challenge arises when trying to compare the level of performance resulting from the performance-based engineered solution with the code compliant one based on prescriptive requirements. This is often not possible on an appropriate or comprehensive basis in part, as well, due to the fact that there is currently insufficient guidance as to even how to determine the most influential factors to assess, or necessary information to provide during evaluation of trial design. For example, the assumption of "idealized" performance of fire protection measures might be used, but never compared with "real life" performance of installed measures that change over time when impacted by age, occupant action and related issues. Many input values may be taken from the literature and used in analysis and modelling without a sensitivity analysis or other demonstration that the values are appropriate and/or utilized appropriately [39]. Finally, the focus of a PBD analysis may often be placed on the consequences of a given design fire scenario solely with respect to the occupants, or only on the structure, or might lean toward only one narrow aspect of building performance without adequately defining the whole picture of fire performance. Again, the limitations inherent in current application of PBD methods pose their own challenges when utilized in design of fire safety solutions related to rehabilitation of Canadian heritage buildings.

From the analysis of the strengths and weaknesses of working within a prescriptive-based, objective-based and performance-based framework above, a decision was made on what framework or combination of frameworks will be best suited for use in heritage rehabilitation projects. This is outlined in the section below.

2.5.4 Choice of Fire Protection Framework for Rehabilitating Heritage Buildings

The optimal fire protection framework for heritage rehabilitation projects amongst the three frameworks described above must allow a user to satisfy the needs and objectives related to both heritage protection and fire protection. In this respect, prescriptive-based fire protection codes would not be suitable because the prescriptive nature of the code makes the provisions too specific to apply to unique situations that could be encountered in a heritage building rehabilitation project. Performance-based codes do provide the flexibility for developing creative solutions to achieve a minimum acceptable level of fire protection; however the generic nature of the code provisions may result in important fire protection options or concerns being missed. Further, specification and control of input parameter values can be difficult and a universally accepted method for comparative analysis between the levels of performance for a performance-based engineered fire safety solution with one based on prescriptive requirements currently does not exist.

At the present time, it was concluded that the most suitable fire protection code type for use in heritage rehabilitation projects, and therefore the method to be used in this thesis, is the objective-based code formulation. Objective-based codes provide better understanding behind the required provisions in the code than do prescriptive options, as well as being formulated through a logical progression from the prescriptive-based codes with which fire protection engineers, designers, owners and occupants are familiar. They are easier to use to evaluate innovative alternative solutions because the intent, objectives and functional statements can be directly linked to a prescriptive code provision more easily. The greatest asset of objective-based codes, however, is also one of their chief weaknesses. There is still difficulty with how to document and evaluate alternative solutions for comparison against prescriptive-based design. With the decision to pursue heritage rehabilitation under an objective-based fire protection decision making framework, the next challenge is to find or develop a consistent method for evaluating alternative solutions so that there are consistent guidance and expectations for the various fire protection stakeholders to proceed with alternative fire safety design and evaluation.

2.6 Evaluating Alternative Solutions in an Objective-Based Framework

It is a difficult challenge to evaluate a set of alternative fire protection solutions for a single situation, even though all are designed to satisfy the functional and objective statements stipulated in objective-based codes. Since objective-based codes do not provide specific assessment criteria, establishing performance criteria and evaluating the design against those criteria would be an extremely difficult task and therefore will not be pursued in this thesis. Rather, fire risk assessment methods will be reviewed and developed for use in evaluation of alternative solutions. The criteria important in development of an assessment method for evaluating alternative solutions for compliance with the objective-based codes are 1) ease in determining equivalency with objective and functional statements, 2) ease of use by fire protection engineers, and 3) ease in understanding by fire protection stakeholders. There are many categories of fire risk analysis that might be used in this application; however, these vary widely in complexity. Thus this thesis will discuss quantitative and qualitative fire risk assessment methods in general before proposing a more specific fire risk assessment framework that is suitable for evaluating alternative solutions for heritage rehabilitation projects in Canada.

2.6.1 Fire Risk Assessment and Management

Fire Risk Assessment (FRA) is a process that characterizes the risk associated with fire. A typical analysis addresses the fire scenarios of concern, their probability, and their potential consequences [40]. Such an approach mirrors the fact that fires can occur anywhere, at any time, and that building and fire codes try to manage the risks to a tolerable level of performance [41]. The probability and potential consequences of the multiple fire scenarios can then be studied and addressed so that the three basic questions: 'what can happen?', 'how likely is that to happen?' and 'what are the consequences?' can be answered [41]. In a building regulatory framework, FRAs can be used in the design stage to demonstrate adequacy of an existing facility, demonstrate adequacy of an alternative design and demonstrate improvement in facility fire protection [40]. When FRA is applied to alternative solutions in heritage buildings, the risks and risk management strategies should consider the positive effects that building maintenance might have, as well as what effects proactive activities undertaken by occupants have on preventing fires and managing the impact of fire. If included, however, these actions should then also be reviewed regularly to ensure that the actions being taken are effective with any "lessons learned" during the process applied to development of longer term policy or procedure. For the purpose of this thesis, it will be assumed that maintenance and proactive actions undertaken are effective and reviewed regularly since such actions are mandated under other federal government regulations such as the NFC, Canada Labour Code - Canada Health and Safety Regulations Part II, and Treasury Board Fire Protection Standard.

Before beginning an FRA, the stakeholders who have an interest in fire safety, whether related to financial, personnel safety, public safety, or regulatory compliance, should be identified and assembled early in the project in order to define the problem and objectives, choose the category of fire risk assessment to be conducted, and establish any acceptance criteria. For heritage rehabilitation projects, the stakeholders can include regulators, building owners, building operators, occupants of the building, emergency responders, members of the community, investors, design and construction teams, as well as those who are preparing the FRA itself. The purpose of the FRA might be to identify methods of lowering the risk of fire in an existing building, or to identify methods of providing a level of fire risk deemed acceptable in a renovated building. Many methods, including what-if analyses, risk matrices, risk indexes, fire safety concepts trees, actuarial/loss statistics analyses, stand-alone event tree analyses, enclosure fire models for selected fire scenarios, combined event tree - fire models, and computational models that incorporate probability, consequences and cost data in an integrated manner, are available for use in an FRA. Heritage projects can utilize any of these fire risk assessment methods depending on the level of sophistication needed for analyzing a particular alternative solution [40].

Once the stakeholders have been assembled, with the problem and objectives of the fire risk assessment established, it is time to go into more depth in order to choose the category of fire risk assessment and establish the acceptance criteria. This begins with clarifying the exposed targets and fire stimuli that affect fire risk. Exposed targets at risk may include people (occupants, employees, general public, emergency responders), property (structures, systems, components of the built environment), and mission (heritage preservation, business continuity). The fire stimuli which affect the targets may include heat (radiant flame, convective gases), smoke (obscuration, impact on respiration), and gases (toxicity). The transport phenomena that bring the fire stimuli into contact with the exposed targets need to be clarified in order to understand the effects and impact of the fire [40]. Finally, acceptance criteria can be developed based on specifications taken from prescriptive regulations, or determined from performance regulations, from other agreed-to criteria or from any standards and guides which produce a quantitative or a comparative value of risk [40]. Different approaches taken throughout the process will lead to either qualitative or quantitative assessment approaches as described further in the following two sections.

2.6.2 **Quantitative Fire Risk Assessment**

Quantitative fire risk assessment involves identification of fire scenarios and their likelihood, and quantification of the consequences of those scenarios [33]. Quantitative fire risk assessments are useful as they provide a sense of proportion to a certain risk and can account for the effects of any risk reduction actions taken [33]. In a quantitative FRA approach, after all the preliminary planning work described in 2.6.1 is completed, the next step is to identify all the hazards that may impact the heritage building being studied. Potential hazards can include fire ignition sources, and potential building code deficiencies such as impeded egress, lack of fire stops, damaged fire separations, incomplete sprinkler and fire alarm system coverage. Other hazards can come from fire load quantity and arrangement, and potential lapses in operations and maintenance in fire safety planning, fire emergency organization, maintenance quality and housekeeping standards. All the identified hazards need to be considered for the site and when evaluating the alternative solution. The personnel responsible for identifying fire hazards must have a general knowledge of combustion, fire safety, the characteristics of various fire protection systems, and familiarity with the operational aspects of the space [43].

After the hazards are identified, the task of determining fire scenarios and their likelihood of occurring as well as the resulting consequences need to be completed. Fire risk can be calculated as the sum of the expected losses incurred from a fire scenario that is applicable to a fire protection strategy as shown in Equation 1.

Equation 1
$$\mathrm{RISK} = \sum_{i=0} \mathrm{P_i C_i}$$

Where P_i is the likelihood of scenario i, C_i is the consequence for scenario i. While it is well known that risk calculation is person dependent, the resulting risk assessment provides information that can help focus attention on important aspects of fire safety decision making [33]. In the context of a quantitative fire risk assessment, determination of the likelihood of particular fire scenarios occurring, such as cooking fires or fires in which cigarettes are the ignition source, is based on statistical data [43]. A fire scenario can then be modelled as a timed sequence of events after an ignition. How a fire develops depends on fuel quantity, fuel arrangement, characteristics of the built environment, and the performance of various fire protection measures. Since there can be infinite diversity in the possible combinations of fire scenarios, and the resources to analyze the fire scenarios are finite, it is necessary to structure the wide range of fire scenarios into a manageable number of scenario clusters for evaluation [43].

Once the clusters are established, event trees are used to visually represent scenario events and consequences that can occur in a system. Each consequence (C_i) and the contributing sequence of events that must occur leading up to the consequence must be identified in the event tree. For example, consider a simple heritage building that is 2 storeys high and 200 m^2 in building area. The building occupants employ a combination of hazard mediation actions such as good housekeeping, proper handling and storage of dangerous goods in accordance with the Canada Labour Code Part II and NFC, and daily walkthroughs to reduce ignition sources. The building also incorporates a sprinkler system and fire alarm system in order to protect, and thus reduce the fire hazard, to the occupants. The hazard mediation activities, fire alarm system and sprinkler system supersede the requirements in the NBC and NFC however, on closer examination the fire separations in the building are found to provide only 2/3 of the required fire resistance ratings required in the acceptable solution.

Figure 2 shows a simple example of an event tree that explores the consequences of a fire incident in the above building and the interactions between the fire alarm system and evacuation of building occupants. Using the event tree, two outcomes of hazard mediation activities such as good housekeeping, or eliminating ignition sources, are evaluated. The two possible outcomes of these mediation activities is either no fire or a fire occurring. No further analysis is needed in situations where hazard mediation is effective and no fire occurs. If hazard mediation fails, then we have a fire incident and the effect of the fire alarm system on evacuation can be studied. If the fire alarm is effective, the fire alarm system will detect the products of combustion in the early stages and the resultant alarm will notify occupants, providing them the time and chance to evacuate early. If the fire alarm system malfunctions, there are two anticipated outcomes, the first is occupants can detect the fire using other fire cues and evacuate or the second is that there is no evacuation. Evacuation can result in either safe evacuation or injury or death. No evacuation results in only injury or death.

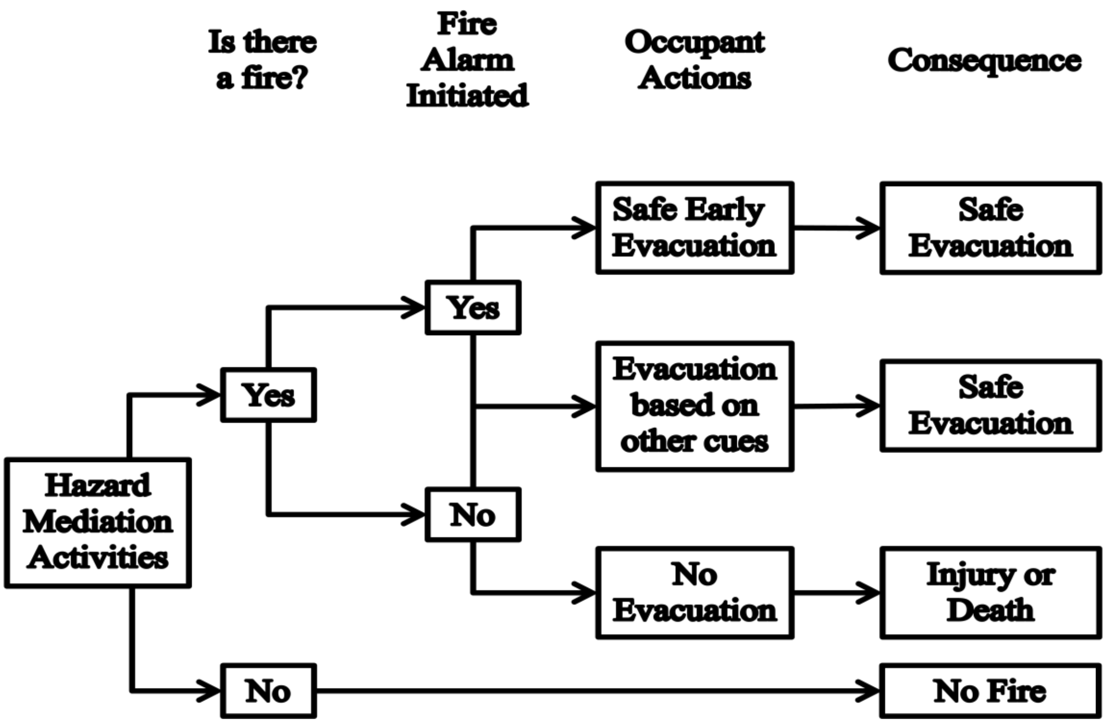

Figure 2 - Event Tree for Hazard Mediation and Fire Alarm System Failure

Figure 3 shows a different event tree that tracks the consequences of failure of fire suppression strategies after fire ignition to illustrate a case when hazard mediation activities fail. In this event tree, fire extinguishers are considered, which are required by the NFC and easy to implement. The sprinkler system and its effects are also included to show the impact that a sprinkler system would have in terms of saving the building in the event of fire.

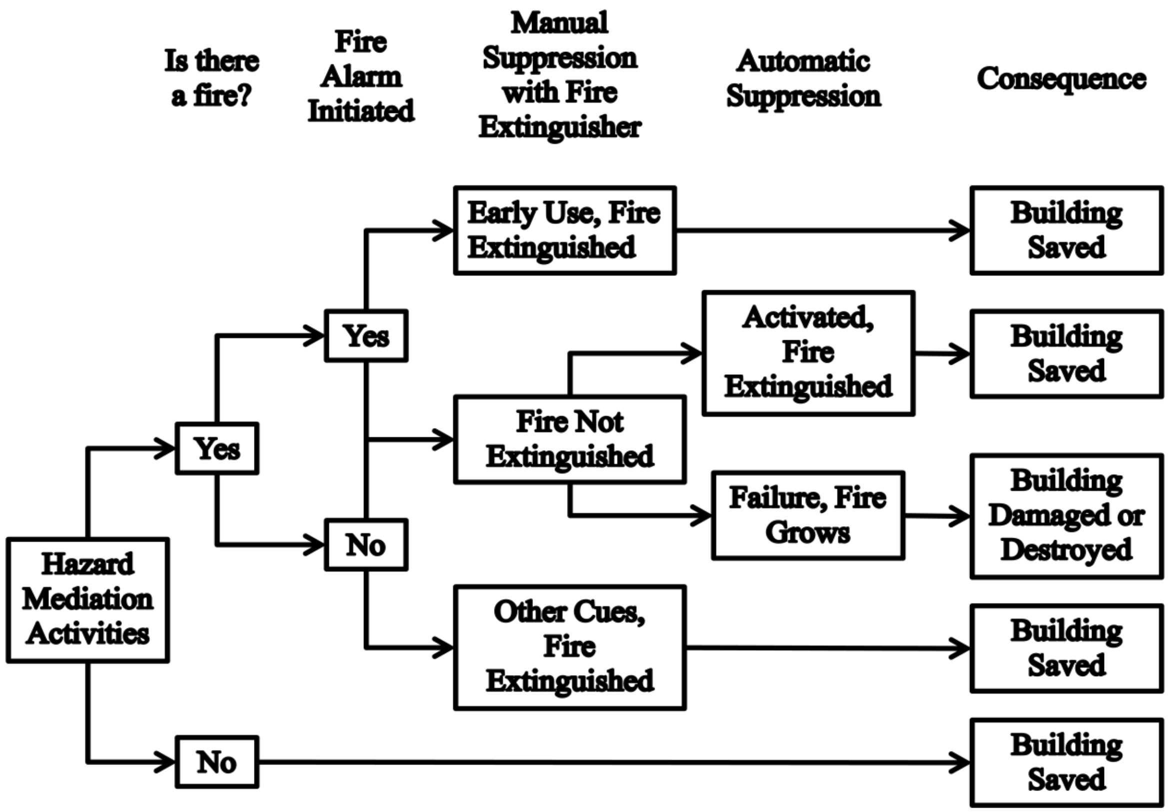

Figure 3 - Event Tree Showing Consequences to the Building When Fire Suppression Strategic Fails

Probability data based on fire statistics must be available so that the information can be used in event trees such as the above to determine the probability (P) of an event based on the outcomes of each event that is included in the chronological sequence of events leading up to it. Both the success and/or failure of each system component is included in the sequence. By analyzing all possible outcomes, the percentage of outcomes that lead to the desired result can be determined [33]. Determining fire event, human behaviour and equipment failure frequencies and probabilities should be done by an experienced fire risk assessment team. The people on the team need to be able to determine failure frequencies and probabilities based on generic industry wide data and make any required variations or adjustments to those data in order to reflect a specific example being studied [33].

Rigorous quantitative fire risk assessments require a large amount of effort, as well as historical data, statistical distributions, knowledge and experience. The type of detailed information required for such an analysis is rarely collected, making determination of absolute risk difficult [44]. A relative risk approach is often adopted instead, where the risk of a subject building is calculated and the risk of a similar building designed in accordance with the prescriptive code is also calculated before comparing the two. Relative risk evaluation is widely used throughout the world because the public is generally satisfied with the safety achieved by current regulations, and the buildings designed to current regulations are convenient benchmarks of the risk levels which must be achieved by an alternative solution [44].

One of the main advantages of quantitative fire risk assessments is that the event trees are easy to draw once the sequence of events is established. Event trees are also easy to understand and, when the necessary values are available, probabilities can be computed from the event trees [33]. There are several disadvantages to using quantitative fire risk assessments, however. It is difficult to identify all consequences in an event tree and the event tree can become very large [33]. Few countries collect fire incident data that can be used to describe detailed scenarios and their likelihood of occurrence [42]. The expertise needed by individuals to carry out and evaluate a quantitative fire risk assessment is high, requiring a lot of knowledge and experience working with fire science and generic industry wide data to determine probabilities and frequencies of events [33]. The information used in risk estimation may have significant uncertainties that can arise from errors incurred during needed simplifications of the problem, from the statistics on which the frequencies of occurrence or probabilities are derived, from the estimates of reliability of the fire protection systems and from the calculation methods used [43]. The computational burden required in conducting a full quantitative assessment also discourages its use [44]. Acceptance by the fire community for use of quantitative fire risk assessment is not progressing at a rate that will aid in closing current knowledge gaps or make this type of assessment a popular tool. This is largely due to lack of education and technology transfer to designers and code officials on the use, usefulness and proper validation of the models and methods [42].

Based on the above brief overview of quantitative fire risk assessment through a review of its strengths and weaknesses, a quantitative fire risk assessment framework is not suitable for use in heritage buildings in Canada at this time. The event trees that need to be developed to identify consequences and the data needed to determine frequencies and probabilities of fire events and consequences are complicated and require data as well as knowledgeable and experienced personnel to carry out and review the fire risk assessment. Thus, methods by which to conduct qualitative fire risk assessment will be discussed next to determine their suitability for use in fire safety design for Canadian heritage building rehabilitation projects. In particular, of many of these tools available, the fire safety concepts tree, which is a qualitative fire risk assessment method, will be investigated here for use.

2.6.3 **Qualitative Analysis Using a Fire Safety Concepts Tree**

As mentioned in the previous section, the fire protection community in Canada lacks the data and expertise at this point in time to make quantitative fire risk assessment a popular design tool for fire protection design [42]. Qualitative fire risk assessments may be more suitable for the current fire protection environment in Canada as their focus is on demonstrating how an alternative design satisfies the applicable functional and objective statements.

The fire safety concepts tree is a qualitative fire risk assessment tool that examines the interrelations of fire protection features and their effect on achieving specific fire safety goals and objectives. As such, it has elements that match well with the intent of an objective design method. Figures 4 and 5 show a reproduction of the fire safety concepts tree from NFPA 550 [19]. These indicate that the fire safety concept tree is based on 2 primary fire safety objectives: "To Prevent Fire Ignition" and "To Manage Fire Impact". Each of the branches proposes a distinct path through which to analyze the potential impact of fire safety designs and strategies.

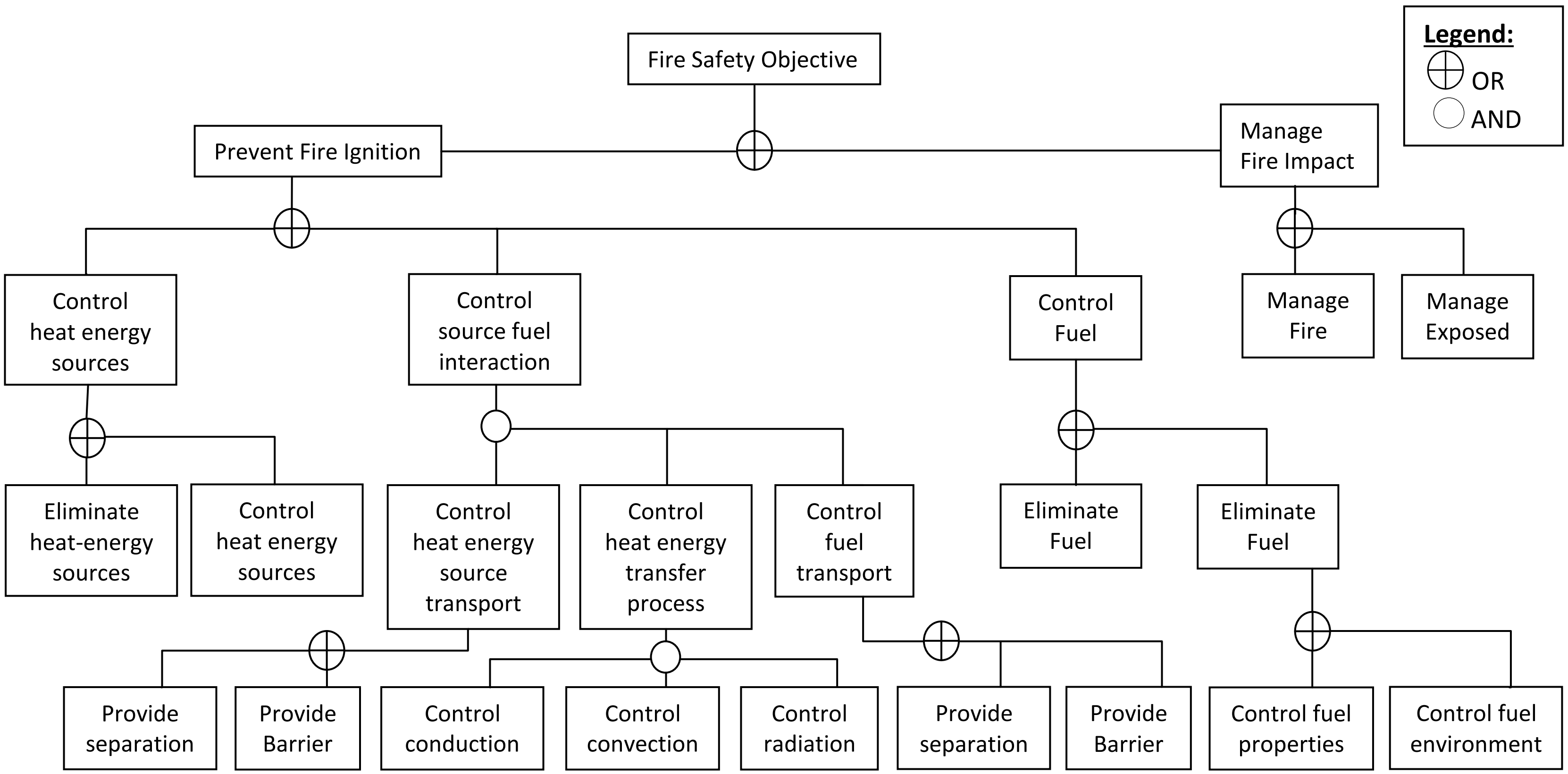

Figure 4 - Fire Safety Concept Tree - Prevent Fire Ignition

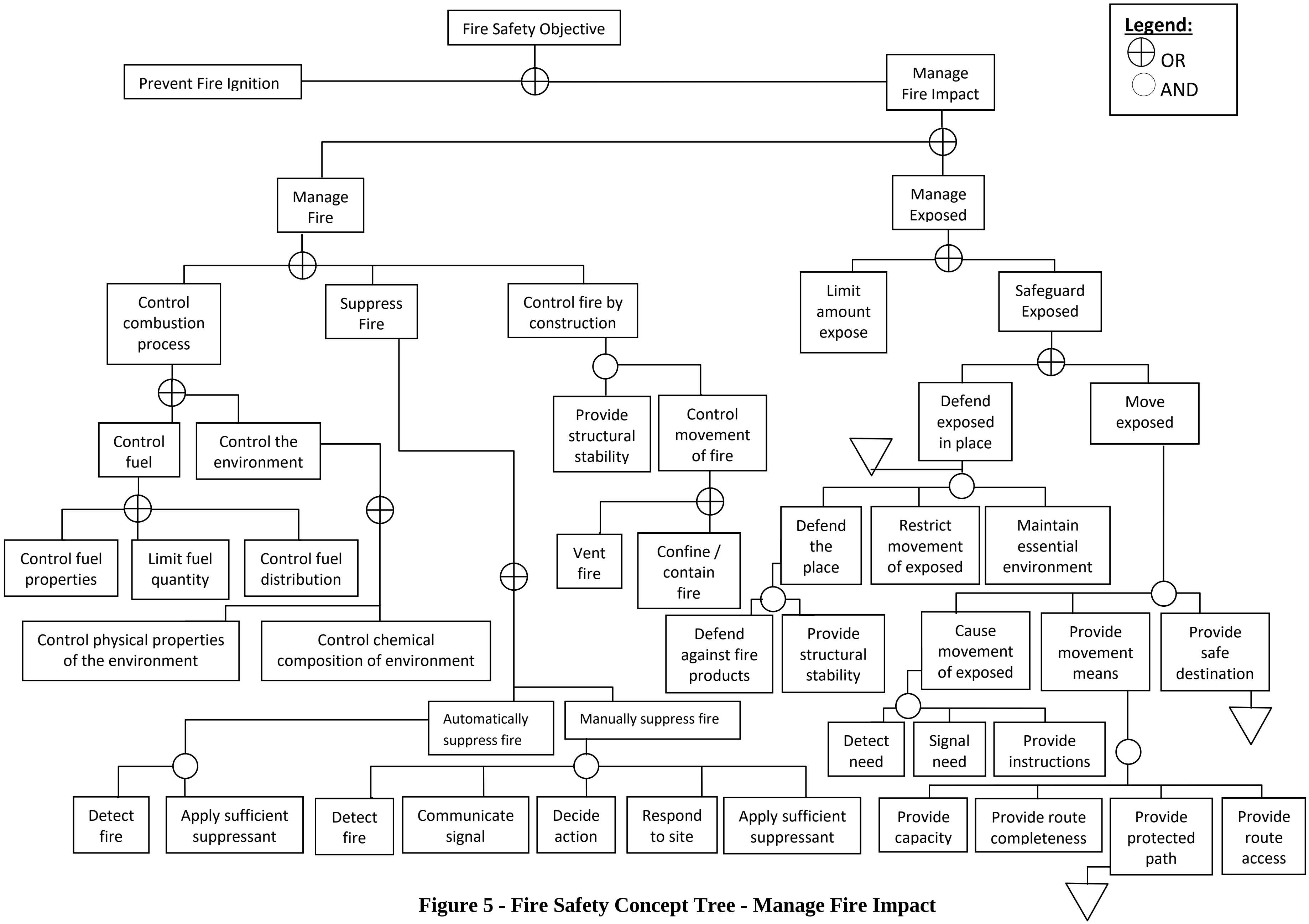

Figure 5 - Fire Safety Concept Tree - Manage Fire Impact

Logic gates are used in each path to show hierarchical relationships amongst fire safety concepts. "OR" gates are used to indicate that concepts below a certain point will cause or have as an outcome the concepts above, and "AND" gates are used to indicate that all the concepts below the gate are needed to achieve the concept above the gate.

For example, consider a two storey heritage office building that is 120 m^2 in building area, with the two storeys connected by an open staircase; the building is equipped with a full fire alarm system. The process for using the tree begins with defining the fire safety objective [19]. The objective of this analysis is to determine whether a fire alarm system provides an equivalent level of fire safety to the building and occupants as is achieved by having proper fire separations between the first and second storeys as designated under the NBC.

Using the NBC, the code prescribes that in buildings having a building area greater than 100 m^2, the stair connecting the two storeys must be enclosed within a fire rated exit stair shaft. The function behind this requirement is to retard the effects of fire on emergency egress facilities. The objective behind this provision is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire. Unacceptable risks addressed in the Code are those caused due to persons being delayed in, or impeded from moving to, a safe place during a fire emergency. On the other hand, the installation of a full fire alarm system exceeds the minimum code requirement for a building of this size. The functional statement behind the system is "to notify persons, in a timely manner, of the need to take action in an emergency". The objective behind a fire alarm system is to limit the probability that a person in, or adjacent to, the building will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire are the same as the above in this case which is risk caused by persons being delayed in or impeded from moving to a safe place during an fire emergency [14].

The first step in using the tree to examine the intent of installing a fire alarm system against the code requirements, then, is to assess the lowest elements in the tree and estimate the extent to which each element is present as a fire protection feature. A four point scale such as the following may be used (1) nonexistent, (2) below standard, (3) standard, and (4) above standard. The process is to proceed up the tree and qualify each output on the basis of the quality of the inputs and the logic gates that connect them. Where the lowest level elements are inputs to an "or" gate, the value of the output will be at least as high as the highest valued input. Where the lowest level elements are inputs to an "and" gate, the quality of the output should be limited to that of the least-valued input [19].

The fire safety concepts tree can now be used to assess the impact of the lack of fire protection around the open staircase. The lack of protection of an egress route stairway results in "route completeness" and "protected path" that are identified as being below standard. Working up the tree to the first OR gate, these two below standard conditions result in below standard "provide movement means". Working up the tree another level is another OR gate where "move exposed" is below standard. The next level up is another OR gate where "safeguard exposed" is below standard. The next level up is another OR gate where "limit amount exposed" becomes below standard, and the final level up is an AND gate which also results in "manage exposed" being below standard.

In comparison, the fire safety concepts tree can now be used to assess the same stairwell with the fire alarm system installed. The inclusion of a fire alarm system in this building results in "detect need", "signal need", and "provide instruction" all being above standard. The next level up is an AND gate and since all three inputs are above average, "cause movement of exposed" is also above average. The next level up is "move exposed" which is another AND gate which requires "provide movement means" and "provide safe destination" to at least be to standard in order for "move exposed" to be at least to standard. This is where a qualitative analysis done using the fire safety concept tree can be useful to formulate an argument that the stairwell with a fire alarm system exceeds the minimum code requirement. Also, since the fire alarm system is an automatic system, it will provide early detection to building occupants of a fire and thus allow for the stairway to be used to evacuate building occupants earlier, before the products of fire make the exit pathway untenable. If this argument is accepted, then all the inputs for the AND gate leading into "provide movement means" can be considered to be standard. Assuming that the stair is constructed of solid wood with the underside covered with plaster or gypsum and the floor plans are set up in such a way to maximize fire compartmentation within the floor area, it could also be argued that all the inputs for "provide safe destination" have also been met satisfactorily resulting in a standard level of safety. With "cause movement of exposed", "provide movement means" and "provide safe destination" all having a standard level of safety, the AND gate for "move exposed" will also be to standard. Going up one level is an OR gate for "safe guard exposed" which also has a standard level and finally, the OR gate for "manage exposed" is also at standard.

In this case, since the heritage office building will be designed and constructed with the added fire alarm system and since traditional construction methods were used, an argument could be made, via assessment with the fire safety concepts tree, that the deficiency caused by the exit stair not being enclosed in a fire rated exit stair shaft has been compensated for by the fire alarm system and the way the building is built.

As can be deduced from the example above, the advantages of the fire safety concepts tree as applied to fire protection in heritage buildings are that

- the fire safety concepts tree is a qualitative guide and easy to use assessment tool;
- it allows alternative solutions and combinations of fire safety measures such as construction materials, combustibility of materials, fire protection devices, fire detection devices, and characteristics of occupants to be evaluated singularly or as a whole in order to identify redundancies and gaps in a design;
- it provides an overall structure with which to analyze the potential impact of fire protection strategies, identify gaps and areas of redundancy in fire protection strategies;
- the concepts tree is a tool that fire protection engineers can use to communicate fire protection concepts to stakeholders when a design is being evaluated;

- it can be used in the analysis of a design and can also be used to study other fire protection codes and standards to determine if a minimum acceptable level of safety is achieved when complying with the code [19]; and
- it can establish the relative importance of various components of a fire protection strategy [45].

Despite the above advantages, however, several disadvantages with using the Fire Safety Concepts Tree also exist. They are:

- the structure of the tree does not adequately consider multiple interactions between fire safety concepts because concepts at the same level in the tree that affect each other cannot be portrayed;
- the temporal aspect of fire development is not represented in the tree. The logic gates stipulate that avoidance of fire casualties can be accomplished by enduring a fire or escaping it. To escape means to move faster than the fire and its products of combustion. An attempt to explain this relationship was directly stated in the example above but there was no mechanism within the tree to demonstrate the importance of this to the defined scenario;
- it cannot deal simultaneously with multiple objectives; and
- the fire safety concepts and scenarios being analyzed by the tree do not consider probabilities of occurrence. As such, the fire safety concepts tree can be described as being more abstract than other fault tree analyses that incorporate probabilities of occurrence [19].

Use of the fire safety concepts tree as an approach to managing fire safety in heritage buildings would require focus on either prevention of fire ignition or management of fire impact. Some of the most common actions that can be taken to prevent fire ignition are to eliminate the improper use of temporary light fixtures, excessive use of extension cords, use of space heaters or heat guns, smoking, and use of open flames [46]. Even if all these fire prevention actions are taken, it is impractical to expect that these measures will be 100% effective [43]. With preventing fire ignition not 100% effective, the approach would turn to managing fire impact. Following the layout of the tree, this can be satisfied by either 'Managing the Fire' or 'Managing the Exposed'. Managing fire through use of fire protection systems that limit fire spread, contain fires or incorporate firefighting equipment in heritage buildings will further reduce the risks and consequences of fires [46]. Managing the exposed, on the other hand, requires a strategy that either 'Limits Amount Exposed' or 'Safeguards Exposed'. It is difficult to 'Limit Amount Exposed' as that would require restricting the number of people or amount of contents in a space which may be impractical when dealing with heritage buildings since many are used as museums. 'Safeguarding the Exposed' is the most common tactic used in building projects and most prescriptive buildings codes and regulations try to achieve this objective. Potential measures that can be used towards this end include use of fire alarm systems, egress systems, fire-resistant elements, fire suppression systems, smoke management systems, fire safety plans, fire emergency organization, emergency lighting, exit signs, and voice communication systems [43].

Based on the assessment above, then, the Fire Safety Concepts Tree, while very useful, appears best suited to evaluate designs that utilize alternative solutions that are trying to achieve a limited number of objectives. In scenarios where multiple objectives must be achieved, multiple fire safety concepts tree analyses will need to be done resulting in a heavy administrative burden for the designer and reviewer. The temporal nature of fire events and how certain fire protection strategies are most effective for early detection and early warning to occupants so they can evacuate are not adequately captured in the tree. Similarly, the probability of a fire occurring, as well as differing probability of different types of fires occurring, is not considered by the tree. Probability is an important factor however, and one that should be considered in fire safety analysis of heritage buildings, since the incremental contribution of various fire protection strategies can impact the overall effectiveness of an alternative solution [19].

The concept of relative risk was introduced in this section and the previous section where the risk of a subject building is compared against a similar building that is compliant with the prescriptive code. In cases where an alternative solution is used, applying the principle of relative risk may be useful in focusing the review of an alternative solution towards identification of potential deficiencies in design and assessing whether the alternative solution has addressed the deficiency; however, it falls short in terms of facilitating evaluation based on the relative probabilities amongst multiple possible scenarios or paths of fire development. Therefore, use of a fire risk index, which is a semi-quantitative assessment tool for comparison of relative fire risk, will be studied in this context in the following section.

2.6.4 **Semi-Quantitative Fire Risk Assessment with Fire Risk Indexing**

Fire Risk Indexing (FRI) is a sub-set of fire risk assessment that links fire science, fire safety and safety culture. Fire safety decisions are often made under conditions where data are sparse and uncertain such that probabilities are difficult, if not impossible, to define. In these situations, FRI can provide a cost effective means of risk evaluation that is useful and valid [47]. When FRI is used to study a heritage building, its design and proposed fire safety features focus on specific building safety parameters. Each building safety parameter, such as fire separations, building size, type of fire alarm to be used, and type of sprinkler system to be used, is evaluated and then assigned its own risk index, a numerical value that is based on the building and site conditions and the proposed design. The fire safety solutions for the proposed design are thus evaluated using professional judgement, experience, latest knowledge in fire safety science and prevailing regulations. The values in a risk index for each parameter can be either positive or negative as appropriate to reflect that the value represents the relative risk for that building safety parameter. The scores for each building safety parameter that is applicable to an analysis are then summed to achieve a single value representing the overall building safety risk. In order to determine a relative ranking of risk for different design solutions, the overall building safety risk value of a subject building can be compared against the overall building safety risk values from the baseline building that complies with the prescriptive requirements of the governing code [48].

Table 1 shows an example of a fire risk index for the building safety parameter of building height with indices referenced to building heights allowed for a particular building area under the prevailing code [49].

Table 1 - Building Safety Parameter Number of Stories [49]

Number of Storeys	Numerical value (per storey)
Each storey above the maximum number of storeys allowed	-5
Complies with prevailing code	0
Each storey below the maximum number of storeys	+5 (maximum value, +10)

When considering a heritage building that is 2 storeys high with a building area of 200 m^2 and used primarily as an office, working through Table 1 would result in a score of +5 for this building safety parameter. This is because the NBC currently allows an office building with a building area of 200 m^2 to have a maximum height of 3 storeys [14]. Had this building been 3 storeys tall with the same building height and occupancy type, working through Table 1 would have resulted in a value of 0 for this fire safety parameter. The difference in value of the index between an office building that is 2 storeys versus 3 storeys in height reflects the fact that a building that is 2 storeys tall would be relatively safer in the event of a fire than a 3 storey building. As can be seen in the above example, the goal of FRI is not to work towards an optimal design of fire protection solution. Rather, the goal is to utilize various methods of analyzing and scoring fire hazards and fire protection and life safety system attributes to produce an estimate of relative fire risk of at least two solutions under evaluation. FRI has been shown to be sufficient for demonstrating that an alternative solution is as safe as, if not safer than a comparable prescriptive solution [50].

One example where FRI method has been applied to evaluate heritage buildings and determine their relative safety is in Wisconsin where the Building Evaluation Method from Chapter ILHR 70 of the Wisconsin Administrative Code is used. This method assesses the relative effectiveness of different designs of fire protection measures in heritage buildings by comparing the building characteristics in the heritage building of interest against what is required by the prevailing building code. The Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code has identified 17 building safety parameters that should be used to evaluate a qualified historic building. They are Number of Storeys, Building Area, Building Setback, Attic Compartmentalization, Firestopping, Mixed Occupancies, Vertical Openings, HVAC Systems, Smoke Detection, Fire Alarms, Smoke Control, Exit Capacity, Dead ends, Maximum Travel, Emergency Lighting, Elevator Control, and Sprinklers. Further, each parameter has its own risk index, where positive and negative values are assigned to building conditions that fall within the scope of that parameter. Based on actual site conditions and the proposed design, a score is determined for each specific building parameter depending on whether the situation exceeds or fails to comply with the requirements of the prevailing prescriptive code [49]. In general, the relative risk is determined by evaluating the building characteristics for the heritage building against a fully prescriptive code compliant building. If a building characteristic in the heritage building has less protection than what is required by the prevailing code, a negative value is assigned to that building parameter. Alternately, if a building characteristic in the heritage building exceeds what is required in the prevailing code, a positive number is assigned. Once all the applicable building characteristics have been assigned a value and those values have been summed together, an overall positive value means the heritage building is compliant with the prevailing codes and a negative number means the building does not provide an equivalent level of fire protection as that specified in the codes [50], in which case additional fire safety measures would have to be implemented.

The main advantages of using a fire risk indexing method are that it is easy to use and it considers a heritage building holistically by considering the status of different building elements within the building as a whole in order to determine the relative risk of the building. The method also entails a systematic review process that allows for a degree of certainty and consistency with respect to design approvals [50].

There are several disadvantages to fire risk indexing. It is criticised for being a qualitative, and potentially subjective, measure of fire safety in which the relationship between the indices and statistical data on fires are not clearly linked. The indices are specified by experts, however the process of specification is often not documented. It is difficult to understand why a specific value is assigned to the building safety parameter and whether or not it can be changed [47]. There are also concerns revolving around the fact that the application of a predefined building attribute ranking system may miss important fire protection concerns and does not include information for specific situations. Potentially important factors that may not be included are

1. Occupant characteristics, such as whether occupants are awake and alert, and familiar with evacuation from the building. These occupant characteristics affect building evacuation and hazard remediation;
2. Fire dynamics related to the expected type of fires that will occur in the building being studied;
3. Fire statistics and the likelihood of fires occurring in the heritage building; and
4. Determination of potential deficiencies since the performance of the heritage building is evaluated as a whole, rather than against a set of specific design features.

From the brief description of the tools above for semi-quantitative fire risk assessment above, fire risk indexing will be investigated further in this thesis. Despite any potential limitations, it is a framework that is effective at comparing relative risk of various design solutions, easy to use and the qualitative nature of this framework will provide the flexibility to create additional fire risk indices to address important fire protection concerns as they arise for project specific situations.

2.6.5 Best method to evaluate alternative solutions

The brief overview of quantitative fire risk assessments, Subsection 2.6.2, showed that it is not ideal for evaluating alternative solutions in heritage rehabilitation projects in Canada due to limited statistical data available for determining the likelihood of fire scenarios occurring and quantification of the consequences of the fire scenarios. The fire protection community has not widely accepted quantitative fire risk assessments due to lack of education and technology transfer to provide necessary data to educate designers and code officials on the use and usefulness of quantitative fire risk assessment methods. The Fire Safety Concepts Tree, a qualitative fire risk assessment method, was easier to use but is also not ideal for use in alternative solutions where multiple objective and function statements need to be met. Fire risk indexing, a semi-quantitative method, appears most suitable for use in heritage rehabilitation applications since it is easy to use, follows a systematic review process that allows for a degree of certainty for approval, and considers a building holistically.

The fire risk indexing method described in the Wisconsin Administrative Code Chapter Industry, Labor and Human Resources (ILHR) 70 Historic Building Code is a logical starting point for this research since it has been in effect in some form or another since 1955 [51]. The Wisconsin Administrative Code Chapter ILHR 70 was selected in this thesis over the more recent Wisconsin Administrative Code - Department of Commerce Chapter Comm 70 Historic Buildings for further investigation because ILHR 70 can be applied to a wider variety of occupancy types in heritage rehabilitation projects [49]. Several municipalities in Wisconsin continue to adopt both these codes when working with heritage buildings [52]. It is postulated here that the disadvantages identified above in Subsection 2.6.4 can be addressed by creating additional fire risk indices to deal with any additional fire safety parameters of concern in Canadian heritage rehabilitation projects.

In this light, it will first be explored whether the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code in its present form is suitable for use in a Canadian context. Case studies will then be undertaken to further evaluate and develop a new fire risk assessment method, based on fire risk indices inspired by the Wisconsin Administrative Code, for Canadian heritage buildings projects. Based on results, recommendations will be made on any changes that would enhance the methodology for use in this country, and a final modified framework for use for heritage rehabilitation projects in Canada will be presented.

2.7 Solution - Fire Protection Framework using Fire Risk Indexing

The flexible fire protection framework for heritage rehabilitation projects proposed in this thesis utilizes fire risk indexing to evaluate alternative solutions. The analysis of existing codes, design frameworks and analysis methods outlined above has found fire risk indexing easy to use and its holistic approach to building evaluation appears to lend itself well to application within the existing Canadian fire protection and heritage protection frameworks. The objective-based nature of the governing building and fire code allows for alternative solutions in building design and the systemic review process based on fire risk indexing allows for some degree of certainty for design approval as fire risk indexing is effective for comparing and communicating relative risk across solution options. Also, fire risk indices can be updated, amended, and created based on the latest information available in order to facilitate on-going improvement of the analysis framework for assessment of alternative fire safety solutions.

To summarize then, the final overall fire protection framework must first establish the overall project objective, and clearly specify the heritage value and character of the building in order to determine what aspects of the building need to be protected. The method for determining the relative risk of the subject building against an alternative solution(s) must be established and demonstrated in order to verify its veracity going forward as an acceptable fire protection framework. For this, a subject building must be compared to a theoretical code compliant building of similar occupancy, height and building area. By comparing the existing heritage building against the theoretical building of similar occupancy, building height and size that is fully compliant with the NBC, potential deficiencies in the heritage building will be identified whilst carrying out the building code review. The functional and objective statements behind the code provisions for any non-compliances will then form the basis for development of an alternative solution that fully satisfies the functional and objective statements. This will be accomplished by use, and/or adaptation as necessary, of fire risk indices included in the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code based on fire science, experience, and available statistical data of fire occurrence. Additional fire risk indices for additional fire safety parameters that should be considered when evaluating an alternative solution will be created as necessary to provide a more accurate evaluation of alternative solutions using the new fire risk index approach proposed below.

The following chapter will elaborate on the steps taken in development of the new FRA framework for fire safety assessment during rehabilitation of heritage buildings. Specific topics in fire science and fire statistics are discussed in order to update or create new fire risk indices to be used in the final version of the framework as well.

3 Methodology

3.1 The Fire Protection Framework for Heritage Rehabilitation Projects in Canada

As stated in earlier chapters, heritage buildings are cultural resources in which the heritage value must be protected. Rehabilitating heritage buildings for modern uses will allow these types of buildings to be utilized and will provide owners with the resources needed to maintain and operate the building. The objective-based code format of the NBC and NFC provides the flexibility needed so that alternative fire safety solutions may be developed for, and utilized in these buildings. However, objective based codes do not provide specific guidance on how to evaluate whether an alternative fire safety solution satisfies the minimum requirements of the code [25]. In order to address this concern, fire risk indexing based on the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code [49] was chosen as the best method to evaluate relative fire risk between an acceptable design solution and an alternative design solution. From this starting point, a new FRA framework is developed for fire safety management of Canadian heritage building rehabilitation projects. Case studies are then employed to demonstrate that the final framework is flexible and consistent for use.

In general, the proposed framework combines heritage feature identification, definition of design objectives, building code analysis, development of alternative solutions and fire risk indexing as follows:

1. Describe the base building characteristics and summarize the heritage value of the building.
2. Create a design brief that states the objectives of the heritage rehabilitation project.
3. Conduct a building and fire code analysis of the proposed design of the heritage building and a theoretical building that complies with the acceptable solutions based on the objective based codes.
4. List all deficiencies that the heritage building has with respect to the acceptable solutions including how they are related to all objective and functional statements.
5. Describe the basis behind the alternative solution.

6. Use fire risk indices to compare the fire safety design for the rehabilitated heritage building and the theoretical acceptable design solution building. Develop new fire risk indices when necessary and when clearly supported by fire safety science or statistics.

The following sections of this chapter outline the key sections of this framework in turn, with discussion of the main elements and major considerations to be addressed at each stage of the analysis.

3.1.1 **Describe Base Building and Determine Heritage Value**

The first step in a heritage rehabilitation project is to describe the base building in terms of building height in storeys, building area (building footprint), building materials, fire protection systems and exiting provisions. Once the building is known, the heritage value of the building needs to be determined based on the official heritage character statement for the building. Pertinent information must be summarized as it relates to aspects of the building which are important from the perspective of heritage preservation. This phase is very important so that all of the project stakeholders understand what the heritage preservation objectives of the project are. Through establishing what can and cannot be altered in a heritage building, the designer can begin working on a design that can balance heritage protection and fire safety.

3.1.2 **Design Brief**

Next, a design brief is created that states all of the objectives of the heritage rehabilitation project. The existing condition of the building may be elaborated on further to establish the initial conditions of the rehabilitation project prior to describing how the building will be used going forward. Any heritage character and features that need to be protected, as identified from the heritage character statement above, must also be stated in the design brief.

3.1.3 **Building and Fire Code Analysis**

The third step is to undertake a building code analysis, and where necessary a fire code analysis, of the rehabilitated heritage building and a code compliant building of similar size, occupancy type and construction type that complies with the acceptable solution under the NBC. A building and fire code analysis is done by working through a building code data sheet or building code matrix similar to one that typically can be found on construction drawings. Table 2 shows the building code data sheet that will be used to compare a fully acceptable solution (ie. code compliant building) and the heritage building being studied. It is based on the building code data sheet that was used by Fire Protection Services Labour Program, Human Resources and Skills Development Canada [53]. Comparison between the code compliant building and heritage building is done this way to make it easier to communicate amongst stakeholders, as well as easier to compare relative risk while at the same time reducing the number of fire risk indices that need to be used out of the 17 building safety parameters from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code.

Table 2 - Modified Building Code Data Sheet for comparing Code Compliant Building and Heritage Building

	Code Compliant Building	Heritage Building	Functional and Objective Statements Attributed to Code Provision
Year of Original Construction			
Major Occupancy Classification(s)			
Governing Code Part			
Fire Resistance rating of floor assemblies (hrs)			
Building Area (m2)			
Building Height (Storeys)			
Cross-over Floors			
High Building (see NBC Article 3.2.6)			
Interconnected floor space			
Mezzanines			
Sprinklers			
Building Faces No. of Streets (for fire department access)			
Type of Construction			
Fire Resistance Rating of Roof Assembly			
Total Building Occupant Load			
Fire Alarm System			
Voice Communication			
Fire Alarm System Monitoring			
Standpipe & Hose			
Emergency Power			
Smoke Control Measures			
Fire Pumps			
Maglocks			
Special Extinguishing Systems			
Water Supply			
Spatial Separations			

Knowing the year of construction, building size, occupancy type and building height provides sufficient information to begin determining the applicable fire protection provisions such as fire resistance ratings, fire alarm system requirements, sprinkler requirements and construction type. The following list elaborates on each row of the Modified Building Code Data Sheet:

- The year of construction refers to when the building was built and gives the designer and reviewer insight into which building code was applied at the time of construction.
- The occupancy classification refers to how the building will be used by the occupants. Occupancy classification will be done using the nomenclature in the NBC.
- Governing code part refers to whether the fire protection requirements in Part 3 or Part 9 of the NBC are to be applied in a particular project. This is determined by knowing the occupancy classification, building area (building footprint), and building height (in storeys).
- The fire resistance rating of floor assemblies refers to the minimum fire resistance rating required by the NBC to separate different floors into separate fire rated compartments. The required minimum fire resistance rating is determined by the building height, building area, construction type, occupancy type, and sprinkler system status.
- The building area refers to the building foot print area and is measured in square meters.
- The building height refers to the number of storeys the building has above grade [14].
- A cross-over floor is a designated floor in a building where occupants in an exit stairwell can re-enter the floor and proceed to another exit stairwell. There cannot be more than 4 storeys separating cross-over floors and the top floor or second to top must also be a cross over floor [54].
- High buildings are defined by the NBC based on building height and occupant load. The building height in this case is the distance measured between grade and the floor of the top storey. High buildings require additional smoke control, fire alarm system monitoring, voice communication, sprinkler system, elevator, emergency power and venting requirements [14].
- Interconnected floor spaces means superimposed floor areas or parts of floor areas in which floor assemblies that are required to be fire separations are penetrated by openings that are not provided with closures. The NBC has specific prescriptive conditions where interconnected floor spaces are permitted [14].

- Mezzanines are intermediate floor assemblies between floor and ceiling of any room or storey and include an interior balcony. The NBC has prescriptive conditions on when mezzanines are permitted and the maximum allowable size a mezzanine is permitted to be before additional fire protection requirements are mandatory such as proper fire resistance rating of floor assemblies and fire separated exit enclosures.
- Sprinkler refers to whether the NBC requires a sprinkler system in the building. This requirement is determined by building height, building area, and occupancy type.
- The "Building faces number of streets" refers to the number of streets the building has direct access to. The number of streets a building faces implies that the fire department has multiple ways to fight a fire incident in the building. The number of streets a building faces will impact the maximum building area permitted for a given occupancy type.
- Type of construction refers to whether or not a degree of fire safety has been attained by the use of non-combustible materials for structural members and other building assemblies. A non-combustible material is defined in the NBC as a material that meets the acceptance criteria of CAN/ULC-S114, "Test for Determination of Non-combustibility in Building Materials" [14].
- The fire resistance of roof assembly refers to the fire resistance rating of the barrier between the top floor and the roof.
- Total occupant load refers to the maximum number of people that can safely occupy the subject building. It is determined by occupancy type and floor area or exit width [14].
- Fire alarm system refers to whether fire alarm system requirements in the NBC apply in this project. All applicable fire alarm system requirements are to be implemented.
- Voice communication system refers to whether the NBC requirement for additional communication functions are required in the fire alarm system. Voice communication in this case allows for two way communication between the central alarm and control facility or mechanical control centre,

and each floor. The central alarm and control facility will also have the ability to control loudspeakers so that messages can be transmitted to all parts of the building.

- Fire alarm system monitoring refers to whether the NBC requirement for the fire alarm system to be monitored is applicable for a project. Fire alarm system monitoring is a separate function to the fire alarm system and it can be delivered by having fire alarm signals transmitted directly to the fire department or an accredited third party fire alarm signal receiving centre.
- The standpipe and hose system refers to whether a standpipe and hose system is required in the building. A standpipe and hose system is defined as “An arrangement of piping, valves, hose connections and allied equipment installed in a building or structure, with the hose connections located in such a manner that water can be discharged in streams through attached hose and nozzles, for the purposes of extinguishing a fire, thereby protecting a building or structure and its contents in addition to protecting the occupants. This is accomplished by means of connections to water supply systems or by means of pump tanks and other equipment necessary to provide an adequate supply of water to the hose connections" [55]. The NBC prescribes when a standpipe and hose system is required for a proposed project.
- Emergency power refers to the minimum time a back-up power supply must be capable of supplying power for building life safety systems. The NBC specifies the minimum time the back-up power supply must be rated for and which life safety systems need to be powered by the back-up power supply. Emergency power can be supplied from batteries or emergency generators.
- Smoke control measures refer to whether the NBC requires this capability in the subject building. Smoke control measures refer to engineered systems that can be used singly or in combination to modify smoke movement [56].
- Fire pumps refer to specifically designed and listed mechanical pumps that provide adequate pressure and water supply to the water-based fire suppression systems in the building. Whether this is required by the NBC in the subject building should be identified in the building code data sheet.

- Mag locks refer to whether electromagnetic locks will be used in the building. The NBC has specific requirements that accompany electromagnetic locks such as fire alarm system requirements, door hardware and door operation requirements.
- Special extinguishing systems refer to whether special fire suppression systems that are not sprinklers will be installed in the building. These types of systems are specified where water based system may damage the contents within a space, such as in server rooms and art galleries.
- Water supply refers to whether the building is provided with adequate water supply to facilitate firefighting needs. The NBC specifies what water supply will be required in a specific situation.
- Spatial separations refers to the distance between the subject building and an adjacent building, as fire from a neighbouring building can affect the subject building and vice versa. The NBC requirements ensure that there is a minimum distance between adjacent fire compartments to minimize the risk of fire spreading from one building to another. Distances vary depending on whether a fire separation with the required fire resistance rating is present and whether openings within the fire separation are protected or not [14].

With this information filled in for the subject building, the building code data sheet captures the basic information that is relevant to designers and AHJs. It also provides a systematic manner by which to document those building code requirements that are applicable and must be implemented for each design to comply with the appropriate code or set of codes in force at the time of rehabilitation.

3.1.4 **Tracking Deficiencies**

The "acceptable solutions" derived in the NBC and NFC at the time of the rehabilitation project are to be used when filling out the "Code Compliant Building" column in Table 2. This establishes the baseline against which the relative risk comparison is conducted. The analysis of the heritage building will be done by noting the actual building conditions and characteristics that exist. It must be emphasized that the information recorded in Table 2 does not provide a comprehensive list of deficiencies that may arise in a building code review. Additional fire safety deficiencies not covered by the building code data sheet above must also be identified and recorded so that the stakeholders are aware of all deficiencies that require attention in the building. Table 3 shows one example of a second table that should be used to track all the fire protection deficiencies that exist in the building being studied. In this Table, each non-conformance to the acceptable solution is summarized and entered, then the code provision reference is recorded along with the corresponding functional and objective statements attributed to that code provision which for ease of later use and communication can be expanded in full. With the deficiencies summarized and connected to the corresponding code provisions and matching functional and objective statements, the designer will know what the alternative solution must address in order to obtain approval from the AHJ.

Table 3 - Sample table to track fire protection deficiencies

Item	Non-Conformance	Code Requirements	Functional and Objective Statements Attributed to Code Provision
1	Exit doors swing in.	9.9.6.5 - Except for doors serving a single dwelling unit, exit doors that are required to swing, shall swing in the direction of exit travel.	**[F10-OS3.7]** F10 - To facilitate the timely movement of persons to a safe place in an emergency. OS3.7 - An objective of this Code is to limit the probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency.

3.1.5 **Alternative Solution**

Protection of heritage features of a building is often the primary reason why simple compliance with the acceptable solution outlined in the objective-based codes is not possible. Therefore, once the deficiencies are identified the designer will develop an alternative solution, explain the rationale behind the proposed solution(s), acknowledge the functional and objective statements that have been identified as part of the existing deficiencies, and explain how the alternative solution addresses the functional and objective statements. All assumptions and idealizations for the alternative solution must also be clearly stated so that the AHJ can understand the basis of design. As in the example with the open staircase discussed in Subsection 2.6.3, alternative solutions may include incorporating fire protection systems that exceed the minimum requirements of the acceptable solution. After the alternative solution is designed, its conformance with the acceptable (prescriptive) code solution is analyzed using the new fire risk index which is outlined in the following section.

3.1.6 Analyze the Alternative Solution by Applying Fire Risk Indexing

The final stage of evaluating the alternative solution for the heritage rehabilitation project, therefore, is to use the fire risk indices to determine its final score as it relates to a risk index for the comparable code compliant building. For this, the indices from the building safety parameters of the Building Evaluation Method of the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code are first applied. Following this and where applicable, any amendments to the Wisconsin fire risk indices are developed based on additional building safety parameters and used to fully evaluate the alternative solution for the heritage rehabilitation project as will be discussed in Section 3.2 below.

For the initial analysis, Table 4 shows the full Building Evaluation Table from the Wisconsin Administrative Code Chapter ILHR 70 that would be used to evaluate an alternative solution from the point of view of fire safety, means of egress and general safety. Each empty cell in the Table would be populated with the value of index applicable to the level of compliance associated with the corresponding attribute for the heritage building, and the total compared to the value obtained for the same analysis applied to the compliant reference building.

Table 4 - Building Evaluation Table from the Wisconsin Administrative Code Chapter ILHR 70 [49].

Safety Parameters	Fire Safety	Means of Egress	General Safety	Comments
1. Number of Storeys				
2. Building Area				
3. Building Setback		N/A		
4. Attic Compartmentalization		N/A		
5. Firestopping		N/A		
6. Mixed Occupancies		N/A		
7. Vertical Openings				
8. HVAC Systems				
9. Smoke Detection				
10. Fire Alarm System				
11. Smoke Control	N/A			
12. Exit Capacity	N/A			
13. Dead Ends	N/A			
14. Maximum Travel Distance	N/A			
15. Emergency Power	N/A			
16. Elevator Control				
17. Sprinklers				

In this thesis, not all 17 fire risk indices will be used when summing up the table. Instead, only fire risk indices that are associated with addressing instances of non-conformance between acceptable and alternative solutions will be recorded in the Table above. This approach is used because there is no difference in value of the fire risk index between the code compliant and actual building in areas where the building exactly complies with the acceptable solution specified in the prevailing code. This approach is also adopted because it identifies positive features (credits) but perhaps more importantly isolates and highlights the fire safety deficiencies and captures the impact that proposed alternative solutions have on the overall fire safety of the rehabilitated building. By summing the scores from all the applicable fire risk indices related to the deficiencies and credits related to the alternative solution, stakeholders can see and compare what impact deficiencies have on the overall building and whether the alternative solution has addressed them or not. If the summation in the Table above has a value greater than or equal to zero, the heritage building with the alternative solution could be deemed to provide an equivalent level of safety and protection as the code compliant building. A higher magnitude of the final value does not necessarily mean the building is significantly safer, instead, what the Table above shows is whether the alternative solution, as applied in addressing the deficiency results in a relative risk that is equivalent to that in a building that complies with the acceptable solution.

It is expected that each alternative solution for each heritage rehabilitation project may need to utilize a different set of fire risk indices based on site specific conditions, availability of statistics and experience of the designer. Thus it is important that as a framework such as that described above is adopted and used, the decisions made and conclusions on the validity of the fire risk indices and assessment methodology should be documented in order to improve the proposed method over the longer term as well.

It was also recognized at this point in development of the proposed fire risk assessment framework that, in addition to the building safety parameters included in the Wisconsin Administrative Code Chapter ILHR 70, additional parameters with associated fire risk indices might need to be developed due to the unique nature of many heritage building rehabilitation projects. These indices may be taken from concepts based in fire science, they may relate to human behaviour in fire, or they may be derived from fire statistics depending on the information that is available. Use of such information may also require modification of the existing 17 fire safety parameters from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code. In addition to documenting the above decisions then, central documentation pertaining to development of any new or modified fire risk indices would also be extremely helpful in establishing and refining fire risk indices for the new fire risk assessment framework for Canadian heritage rehabilitation projects proposed above.

3.2 Considerations for Fire Risk Indexing

A new fire risk assessment system and methodology for heritage rehabilitation projects has been established as described in Section 3.1. Preliminary investigations into use of the method, showed that for certain cases, the full spectrum of fire safety considerations was not explicitly accounted for in the existing Wisconsin indices suggesting that the method could be further improved through the creation of new fire risk indices that might relate to specific rehabilitation projects. The important additional considerations can be broadly grouped into categories related to occupant activities, fire dynamics, fire resistance ratings, occupancy separations, exiting capacity and fire alarm systems. The background for, and development of proposed new indices related to each of these categories are discussed in the sections below.

3.2.1 Development of Occupant Activities Risk Index

The Building Evaluation Method of the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code does not include any information or risk indices related to the activities of the occupants in a heritage building after it is rehabilitated. Yet, it is well known that there are direct relations between the activities of building occupants and use of the building with the likelihood and impacts of fires [16]. For example, the day-to-day activities of the occupants may directly affect the probability of fires occurring. Fire safety plans and training, and thus occupant actions during a fire, may reduce the impact of the fire and increase the probability of safe evacuation by building occupants. Therefore, a fire risk index that takes into consideration key aspects of occupant activity and fire safety planning was developed for inclusion in the overall fire risk assessment framework. Development of this index was twofold - one portion was based on fire statistics related to occupant activities within a structure and the other on the level of fire safety planning and training as related to occupant evacuation. Background for development of these form the subject of next three sections, leading to a final section in which the overall risk index is outlined.

3.2.1.1 Fire Statistics

There is no question that specific activities that are, or are not undertaken by occupants in a building may impact the probability of a fire occurring on that site [16]. There are also inherent assumptions within the code as to how occupants will ‘normally’ function within a space. For example, the NBC and NFC do not deal with fire hazards that can be encountered in day to day building operation due to poor process control or housekeeping. Instead, the NFC generally focuses on fire hazards related to specific functions in larger commercial and industrial operations such as indoor and outdoor storage; the storage, handling, use and processing of flammable and combustible liquids; specific processes and operations that involve a risk from explosion, or high flammability zones or related conditions that create a particular hazard to life safety [14]. Once a building is occupied, there are no provisions in either the NBC or NFC that explicitly prevent occupants from cooking, smoking, using candles, or using space heaters in a building. Finally, it is implicitly assumed across the legislation that all occupants and building owners will comply with all applicable warrantees, codes and legislation in terms of maintaining fire protection devices, equipment and systems as well as with respect to how dangerous goods are handled and stored if they are used on the premises.

As a first stage in development and use of an appropriate fire risk index to account for the potential impacts (positive or negative) of occupant actions on building fire safety, applicable fire statistics for the intended building type and use must be found and analyzed. These can then be used to estimate the type(s) of fires that can potentially occur within a certain space, the likelihood that each of these types of fire might occur and the severity of loss and damage (consequence) should they occur. While such statistics will vary from province to province in Canada, the buildings being studied in the analyses and case studies related to this thesis are all located in Ontario. Thus, fire statistics available from the Office of the Fire Marshal and Emergency Management (OFMEM) in Ontario are outlined below and used in the following discussion. From 2011 to 2015, there were 36,508 structure fires which resulted in injury, fatality or dollar loss as reported to the OFMEM in the province of Ontario [57]. Table 5 shows the distribution of these fires across the different property classes. In addition, Table 6 lists the different types of ignition sources reported, and the percentage of fire initiated by each ignition source from 2011 to 2015.

Table 5 - Loss Fires Property Class: Structure only [57]

Property Class	Percentage distribution of structure loss fires in Ontario from 2011-2015
Group A - Assembly Occupancies	4 %
Group B - Care and Detention Occupancies	1 %
Group C - Residential Occupancies	73 %
Group D - Business and Personal Services Occupancies	3 %
Group E - Mercantile Occupancies	4 %
Group F -Industrial Occupancies	7 %
Properties not classified by the OBC	8%

Table 6 - Structure fires: Ignition Source [57]

Ignition Source	Percentage distribution of Ignition Sources in Structure Fires in Ontario
Arson/Vandalism	9 %
Cooking	18 %
Miscellaneous (exposure fires, natural causes, chemical reactions)	11 %
Heating/cooling	8 %
Electrical distribution equipment – wiring	9 %
Cigarettes	7 %
Appliances	5 %
Other open flame tools (excluding matches, lighters)	3 %
Other electrical or mechanical	4 %
Candles	2 %
Lighting (excluding candles)	2 %
Matches or lighters	1%
Processing equipment	1 %
Undetermined	20%

Each type of ignition source listed in Table 6 can be cross-correlated with the property classes in which fires took place. This was done for the fire statistics registered for 2015. It was found that: 91% of the fires that were ignited by cooking equipment occurred in residential occupancies, as did 67% of the fires that were ignited by electrical distribution equipment, 82% of fires that were ignited by heating equipment, 89% of fires that were ignited by lit smoking materials (cigarettes, cigars, pipes, excluding matches or lighters), 82% of fires that were ignited by appliances, and 97% of fires that were ignited by candles [57].

Clearly, the majority of fires occurred in residential occupancies and thus the majority of the common fire ignition sources are related to the fires in residential occupancies as well [4]. On the other hand, the majority of heritage buildings being studied in this thesis are used as Group A: Assembly and Group D: Business and Personal Services occupancies [4]. For these building categories, the incidence of structure fires with loss was much lower than that in residences - only 4% and 3% of all fires respectively. Further, it is reasonable to extrapolate that the probability of fire occurring in heritage buildings is significantly lower than these statistics indicate since common ignition sources are minimized. In this thesis, heritage facilities are non-smoking, contain minimal to no cooking equipment, and have properly installed and maintained building HVAC systems so space heaters do not need to be used [59].

To investigate this further, the risk and probability of fires occurring in office and assembly type occupancies in Government of Canada occupied spaces were researched in more detail. It was found that the potential for ignition and fire was indeed reduced in these occupancies through policies and activities that are targeted to address and mitigate 76% of the common ignition sources in these buildings types, as listed in the statistics above. For example,

1. The 9% probability and impacts from fires caused by arson and vandalism is reduced in federal heritage buildings since they are monitored by a security system or fire alarm system. Even if a fire was started, the fire situation will be detected and the fire department will respond quickly limiting the damage the fire can cause. With the building being occupied, the exterior of the building is maintained and better lit making the heritage building a less attractive target for vandalism and arson than many other structures [58].
2. The majority of federal work places do not contain cooking equipment like stovetops, but instead are typically equipped with a microwave and fridge [59]. This mitigates the potential for the 18% of fires that are normally ignited by cooking equipment and cause damage to a building, however, since microwaves and fridges are both electrical equipment (see point 7 below) this risk of fire would not be fully eliminated.

3. The 11% of fires caused by exposure to fires in neighbouring structures or fires due to natural causes can be greatly reduced if heritage buildings are located in the middle of a park where the grass is properly maintained and there are no buildings close enough to pose an exposure protection risk. In urban settings, the situation is clearly different but a building can be protected from exposure risks with fire walls or other means.
4. The 8% of fires caused by heating and cooling systems may be mitigated since Heating, Ventilation and Air Conditioning (HVAC) systems in heritage buildings are specifically designed to support the occupancy type, occupant load and expected operations. It is also expected that the heating and cooling systems are professionally managed in federal buildings alleviating uncertainty that could otherwise be associated with their state of maintenance and repair.
5. The 9 % of fires caused by electrical wiring and distribution can be effectively mitigated when wiring is upgraded to the most recent standards under the Canadian Electrical Code and the electrical system is designed to accommodate the proposed use of the building. This upgrading and proper design of wiring should reduce the probability of specific circuits being overloaded. The probability of an electrical fire is further reduced if regular visual safety inspections are carried out since these would quickly identify and correct hazardous conditions such as overloaded electrical outlets, extension cords used as permanent wiring, and "daisy-chaining" power strips to power appliances and equipment beyond the original electrical design for the building;
6. The 7% of fires caused by cigarettes is effectively eliminated in public buildings since most public spaces are now mandated as smoke free environment.
7. The 7% of fires caused by appliances and lighting is lessened by the policy of the Government of Canada to only procure appliances and equipment that have been listed and labelled by an accredited certification organization such as ULC.
8. The 7% of fires caused by open flames, candles, matches and lighters are mitigated as these are not permitted in an office occupancy except under exceptional circumstances such as birthday cakes and

smudging ceremonies for First Nations clients. Under those circumstances, the open fire sources (candles, etc) are monitored closely so that risk of ignition of surrounding materials is minimized.

This analysis of current fire statistics in Ontario coupled with knowledge of primary building functions and existing policies for Canadian federal heritage buildings, point towards creation of a new fire risk index to account for how existing measures might mitigate the risk of fire. As appropriate, then, these factors could be included in the overall fire risk index methodology for assessment of fire safety design for heritage buildings. Before defining the final proposed occupant activity index further, several other considerations related to occupant activity also merit discussion.

3.2.1.2 **Fire Safety Planning and Evacuation**

Another consideration important in evaluation of occupant activity as related to alternative fire safety solutions in heritage buildings relates to the existence of fire safety organization and planning measures for many public spaces and their impact on occupant evacuation in a fire situation. It is known that there is significant room to use good fire safety planning and fire emergency organization to enhance fire safety in an occupied space [60]; however, this aspect of a fire safety design is generally not recognized as pertinent in a code-based solution. This is most probably because there can be widely varying degrees of implementation of a fire safety plan, although, perhaps equally, it could be argued that if credit were given to good planning and execution, implementation would be more consistent as well. At the present time, one can assume the minimum - that fire safety plans will describe the procedures to be followed in a fire emergency according to guidance contained in the NFC as to the following:

- What types of occupancies are required to have a fire safety plan,
- The role of supervisory staff in providing instruction to building occupants, assist vulnerable persons with movement to an area of safety, initiate smoke control or fire emergency systems, and facilitate fire department access,
- Emergency procedures to follow in event of a fire

- Assemble floor plans, diagrams showing the type, location, and operation of the building emergency system, and shut off valves and switches for building utilities as documents within the plan,
- Establish the frequency of fire drills,
- Control of fire hazards in the building, and
- Provision of alternative measures for the safety of occupants during any shutdown of fire protection equipment or system [15].

In contrast to practice in many organizations, in work spaces that are federally regulated the NFC and the Canada Labour Code (CLC) Part II - Health and Safety Regulations prescribe how fire safety planning is to be implemented through their incorporation into the Treasury Board Standard for Fire Safety Planning and Emergency Organization - Chapter 3-1. This standard establishes the minimum requirements for fire safety plans including the organization of designated staff for fire emergency purposes, designation of people who are responsible for fire safety planning in Government of Canada workplaces, and how the planning should be initiated and implemented [60]. One aspect is a very detailed description of members of the fire emergency organization for each space and their roles and responsibilities such as floor wardens and monitors for persons with mobility impairments. Another unique aspect of the Treasury Board Standard is the section mandating regular inspections of the work space to reduce fire hazards. Typically carried out by members of the fire emergency organization, these proactive actions can reduce the chance of fires starting or increase the chance that engineered systems, such as fire doors, can work as designed. Since these measures exist and are well documented for federal government buildings in Canada, it needs to be assessed whether and how they could be accounted for in the overall fire risk index methodology via an occupant activity risk index as well.

3.2.1.3 **Evacuation Time and Occupant Factors Affecting Evacuation**

In addition to having a fire safety plan and emergency organization in place, any factors which directly impact evacuation time constitute further important considerations in determining the level of fire safety in an occupied space [61] and could therefore also be included in any new occupant activity index. One way this can be done is via the general procedures used in calculating evacuation time. Determining evacuation time starts at what is commonly referred to as Required Safe Egress Time (RSET). This is calculated by adding the following time intervals together:

1. Detection Time - the time between fire ignition and the first detection of the fire by a device or an individual.
2. Alarm Time - the time between the detection of the fire and the time at which an alarm signal is activated or notification takes place.
3. Pre-movement Time - the time it takes a fire alarm signal to be perceived and understood as indicating that there is a fire emergency and evacuation begins.
4. Movement Time - the time when evacuation starts and extending until the time when all occupants reach a place of safety [62].

In the present analysis, the positive and negative impacts of installed systems on detection time and alarm time will not be discussed since they arise during later discussion of the fire indices that are directly associated with those systems. Movement time is also not considered here; it remains unchanged between a code compliant and any other fire safety solution, since it begins at the time when an evacuation starts and extends to the time when all occupants reach a place of safety [62]. Therefore, pre-movement time is of most importance with respect to assessment of potential occupant factors and actions that could affect safe egress in the event of a fire. This is of particular interest in this work since pre-movement times are known to vary amongst different occupants and in different situations [63], but also because measures can be implemented to reduce pre-movement times during occupant evacuation as discussed below [63].

Studies have shown that there is some delay between perception of fire cues and evacuation and that there are several factors that affect pre-movement time for building occupants. For example, pre-movement times are longest when recognition of a fire event relies on occupants understanding fire cues such as smelling something burning or seeing smoke. Such cues are very ambiguous, and tends to slow perception of fire since they prompt an investigation response rather than a move towards evacuation of the space. On the other hand, a fire alarm is effective at alerting people that something might be happening although it is conversely known that depending on occupant training, and the history of alarms in a given establishment, fire alarms may sometimes be ignored for a period of time until occupants are cued in some other manner. This is particularly true for people who are committed to a task, since they tend to take a longer time to turn their attention toward an unexpected situation, particularly if the cues are not direct and meaningful [61]. Obtaining a warning delivered directly by others appears to be perceived as a better indication that there is an actual problem. For example, messages delivered through a voice communication system or directly by staff seem to be the signals that are taken most seriously by occupants as indicating a requirement to promptly leave the area. Thus, a good fire safety plan and a trained fire emergency team can facilitate quicker response and evacuation of building occupants, as well as earlier notification of the fire department, in the event of a fire [61].

Following identification of a fire event, many factors impact occupant behaviour and response. One of these relates to building characteristics. Occupants need time to gather information on their surroundings, building layout, and wayfinding prior to processing them and devising a plan of action [61]. Therefore, building occupants who are familiar with a building and emergency procedures are more likely to start evacuation rapidly [63]. Similarly, visual access to general activity within a space allows building occupants to observe the behaviour of others and more quickly interpret fire cues. Activation of visual signal devices and signs directing occupants to the nearest and alternate exits similarly reduce the time required to respond and take action in the event of fire. Thus level of familiarity with a building, visual access, and installation of good signage could also be taken into account in assessing overall level of fire risk related to occupant activity in heritage buildings.

As noted above, training of both staff and potentially also occupants is critical to a fast occupant response. Effective fire emergency planning requires organization and training of staff that is tailored directly to the necessary evacuation procedures for each building. It must also involve sufficient numbers of trained personnel to execute their responsibilities in terms of prompting and facilitating evacuation of building occupants. Implementing such measures is of paramount importance because the speed with which occupants will respond to the fire alarm or other fire cues is largely dependent on their status in the building and the behaviour and instruction of staff [61]. This has always been recognized as being of critical importance in public buildings such as museums, malls, passenger terminals, and campuses where occupants are unlikely to be trained for evacuation and are reliant on being instructed on what actions to take [63]. In these situations as well, it is usually recognized that building occupants may have some physical, perceptual, or intellectual limitations, which may extend their response time to begin evacuation. The proportion of occupants with limitations is normally estimated and managed as part of an effective fire safety management plan. This would generally be the case for federal heritage buildings as well [61].

From the discussion in the sections above, it is evident that occupant activities and fire risk are related in several key areas. First, any actions taken to lower the probability of occurrence of fire incidents that go above and beyond the minimum requirements will make a building relatively safer than one in which only the minimum requirements in the codes were met. Secondly, pre-movement time in a fire situation can be reduced by having a well designed fire safety plan and occupants well organized and trained on specific actions to take in a fire emergency. Practicing evacuation will reduce pre-movement time, as occupants who are familiar with a building and emergency procedures are more likely to start evacuation quickly [63]. Finally, spaces that are designed with clear wayfinding and maximum visual access to activities of other building occupants will also improve egress time in event of an emergency. A fire risk index that considers these proactive steps to improve fire safety and reduce evacuation time will be proposed in the following subsection and tested in subsequent case studies to determine if it is appropriate for inclusion as a fire risk index in the present methodology for assessment of fire risk in heritage buildings.

3.2.1.4 **Occupant Activities Risk Index**

In this section, a fire risk index is developed to account for the many measures that can be taken by building occupants to reduce the probability of fires occurring, to reduce the impact fires should one occur, and/or to increase the probability of safe evacuation by building occupants during a fire. Table 7 shows the proposed new fire risk index for Occupant Activities. The rationale behind this fire risk index is centred on existing policies for fire safety management in Canadian Government buildings, including heritage buildings. The intent of adding this index into the overall analysis framework is to capture the positive effects on fire safety that result from proactive policies towards eliminating the most common fire ignition sources, from actions taken to eliminate fire hazards and from policies, training and actions that facilitate quicker evacuation in the event of a fire. The values of each was chosen to mirror the approximate percentage of fires attributed to certain ignition categories based on the statistical analysis outlined in Section 3.2.1.1. Therefore, since 14 % of fires were caused by cigarettes and open flames and another 18% by cooking, scores of 0.14 and 0.18 were assigned as indices related to fires caused by open flames (including cigarettes) and cooking respectively.

In federal work spaces, heating and cooling is managed by the building automation system. Use of individual space heaters is prohibited except for instances of duty to accommodate requests for medical reasons. In instances where individual space heaters are warranted, the employer provides an appropriate space heater that is listed and labelled by an accredited certification organization. While this potential ignition source is generally eliminated or tightly monitored, a score of 0.1 was assigned to indicate that there is still some small potential risk of fire due to use of space heaters.

Several aspects of the modest benefits to fire prevention and evacuation from a fire emergency organization that is well trained and building occupants who know what to do in an emergency have been captured in the remaining index values based on results from various evacuation studies [61]. Federal heritage buildings will have a fire emergency organization that includes personnel trained to facilitate evacuation and eliminate fire hazards, as well as oftentimes occupants trained in emergency procedures and evacuation, so scores of 0.1, 0.15 and 0.15 have been applied respectively for each of these categories of occupant ‘activity’.

Finally, the positive effects to timely evacuation when building occupants are awake and alert, and familiar with the building, have also been recognized and been assigned a value of 0.1 for each action. Table 7 shows the new Occupant Activities risk index.

Table 7 - Occupant Activities Risk Index

Occupant Activities Risk Index (Cumulative)	Numerical Value
No smoking and no open flames	0.14
No cooking	0.18
Use of space heaters and heat generating appliances tightly controlled	0.1
Fire emergency organization trained to identify and remediate fire hazards	0.1
Fire emergency organization facilitates emergency evacuation	0.15
Occupants trained in emergency procedure and evacuation	0.15
Awake and alert	0.1
Familiar with the building	0.1

The values for each occupant action is assigned a small value so that any and all actions taken by occupants to enhance fire safety within a heritage building are cumulative. Taken together they will not compensate for serious deficiencies that might be discovered during a building code analysis. Instead, they will have to be coupled with other fire safety design features and actions to generate the alternative solutions needed in order to fully compensate for potential deficiencies in particular heritage buildings.

3.2.2 **Fire Dynamics**

Recent advances that have taken place in fire science lead to another set of factors that can potentially be considered in proposing updates to existing fire risk indices or creation of new fire risk indices to be used in assessment of fire safety of heritage buildings. Fire dynamics is the study of how a fire is expected to burn, grow and spread in a building leading to various theories that are available for fire protection engineers to use in the design and evaluation of alternative solutions. Having an overall understanding of fire behaviour and recent progress in this area will allow the designer to assess the types of fires that might occur within a structure, as well as to develop and evaluate strategies to slow the growth, and thus regard the spread, of fires.

3.2.2.1 **Design Fire**

One of the key components of modeling a fire is defining an appropriate 'design fire' on which to base the potential fire scenarios of interest and against which to optimize the final fire safety system design for that building. In simplest terms, design fires can be one of three main types: smouldering fires, flaming fires or fully developed (post flashover) fires. Which of these types of fire is determined to be most likely for a given building will definitely affect any assumptions about the details of fire growth and development and thus is inherently linked to the strategies chosen in design of the building fire safety systems. Despite the importance of the 'design fire' in performance based design, the Building Evaluation Method of the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code does not include any information by which to distinguish relative risk in relation to the anticipated types of fires that might be encountered in a heritage building. To address this, it is proposed here to develop a new risk index for Expected Fire Type and to include that index in the overall fire risk assessment framework being developed here for heritage buildings. This is based on fundamental concepts of fire dynamics, as discussed below.

Oxygen, heat and fuel are the three necessary components to sustain a fire, which is a chemical reaction that occurs when fuel is exposed to enough heat that fuel vapour is produced and mixed with enough air to maintain a flame. The chemical reaction between the fuel and air provides the necessary heat to maintain the fire [64]. In a structure, the fire can interact with a compartment in different ways, but for the purposes of this thesis, a 2-layer model of compartment fire development is assumed. In this model, the situation is idealized such that it is assumed that a hot gas layer forms near the ceiling that descends with time as the fire plume gases continue to flow upwards. Near the floor, is a cool lower layer of predominantly fresh air. The model further assumes that the compositions of each of these layers is uniform with a sharp demarcation between the hot upper layer and the air in the lower part of the compartment. Transfer between the two layers occurs via the fire plume [65].

Examining a fire further, compartment fires generally go through 4 stages:

1. Fire plume/ceiling jet stage - where air is mixed with the fuel that is released from the fuel surface, enters the flame region and burns. The energy released increases the temperature of the combustion products or smoke and reduces the density so that it rises above the surrounding air in a fire plume. Air continues to mix into the fire plume causing the temperature and smoke concentration to decrease while the volume of smoke increases with increasing height. When the plume reaches the ceiling it turns and spreads out radially beneath the ceiling as a thin layer known as a ceiling jet.
2. Enclosure smoke filling stage - where smoke begins to accumulate underneath the ceiling and after the ceiling jet reaches the compartment boundary, it turns downward. Smoke is injected into the developing smoke layer through the fire plume and the smoke layer interface will descend until there is an opening for smoke to escape or the smoke layer reaches the floor.
3. Pre-flashover vented stage - where the hot smoke layer descends to an elevation that it reaches openings in the compartment walls and the compartment is vented. Smoke flows from the compartment into the adjacent space and air flows into the room with a balanced flow rate.
4. Post flashover vented stage - where the smoke layer reaches a temperature sufficient to cause the radiant ignition of exposed combustible surfaces within the compartment. This is typically achieved when the smoke layer reaches 600 ˚C [66].

Figure 6 schematically illustrates the time history of a fuel limited fire, which is often shown as a representative fire development curve.

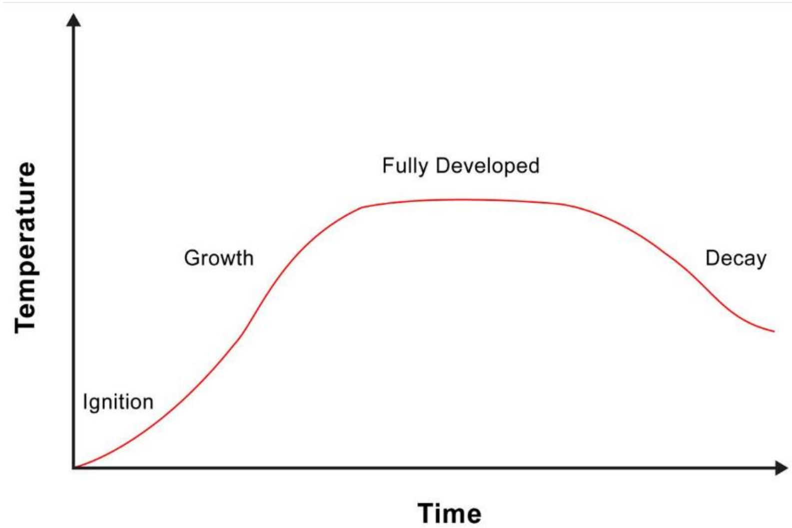

Figure 6 - Traditional Fire Development Curve of temperature over time [67]

Stages 1 to 3 characterize the ignition and growth stages of the fire. Stage 4 is the full developed portion of the curve. As the fuel is then consumed, the fire runs out of new fuel to sustain the combustion process and the fire begins to decay [67]. Despite the utility of this curve to discuss general principles of fire development, it must be cautioned that this is an idealized picture of the evolution of a well ventilated fire, ie. a fire for which there is always sufficient air available that the fire development remains limited by the availability of fuel vapour (rather than availability of air) throughout its life.

The NBC presumes there is only one fire at any given time in a structure or compartment [14] and the appropriate design fire behaves in accordance with the "Standard Fire" curve [68] which was developed for fire resistance testing (Section 3.2.2.2 below) and is illustrated as the blue curve in Figure 7 [72]. Although having a different curve than that shown in Figure 6 above, the standard fire curve is again based on how a fire would behave in a room if there is sufficient fuel and ventilation that its development was not restricted by availability of air [72]. In reality, fires are affected by fuel load and orientation, room geometry and ventilation meaning that the time-temperature curve of an actual fire may be quite different from either of the above mentioned fire curves. Development of more simplified curves is necessary for fire safety design however, because of the almost infinite variability due to changes in fuel supply, compartment ventilation and interior finishes. As a result, current prescriptive fire protection practices generally do not account very well for realistic thermal effects due to fire, but instead attempt to err on the side of defining a conservative design fire which may lead to inefficient, uneconomical, and even sometimes inadequate, design solutions [69].

One example of a fire that does not follow either of the simplified time-temperature fire curves is shown in Figure 7 as the smouldering fire curve. After ignition, fires may smoulder for a period of time before developing into a flaming stage [70]. Smouldering fires begin with a slow, low-temperature, and flameless combustion process where oxygen attacks the surface of a solid fuel such as coal, wood, cotton, polymers, and cellulose. Smouldering fires can begin on their own through self-oxidation processes or can be initiated by specific heat sources like discarded cigarettes or overheated wiring. The oxidation produces smoke (including common gaseous combustion produces) and generally small amounts of heat leading an initial period of low temperature increase. As smouldering continues unchecked, flames will begin to appear and a flaming fire can start. If the fire progresses, it may eventually follow a time-temperature curve with a shape similar to the green curve in Figure 7 [71].

In other fire situations there may be abundant fuel that can ignite and form fuel vapours quickly (for example, a flammable liquid fire). This will result in a fast flaming fire and thus potentially shortens the time to flashover [42]. A time-temperature development curve for this so-called "fast flaming fire" is also plotted against the standard fire and smouldering fire in Figure 7 from initiation until they approach the fully developed stage.

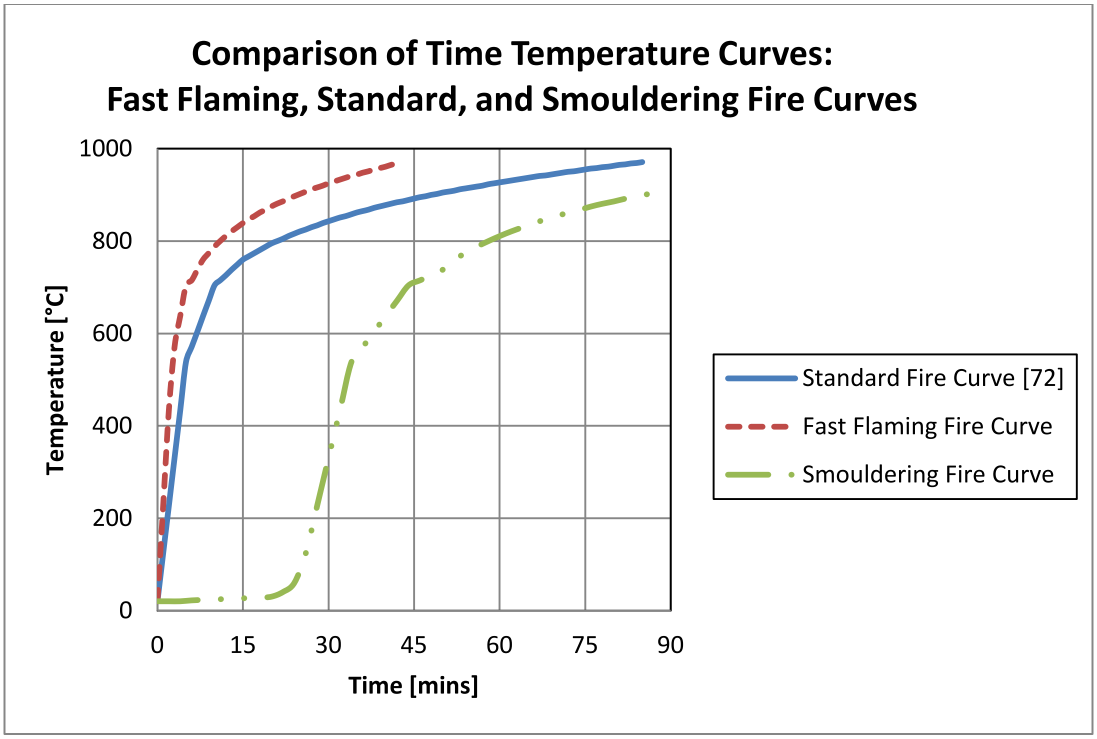

Figure 7 - Comparison of Time Temperature Curves: Fast Flaming, Standard and Smouldering Fire Curves

The probability of a fire reaching flashover and the time it takes for flashover to occur varies. In Canada, statistics suggest that 24% of all office fires reach flashover and become fully developed fires, 54 % are flaming fires that do not reach flashover and the remaining 22% are smouldering fires that do not reach the flaming stage [42]. Consideration should also be given in the fire risk index to the rate of injuries and death from smouldering and fast flaming fires however, fire statistics information is not captured in this way [57]. Fire type information can be inferred from the causes of fire, such as fires caused by smoking might be assumed to be smouldering fires however, since the rate of injury and death from smouldering and fast flaming fires are presently unavailable, it will not be considered in the fire risk index and it is recommended that the AHJ begin keeping track of fire cause, resultant fire type and correlate that to incidents of injuries and death.

Estimating how a fire will develop and grow in a particular heritage building can be a significant factor in assessing the overall fire safety of the structure since the probability of occurrence of different types of fires can have a bearing on how quickly the fire is detected, how much time there is for safe evacuation, the possible extent of property damage and loss, and whether firefighting efforts are likely to be effective. With this in mind, a new risk index for expected fire type is proposed to capture differences in overall fire safety of a site depending on the type of fire that is expected and how it affects the buildings and occupants inside. Since smouldering fires will generally lead to extended times for escape (albeit with the rider that light smoke might accumulate in a space even before the fire is detected), a limiting value of 1 for scenarios with expected smouldering fires and -1 for expected fast flaming fires were assigned to the index. Further than this, it will be up to the designer to explain the rationale behind a particular choice of index value, and for the AHJ to accept the premise as well. Table 8 shows the new Expected Fire Type Fire risk index.

Table 8 - Expected Fire Type Risk Index

Fire Type	Numerical Value
Smouldering Fire	1
Standard Fire	0
Fast Flaming Fire	-1

3.2.2.2 **Fire Resistance Rating**

Once the type of fire is determined, attention becomes focussed towards assessment of the fire resistance ratings for separations within the building. In general, fire separations are used to retard the effects (spread) of fire away from the area of fire origin. More specifically, one objective of specifying and using fire separations in a building is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire. The types of unacceptable outcomes addressed in the Code are those related to persons being delayed in, or impeded from, moving to a safe place during a fire emergency [14]. Another objective is to limit the probability that, as a result of its design or construction, the building will be exposed to an unacceptable risk of damage due to fire. Closely linked is a third objective of limiting the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire. The risks of injury due to fire addressed in the Code for these situations are those caused by a fire or explosion impacting areas beyond its point of origin, or collapse of physical elements due to a fire or explosion [14].

Sometimes, the heritage character of the building prevents the construction or upgrading of fire separations to those required by the current edition of the Code. In these situations, other solutions must be considered to compartmentalize the building or to retard the effects of fire on emergency egress or on areas beyond the point of origin, whilst also slowing down the failure or collapse of any building elements or assemblies during the fire [14]. A modified index based on that outlined in the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code is proposed to account for the impact of different fire compartment separation measures that might be employed in an alternative design needed to preserve the heritage character of a building.

In general, the fire resistance ratings of fire separations are used to assess whether there are acceptable fire separation measures included in the design of a building. These are determined by subjecting a proposed assembly to the standard fire test described in 3.2.2. In these tests, a sample of the assembly is constructed in a lab, and, using large propane burners, uniformly subjected to the time profile of temperatures defined by the standard fire. The assembly is evaluated on how long it can continue to support a specified design load, prevent the ignition of cotton waste placed on the unexposed surface, or prevent through transmission of heat such that the average unexposed surface temperatures does not rise by more than 121 °C above the initial temperature or by 163 °C at any one thermocouple on that side [73]. The time that the assembly can withstand the rigors of the test corresponds to the fire resistance rating of the assembly. Fire resistance ratings start at 20 minutes, then progress to 45 minutes, 1 hour, 1.5 hours, 2 hours, 3 hours and 4 hours [14]. As an alternative to testing, the fire resistance of assemblies can also be determined by obtaining appropriate values of test ratings from the literature, or from manufacturers, or they can be calculated by assuming 1 dimensional heat transfer and using simple heat transfer calculations to estimate the temperatures within the exposed assemblies [74].

Depending on the type of fire that is expected in a building, it is possible that existing assemblies, although not specifically rated for the fire resistance required under the Code, can achieve an effective fire resistance rating equivalent to the time required in the acceptable solution. In this case, building occupants and fire fighters are still afforded sufficient time to evacuate and fight the fire, respectively, and the intent of the Code would be satisfied. There are a number of methods by which to do this. For example, existing floors and ceilings that are of plaster construction, rather than gypsum, can have a modified 30 minute fire resistance rating [75]. These plaster assemblies can further be fortified with intumescent paint to provide added protection on the plaster surface and the assembly. With similar intent, intumescent paint can be applied to existing heritage doors to increase their fire resistance rating to 30 minutes without the requirement to add new, non-heritage material to the panels of the door [76]. On both the doors and plaster, when activated by heat or fire, the intumescent paint forms a dense carbon char that shields the substrate from the effects of the fire thus extending the time that the separation will hold its integrity in a fire [76]. When integrity of separating doors are of concern, adding door closers to keep all doors closed will also delay fires from spreading from the area of origin into other sections of the building, again effectively increasing the achievable fire separation time.

Considering that one code objective under fire separation is related to preventing the chance that persons will be delayed in, or impeded from, moving to a safe place, another option that can be employed to extend the time available for egress is the use of draft stops. These can be used to limit the probability that smoke and heat from a fire in a storey adjacent to a floor opening will migrate into the interconnected floor space, potentially bypassing sprinklers and smoke detectors without actuating them. For example, incorporating draft stops that are 500 mm deep (measured from the ceiling down to the underside of the draft stop) at each floor level within an interconnected floor space, immediately adjacent to and surrounding the openings can limit the effect and severity of fire, while at the same time be instrumented with sensors that will notify persons and emergency responders in a timely manner of the need to take action in an emergency [14]. Thus, draft stops used in conjunction with a fire alarm system can promptly notify persons of a fire situation and thus facilitate initiation of evacuation and emergency response very quickly as well [14].

With the many options available to apply alternative measures to prevent fire and combustion products from spreading beyond the area of origin, and thus affecting people and structural elements outside the fire compartment, it is proposed that consideration be given to account for such measures within the overall fire risk indexing calculation. To accomplish this, a new Fire Ratings of Assemblies risk index is being proposed and shown in Table 9. Due to the connection of some elements, such as draft stops, to fire separations around vertical openings, the index values proposed in this section are based on the "Vertical Openings" risk index from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code which is also retained and will be used in this methodology to specifically cover openings in those vertical assemblies such as stairway exits, elevator shafts, and other shafts that are required to have fire resistance ratings. The new Fire Resistance Rating of Assemblies risk index will then be used to capture, for example, the impacts on the overall fire safety of the building due to measures such as the use of draft stops, consideration of documented values for fire resistance ratings for plaster protected floor, wall and roof assemblies or protection of existing doors with intumescent paint and application of door closers to compartmentalize the full space into smaller, better protected fire compartments.

Table 9 - Fire Rating of Assemblies Risk Index

Fire Rating of Assemblies Risk Index	Numerical Value
Fire rated assembly provides 2hr below required protection level	- 2
Fire rated assembly provides 1hr below required protection level	- 1
Fire rated assembly provides 0.75hr below required protection level	- 0.75
Fire rated assembly provides 0.5 hr below required protection level	- 0.5
Fire rated assembly provides 0.25hr (15 mins) below required protection level	- 0.25
Complies with code	0
Draft stops used to retard flow of combustion products and extend usability of egress routes (per opening)	0.25
Use intumescent paint and door closers on existing wood doors to compartmentalize rooms from rest of building	0.25
Total Fire Rating of Assemblies Score	

In the Vertical Openings risk index, a score of 0 was originally assigned for a situation that "complies with the prevailing code" so that is retained in the Fire Ratings of Assemblies index as listed in Table 9. A score of -1 was assigned for the assembly that provides a fire resistance rating that is 1 hour less than that specified for the required protection level. Linear interpolation was used to determine values of -2 for a fire rated assembly that provides 2 hours below the required level of protection, -0.75 for fire separation that provides 0.75 hour below required protection level, and -0.25 for those providing 0.25 hours below the required protection level. Credits for actions taken to lengthen the time taken for smoke to spread from one portion of a structure to another and/or to extend the fire resistance rating of existing assemblies are also proposed. Draft stops and intumescent paints are two strategies that can delay fire and combustion products from spreading beyond the area of origin, provide compartmentation for earlier fire detection, and delay making other areas of the building untenable. A credit of 0.25 was added for including draft stops around each opening in a horizontal opening that did not otherwise meet the fire separation requirements under the code. The NBC requirement to install smoke detectors in the vicinity of draft stops must also be complied with in order for a credit of 0.25 to be applied to a given draft stop. Another score of 0.25 was applied for application of intumescent paint on doors with door closers that maximize fire protection for the closure in a vertical fire separations. Use of either of these measures will need to be discussed with the AHJ in order for a score of 0.25 to be added to the overall fire risk index for the building.

The final value for the Fire Rating of Assemblies risk index will be the sum of values for the fire separations to be used in the alternative solution plus any other mitigation measures that are instituted in the project. This fire risk index is slightly different than some of the others as the total score for the index needs to be calculated before including it as the entry for the new Fire Ratings of Assemblies risk index in the overall fire risk indexing framework assessment. It is intended that this index could be used to evaluate the additional fire protection measures taken to compensate for existing openings between floors and corridors each time there is a fire separation that falls outside the Vertical Openings and Separation of Occupancies risk indices.

3.2.2.3 **Occupancy Separations**

The Occupancy Separations risk index from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code that is shown below in Table 10 must also be revised to account for fire resistance rates of separations that are commonly encountered in heritage buildings. In particular, it must be extended to ensure that fire separations that provide fire resistance ratings of between only 3/4 hour and 0 hour are captured in the final overall fire risk framework for heritage buildings.

Table 10 – Occupancy Separations Risk Index

Occupancy Separations	Numerical Value
No separation provided, but required	-5
Provided, but 2-hours less than required	-4
Provided, but 1-hour less than required	-2
Complies with prevailing code for fire resistive ratings or no separation is required (where a 3 hour required and a 4 hour is provided, the value shall be 0.)	0
Provided and 1 or more hours greater than required	+2

From the basis provided in Table 10, values were linearly interpolated to produce numerical values for situations where a fire resistance rating is provided but it is 0.75 hour, 0.5 hour and 0.25 hour less than required. The changes are summarized in the Revised Occupancy Separations fire risk index shown in Table 11.

Table 11 - Revised Occupancy Separations Risk Index

Occupancy Separations	Numerical Value
No separation provided, but required	-5
Provided, but 2-hours less than required	-4
Provided, but 1-hour less than required	-2
Provided, but 0.75-hour less than required	-1.5
Provided, but 0.5-hour less than required	-1
Provided, but 0.25-hour less than required	-0.50
Complies with prevailing code for fire resistive ratings or no separation is required (where a 3 hour required and a 4 hour is provided, the value shall be 0.)	0
Provided and 1 or more hours greater than required	+2

3.2.2.4 Exit Capacity Risk Index

Exiting considerations need to be accounted for when evaluating any proposed alternative solutions. Certain concerns arising from the spread of fire and spoke from the place of origin and thereby generally affecting times for egress have been addressed in the previous section, through development of the new Fire Rating of Assemblies and revision of the existing Occupancy Separations risk indices. There are a series of other considerations directly related to exit flow and capacity during egress that can be particularly important in the case of heritage buildings. For example, the exit doors in a heritage building sometimes do not swing in the direction of exit travel which is immediately in contravention of the acceptable code solution because this situation can negatively impact the timely movement of, and thus increases the risk of injury to, persons in an emergency [14]. In addition to incorrect door swing, both handrail and guardrail heights may be lower than the minimum standard necessary to meet current accessibility requirements. There may also be landings missing at the top or bottom of stairs, either of which increases the risk of injury to persons as a result of tripping, slipping, or falling and does not facilitate the timely movement of persons to a safe place in an emergency [14]. Due to these real considerations related to heritage buildings and their link to the Exit Capacity risk index in the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code, it was determined that this index should be amended to capture these additional egress considerations in the overall fire risk assessment framework being developed. Table 12 shows the existing Exit Capacity risk index while Table 13 shows the Revised Exit Capacity risk index. .

Table 12 – Exit Capacity Risk Index

Exit Capacity	Numerical Value (per exit)
Complies with prevailing code	0
Horizontal exits are provided in addition to the required exits (no more than one-half the exits may be horizontal exits.)	+2
Exits to grade or enclosed stairs exceed the minimum number of exits (exits shall be at least 20 feet apart.)	+3
Eliminate a fire escape exit and provide a code complying enclosed stairway exit serving 3 or more levels	+5

Table 13 - Revised Exit Capacity Risk Index

Revised Exit Capacity	Number value (per exit)
Occupant load exceeds 60 and exit door does not swing in direction of exit travel	-2
Occupant load is 60 or less and exit door does not swing in direction of exit travel	-1
Delay in egress from each instance of non-compliance for handrail height, guard rail height and landing dimensions.	-0.5
Complies with prevailing code	0
1 more exterior exit than required by Code (exits shall be at least 6.1 m apart)	+0.5
Horizontal exits are provided in addition to required exits (no more than one-half the exits may be horizontal exits)	+2
Exits to grade or enclosed stairs exceed the minimum number of exits (exits shall be at least 6.1m apart)	+3
Eliminate a fire escape exit and provide a code complying enclosed stairway exit serving 3 or more levels	+5
TOTAL Score for applicable criteria	

In the revised index, additional factors have been added for the swing on the exit door, the allowed occupant load coupled to the swing on the exit door, the handrail height and whether or not there are additional exterior exit doors. In the first case, if the exit door does not swing in the direction of exit travel, the index was assigned a value of -1 in recognition of the deficiency and its potential to impede egress and increase potential for injury in the event of a fire. A worse score of -2 was assigned if the occupant load for the building is expected to exceed 60 people. This is because rooms containing more than 60 people are required by Code to have all egress doors swinging in the direction of exit travel. A score of -0.5 is given to every instance where there is a non-compliant handrail height, guard rail height or for landing dimensions that are smaller than the minimum required under the current Code as these deficiencies increase the risk of tripping, slipping or falling during egress and may also delay timely movement of persons to a safe place in the event of an emergency. Additional exterior exits from a building were considered to assist in the timely movement of persons to a place of safety during an emergency so a score of +0.5 was assigned for each additional exit over the minimum specified in the Code. The final value for the Revised Exit Capacity risk index will be the sum of values for the existing exit conditions and deficiencies coupled to those for any additional beneficial exit conditions that might exist. Thus, the total score for this index again needs to be calculated before inserting the value for the overall Exit Capacity index into the total fire risk framework.

3.2.2.5 Fire Alarms Risk Indices

The Fire Alarms risk index from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code cannot be applied as defined in Canada because the fire alarm system requirements in Canada are different than those in the United States. In Canada, the NBC and CAN/ULC-S524 Standard for the Installation of Fire Alarm Systems specifies when a fire alarm system is required, which devices are required and where those devices are to be installed. Table 14 shows the original Fire Alarms risk index from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code.

Table 14 - Fire Alarms Risk Index

Fire Alarms	Numerical Value
Manual fire alarm system required but not provided	-5
Manual fire alarm system required and provided but does not comply with acceptable solution	-2
Complies with acceptable solution	0
Manual fire alarm system provided but not required (Note: If a numerical value of +5 is taken under the smoke detection fire risk index, the numerical value for this section is 0)	+1
Manual fire alarm system provided with voice communication system (Note: Voice alarm and public address system shall be activated from a location which is occupied by an employee during all periods of building occupancy)	+3
Central control station (Note: The central control station must comply with S.ILHR52.01(2)(f); and Fire department may require systems to be interconnected with the fire department)	+4
Central control station and interconnected to a remote control station which is permanently monitored (Note: The central control station must comply with S.ILHR52.01(2)(f); and Fire department may require systems to be interconnected with the fire department)	+5

Table 15 shows the Revised Fire Alarms risk index amended for application in Canada.

Table 15 - Revised Fire Alarms Risk Index

Revised Fire Alarms	Numerical Value
Fire alarm system required but not provided	-5
Fire alarm system required and provided but does not comply with acceptable solution	-2
Complies with acceptable solution	0
Fire alarm system provided but not required (Note: If a numerical value of +5 is taken under the smoke detection fire risk index, the numerical value for this section is 0)	+1
Fire alarm system provided with voice communication system that complies with the NBC	+3
Fire alarm system includes a central alarm and control facility and automatic signals to fire department when not required	+4
Fire alarm system provided with automatic signals to fire department and interconnected with a monitoring company that is permanently monitored when not required	+5

In the revised index, the numerical values remain the same as in the original index but the explanation for each item was amended to address two main differences in requirements. The Fire Alarms risk index in the Wisconsin Code permits a "manual fire alarm system" which is a fire alarm system consisting of manual pull stations and notification devices [77]. In contrast, the NBC requires a fire alarm system to have more features like fire detectors, smoke detectors, and an annunciator system [14] which is a more robust fire alarm system than a "manual fire alarm system". Therefore, to adjust the original index to accommodate Canadian requirements, the numerical values for the presence of a fire alarm system were kept the same but the fire alarm system requirements were adjusted to conform with language and requirements used in the NBC.

The central control station used in the Wisconsin Fire Alarms risk index is equivalent to a fire alarm system command and control facility in Canada [78] since the central control system for fire department operations has to be provided in a location approved by the fire department and the location may contain a voice communication system panel, fire detection and alarm system panels, status indicators and controls for elevators, smoke venting and air handling systems, controls for unlocking stairway doors, a public telephone, sprinkler valve and water flow detectors, and standby power controls. In addition, all fire alarm and water flow signals have to be transmitted directly to the systems indicated in s. ILHR 52.01 (2) (d) 3 [78] as they would in an equivalent Canadian fire alarm system command and control facility. As a result, the wording is changed in the revised Fire Alarms index here but the intent of the systems is very similar so the risk index values have been retained.

The Smoke Detection risk index from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code is intended to be used together with the Fire Alarms risk index therefore is also had to be revised to align with Canadian practice. Table 16 shows the Smoke Detection risk index found in Chapter ILHR 70.

Table 16 - Smoke Detection Risk Index

Smoke Detection	Numerical Value
Complies with prevailing code	0
Elevator lobby only and not required by chs. ILHR 50-64	+1
HVAC return only and not required by chs. ILHR 50-64	+2
HVAC return and elevator lobby and not required by chs. ILHR 50-64	+3
All corridors, in addition to those required by the code, including elevator lobbies	+4
Total space with interconnection of smoke detectors and building fire alarm system not required by chs. ILHR 50-64	+5

For this index, the NBC covers the same areas as areas covered under the ILHR sections 50-64 so the references and descriptions were directly modified to align with the NBC in the Revised Smoke Detection risk index presented in Table 17.

Table 17 - Revised Smoke Detection Risk Index

Smoke Detection	Numerical Value
Complies with prevailing code	0
Elevator lobby only and not required by the NBC	+1
HVAC return only and not required by the NBC	+2
HVAC return and elevator lobby and not required by the NBC	+3
All corridors, in addition to those required by the NBC, including elevator lobbies	+4
Total space with interconnection of smoke detectors and building fire alarm system not required by NBC	+5

In closing, it should be noted that the above two indices have to be used with care since the values in one are inherently linked to the values in the other. For example, if a numerical value of +5 is taken under the Revised Smoke Detection risk index, the numerical value for the Revised Fire Alarm risk index is 0 [49] so that the same system is not included more than once in the analysis.

3.3 Fire Risk Assessment using Fire Risk Indexing

Once the deficiencies existing in the heritage building are identified and important elements in the proposed alternative solution that compensate for the deficiencies are scored using the applicable fire risk indices identified in the sections above, the numerical values are entered into the columns and rows of the Fire Risk Indexing Table shown in Table 18 below. In this way, the full fire risk assessment is completed for each proposed fire safety solution for the heritage building under study.

Table 18 - Fire Risk Indexing Table

Safety Parameters	Fire Safety	Means of Egress	General Safety	Comments
1. Number of Stories				
2. Building Area				
3. Building Setback		N/A		
4. Attic Compartmentalization		N/A		
5. Firestopping		N/A		
6. Revised Occupancy Separations		N/A		
7. Vertical Openings				
8. HVAC Systems				
9. Revised Smoke Detection				
10. Revised Fire Alarms				
11. Smoke Control	N/A			
12. Revised Exit Capacity	N/A			
13. Dead ends	N/A			
14. Maximum travel distance	N/A			
15. Emergency Power	N/A			
16. Elevator Control				
17. Sprinklers				
18. Fire Rating of Assemblies				
19. Fire Type Risk Index				
20. Occupant Activities Risk Index				
TOTAL Safety Score				

Table 18 includes the 17 building parameters with any revisions that are used in the Wisconsin Administrative Code fire risk index method plus the additional proposed fire risk indices of Fire Ratings of Assemblies, Fire Type, and Occupant Activities. The revised fire risk indices for parameters 6, 9, 10 and 12 plus the new parameters for 18, 19, and 20, highlighted in yellow, will be used to determine the numerical values for each parameter that will be used to calculate the final Safety Score. The items categorized as N/A are parameters that the Wisconsin Administrative Code deemed to have no impact on fire safety, if N/A is in column 1, or on means of egress when N/A in column 2. When using the Table to evaluate the case studies in section 4, certain cells may be assigned a "null" designation to indicate that the safety parameter in the heritage building being studied is the same as that in the code compliant building. After all of the individual values are entered into the Table, the entries in each column will be summed to calculate the final score for each solution for a given building. A value greater than or equal to 0 can be interpreted to mean that the alternative solution provides an equivalent level of protection as the acceptable solution under the existing Code. A negative value means the alternative solution does not provide an equivalent level of protection as an acceptable solution under the existing code. In no case, however, should the magnitude of the total safety score be interpreted as a determination of relative safety of the alternative solution beyond determining whether or not it demonstrates an equivalent level of safety as a code compliant building.

4 Case Studies

In this Chapter, the fire protection framework proposed in Chapter 3 using FRA with fire risk indexing will be applied to case studies involving heritage buildings that will be rehabilitated for new use in order to validate the framework and identify any gaps. The case studies will be based on existing heritage buildings where the building height, area, and current occupancy use will be described. The corresponding Heritage Character Statement will be used to establish the important features of the building that need to be protected. The design brief will describe the rehabilitation objective for the heritage building before undertaking a building code analysis and proposing an alternative solution. Observations on the effectiveness and usability of the framework as well as recommendations for improving the framework will be summarized in Chapter 5.

4.1 Case Study 1

The first case study will apply the full fire protection framework to develop and evaluate the alternative solutions for a heritage building intended for use as a small office. The evaluation of the necessary alternative fire safety design solution will use the fire risk indices from the 17 building safety parameters listed in the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code together with the other fire risk indices proposed in Chapter 3. The heritage building being studied was constructed in the 1890s and designed in the Second Empire Style characterized by a mansard roof and central pavilion [79] as shown in Figure 8.

Figure 8 - Example of Second Empire Style Building with Central Pavilion and Mansard Roof

The building is built with red sandstone from the local area. It is currently 3 storeys tall with a basement. The attic, which is the 3rd storey, and the basement are currently set up for occupancy. The building area (or building foot print) is 108 m^2, so that it has 216 m^2 of floor area over the 2 main floors. Inside, it is currently used as a combination of museum and office occupancy; however, it is to be renovated for exclusively office use. Given this brief introduction to the case, the following sections describe the various steps taken in completing a fire risk assessment using the overall framework and indexing methods proposed in Chapter 3.

4.1.1 **Heritage Character Statement**

As stated in the methodology section, the heritage character statement must be determined and expressed so that features that are important for the building are established. The heritage character statement can be found on the Canadian Register of Canada's Historic Places (www.historicplaces.ca) and is reiterated here.

The heritage statement for the building in case study 1 is as follows: The building is an example of the late second empire style that was popular in Canada in the 1870s and 1880s. The building is characterized by a mansard roof and central pavilion. The sandstone is laid in random courses and has limestone quoins, window and door surrounds. The building is part of a complex of buildings in a public park that were built in the same era and the integrity of the relationship between the various buildings and landscape has remained unchanged since they were constructed.

In summary, any renovations to the building must preserve the exterior appearance of the building. This restriction will also limit how the interior of the building can be utilized as the exterior original details, such as windows and doors for example, should be maintained.

4.1.2 **Design Brief**

The objective of this project is to renovate the current building to provide office space for 14 staff. The building is presently used as a museum on the main floor, offices on the 2nd floor and attic, and storage and building services in the basement. The redesigned building will be used entirely for office space, with the first floor consisting of a staff room with lockers, kitchenette, 2 private offices, 6 workstations, a barrier free washroom, and collaboration space. The second floor will have 2 private offices, 2 semi-private offices, a boardroom, 3 workstations, and administrative space for photocopying and printing. The attic will be closed off making the building a 2 storey building. The basement will continue to be used for building services, a LAN room, and general storage. The first and second floors are served by a central stair case and at the top and bottom of the stairs is a hallway with doors that lead into the office areas. Figure 9 shows an example of how the hallway on the first floor interacts with the stairs and the doors that open into the different office and support spaces.

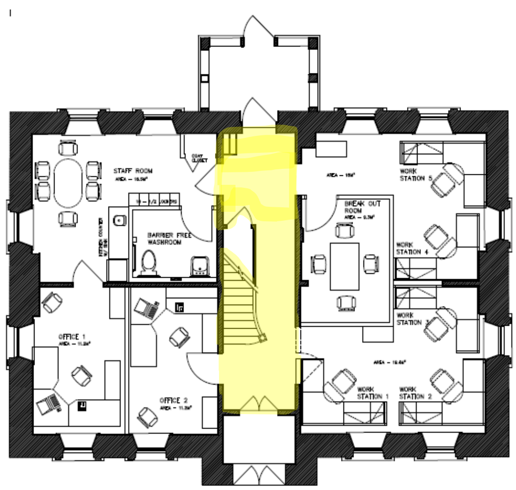

Figure 9 - Relation between open staircase, hallway and offices

Protecting the interior layout, finishes and materials while undertaking the building renovations is also a key objective. What this means practically is that the open stair case connecting the 1st and 2nd floor must preserved, and any detailing in the wood and plaster finishes on the walls and ceilings must be preserved and protected as much as possible. By way of example, Figure 10 shows some of the interior finishes that should be preserved. As an alternative, construction of new exit stairs, fire escapes and exterior ramps may impact the exterior appearance of the building which again is not allowed under the heritage statement provided.

Figure 10 - Photo of Ornate Wood Railing in Open Central Stair Case for Case Study 1.

Other existing site conditions which should be noted in relation to fire safety solutions are that the basement has two exits, and that the attic is separated from the first and second floor by a fire separation but is accessed by an open stair case. In addition, the building has a fully functional fire alarm system that is monitored by a monitoring company. This fire alarm system exceeds the fire protection requirements of the NBC and will be retained in the new office space.

With this background in hand, the next step is to undertake a thorough NBC and fire analysis in order to determine how the fire safety aspects of the heritage building compare against a theoretical building that complies with the current acceptable solution of the NBC for small office buildings.

4.1.3 **Building Code and Fire Code Analysis**

Based on the information provided above, a detailed building code analysis can be done to determine how well the existing building compares against the acceptable provisions of the building code and fire code. A summary of the building code requirements and the condition of the existing building are recorded in Table 19. The proposed use of the building as an office means that the building will have a Group D occupancy according to the National Building Code of Canada [14]. Starting with the building size, building height and occupancy type, the corresponding requirements in the NBC and NFC can be entered into Table 19 in the column titled "Code Compliant Building". The characteristics of the existing building are entered in the "Heritage Building" column and compared with those for the code compliant building. For the rows where the heritage building does not provide the same level of protection as the code compliant building, references to the applicable functional and objective statements are also recorded [14].

Table 19 - Building Code Analysis for Case Study 1

	Code Compliant Building	Heritage Building	Functional and Objective Statements Attributed to Code Provision
Year of Original Construction	2016	1896	N/A
Major Occupancy Classification(s)	Group D - Business and personal services occupancies	Group D	N/A
Governing Code Part	Part 9 [14]	Part 9	N/A
Fire Resistance rating of floor assemblies (hrs)	45 minutes [14]	45 minutes in floor assembly separating basement and first floor. 30 Minutes between 1st and 2nd floor	[F03-OS1.2] [F04-OS1.2, OS1.3] [F03-OP1.2] [F04-OP1.2, OP1.3]
Building Area (m^2)	Max 100m^2, limited by interconnected floor space [14]	108	F05-OS1.5 [14]
Building Height (Storeys)	Max 2, limited by interconnected floor space [14]	2	F05-OS1.5 [14]
Cross-over Floors	No cross-over floor in building	No crossover floor in building	N/A

High Building (see NBC Article 3.2.6)	N/A	N/A	
Interconnected floor space	Interconnected floor space permitted between 1st and 2nd floor [14]	Interconnected floor space existing between 1st and 2nd floor.	F05-OS1.5 [14]
Mezzanines	N/A	N/A	N/A
Sprinklers	Not required	Not required	N/A
Building Faces No. of Streets (for fire department access)	3	3	N/A
Type of Construction	Combustible with a 45 minute fire resistance rating permitted [14]	Combustible with a 30 minute fire resistance rating for roof assembly.	F05-OS1.5 [14]
Fire Resistance Rating of Roof Assembly	45 minutes [14]	30 minutes	[F03-OS1.2] [F04-OS1.2, OS1.3] [F03-OP1.2] [F04-OP1.2, OP1.3]
Total Building Occupant Load	Max allowed persons 23	Intended number of persons 14	
Fire Alarm System	Not required	Installed	
Voice Communication	Not required	Not installed	
Fire Alarm System Monitoring	Not required	Installed	
Standpipe & Hose	Not required	Not installed	
Emergency Power	30 minute battery	30 minute battery	
Smoke Control Measures	Not required	None installed	
Fire Pumps	Not required	None installed	
Maglocks	Not required	None installed	
Special Extinguishing Systems	Not required	None Installed	
Water Supply	Adequate	Adequate	
Spatial Separations	Adequate	Adequate	

Table 19 shows that for the most part the heritage building complies with the acceptable solution as prescribed by the NBC [14]. From the occupancy type, building area and building height, this building is governed by Part 9 of the NBC [14]. A building of this size, height and occupancy type is permitted to be built with combustible construction provided that the structural elements, floor assemblies and roof assemblies are protected and have a minimum fire resistance rating of 45 minutes. An indication of N/A in the building code matrix means that the specific building item is not present in the building and the corresponding requirements in the prevailing code will not be considered. An indication of "not required" means that specific item is not required by the prevailing code for the historic building being studied. A "none installed" was assigned to items that are not required by the code and not present in the heritage building. The total occupant load is calculated using the total floor area and dividing it by the area per person that corresponds with the occupancy type in table 3.1.17.1 in the NBC. The comment of "Adequate" means the specific items comply with the prevailing code. In this case, the water supply is coming from a municipal main so it is "adequate" and the spatial separation is also "adequate" since the building is sufficiently far away from other buildings on the property that it is essentially a standalone building.

The fire alarm system and monitoring of the fire alarm system exceeds the minimum requirements of the code. A building of this size and occupancy type is also required to have an emergency power supply that can operate emergency lights and exit signs for a minimum of 30 minutes. The heritage building has this.

There are six deficiencies identified on Table 19, all related to separation of different compartments. These can be grouped into interconnected floor space, fire resistance rating of floor separations and fire resistance rating of the roof assembly. The first deficiency relates to the existing interconnected floor space between the first and second floors. Table 9.9.4.7 of the NBC states that a building that has a building area less than 200 m^2 and less than 25 m travel distance to an exit is permitted to be served by one exit provided that exit is in its own fire rated enclosure. The exit stair is not in a separate fire rated enclosure; thus the open staircase is not in compliance because the existing building area exceeds by $8m^2$ the maximum building area permitted in the code. The functional and objective statements behind the provision for limiting the floor area to $100m^2$ are FS5-OS1.5. The other deficiencies identified in the Table both relate to fire resistance ratings of separations. In both cases, the floor assembly separating the first and second floor and the roof assembly are fire separations constructed of wood beams protected by plaster that will provide a minimum fire resistance rating of only 30 minutes [75] instead of the 45 minute rating that is required under the current code [14]. The functional and objective statements behind the fire resistance rating of the fire separations for the floor and roof assemblies are F03-OS1.2, F04-OS1.2, OS1.3, F03-OP1.2, and F04-OP1.2, OP1.3 [14].

A fire protection engineering survey was also conducted to further assess code compliance of the heritage building. This consisted of a visual inspection of the heritage building to evaluate overall compliance and identify any deficiencies in the building. There were several additional deficiencies that were not captured by the building code data sheet that must be considered as part of the overall evaluation of the building and any alternative solutions. These additional deficiencies plus the deficiencies identified in the building code data sheet are captured in Table 20 below along with the specific code provisions and functional and objective statements attributed to the code provisions [14]. These were not recorded directly in the building code data sheet because the building code data sheet organizes, summarizes and presents critical building code compliance data that forms the basis for design of a building [80].

Table 20 - Summary of non-conformances and objectives and functional statements behind the prescriptive code provision

Non-Conformance	Code Requirements	Functional and Objective Statements Attributed to Code Provision
1) Stair not constructed as exit stair, 2) the area occupied by the suite is greater than $100m^2$ per storey. 3) Fire separation of the floor assembly has a fire resistance rating less than 45 minutes.	9.9.4.7(1)(e) - Where a suite of Group D or E occupancy is located partly on the first storey and partly on the second storey, stairways serving the second storey of that suite need not be constructed as exit stairs provided, c) the area occupied by the suite is not greater than 100 m2 per storey, e) the floor assemblies have a fire-resistance rating of not less than 45 minutes or are of non-combustible construction.	**[F05-OS1.5] - Items 1-3 has the same functional and objective statements for Sentence 9.9.4.7(1)** F05 - To retard the effects of fire on emergency egress facilities. OS1.5 - An objective of this code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to fire addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during a fire emergency.
4) Fire separation of the roof assembly, and 5) fire separation of floor assembly must have a minimum fire	9.10.8.1 - The fire resistance rating of floors and roofs shall conform to Table 9.10.8.1 (45 min fire resistance rating of roof assembly and floor assembly).	**[F03-OS1.2] [F04-OS1.2, OS1.3] and [F03-OP1.2] [F04-OP1.2, OP1.3] - Item 4-5 has the same functional and objective statements for Article 9.10.8.1.** F03 - To retard the effects of fire on areas beyond its point of origin.

resistance rating of 45 minutes.		F04 - To retard failure or collapse due to the effects of fire. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin OS1.3 - collapse of physical elements due to a fire or explosion. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OP1.3 - collapse of physical elements due to a fire or explosion.
6) Exit doors do not swing in direction of exit travel.	9.9.6.5(1) - Except for doors serving a single dwelling unit, exit doors that are required to swing, shall swing in the direction of exit travel.	**[F10-OS3.7]** F10 - To facilitate the timely movement of persons to a safe place in an emergency. OS3.7 - An objective of this Code is to limit the probability That, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency.
7) No landing at the top of the basement stairs.	9.8.6.2(1)(a) - A landing shall be provided at the top and bottom of each flight of interior and exterior stairs.	**[F30-OS3.1] [F10-OS3.7]** F30 - To minimize the risk of injury to persons as a result of tripping, slipping, falling, contact, drowning or collision. OS3.1 - An objective of this Code is to limit the probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by tripping, slipping, falling, contact, drowning or collision. F10 - To facilitate the timely movement of persons to a safe place in an emergency. OS3.7 - An objective of this Code is to limit the

		probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency.
8) Handrails at 740 mm, guards at 800 mm	9.8.7.4(2) - The height of handrails on stairs shall be not less than 800 mm and not more than 965mm. 9.8.7.4(3) - Where guards are required, handrails required on landings shall be not more than 1070 mm in height.	**[F30-OS3.1] [F10-OS3.7]** F30 - To minimize the risk of injury to persons as a result of tripping, slipping, falling, contact, drowning or collision. OS3.1 - An objective of this Code is to limit the probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by tripping, slipping, falling, contact, drowning or collision. F10 - To facilitate the timely movement of persons to a safe place in an emergency. OS3.7 - An objective of this Code is to limit the probability that, as a result of design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this Code are those caused by persons being delayed in or impeded from moving to a safe place during an emergency.

Table 20 summarizes all the deficiencies identified in the heritage building in terms of non-compliance with the acceptable solution of the NBC and NFC. The objective and functional statements attributed to the code provision are listed in the third column of the Table. Items 1 through 3 in the Table outline three site conditions relating to the interconnected stairway in the building that do not comply with the code. This constitutes a potentially significant fire safety concern since not meeting the three conditions means that should a fire start in the building, fire and combustion products can impede egress. Fire and smoke obstructing the only stairwell from the second floor will negatively affect the timely egress of occupants from the facility.

Items 4 and 5 deal with the situation that the fire resistance ratings of the roof and floor assembly demonstrate less than the 45 minutes required by the code. Fire separations with fire resistance ratings less than the minimum required in an acceptable solution could fail in their intent to prevent fires from spreading beyond the point of origin and also to delay collapse of assemblies from the effects of fire.

The remainder of the items listed in the Table deal in one way or another with the timely movement of people in the event of a fire. Item 6 captures that the exit doors swing inwards rather than in the direction of exit travel. This condition is contrary to the requirements in the acceptable solution and the functional and objective statements explain that the situation can impede timely movement of people to safety. Item 7 captures the reality that there is no landing at the top of the stairs leading from the basement to the main floor. This situation presents a tripping hazard and would negatively impact the timely movement of people to safety. Finally, Item 8 identifies the height of the handrails are only 740 mm and the guards only 800 mm high which is shorter than what is specified in the acceptable solution. Proper handrail and guardrail heights again facilitate movement of people and reduce the risk of tripping when people are moving to an area of safety.

Clearly several important, additional deficiencies were identified during the fire protection engineering survey on this heritage building, as listed in Table 20. Conducting the survey in conjunction with a more standard Building Code Analysis therefore form two critical steps in the proposed risk assessment framework, since they facilitate cross-checking that all pertinent, code-related building features are being accounted for before proceeding with the next steps in the process: generation of the alternative design and fire risk indexing.

4.1.4 Case Study 1 - Alternative Solution

An alternative solution is needed in this building to protect the heritage character of the building while at the same time making the building usable from a fire protection and life safety standpoint. With the deficiencies in the existing heritage building clearly identified and information gathered on how these deficiencies impact the building and building occupants in the event of fire, an alternative solution can be developed to directly address the shortfalls in the base building design. In summary, these shortfalls, as identified in Table 20, relate to keeping exits usable in an emergency, reducing situations that delay timely movement of people to exits, delaying fires from spreading beyond the point of origin, and protecting the building from structural failure. The alternative solution will need to demonstrate how these deficiencies have been addressed.

On the other side of things, there are some features in the heritage building that are not required by the code but can be used to advantage in an alternative solution. In particular, the existing fire alarm system, which is not required for an acceptable solution, will remain operational and additional smoke detectors will be installed on each floor, as well as in the vicinity of draft stops which are proposed (see below) as an added element in the design as well. The presence of the fire alarm system and increased smoke detector coverage is expected to provide early detection of smoke and products of combustion, hence signal the existence of a fire, initiate an alarm and evacuation of building occupants, and notify the fire department early in a fire event. This level of protection is superior to the minimum requirement in the code-compliant building where a fire alarm system is not required to protect the building. Due to the presence of the fire alarm system in the building, a fire risk index value to account for this should be included in the overall fire risk analysis.

Due to the deficiencies identified with fire separation in the heritage building, the alternative fire safety design needs to include solutions to retard the effects of fire on areas beyond the fire origin and on the egress routes in the building. The potential for impacts of fire outside the room of origin and on egress routes can be lessened by subdividing the first and second floors, which consist of private offices, meeting rooms, and open offices, into smaller fire compartments in order to delay the spread of fire to other areas in the building. This will be done by using intumescent paint on existing doors to enhance the fire resistance rating of the doors currently leading from the office space into the hallway serving the stairs. Door closers will also be used to keep these doors in the closed and latched position when they are not being used. Adding draft stops around the interconnected stairwell and additional smoke detectors will facilitate early smoke detection as the ceiling jet is stopped by the draft stops [66] and delay the movement of smoke into the egress routes. The smoke detectors will also notify building occupants of a fire while the egress routes are still clear. Finally, the fire department will be notified earlier giving the fire department more time to intervene in firefighting and rescue of building occupants.

The existing wall, ceiling and roof assemblies are constructed of wood with plaster covering and there is some literature that attributes a 30 minute fire resistance rating to these assemblies when protected with plaster [75]. The acceptable solution treats a fire separation that does not provide a 45 minute fire resistance rating as non-compliant and does not consider whether the fire separation provides a fire resistance of 45 minutes or 0 minutes. The 30 minute fire resistance rating although less than what is required, is better than no fire resistance rating at all. This can be dealt with using the Fire Rating of Assemblies risk index from Table 9 which will capture the deficiency but add credit for the positive measures taken to retard the effects of fire. Thus, this risk index should definitely be applied during the fire risk assessment stage of the analysis.

Several additional factors are anticipated to play large roles in the fire safety of this heritage building. As noted above, the building is constructed with plaster walls and ceilings which are non-flammable. Flammables inside the building include wood panels, paper files and books, all of which consist of cellulosic fibres which tend to produce slower growing fires relative to polymer based materials or smouldering fires [81]. In addition, the designer will specify that carpets, office equipment and furniture be treated with a fire retardant finish. In the unlikely event of a fire, since these materials will be more difficult to ignite, they are anticipated to contribute to slower fire growth compared to a standard or fast flaming fire. As a result, the Fire Type risk index will be used as part of the fire risk assessment.

A Government of Canada department will occupy the space and comply with Treasury Board Standard for Fire Safety Planning and Emergency Organization Chapter 3-1. As discussed in Section 3.2, the standard exceeds the requirements for fire safety planning and fire emergency organization found in the NFC and Canada Labour Code (CLC). Under the Standard for an office space, the occupants are expected to be familiar with the building, awake and alert, and they should be familiar with emergency procedures for the building. Regular visual inspections and elimination of hazards reduce the risk of ignition and fire. Restrictions on smoking, on use of additional heaters without authorization and on cooking further reduce risk of fire as common ignition sources are eliminated or tightly managed. Finally, electrical wiring will be upgraded to meet the current edition of the Canadian Electrical Code which also reduces the risk of ignition from old or poorly maintained electrical wiring. Since all of these measures are specific to the people who will occupy the space and their actions, the combined impact should be accounted for by using the Occupant's Activity risk index outlined in Table 7.

4.1.5 Case Study 1 - Fire Risk Assessment Using Fire Risk Indices

The final fire risk assessment to evaluate the adequacy of the elements incorporated into the alternative solution will be done by first finding values related to:

1. deficiencies captured on Table 20 and the level to which they are addressed in the acceptable solution, and
2. strengths discussed in Section 4.1.4 and level to which they enhance fire safety in the building.

The values from each risk index will be determined using the 17 building safety parameters from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code, including the revised fire risk indices presented in Section 3.2 and appropriate values for any new fire risk indices that are necessary to capture the full extent of fire safety deficiencies and rectification measures that are in the building. As a final step, these values will be combined to determine the overall fire risk index for the heritage building including all fire safety measures contained in the alternative solution outlined in Section 4.1.4.

4.1.5.1 Vertical Openings Fire Risk Index

One fire risk index assessed for this heritage building relates to the open staircase. Under the NBC, a building that has an area less than 200 m^2 and less than 25 m travel distance to an exit is permitted to be served by one exit provided it is in its own fire rated enclosure. The central stair is a heritage feature that cannot be enclosed in a fire rated enclosure, therefore it is accounted for in the fire risk assessment using the Vertical Openings risk index in the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code [49]. Table 21 shows the allowed values for this fire risk index with the recorded score of -3 for a non-enclosed opening highlighted.

Table 21 - Case Study 1: Vertical Openings Risk Index

Vertical Openings	Numerical Value per shaft or opening
No enclosure	-3
Enclosure with no rating	-2
Enclosure provided but 1-hour below the required protection level	-1
Complies with prevailing code	0
1-hour required, but 2-hour provided	+1

4.1.5.2 **Fire Alarm Related Risk Indices**

When an alternative solution includes a fire alarm system, the decision on whether to apply the Revised Smoke Detection risk index and Revised Fire Alarm risk index in the overall fire risk analysis must be determined. Designing a fire alarm system that exceeds the minimum code requirements may offset some underlying code deficiency in the building. The decision must begin first with the Revised Smoke Detection risk index because as explained earlier in 3.2.2.5, when a numerical value of +5 is taken under the Smoke Detection risk index, the numerical value for the Fire Alarms risk index is 0 [49]. The code does not require a fire alarm system to be installed in this building and the existing fire alarm system exceeds the minimum requirements of the code and includes an annunciator near the main entrance, heat detectors and smoke detectors are installed in areas prescribed by the NBC as if a fire alarm system was required. Additional smoke detectors will be installed as part of the alternative solution throughout the interconnected floor space and in the vicinity of draft stops. The fire alarm system is currently monitored by a fire alarm system monitoring company and the fire department is automatically notified in the event of a fire alarm. Table 22 shows the Revised Smoke Detection risk index that will be used and the resultant numerical value of +5 assigned in this case.

Table 22 - Case Study 1: Revised Smoke Detection Risk Index

Smoke Detection	Numerical Value
Complies with prevailing code	0
Elevator lobby only and not required by the NBC	+1
HVAC return only and not required by the NBC	+2
HVAC return and elevator lobby and not required by the NBC	+3
All corridors, in addition to those required by the NBC, including elevator lobbies	+4
Total space with interconnection of smoke detectors and building fire alarm system not required by NBC	+5

A score of +5 is recorded for the alternative solution and will be used in the fire risk assessment with fire risk indexing. There is no need to consider the Revised Fire Alarm risk index because of the +5 score in the Revised Smoke Detection risk index.

4.1.5.3 **Fire Rating of Assemblies Risk Index**

The Fire Ratings of Assemblies risk index shown in Table 23 below captures key elements of the alternative solutions including the use of draft stops, application of literature values for fire resistance ratings for plaster protected floor, wall and roof assemblies and the additional measures undertaken to protect the existing doors with intumescent paint and apply door closers to compartmentalize the space into smaller fire compartments. While a deficit is recorded due to the less than minimum fire rated assemblies in the building, it is offset by the positive impacts of the draft stops and intumescent paint in terms of overall fire safety in the building.

Table 23 - Case Study 1: Fire Rating of Assemblies Risk Index

Fire Rating of Assemblies Risk Index	Numerical Value
Fire rated assembly provides 2hr below required protection level	- 2
Considers how Fire rated assembly provides 1hr below required protection level	- 1
Fire rated assembly provides 0.75hr below required protection level	- 0.75
Fire rated assembly provides 0.5 hr below required protection level	- 0.5
Fire rated assembly provides 0.25hr (15 mins) below required protection level	- 0.25
Complies with code	0
Draft stops used to retard flow of combustion products and extend usability of egress routes	0.25
Use intumescent paint and door closers on existing wood doors to compartmentalize rooms from rest of building	0.25
Total Fire Ratings of Assemblies Score	0.25

4.1.5.4 **Exit Capacity Risk Index**

The occupant load in this building consists of 14 staff. It is not expected for the population in the building to ever exceed 60 persons. There is one exit door that does not swing in the direction of exit travel which must be kept to preserve the heritage nature of the building. The central stair has handrails and guardrails that are shorter than required for accessibility requirements. The potential delay in egress from the landing at the top of the stairs from the basement must also be captured. Table 24 captures values for both deficits and positive fire safety measures through the Revised Exit Capacity risk index and highlights the features that need to be considered in the overall fire risk assessment.

Table 24 - Case Study 1: Revised Exit Capacity Risk Index

Revised Exit Capacity	Number value (per exit)
Occupant load exceeds 60 and exit door does not swing in direction of exit travel	-2
Occupant load is 60 or less and exit door does not swing in direction of exit travel	-1
Delay in egress from each instance of non-compliance for handrail height, guard rail height and landing dimensions. (x3)	-0.5
Complies with prevailing code	0
1 more exterior exit than required by Code (exits shall be at least 6.1 m apart)	+0.5
Horizontal exits are provided in addition to required exits (no more than one-half the exits may be horizontal exits)	+2
Exits to grade or enclosed stairs exceed the minimum number of exits (exits shall be at least 6.1m apart)	+3
Eliminate a fire escape exit and provide a code complying enclosed stairway exit serving 3 or more levels	+5
TOTAL Score for applicable criteria	-2

4.1.5.5 **Occupant Activities Risk Index**

How the occupants will utilize the building was described in Section 4.1.4 and the characteristics of these occupants and the proactive actions they take reduces the chances of fire occurring and increases the chances that occupants can evacuate quickly. Table 25 below captures all the applicable points that can be applied based on the actions of the occupants and shows the final score that should be used to calculate the overall fire risk assessment with fire risk indexing score.

Table 25 - Case Study 1: New Occupant Activities Risk Index

Occupant Activities Risk Index (Cumulative)	Numerical Value
No smoking and no open flames	0.14
No cooking	0.18
Use of space heaters and heat generating appliances tightly controlled	0.1
Fire emergency organization trained to identify and remediate fire hazards	0.1
Fire emergency organization facilitates emergency evacuation	0.15
Occupants trained in emergency procedure and evacuation	0.15
Awake and alert	0.1
Familiar with the building	0.1
TOTAL Occupant Activities Score	1.02

4.1.5.6 **Fire Type Risk Index**

The fire type expected in this building is a slower fire growth based on the materials, and operations described in the design brief. Table 26 shows the Expected Fire Type risk index with the numerical value identified that will be used in the final fire risk analysis.

Table 26 - Case Study 1: Expected Fire Type Risk Index

Fire Type	Numerical Value
Smouldering Fire	1
Standard Fire	0
Fast Flaming Fire	-1

4.1.5.7 **Fire Risk Assessment with Fire Risk Indexing for Case Study 1**

The fire risk analysis with fire risk indexing will combine all the applicable fire risk indices from Case Study 1 to determine if the alternative solution is at least equivalent to and potentially relatively safer than a building that complies with the acceptable solution. Table 27 shows the final fire risk assessment for case study 1.

Table 27 - Fire Risk Assessment for Case Study 1

Safety Parameters	Fire Safety	Means of Egress	General Safety	Comments
1. Number of Stories	null	Null	Null	Same for heritage and code compliant building
2. Building Area	null	Null	Null	Same for heritage and code compliant building
3. Building Setback	null	N/A	Null	Same for heritage and code compliant building
4. Attic Compartmentalization	Null	N/A	Null	Same for heritage and code compliant building
5. Firestopping	Null	N/A	Null	Same for heritage and code compliant building
6. Revised Occupancy Separations	N/A	N/A	N/A	Group D occupancy
7. Vertical Openings	-3	-3	-3	From Table 21
8. HVAC Systems	Null	Null	Null	Same for heritage and code compliant building
9. Revised Smoke Detection	+5	+5	+5	From table 22
10. Revised Fire Alarms	0	0	0	From table 22
11. Smoke Control	N/A	N/A	N/A	No smoke control
12. Revised Exit Capacity	N/A	-2	-2	From Table 24
13. Dead ends	N/A	Null	Null	Same for heritage and code compliant building
14. Maximum travel distance	N/A	Null	Null	Same for heritage and code compliant building
15. Emergency Power	N/A	Null	Null	Same for heritage and code compliant building
16. Elevator Control	Null	Null	Null	No elevators in building
17. Sprinklers	Null	Null	Null	No sprinklers in building
18. Fire Rating of Assemblies	0.25	0.25	0.25	
19. Fire Type Risk Index	1	1	1	
20. Occupant Activities Risk Index	1.02	1.02	1.02	
TOTAL Safety Score	4.27	4.27	4.27	

Table 27 shows that the alternative solution of using draft stops around the central exit stairs to extend the time the exit stair can be used rather than leaving it unchanged, door closers on all doors to enhance compartmentation in the building, a fully functional fire alarm system with additional smoke detector coverage, an effectively trained fire emergency organization and the space being used as an office occupancy relatively provides at lease an equivalent, and potentially a higher level of safety than a building and occupant practices that meet the minimum requirements of the NBC and NFC.

4.2 Case Study 2

The second case study that was undertaken in this research involves assessment of a building built in 1915. This is a 2 storey, 814 m^2 building with a basement. The building is constructed with a mixture of combustible and noncombustible construction and is fully sprinklered on the 2nd floor and in the basement and partially sprinklered on the 1st floor. There is an interconnected floor space between the 1st and 2nd floor. The building is currently occupied by a single tenant and used as an office. The fire protection framework proposed in Chapter 3 will be used to develop and evaluate an alternative solution for the building based on the desire by the owner to change to overall function of the building.

4.2.1 Heritage Character Statement

The building is built in Beaux Arts style with symmetry and balance of the exterior carried through into the public spaces in the interior. The architectural significance of this building is that it has remained largely unaltered through time and also serves as a landmark in its town. The heritage value of the building is defined by the two-storey composition of the main entrance façade and the symmetrical composition with a monumental portico over the entrance flanked by colonnaded porches as shown in Figure 11.

Figure 11 - Example of Beaux Arts Style Building

The main level interior has a carefully orchestrated sequence of spaces highlighted by a central court with a large stained-glass dome shown in Figure 12.

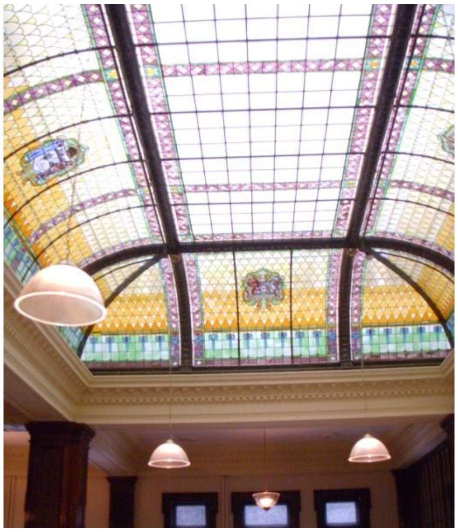

Figure 12 - Stained Glass Dome

4.2.2 Design Brief

The objective of this project is to rehabilitate the building so that it can accommodate two tenants and comply with the NBC and NFC. In this case, the owner would like to reduce the allocation of office space to the existing occupant and make room on half of the second floor for a college that consists of a classroom and college administrative offices. The rehabilitation work will be done inside the building; since this is a heritage building, any work has to be sympathetic to the original design. This means that the following character defining elements need to be maintained:

1. the original layout, original trim and detail on the second floor should be retained,
2. the grand marble staircase with heavy oak handrail that connects the two levels should be preserved and remain lit by the large stain-glass window that is part of the stairs (not the stained glass dome),
3. the balanced disposition of spaces around the central axis of the building should be preserved, and
4. any necessary changes should be enhanced by use of marble, bronze, oak and ornate plaster work [82].

Every effort should be taken to maintain, recover and restore the original design, respectively.

4.2.3 Building Code and Fire Code Analysis

Based on the information provided, a building code and fire code analysis was done. A summary of the building code requirements and the condition of the existing building are recorded in Table 28.

Table 28 - Building Code Analysis for Case Study 2

	Code compliant Building	Heritage Building	Functional and Objective statements
Year of Original Construction	2016	1915	N/A
Major Occupancy Classification(s)	Group A2 and D	Group A2 and D	N/A
Governing Code Part	Part 3	Part 3	
Fire Resistance rating of floor assemblies (hrs)	45 minutes 3.2.2.25(2)(a) and (d)	45 minutes separating basement from main floor. Alternative solution needed to separate first and second floor.	[F03-OP1.2] [F04-OP1.2, OP1.3] [F03 -OS1.2] [F04-OS1.2, OS1.3]
Building Area (m^2)	814	814	
Building Height (Storeys)	2	2	
Cross-over Floors	N/A	N/A	
High Building (see NBC Article 3.2.6)	N/A	N/A	
Interconnected floor space	Not Permitted 3.2.8.2(6)(d)	Alternative solution needed to separate first and second floors.	No functional and objective statements attributed to this requirement so use intent statement.
Mezzanines	N/A	N/A	
Sprinklers	Not required	Partial system installed. 2nd floor and basement fully sprinklered. Main floor partially sprinklered (back staff area, enclosed offices, under the stained glass dome and grand staircase). Approx. 75% protected	
Facing No. of Streets	2	2	
Type of Construction	Combustible construction permitted	Mix of combustible and non combustible construction	
Roof Assembly	45 minutes 3.2.2.25(2)(c)	Unsure. Drywall and plaster ceiling present.	[F04-OP1.3] [F04- OS1.3]

Total Building Occupant Load	195 3.4.3.2.(1)(c)	100	
Fire Alarm System	Full fire alarm system required	Full fire alarm system installed	
Voice Communication	Not required	Not installed	
Fire Alarm System Monitoring	Not required	Yes	
Standpipe & Hose	Not required	Not installed	
Emergency Power	30 minutes battery	30 minute battery	
Smoke Control Measures	Not required	N/A	
Fire Pumps	Not required	N/A	
Maglocks	Permitted	Installed	
Special Extinguishing Systems	Not required	N/A	
Water Supply	Municipal	Municipal	
Spatial Separations	Adequate	Adequate	

The building code data sheet shows that the building is a large building that is covered by part 3 of the NBC. The building code analysis shows that the majority of the building complies with, or exceeds, the requirements of the acceptable solutions under the NBC [14]. The partial sprinklering of the building, and monitoring of the fire alarm system by a fire alarm monitoring company exceed the requirements stipulated under the Code.

On the other hand, Table 28 shows the existing building has deficiencies in the fire separations. The fire resistance rating of the floor assembly between the 1st and second floor and the roof assembly do not provide the required 45 minutes fire resistance rating. The fire resistance rating of the floor assembly that separates the first and second storey is unknown due to presence of the non-fire rated stained glass dome that connects the two floors.

The roof assembly is a mixture of gypsum board and plaster and an assembly that includes plaster is not part of a recognized fire separation design that provides a minimum fire resistance rating of 45 minutes. It is critical to maintain the ornate plaster finish from a heritage conservation standpoint, but there are no listed fire rated assemblies that incorporate plaster into their design. Therefore, this gap has to be considered in designing the final fire safety solution for the building.

As well as the building code survey outlined in Table 28 a fire protection engineering survey of the building was conducted. This consisted of a visual inspection of the building in order to evaluate the current condition and overall compliance of the building with the prevailing code and thereby identify any deficiencies that may exist in the building. During the survey, the records for fire drills were available for review and an evacuation time of 90 s was noted from the previous fire drill and this information will be retained for future consideration. There were additional deficiencies captured during the fire protection engineering survey that were not captured on the building code data sheet. One relates to fire protection of one of the exit stairs. Buildings of this size are required to be served by 2 exits [14]. Figure 13 shows a picture of the top of the grand stair case that opens directly into the main floor and it is clear that it is not enclosed in a fire separation, as required under the Code. This open stair case does not limit fire spread beyond the main floor if a fire were to occur there, it can delay evacuation of building occupants and delay emergency responder access.

Figure 13 - Top of Grand Stair Case

The area above the grand stair case is protected by smoke detectors and concealed sprinkler heads in each coffered section as shown in Figure 13. The height of the guard rail at the top of the stair has been raised to meet the minimum requirements of the NBC.

Table 29 below summarizes all the deficiencies so that they can be evaluated and used to generate alternative solutions that can fully address all the deficiencies. Functional and objective statements behind the associated code provisions for each deficiency are also recorded.

Table 29 - Case Study 2 Complete List of Deficiencies

Non-Conformance	Code Requirements	Functional and Objective Statements
1) Fire separation of the floor assembly between the 1st and 2nd floor has a fire resistance rating of 30 minutes.	3.2.2.25(2) (a) - The fire resistance rating of floors and roofs shall have a minimum fire resistance rating of 45 min	**[F03-OP1.2 and OS 1.2]:** F03 - To retard the effects of fire on areas beyond its point of origin. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin **[F04-OP1.2, OP 1.3 and OS 1.2, OP1.3]:** F04 - To retard failure or collapse due to the effects of fire. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OP1.3 - collapse of physical elements due to a fire or explosion. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design

		or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin OS1.3 - collapse of physical elements due to a fire or explosion.
2) This building is not permitted to have an interconnected floor space. Floor area is 814 m^2. Maximum floor area in unsprinklered building is 1000m^2. Since 814 is more than one half of 1000 the interconnected floor space is not in conformance with the code	3.2.8.2(6)(d) - An interconnected floor space need not conform to the requirements of 3.2.8.3 to 3.2.8.9 provided the building area is not more than one half the area permitted by subsection 3.2.2	No functional and objective statements attributed to Sentence 6. To exempt certain interconnected floor spaces from the requirements of Sentence 3.2.8.1.(1) and Articles 3.2.8.3. to 3.2.8.9., which would otherwise require a vertical fire separation or certain fire protection measures, if: • the location and number of interconnected floors is limited, which will minimize: ○ vertical fire spread, and ○ delays in emergency responder access and evacuation of occupants, • the openings through the floor are used only for stairways, escalators or moving walks, or the interconnected floor space is sprinklered, which will minimize vertical fire spread, • the interconnected floor space contains only certain major occupancies, which will minimize fire risks, and • the building area is limited, which will minimize delays in emergency responder access and evacuation of occupants
3) Fire separation of the roof assembly has a minimum fire resistance rating of 30 minutes.	3.2.2.25(2)(c) Roof assembly shall have minimum fire resistance rating of 45 minutes. However, 2nd floor is fully sprinklered and if the whole building was fully sprinklered, the roof would not need to be rated.	**[F03-OP1.2 and OS 1.2]:** F03 - To retard the effects of fire on areas beyond its point of origin. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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

		OP1.2 - fire or explosion impact areas beyond its point of origin. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin **[F04-OP1.2, OP 1.3 and OS 1.2, OP1.3]:** F04 - To retard failure or collapse due to the effects of fire. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OP1.3 - collapse of physical elements due to a fire or explosion. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin OS1.3 - collapse of physical elements due to a fire or explosion.
4) Grand stair near the main entrance is not	3.4.4.1(1) Every exit shall be separated from the remainder of the building by a fire	**[F05-OS1.5]** F05 - To retard the effects of fire on emergency

separated from the remainder of the building by a fire separation having a minimum fire resistance rating of 45 minutes.	separation having a minimum fire resistance rating of 45 minutes.	egress facilities. OS1 Fire Safety - An objective of this code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.5 persons being delayed in or impeded from moving to a safe place during a fire emergency. **[F06-OS1.5, OS1.2]** F05 - To retard the effects of fire on emergency egress facilities. OS1 Fire Safety - An objective of this code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 fire or explosion impacting areas beyond its point of origin OS1.5 persons being delayed in or impeded from moving to a safe place during a fire emergency. **[F03-OS1.2]** F03 - To retard the effects of fire on areas beyond its point of origin. OS1 Fire Safety - An objective of this code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 fire or explosion impacting areas beyond its point of origin **[F06, F03-OP1.2]** F06 - To retard the effects of fire on facilities for

		notification, suppression and emergency response. F03 - To retard the effects of fire on areas beyond its point of origin. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin.
5) The assembly type occupancy should be separated from adjoining suites by a fire separation having a fire resistance rating of 45 minutes.	3.3.1.1.(1) Major occupancies should be separated from adjoining major occupancies by fire separations having fire resistance rating of 1 hour.	**[F03-OS1.2]** F03 - To retard the effects of fire on areas beyond its point of origin. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin **[F03-OS3.4]** F03 - To retard the effects of fire on areas beyond its point of origin OS3 Safety in Use - An objective of this Code is to limit the probability that, as a results of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this code are those caused by OS3.4 exposure to hazardous substances.

Having a complete list of deficiencies for this heritage building allows the designer to quickly identify where any compensating measures must be included in an alternative solution to achieve code compliance for the final overall design. Items 1, 3 and 5 deal with fire resistance ratings of the floor, roof and wall assemblies within the building. They are listed with the associated functional and objective statements which must be properly addressed in order for the final building to meet the criterion stipulated in the Code.

In contrast to fire resistance related deficiencies, item 2 deals with interconnection between floor spaces in the area around the stained glass dome. As shown in figure 14, there is an enclosed space around the dome where the second floor overlooks the top of the dome.

Figure 14 - Overlooking the Stained Glass Dome From the 2nd Floor

Windows run along 3 of the walls overlooking the stained glass dome, the fourth wall is the exterior wall. Each set of windows is mounted in plaster wall assembly rising 1100mm above the finished floor. The windows are in wooden frames with frosted glass panes and so the assembly is not a listed and labelled wall and window assembly. The north and north-east portion of the perimeter consist of wood stud walls with slab-to-slab lathe and plaster which is also not a listed and labelled fire separation or closure. In assessing the compliance of the existing construction an important interpretation relates to sentence 6 "An interconnected floor space need not conform to the requirements of 3.2.8.3 to 3.2.8.9 provided the building area is not more than one half the area permitted by subsection 3.2.2"; however, the NBC has not clearly attributed functional and objective statements for this sentence. In assessing this feature of the building then, it is necessary to examine the intent(s) of this clause in the code. Here, the intent is to exempt certain interconnected floor spaces from the requirement for vertical fire separation or from certain fire protection requirements, provided that the building area, as well as the location and number of interconnected floors are limited, the openings through the floor are used only for stairways, escalators or moving walks, or that the interconnected floor space is sprinklered, or contains only occupancies with minimal risks. The objectives that would be aligned with this intent are to limit the vertical spread of fire, and minimize delay in the evacuation of occupants as well or emergency responder access.

Item 4, deals with the grand stair case in the building that is not housed in a fire rated enclosure. In this case, there is a requirement for two exits and those exit pathways must be protected so occupant evacuation is not delayed and emergency responders are not delayed in accessing the building when they respond to a fire emergency.

With the deficiencies identified and understood in context of the applicable code requirements, the next step in the process is to develop an alternative solution that brings the heritage building into compliance with current Code for the occupancy defined. The solution will need to contain strategies by which to address all the functional, objective and intent statements related to the deficiencies summarized in Table 29 in a fashion that brings the overall fire safety solution for the building at least to the level specified as the existing acceptable solution.

4.2.4 **Case Study 2 - Alternative Solution**

The proposed alternative solution for this building must protect the heritage features of the building, while ensuring that all the deficiencies noted in Table 29 are addressed. First, there must be adequate fire separations between the college occupancy and the office occupancy. Any fire separations that do not meet the prescriptive requirements of the NBC for exits, floor and roof assemblies also need to be addressed so that if there is a fire, the building does not prematurely collapse, the fire does not spread beyond the point of origin and the exit pathways are kept tenable long enough that occupants can exit and fire fighters can enter the building to fight the fire.

The first design decision is to continue to maintain the current sprinkler system and fire alarm system in the building. The 2nd floor and basement are fully sprinklered. Approximately 70 percent of the main floor is sprinklered as well, including areas underneath the stained glass dome, on the grand staircase, and in enclosed offices and staff areas. The only area on the main floor that is not covered by sprinklers is the open office directly underneath and adjacent to the perimeter of the glass dome. This area cannot be fitted with sprinklers because of the heritage value of the ornate plaster covering the ceilings. Since this feature has to be protected, ripping it apart to install plumbing and sprinkler heads is not an option. In addition to the sprinklers, the current fire alarm system affords another line of defence. It is designed to directly notify the fire department, through a fire signal and receiving centre, when an alarm signal has been initiated. This automatic fire department notification ensures that when there is an incident, the fire department response is as short as possible. The presence of the partial sprinkler system, fire alarm system monitoring and automatic fire department notification all exceed the NBC requirements for a building of this size, height and occupancy type. In the rare case of a fire within the building, the sprinkler system is expected to control the growth of the fire and perhaps extinguish it, while early notification greatly reduces response time for fire department personnel. Due to the presence of the above systems then, appropriate values will be entered into the related Wisconsin Sprinklers, and Revised Smoke Detection and Revised Fire Alarm risk indices as part of the overall fire risk assessment.

Due to general non-compliance of the grand staircase as an exit option and the fire separations in the building, other solutions need to be proposed that will retard the spread of fire to areas beyond the fire origin. An exit stair shaft that is separated from the remainder of the building by fire separations with a fire resistance rating of 45 minutes would be the normal configuration for exit in a building such as this. Since the grand staircase is a heritage feature of the building, however, enclosing it in an exit stair shaft is not an option so alternative measures are needed to ensure it can be used safely for exiting in a fire emergency. To facilitate this, additional smoke detectors should be installed throughout the main floor open office areas to improve smoke detection coverage and to initiate the fire alarm, notify the fire department, and warn people to begin evacuation as early as possible. It can be further protected by having the fire emergency organization do regular inspections of the work place and mitigate fire hazards. Combustibles like brochures and bulletin boards in the vicinity of the staircase will be removed. This will reduce the amount of materials that can ignite in the area and make the grand stair case unusable in the event of fire. Wood finishes will be painted with clear intumescent paint which will further protect the wooden elements from the effects of fire. Finally, the grand stair case will continue to have smoke detector coverage at the top of the stairs and have sprinkler protection. The Fire Ratings of Assemblies risk index will be used in analyzing the alternative solution for this situation.

Draft stops with adjacent smoke detectors will be used to compartmentalize the transition area between the main floor and the grand staircase so that any smoke that might be generated in the office area during a fire is contained by the draft stop, after which a fire alarm is initiated, the fire department is notified and evacuation begins. The fire separation between the first and second floor also needs to be improved as the stained glass dome and glass windows on the second floor overlooking the top of the dome are not rated fire separations and the plaster floor assembly provides a fire resistance rating of only 30 minutes. The top of the grand staircase is separated from the second storey by a fire separation that has a fire resistance rating of 45 minutes. The first step in addressing these latter issues is to use draft stops around the perimeter of the glass dome on the first storey, coupled with additional smoke detectors to detect any smoke that might become trapped in that area. The second location where draft stops and increased smoke detector coverage will improve the fire safety design is at the edge of the first floor ceiling before it opens up into the grand staircase. The floor assembly itself is made of ornate plaster covering the lathe and structural elements within. Since this configuration does not have a listed rating, intumescent paint can be applied to the underside of the floor assembly to enhance the fire resistance of the overall finish. The use of intumescent paint can extend the fire resistance, providing 60 minutes of insulation, integrity and load-bearing depending on plaster thickness, and material underneath [83]. The area under the dome is sprinklered and the second floor is fully sprinklered thus lowering the risk that a fire that occurs under the dome would spread to the 2nd floor, since the sprinklers will go off and control the growth of the fire and possibly extinguish it. The full sprinkler coverage on the 2nd floor increases the chances that a fire that starts on the second floor will be controlled and extinguished early, thus preventing the fire from spreading into the window enclosed area that overlooks the dome as well (Figure 14).

The materials used in this building consist of plaster on the walls and ceilings which is non-flammable and wood, paper files, and books made of cellulosic fibres that will tend to produce smouldering fires [81]. The alternative fire safety design includes protecting the wood with clear intumescent paint and the plaster with white intumescent paint. Furthermore, the specifications for carpets, furniture, and office equipment will call for fire retardant finish. These types of specifications will skew the expected type of fires towards smouldering fires. To address this, the Fire Type risk index will be used in the fire risk assessment of the overall design.

The building will be non-smoking in accordance with the Non-smokers' Health Act, and cooking will be curtailed in accordance with the fit-up standards that do not provide for cooking facilities on site [59]. Fire safety planning and the fire emergency organization will comply with Treasury Board Chapter 3-1 Fire safety planning and fire emergency organization as was discussed in Section 3.2.1.2. Personnel in the fire emergency organization will facilitate evacuation of building occupants in an emergency, and will be trained in identifying fire hazards and mitigating them. They will also help train building occupants and provide direct instructions to them during an emergency so that building occupants will know what to do in case of a fire in the building. As this is a place of work, the occupants are expected to be awake and alert. The electrical wiring will be upgraded to meet the current edition of the Canadian Electrical Code and power will be provided appropriately to satisfy modern office and classroom usage. The use of space heaters will be strictly controlled on site as the base building HVAC system is designed to provide occupants a comfortable environment. Space heaters will only be permitted for use under a duty to accommodate. To account for the impact of these various factors on overall fire safety in the final building, the Occupant Activities risk index will be considered in the final fire risk assessment.

4.2.5 **Case Study 2 - Fire Risk Assessment Using Fire Risk Indices**

The overall fire risk assessment for this heritage rehabilitation project was done using the proposed alternative design, the deficiencies captured in Table 29 and applying the applicable 17 building safety parameters from the Wisconsin Administrative Code Chapter ILHR 70 Historic Building Code, supplemented by new fire risk indices required by the various unique aspects of this project. As a first step, the various fire ratings in the building are considered and summarized in Table 30 the Fire Ratings of Assemblies risk index with the items that need to be considered for the final risk assessment highlighted.

Table 30 - Case Study 2: Fire Rating of Assemblies Risk Index

Fire Rating of Assemblies Risk Index	Numerical Value
Fire rated assembly provides 2hr below required protection level	- 2
Considers how Fire rated assembly provides 1hr below required protection level	- 1
Fire rated assembly provides 0.75hr below required protection level	- 0.75
Fire rated assembly provides 0.5 hr below required protection level	- 0.5
Fire rated assembly provides 0.25hr (15 mins) below required protection level	- 0.25
Complies with code	0
Draft stops used to retard flow of combustion products and extend usability of egress routes	0.25
Use intumescent paint and door closers on existing wood doors to compartmentalize rooms from rest of building	0.25
Total Fire Ratings of Assemblies Score	-0.50

In this building, the interconnected floor space between the main and 2nd floor caused by the stained glass dome is the most prominent site condition that the alternative solution must address. Since the stained glass dome and frosted glass, wood frame wall assembly in Figure 14 are not a listed assembly, it is the most stringent to apply a score of -0.75 for the floor assembly. A credit of 0.25 is applied to acknowledge the draft stops around the openings in the floor assembly such as around the grand staircase and the stained glass dome which are intended to retard the movement of smoke along the ceiling and into other areas of the building.

Table 31 shows the fire risk index for the grand stair case using the vertical openings risk index. Since the stair is not in a fire rated enclosure, this index has a high negative value.

Table 31 – Case Study 2: Vertical Openings Fire Risk Index

Vertical Openings	Numerical Value (per shaft or opening)
No enclosure	-3
Enclosure with no rating	-2
Enclosure provided but 1-hour below the required protection level	-1
Complies with prevailing code	0
1-hour required, but 2-hour provided	+1

The requirement to separate the college occupancy, which includes administrative offices and classrooms, from the larger office tenant with a fire separation having a fire resistance rating of 45 min also needs to be taken into account. Treating the existing plaster walls and wooden doors with intumescent paint will provide a modified fire resistance rating of 30 minutes which is 15 minutes less than what is required for an acceptable separation rating. The highlighted row in Table 32 captures this condition in the evaluation of the alternative solution.

Table 32 – Case Study 2: Revised Occupancy Separations Risk Index

Occupancy Separations	Numerical Value
No separation provided, but required	-5
Provided, but 2-hours less than required	-4
Provided, but 1-hour less than required	-2
Provided, but 0.75-hour less than required	-1.5
Provided, but 0.5-hour less than required	-1
Provided, but 0.25-hour less than required	-0.50
Complies with prevailing code for fire resistive ratings or no separation is required (where a 3 hour required and a 4 hour is provided, the value shall be 0.)	0
Provided and 1 or more hours greater than required	+2

As initially stated in the alternative solution, the existing partial sprinkler system that protects the majority of the building will be maintained in the rehabilitated building. As well as the presence of the sprinkler system, the fire alarm system will be monitored by a fire alarm monitoring company and the fire department will be notified automatically when the fire alarm is initiated. Tables 33 and 34 show how the sprinkler system, fire alarm monitoring and additional smoke detector will be accounted for in the final fire risk analysis.

Table 33 – Case Study 2: Sprinklers Risk Index

Sprinklers	Numerical Value
System required but not provided (if -5 was entered under sub. (2), numerical value is 0.)	-5
Existing sprinkler system is required but does not meet prevailing code (does not apply to partial systems.)	-1
Sprinkler system is not required and not provided	0
Sprinkler system required and provided in accordance with the prevailing code	0
Existing sprinkler system is not required and does not meet prevailing code (does not apply to partial systems.)	+1
Sprinklers provided in unseparated hazardous areas and exit passageways, but not required	+3
Partial sprinkler system is provided throughout at least 75% of the building, but not required	+5
If sprinkler system is required, and regular sprinkler heads are replaced with quick response heads	+5
Complete sprinkler system provided throughout entire building, but not required	+7
Complete sprinkler system complying with NFPA 13 for quick response heads is provided throughout the entire building, but not required (if -5 was entered under sub. (2), numerical value is +5.)	+10

Table 34 – Case Study 2: Revised Fire Alarms Risk Index

Revised Fire Alarms	Numerical Value
Fire alarm system required but not provided	-5
Fire alarm system required and provided but does not comply with acceptable solution	-2
Complies with acceptable solution	0
Fire alarm system provided but not required (Note: If a numerical value of +5 is taken under the smoke detection fire risk index, the numerical value for this section is 0)	+1
Fire alarm system provided with voice communication system that complies with the NBC	+3
Fire alarm system includes a central alarm and control facility and automatic signals to fire department when not required	+4
Fire alarm system provided with automatic signals to fire department and interconnected with a monitoring company that is permanently monitored when not required	+5

How the occupants will utilize the building is an important consideration in the case of this building because their activities can either reduce or increase the potential for fires in the space. In addition, their preparation for, and practice of, fire drills and emergency procedures will affect timely evacuation. Since this office will be utilized by federal government tenants, the following items in Table 35 the Occupants Activities risk index apply in this case.

Table 35 - Case Study 2: Occupant Activities Risk Index

Occupant Activities Risk Index (Cumulative)	Numerical Value
No smoking and no open flames	0.14
No cooking	0.18
Use of space heaters and heat generating appliances tightly controlled	0.1
Fire emergency organization trained to identify and remediate fire hazards	0.1
Fire emergency organization facilitates emergency evacuation	0.15
Occupants trained in emergency procedure and evacuation	0.15
Awake and alert	0.1
Familiar with the building	0.1
TOTAL Occupant Activities Score	1.02

The fire type expected in this building is smouldering fire based on the materials and operations described in the design brief. Table 36 shows the Expected Fire Type risk index with the numerical value that will be used in the final fire risk analysis highlighted in yellow.

Table 36 - Case Study 2: Expected Fire Type Risk Index

Fire Type	Numerical Value
Smouldering Fire	1
Standard Fire	0
Fast Flaming Fire	-1

The fire risk analysis with fire risk indexing then combines all the applicable fire risk indices from Case Study 2 to determine if the proposed alternative solution is equivalent and relatively safer than a building that complies with the acceptable solution. Table 37 shows the full fire risk assessment for Case Study 2.

Table 37 - Fire Risk Assessment for Case Study 2

Safety Parameters	Fire Safety	Means of Egress	General Safety	Comments
1. Number of Stories	null	Null	Null	Same for heritage and code compliant building
2. Building Area	null	Null	Null	Same for heritage and code compliant building
3. Building Setback	null	N/A	Null	Same for heritage and code compliant building
4. Attic Compartmentalization	Null	N/A	Null	Same for heritage and code compliant building
5. Firestopping	Null	N/A	Null	Same for heritage and code compliant building
6. Revised Occupancies Separation	-0.5	-0.5	-0.5	From Table 32
7. Vertical Openings	-3	-3	-3	From Table 31
8. HVAC Systems	Null	Null	Null	Same for heritage and code compliant building
9. Revised Smoke Detection	Null	Null	Null	Additional smoke detector coverage does not affect value
10. Revised Fire Alarms	5	5	5	From table 34
11. Smoke Control	N/A	N/A	N/A	No smoke control
12. Revised Exit Capacity	Null	Null	Null	Same for heritage and code compliant building
13. Dead ends	N/A	Null	Null	Same for heritage and code compliant building
14. Maximum travel distance	N/A	Null	Null	Same for heritage and code compliant building
15. Emergency Power	N/A	Null	Null	Same for heritage and code compliant building
16. Elevator Control	Null	Null	Null	No elevators in building
17. Sprinklers	5	5	5	From Table 33
18. Fire Rating of Assemblies	-0.5	-0.5	-0.5	From Table 30
19. Fire Type Risk Index	1	1	1	From Table 36
20. Occupant Activities Risk Index	1.02	1.02	1.02	From Table 35
TOTAL Safety Score	8.02	8.02	8.02	

Table 37 shows the importance of the sprinkler protection and resulting fire alarm monitoring and automatic fire department notification which were installed but exceed the requirements for a code compliant building of this occupancy type. Together, these compensate for the non-compliant site conditions that must remain to preserve the heritage features of this building. Fortifying the fire separations of the roof, floor and college wall assemblies provide adequate fire compartmentation to facilitate timely evacuation of building occupants, and for the fire department to respond. Installation of draft stops to delay the spread of smoke along the ceiling, combined with smoke detector coverage near the draft stops, will provide for earlier warning of fire via quick initiation of the fire alarm system. An fire emergency organization effectively trained in hazard identification, mitigation and emergency procedures, as well as building occupants who are familiar with emergency procedures will make the working and utility spaces much safer. By use of the full fire risk assessment framework developed in this thesis, it can be shown that with the proposed alternative fire safety solution, the rehabilitated building is at least as safe as, and potentially even relatively safer than a building that simply complies with the minimum requirements specified in the Code.

4.3 Case Study 3

The third case study is based on a historic building that was built in 1861 as shown in Figure 15. The building is 3 storeys tall with a building area of 216 m^2 and has a total floor area of 501 m^2 spread over three floors. The first two floors have a floor area of 216 m^2 each as they include the solarium, shown in Figure 15 below, while the 3rd floor and the basement each have an area of 69 m^2. The building is fully sprinklered and is has a full fire alarm system that monitors the sprinkler system. The fire alarm system itself sends a signal directly to the fire department when the fire alarm is initiated. The basement contains an electrical room, mechanical room, storage, laundry area, hot water closet, vault, library, and archive room. In this case study, alternative solutions will be proposed and analyzed to upgrade the building so that the current usage of the building as a museum for the public and administrative offices for staff can continue. The fire protection framework proposed in Chapter 3 will be used to develop and evaluate the alternative solution.

Figure 15 - Combination of Utilitarian and Colonial Revival Style

4.3.1 Heritage Character Statement

The building was originally designed as a utilitarian building but after a renovation in 1920 it was reworked according to the principles of the Colonial Revival style. It is a brick building that is topped by a wood shingled, high-pitched, gable roof with dormers. The main entrance is defined by a projecting portico with classically inspired motifs in the wood detail. It is domestic in scale, with symmetrical elevations and a conventional centre hall plan. Quality construction and workmanship characterize the exterior and the interior. The building remains in its park-like setting that was created in the 1920s and is a highly visible part of the park and familiar as a museum and interpretation centre for visitors [84]. This building is recognized for its historical associations, architectural importance and for its environmental and local significance.

4.3.2 Design Brief

In this hypothetical scenario, the building will be renovated from a residential dwelling unit to a building that houses a museum on the first floor and part of the 2nd floor, and a separate office space will occupy the part of the 2nd floor and the third floor. The two different occupancies, A2 for the museum and D for the office area, will be separated from each other by a fire separation having a minimum fire resistance rating of 1 hour. The museum space will be occupied by the public and museum staff while the office space is restricted to staff and guests who administer properties in the region, including this building. The basement consists of service rooms and storage rooms for the building. The existing sprinkler system and fire alarm system will remain and be adapted to suit the final design of the space. A fire separation having a minimum fire resistance rating of 1 hour will separate the office space on the 2nd and 3rd floor from the rest of the building.

The building has several sets of stairs providing access to different areas of the building. In the museum area, there is currently one open central stair case that connects the first and second floors. Inside the office occupancy, there is another set of open stairs that connects the 3rd floor and the 2nd floor. The basement has two different sets of stairs that lead directly to the outside and does not require any changes. The 3rd floor is also served by a fire escape, as shown in Figure 16, that utilizes a window to go to the exterior of the building, then a catwalk that leads to a fire escape ladder that must be released so that its length extends to the ground level.

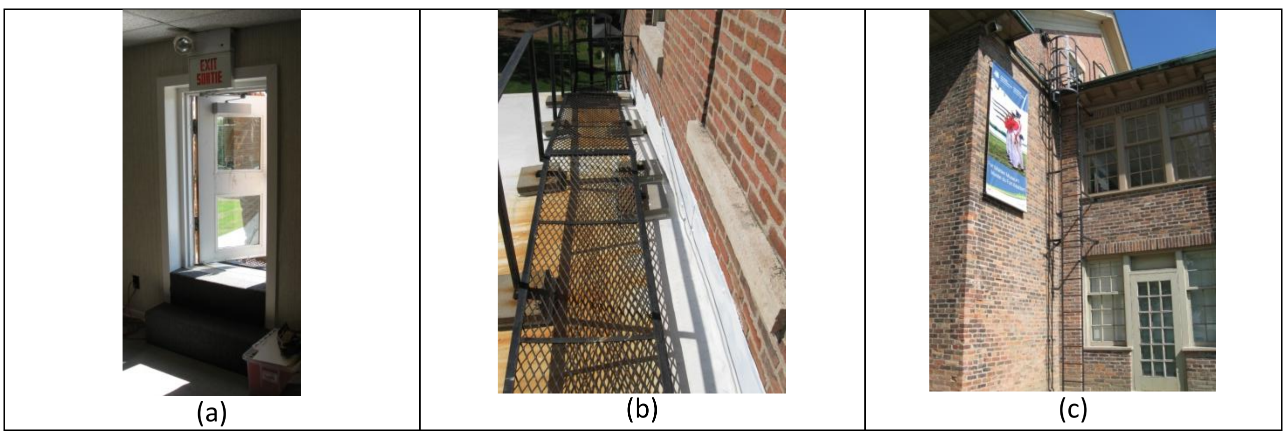

Figure 16 - 3rd Floor Fire Escape (a) from inside 3rd floor; (b) travel along roof; (c) ladder that extends to the ground

The heritage character statement for the building identifies the main entrance, construction and craftsmanship of the interior and exterior of the building as heritage elements that make this building significant. The exterior of the building, especially the front of the building, should not be altered in order to preserve the heritage value of the main entrance. Preserving the interior layout and finishes as much as possible will help to preserve the heritage value of the interior. What this means practically speaking is enclosing an exit stair from the third floor to the main floor would impact the interior layout and finishes which have been identified as having heritage value. An alternative solution must be created that protects the heritage features of the building, while at the same time allowing the owner to utilize the building in the proposed new way.

4.3.3 Building Code and Fire Code Analysis

Based on the information provided on the base building above and the intended new use of the building, there is sufficient information to fill out the building code analysis sheet for case Study 3. Table 38 below contrasts the code requirements for a code compliant building against the features of this heritage building.

Table 38 - Building code analysis for Case Study 3 [14]

	Ideal Building	Heritage Building	Functional and Objective statements
Year of Original Construction	2017	1861	N/A
Major Occupancy Classification(s)	A2 and D	A2 and D	N/A
Governing Code Part	Part 3	Part 3	N/A
Fire Resistance rating of floor assemblies (hrs)	1 hour	1 hour	N/A
Building Area (m2)	216	216	N/A
Building Height (Storeys)	3	3	N/A
Cross-over Floors	No cross over floors in building	No crossover floors in building	N/A
High Building (see NBC Article 3.2.6)	N/A	N/A	N/A
Interconnected floor space	Permitted between first storey and one above or below it ONLY. 3.2.8.2.(6)	Interconnected floor space between 1st and 2nd floor in the museum space. Interconnected floor space between the 2nd floor and 3rd floor office space.	[F02, F03-OS1.2 and OP1.2]
Mezzanines	None present	None present.	
Sprinklers	Required 3.2.2.24	Installed	
Building Faces No. of Streets (for fire department access)	1	1	
Type of Construction	Non combustible 3.2.2.24(2)	Mix of combustible and non-combustible	[F02 -OS1.2] [F02-OP1.2]
Fire Resistance of Roof Assembly	1 hour 3.2.2.24(2)(a)	1 hour	

Total Building Occupant Load			
Fire Alarm System	Required 3.2.4.1.(1)	Installed	
Voice Communication	Not required	Not installed	
Fire Alarm System Monitoring	Required 3.2.4.10(5)	Monitored	
Standpipe & Hose	Not required	Not installed	
Emergency Power	30 minutes	30 minutes	
Smoke Control Measures	Not required	Not installed	
Fire Pumps	Not required	Not installed	
Maglocks	N/A	N/A	
Special Extinguishing Systems	N/A	N/A	
Water Supply	Municipal	Municipal	
Spatial Separations	N/A	Not an issue because it is in the middle of a park where the grass is well groomed and watered.	

Table 38 shows that this building is a Part 3 building as a result of the A2 Occupancy type. The majority of the building appears to comply with the NBC. It is not a high building and it is not required to have crossover floors. The building is fully sprinklered and connected to the fire alarm system. The fire alarm system is fully functional and monitored by the fire department. The roof assembly, main floor assembly and wall assembly separating the museum and office occupancies are all constructed as fire separations having a minimum fire resistance rating of 1 hour. The interconnected floor space between the main floor and 2nd floor is also allowed; however, the other interconnected floor space between the 2nd and 3rd floor inside the office occupancy is not permitted. The building is required to be constructed with non-combustible construction but has to remain a mix of combustible and non-combustible construction in order to preserve some of the key heritage features.

In addition to a building code analysis, a fire protection engineering survey was conducted. The survey consisted of a visual inspection of the building to evaluate the current condition and overall compliance of the building with the prevailing code and thereby identify additional deficiencies that may exist in the building. Two additional deficiencies were identified during the engineering survey that were not captured on the building code data sheet. The first deficiency is each floor level is required to have access to two exits in accordance with Article 3.4.2.1(1) of the NBC. The second deficiency relates to fire escapes and the requirement that fire escapes must be of the stair type in accordance with Article 3.4.7.2(1) [14].

Table 39 identifies and summarizes all the deficiencies in this building against the related code provision and the functional and objective statements attributed to that code provision. Alternative solutions will be developed and evaluated against the functional and objective statements attributed to the deficiencies in Table 39.

Table 39 - Case Study 3: Complete List of Deficiency

Non-Conformance	Code Requirements	Functional and Objective Statements
1) The interconnected floor space between the 2nd and 3rd floor office space	3.2.8.2(6) - An interconnected floor space need not conform to the requirements of Articles 3.2.8.3 to 3.2.8.9 provided a) the interconnected floor space consists of the first storey and the storey next above or below it, but not both, b) the openings through the floor are used only for stairways, escalators or moving walks or the interconnected floor space is sprinklered throughout, c) the interconnected floor space contains only Group A, Division 1,2, or 3, Group D, Group E, or Group F Division 2 or 3 major occupancies, and d) the building area is not more than one half of the area permitted by subsection 3.2.2	**[F02, F03-OP1.2 and OS 1.2]:** F02- To limit the severity and effects of fire or explosions. F03 - To retard the effects of fire on areas beyond its point of origin. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin
2) Building is a mix of	3.2.2.24(2) - Except as permitted by Article 3.2.2.16,	[F02 -OS1.2] [F02-OP1.2] F02- To limit the severity and effects of fire or

combustible and non-combustible construction	the building referred to in Sentence (1) shall be on non-combustible construction, and	explosions. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin F02- To limit the severity and effects of fire or explosions. OP1 Fire Protection of the Buildings - An objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin.
3) 2nd and 3rd floors are required to have two exits	3.4.2.1.(2) - Every floor area intended for occupancy shall be served by at least 2 exits.	**[F10, F12, F05, F06, OS3.7, OS1.2, OP1.2]:** F10 to facilitate the timely movement of persons to a safe place in an emergency. F12 To facilitate emergency response. F05 To retard the effects of fire on emergency egress facilities. F06 To retard the effects of fire on facilities for notification, suppression and emergency response. OS3 Safety in Use - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this code are those caused by OS3.7 - persons being delayed in or impeded from moving to a safe place during an emergency. OP1 Fire Protection of the Buildings - An

		objective of this Code is to limit the probability that, as a result of its design or construction, the building 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 OP1.2 - fire or explosion impact areas beyond its point of origin. OS1 Fire Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building 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 OS1.2 - fire or explosion impacting areas beyond its point of origin
4) The fire escape from the 3rd floor should be stair type.	3.4.7.2(1) - the fire escape shall be of metal of the stair type extending to ground level.	**[F10, F12-OS3.7][F20-OS3.1][F20-OS2.1]:** F10 To facilitate the timely movement of persons to a safe place in an emergency. F12 To facilitate emergency response. OS3 Safety in Use - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this code are those caused by OS3.7 - persons being delayed in or impeded from moving to a safe place during an emergency. F20 To support and withstand expected loads and forces. OS3 Safety in Use - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to hazards. The risks of injury due to hazards addressed in this code are those caused by 3.1 tripping, slipping, falling, contact, drowning or collision. OS2 Structural Safety - An objective of this Code is to limit the probability that, as a result of the design or construction of the building, a person in or adjacent to the building will be exposed to an unacceptable risk of injury due to structural

		failure. The risks of injury due to structural failure addressed in this Code are those caused by 2.1 loads bearing on the building elements that exceed their loadbearing capacity.

The main deficiencies in the building relate to the interconnected floor spaces on floors that are not permitted in the code, the use of combustible materials in a building required to be of non-combustible construction, the lack of two exits for occupants on each floor, and extension fire escapes rather than the required stair type systems.

The interconnected floor space between the 2nd and 3rd floor offices reduces the effectiveness of many of the other measures taken to limit the severity and effects of fire or explosions. A fire may spread more easily from floor to floor, affecting areas beyond its point of origin and exposing the building to an increased risk of damage and occupants to an increased risk of injury from fires or explosions beyond the area of origin. Combustible construction in the building may increase the severity and effects of fire or explosions and contribute to the spread of fire and an increased risk of injury to occupants in areas beyond fire origin. Similarly, occupant egress is impeded when floor areas have less than the required number of exits or, on the other hand, when there are no barriers protecting egress routes, fire and smoke can spread to staircases and into corridors with greater risk to occupants and the structure. Finally, the ladder in the fire escape slows the timely movement of persons to a safe place, may not be usable by emergency responders and may also increase the risk of trips, slips and falls during use.

The alternative solution, then must address the deficiencies noted in Table 39 with an explanation describing how it still satisfies the objective and functional statements behind the code provisions.

4.3.4 Case Study 3 - Alternative Solution

The alternative solution consists of a set of smaller design changes that are intended to protect the quality construction and workmanship of the exterior and interior of the building, maintain the defining feature of the building's main entrance while still achieving the objective and functional statements listed in Table 39. In addition, the combustible materials will be protected and finishes with low flame spread ratings and smoke development classifications will be specified. Draft stops will be installed around interconnected floor spaces and smoke detector coverage throughout the building will be enhanced. Since this is a federal government building, the fire emergency organization at the site will be accounted for in the overall risk assessment. Fire statistics related to these occupancies will be examined and knowledge of fire dynamics used to support some of the assertions behind the alternative solution as well.

The first part of the solution involves designing and installing a new exterior exit from the 2nd storey connecting to the stairs between the 2nd and 3rd floors. The new stair provides a second direct exit from the second storey by which occupants can exit the building without descending a flight of stairs and exiting through the lobby of the building. It similarly provides a second path for emergency responders to access the 2nd and 3rd floors. The new stair is considered a horizontal exit from the building because once occupants exit the building, they are served by a freestanding exterior stair that leads to the ground level and then along an exit pathway that runs down the side of the building, which is a fire wall with no openings, shielding those occupants using the stairs from the effects of fire inside the building. As shown in Figure 17, the exit will be installed on the side of the building away from the front entrance to minimize the impact on heritage character. The stair will be free-standing which further preserves the exterior of the building since the stairs can be removed and the exterior wall restored if the building use changes at a later date.

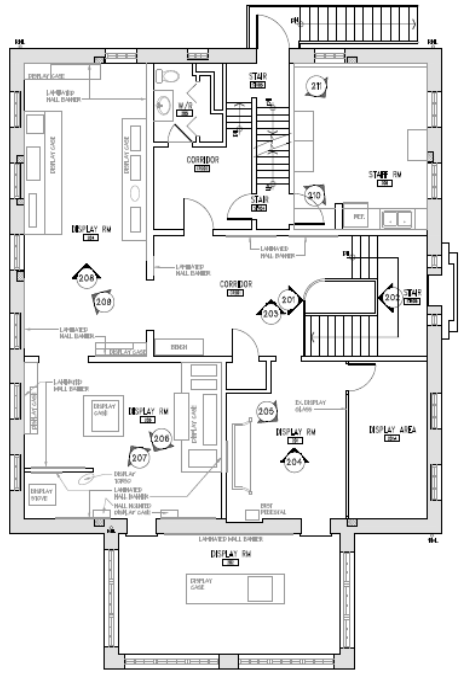

Figure 17 - New Exterior Exit from the 2nd floor on the side of the building [85]

To maintain an appropriate fire rating, a fire rated door will be installed in the fire separation that separates the office space and the museum space. It will swing in the direction of exit travel from the museum into the office space to facilitate egress for museum patrons since the museum is expected to have a higher occupant load than the office space. The door will also be signed as an exit on both sides so that persons anywhere on the 2nd floor will always have access to two exits.

The fire escape will not be changed due to the existing building layout and the need to preserve the exterior of the building as much as possible. The 3rd floor office space is 69 m^2 . The 2nd floor office area consists of stairs, a washroom and a kitchenette which occupies approximately 25% of the 216 m^2 shown on Figure 17 resulting in a total office area that is approximately 123 m^2. Table 3.3.1.5A and Table 3.4.2.1B of the NBC show that an office or museum space with an area of 123 m^2 is permitted to be served by a single means of egress or exit [14]. An argument can then be made that the fire escape on the 3rd floor is no longer a deficiency and instead augments the existing situation where two exits have already been provided for all of the occupants on the second floor.

The original combustible construction used in structural members and other building assemblies will be preserved in the rehabilitation project. The NBC recognizes that there is a degree of fire safety attained by the use of noncombustible materials in structural members and other assemblies [14]. Alternatively, for combustible construction, fire safety can be enhanced by applying intumescent paint to the exterior surfaces of structural members and other building assemblies provide an additional 30 minute fire resistance [76]. In addition, clear intumescent paint will be applied to exposed combustible elements such as ornate finishes, base boards and mouldings since the quality and workmanship was identified in the building's heritage character statement. This should delay fire damage to any exposed combustible finishes and to the combustible structural elements, protecting them from fire damage, slowing the spread of fire and extending the time for egress and protecting building occupants from being exposed to an unacceptable risk of injury due to fire. Further, protection of combustible elements and specification of furniture with low flame spread ratings and smoke developed classifications will make it difficult for fires to ignite and grow making a relatively slow growing or smouldering fire most likely to occur in the building.

As in case study 1 and 2 above, draft stops will be installed around openings for interconnected floor spaces and smoke detector coverage will be enhanced by installing smoke detectors near the draft stops as well. Additional smoke detectors will be installed throughout the museum exhibit floor where historical artifacts are displayed. In this way, any smoke starting in areas outside of stairwells will be detected earlier, providing earlier notification of a fire to building occupants so they can begin evacuation and fire fighters so they can begin fire fighting activities.

This building will be occupied by a federal agency who will comply with Treasury Board Fire Protection Chapter 3-1 Standard for Fire Safety Planning and Fire Emergency Organization. As noted in Section 3.2.1.2. This standard goes above and beyond what is required in the NFC and includes training of fire emergency organization members on both emergency procedures and identifying and mitigating fire hazards. Being a professional work place, all occupants will be alert inside the building which shortens evacuation time. The office and museum will have a properly designed heating, ventilation and air conditioning system to maintain the temperature in the building eliminating the need for space heaters.

Health and safety requirements prohibit smoking in the workplace and there will be no cooking facilities, thus eliminating several possible sources of ignition.

The overall alternative solution combines a new exterior exit, protection of combustible materials from the damaging effects of fire, installation of draft stops to retard smoke spread, enhanced smoke detector coverage for early fire detection, and good workplace practices to reduce the risk and impacts of fire and shortens evacuation time should one occur.

4.3.5 Case Study 3 - Fire Risk Assessment Using Fire Risk Indices

The overall fire risk assessment for this heritage rehabilitation project was done using the same methods as applied in the case studies above. Due to the nature of the rehabilitation project, it was found that in order to assess the alternative solutions, some additions and revisions to the fire risk assessment indices used for Cases 1 and 2 were required. These are discussed in the appropriate sections below.

As a first step, the various fire resistance ratings of fire separations throughout the building are considered and captured in Table 40 Fire Ratings of Assemblies risk index with the items that need to be considered for the final fire risk assessment highlighted.

Table 40 – Case Study 3: Fire Ratings of Assemblies Risk Index

Fire Rating of Assemblies Risk Index	Numerical Value
Fire rated assembly provides 2hr below required protection level	- 2
Fire rated assembly provides 1hr below required protection level	- 1
Fire rated assembly provides 0.75hr below required protection level	- 0.75
Fire rated assembly provides 0.5 hr below required protection level	- 0.5
Fire rated assembly provides 0.25hr (15 mins) below required protection level	- 0.25
Complies with code	0
Draft stops used to retard flow of combustion products and extend usability of egress routes	0.25
Use intumescent paint and door closers on existing wood doors to compartmentalize rooms from rest of building	0.25
Total Fire Ratings of Assemblies Score	-0.75

In this building, the interconnected floor space between the 2nd and 3rd floor is a deficiency that must be captured when assessing the alternative solution. -1 is the value to be applied because the stair is required to have a minimum fire resistance rating of 1 hour. The installation of draft stops around interconnected floor space openings provides a credit for the interconnected floor space and is captured with a score of 0.25. The final score for Case Study 3 using the Fire Ratings of Assemblies risk index is -0.75.

The non-conformance of having combustible construction in this building and the steps taken to retard the damaging effects of fire on those elements is captured through development of a new fire risk index, the Combustible Construction risk index, shown in Table 41.

Table 41 – Case Study 3: NEW Combustible Construction Risk Index

Combustible Construction Risk Index	Numerical Value
Combustible construction used in floor and roof assemblies that are to be of non-combustible construction and required to have minimum fire resistance rating of 2hr	- 2
Combustible construction used in floor and roof assemblies that are required to be of non-combustible construction and required to have minimum fire resistance rating of 1hr	- 1
Combustible construction used in floor and roof assemblies that are required to be of non-combustible construction and required to have minimum fire resistance rating of 0.75hr	- 0.75
Combustible construction permitted for floor and roof assembly or heavy timber used in fire rated assembly that provides the minimum fire resistance rating required by the code.	0
Combustible construction that are to be of non-combustible construction and are protected by systems that provide a 0.5 hour fire resistance rating.	0.25
Combustible construction that are to be of non-combustible construction but are protected by systems that provides a 0.75 hour fire resistance rating.	0.5
Combustible elements that are to be of non-combustible construction but are protected by system that provides a 1 hour fire resistance rating.	0.75
Combustible elements protected by system that provides a 2 hour fire resistance rating.	1.75
Total Fire Ratings of Assemblies Score	-0.5

This index aims to capture the negative effects that can accrue when combustible construction is used in a building required to have fire rated assemblies that consist of non-combustible construction. The premise for this index is based on the inherent fire safety attributed to non-combustible construction. For example, a score of -0.25 will be the result when using this index to evaluate a fire separation that uses combustible construction when non-combustible materials is required for a fire separation that has the minimum fire resistance rating required by the code. The risk index recognizes that combustible elements and assemblies can eventually ignite, and then may contribute to the growth and spread of fire, or ultimately be consumed. The index also captures the added degree of fire safety attributed to heavy timber [14] since wood, when exposed to fire, burns and forms a layer of char which insulates the solid wood underneath

[45] and thus affords some measure of fire resistance. Heavy timber is defined as wood where the smallest dimension is no less than 80 mm [45]. The reason why net values are not used in this risk index is there may be scenarios where a fire separation with combustible construction may employ systems that will provide a fire resistance rating greater or less than what is required by the code. There are many methods where fire separations with combustible construction can have the fire resistance ratings extended to compensate for the lack of "inherent fire safety attributed to non-combustible construction”. Intumescent paints applied to the surface of fire rated assemblies may provide up to an additional 30 minutes of fire resistance on the surface [76] before the fire rated assembly underneath is exposed to fire. The additional 30 minutes of fire resistance afforded by the application of intumescent paint helps protect the building and occupants by allowing more time for the safe evacuation, and potentially more time for emergency responders to operate safely inside the building. Positive benefits of any protection may or may not completely compensate for the additional degree of fire safety attributed to noncombustible construction so the index is designed in a way that fire separations with combustible construction could compensate for fire separations made of non-combustible construction if the right strategy, in the right situation were employed. A score of -0.5 is the best outcome that can be achieved in case study 3, where intumescent paint is applied.

The addition of the new exterior exit door from the 2nd floor with the path down the exterior stair to a safe area has the positive effect that occupants in the basement, main floor and 2nd floor all have access to two exits. The code requires that the third floor should also have access to two exits. The path down the stairs from the third floor to the new exterior exit on the second floor and the existing fire escape provide that; however, in the case of the fire exit, the ladder does not comply with the code and in the case of the stair, it is not enclosed as required by the code. In assessing the entire compliance, it is important to note that the area of the combined office occupancy on the 2nd and 3rd floors are actually small enough that it would be permitted to be served by 1 exit if it was on main level, so with the addition of the 2nd floor exterior exit, the situation is very similar.

It is proposed that the Vertical Openings risk index does not apply in this case study. The justification is that there is an interconnected floor space within a suite that is fire separated from the remainder of the building while at the same time, the suite area is of an appropriate size that, under the NBC, it can be served by 1 exit.

The fire escape is not a stair type but since it is considered to be an extra means of egress above and beyond the stairs leading to the new exterior door, no negative effects will be scored against it here.

The alternative solution also incorporates the installation of additional smoke detectors near draft stops and throughout the museum exhibit space. These additional detectors will be added to the fire alarm system which will be monitored by a fire alarm monitoring company and the fire department will be notified automatically when the fire alarm is initiated. Table 42 shows that the fire alarm monitoring and additional smoke detectors will be accounted for through the Revised Fire Alarms risk index from Section 3.2.2.5 in the final fire risk analysis.

Table 42 – Case Study 3: Revised Fire Alarms Risk Index

Revised Fire Alarms	Numerical Value
Fire alarm system required but not provided	-5
Fire alarm system required and provided but does not comply with acceptable solution	-2
Complies with acceptable solution	0
Fire alarm system provided but not required (Note: If a numerical value of +5 is taken under the smoke detection fire risk index, the numerical value for this section is 0)	+1
Fire alarm system provided with voice communication system that complies with the NBC	+3
Fire alarm system includes a central alarm and control facility and automatic signals to fire department when not required	+4
Fire alarm system provided with automatic signals to fire department and interconnected with a monitoring company that is permanently monitored when not required	+5

How the occupants plan to utilize this building is an important consideration in this case because their activities can either reduce or increase the potential for fires in the space. In addition, their preparation for, and practice of, fire drills and emergency procedures will affect timely evacuation. Since this building has both an office occupancy and museum occupancy that is run by a federal agency, as outlined in more detail in Chapter 3, all of the following items in Table 43, the Occupants Activities risk index apply in this case.

Table 43 - Case Study 3: Occupant Activities Risk Index

Occupant Activities Risk Index (Cumulative)	Numerical Value
No smoking and no open flames	0.14
No cooking	0.18
Use of space heaters and heat generating appliances tightly controlled	0.1
Fire emergency organization trained to identify and remediate fire hazards	0.1
Fire emergency organization facilitates emergency evacuation	0.15
Occupants trained in emergency procedure and evacuation	0.15
Awake and alert	0.1
Familiar with the building	0.1
TOTAL Occupant Activities Score	1.02

The fire type expected in this building is slow growing or smouldering fire based on the materials and operations described in the design brief. Table 44 shows the Expected Fire Type risk index with the numerical value that will be used in the final fire risk analysis highlighted in yellow.

Table 44 - Case Study 3: Expected Fire Type Risk Index

Fire Type	Numerical Value
Smouldering Fire	1
Standard Fire	0
Fast Flaming Fire	-1

The fire risk analysis with fire risk indexing will combine all the applicable fire risk indices from Case Study 3 to determine if the alternative solution is equivalent and relatively safer than a building that complies with the acceptable solution. Table 45 shows the full fire risk assessment for Case Study 3.

Table 45 - Fire Risk Assessment for Case Study 3

Safety Parameters	Fire Safety	Means of Egress	General Safety	Comments
1. Number of Stories	null	Null	Null	Same for heritage and code compliant building
2. Building Area	null	Null	Null	Same for heritage and code compliant building
3. Building Setback	null	N/A	Null	Same for heritage and code compliant building
4. Attic Compartmentalization	Null	N/A	Null	Same for heritage and code compliant building
5. Firestopping	Null	N/A	Null	Same for heritage and code compliant building
6. Revised Occupancies Separation	Null	N/A	Null	Same for heritage and code compliant building
7. Vertical Openings	N/A	N/A	N/A	Office area small enough to be served by one exit and is fire separated from remainder of building.
8. HVAC Systems	Null	Null	Null	Same for heritage and code compliant building
9. Revised Smoke Detection	Null	Null	Null	Additional smoke detector coverage does not affect value
10. Revised Fire Alarms	5	5	5	From Table 42
11. Smoke Control	N/A	N/A	N/A	No smoke control
12. Revised Exit Capacity	Null	Null	Null	Same for heritage and code compliant building
13. Dead ends	N/A	Null	Null	Same for heritage and code compliant building
14. Maximum travel distance	N/A	Null	Null	Same for heritage and code compliant building
15. Emergency Power	N/A	Null	Null	Same for heritage and code compliant building
16. Elevator Control	Null	Null	Null	No elevators in building
17. Sprinklers	Null	Null	Null	Same for heritage and code compliant building
18. Fire Rating of Assemblies	-0.75	-0.75	-0.75	From Table 40
19. Fire Type Risk Index	1	1	1	From Table 44
20. Occupant Activities Risk Index	1.02	1.02	1.02	From Table 43
21. NEW Combustible Construction Risk Index	-0.5	-0.5	-0.5	From Table 41
TOTAL Safety Score	5.77	5.77	5.77	

Table 45 shows that the alternative solution achieves the functional and objective statements behind the code provisions where the building could not comply with the acceptable solution. The design and installation of the new horizontal exit from the 2nd floor was effective at addressing several deficiencies related to building protection and occupant safety. Applying intumescent paint to assemblies in order to provide an additional degree of fire safety partially addressed the functional and objective statements associated with the use of non-combustible construction for situations where combustible construction was a fundamental element of the heritage building. Enhancements to the fire alarm system with additional smoke detectors throughout the exhibit space, monitoring by the fire department, and monitoring by an accredited fire alarm monitoring company should provide earlier detection of fires and thus initiate evacuation and fire department response sooner. This will have a positive effect on occupant safety as well as structural protection in the event of a fire.

While an acceptable alternative solution was found, this case study also uncovered the need to create a new Combustible Construction risk index to take into account the use of combustible construction in many heritage buildings. The Combustible Construction risk index was created to capture steps taken to protect combustible elements in a space that would be required to have noncombustible construction in the code compliant solution.

4.4 Case Study Conclusions

The three case studies demonstrate that fire risk assessment using fire risk indexing can be effectively used to evaluate the acceptability of alternative solutions in heritage rehabilitation projects by comparing them on relative terms to buildings that comply with the acceptable solution in the Code. From the three buildings, it was found that the best way to address non-conformances is to use engineered systems such as sprinklers, fire alarm systems, and fire separations to compensate for deficiencies. Occupant based fire safety systems are resource intensive as they require training and practice; however, they can be effective at contributing to a safe environment for occupants and the building and thus should be weighted with a level of positive impact, although it should generally be less than that of any engineered system in recognition that behaviour is much more variable than an automatic or monitored system.

5 Conclusion and Recommendations

The main contribution of this thesis is the proposal of the new fire protection framework that uses fire risk assessment methods from fire risk indexing for developing and evaluating alternative solutions for Canadian heritage rehabilitation projects and demonstrating that it works. This was done by analyzing the current fire protection framework in Canada and a comparing prescriptive, performance and objective based codes. Objective-based codes provide intent, objective, and functional statements behind code provisions, deepening the understanding of what a provision is trying to achieve so that alternative solutions can be developed and evaluated against that intent. It is also the framework currently in place with which Canadian fire protection engineers, designers, owners and occupants are familiar. Quantitative, qualitative and semi-quantitative fire risk assessment methods were discussed and compared for 1) flexibility and ease in determining equivalency with objective and functional statements, 2) ease of use by fire protection engineers, and 3) ease in understanding by fire protection stakeholders. A semi-quantitative fire risk assessment using fire risk indexing was the framework that best satisfied the three criteria noted.

The fire risk indexing method proposed in this thesis combines the 17 building parameter fire risk indices from the Building Evaluation Method from Chapter ILHR 70 of the Wisconsin Administrative Code, with appropriate amendments, and supplements them with additional fire risk indices that consider occupant behaviour, fire type, combustible construction, and fire separation designs that delay the spread of fire beyond the area of origin and thus reduce the risk of damage to the building and injury to occupants. Gaps in the fire risk indices are then filled by using fire science and fire statistics to revise existing fire risk indices and create new indices as necessary.

The flexibility of fire risk indexing allowed new information on the fire resistance ratings of alternative fire separations to be included in the overall fire safety assessment leading to revision of the Occupancy Separation risk indices and the creation of the Fire ratings of Assemblies risk index. Canadian fire alarm system requirements led to the revision of the Fire Alarm and Smoke Detection risk indices so that they matched Canadian requirements. The revision of the Exit Capacity risk index was done in response to the challenge of heritage preservation objectives that preserved existing hand rails, guard rails, doors, door frames and door hardware which can also impact door swing of exit doors. Studies on human behaviour and fire statistics showed how additional processes undertaken by building occupants could reduce evacuation time and limit fire ignition led to the creation of the new Occupant Activities risk index. Fire dynamics showed that measures taken to slow the growth of fire could provide more time for building occupants to detect, suppress and evacuate in a fire event leading to the creation of the new Fire Type risk index. The heritage buildings studied in this thesis incorporated combustible construction. The NBC requires non-combustible construction for certain types of occupancies so when heritage buildings are rehabilitated for new uses, the existing combustible construction may be a problem. There are several methods available that can further protect combustible construction to provide an additional level of safety and this is captured in the new Combustible Construction risk index.

The final approach was tested on 3 buildings, as outlined in this thesis and was demonstrated to be suitable at developing and evaluating alternative solutions for heritage rehabilitation projects in order to determine equivalency with acceptable solutions. Going forward, this framework should be utilized for more heritage rehabilitation projects in order to increase the sample size for demonstrating the suitability and ease of interpretation of fire safety via this framework. It is envisioned that additional gaps from fire risk assessment with fire risk indexing of heritage rehabilitation projects may be uncovered requiring further revision of some fire risk indices. New indices should be created at the project level to address project specific gaps and, if a similar need arises in multiple projects, a new index should then be incorporated as an added option to the overall framework.

In closing, it is proposed that a new centralized body should be established for the purposes of assessing fire safety solutions for Canadian Heritage Rehabilitation Projects. The body should be composed of individuals with knowledge and expertise in fire science such as designers, fire protection engineers, and AHJs to ensure flexibility and consistency in use of the index in future heritage building projects. The centralized body would review the fire risk assessment with fire risk indexing for each project and track the acceptable fire risk indices used and the rationale behind the accepted fire risk indices. This new centralized body will be the new AHJ for this framework and will also be responsible to provide guidance on application of the fire risk indices and make all accepted fire risk indices available for the fire protection community to use on current and future projects. Research in fire safety science will be ongoing as well with new discoveries and deeper understanding on the subject available to be used in the field. The centralized body can therefore also be proactive in revising and creating new fire risk indices and provide the necessary rationale, guidance and support for ongoing evolution and improvement of the method for more general use in industry.

6 References

[1] Parks Canada, "National Historic Sites Introduction" - http://www.pc.gc.ca/en/lhn-nhs/introduction (17July2017)

[2] Treasury Board Secretariat of Canada, "Directory of Federal Real Property" - http://www.tbs-sct.gc.ca/dfrp-rbif/home-accueil-eng.aspx (17-July-2017)

[3] Federal Heritage Buildings Review Office (FHBRO) under the direction of Victoria Angel, FHBRO Manager "A Guide to Working with the Federal Heritage Buildings Review Office" p. 1-3,© Her Majesty the Queen in Right of Canada, represented by the Chief Executive Officer of Parks Canada, 2009

[4] Watts John M. Jr.; Kaplan, Marilyn E.; "Fire Safe Building Rehabilitation" P. 6-30, © 2003 National Fire Protection Association Inc.

[5] Heritage Perth, "Why Heritage is an Important Community Asset" - http://heritageperth.com.au/your-heritage/why-is-heritage-important-to-communities/ (17-July-2017)

[6] Heritage Resources Branch, Saskatchewan Culture, Youth and Recreation, "Historic Buildings Modern Uses" P. 2-3, March 2007.

[7] Canada's Historic Places, "Parliament Hill Centre Block" - http://www.historicplaces.ca/en/rep-reg/place-lieu.aspx?id=4675&pid=8136&h=Parliament,Hill (5-Jan-2017)

[8] Public Works and Government Services Canada, "Parliament Hill Cam" - http://www.tpsgc-pwgsc.gc.ca/citeparlementaire-parliamentaryprecinct/camera-eng.html (5-Jan-2017)

[9] Parks Canada, "Federal Heritage Buildings Review Office - Introduction" - http://www.pc.gc.ca/progs/beefp-fhbro/index.aspx (4Aug2017)

[10] Petzet, Michael; "Principles of Preservation - An Introduction to the International Charters for Conservation and Restoration 40 Years after the Venice Charter" - International Council on Monuments and Sites, 2004 http://www.international.icomos.org/venicecharter2004/petzet.pdf (23May2015)

[11] International Council on Monuments and Sites, "History of the Venice Charter" - http://www.international.icomos.org/venicecharter2004/history.pdf (23May2015)

[12] Baril, Paul; "Fire Protection Issues for Historic Buildings - CCI Notes 2/6" - Canadian Conservation Institute - Copyright Minister of Public Works, 1998. Cat. No. NM95-57/2-6-1998E ISSN 0714-6221 https://www.cci-icc.gc.ca/resources-ressources/ccinotesicc/2-6-eng.aspx (10April2015)

[13] Hadjisophocleous, G.V.; Bénichou, N.; "Development of Performance-Based Codes, Performance Criteria and Fire Safety Engineering Methods", International Journal on Engineering Performance-Based Fire Codes, Volume 2, Number 4 p127-142, 2000.

[14] Canadian Commission on Building and Fire Codes National Research Council of Canada, "National Building Code of Canada 2010", © National Research Council of Canada 2010, Ottawa, World Rights Reserved

[15] Canadian Commission on Building and Fire Codes National Research Council of Canada, "National Fire Code of Canada 2010" © National Research Council of Canada, Ottawa, World Rights Reserved

[16] Confederation of Fire Protection Associations (CFPA) Europe, "European Guideline CFPA-E-No 30:2013 F - Managing Fire Protection of Historic Buildings" P.4-7 - http://cfpa-e.eu/wp-content/uploads/files/guidelines/CFPA_E_Guideline_No_30_2013_F.pdf (24 May2015)

[17] "5 Reasons to enter the Field of Fire Protection Engineering" - http://www.fireengineering.com/articles/2013/09/5-reasons-to-enter-the-field-of-fire-protection-engineering.html (4August2017)

[18] The Association of Professional Engineers and Geoscientists of the Province of British Columbia - "Guidelines for Fire Protection Engineering Services for Building Projects" P. 1-5, © September 2013 https://www.apeg.bc.ca/getmedia/c7dcdae8-a379-4c8c-9697-9d80f57a5800/APEGBC-Guidelines_for_Fire_Protection_Engineering_Services_for_Building_Projects.pdf.aspx

[19] National Fire Protection Association (NFPA), "NFPA550 Guide to the Fire Safety Concepts Tree 2012 Edition" © 2012 National Fire Protection Association. All Rights Reserved

[20] Treasury Board Policy on Management of Real Property - http://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=12042 (4July2013)

[21] Federal Heritage Buildings Review Office - Roles and Responsibilities - https://www.pc.gc.ca/en/culture/beefp-fhbro/roles/beefp-fhbro (4Aug2017)

[22] "A Guide to Working with The Federal Heritage Buildings Review Office" P. 29, © 2009 by Her Majesty the Queen in Right of Canada, represented by the Chief Executive Office of Parks Canada

[23] "Federal Heritage Buildings Review Office - Processes - Heritage Evaluation" - https://www.pc.gc.ca/en/culture/beefp-fhbro/process/evaluation (4Aug2017)

[24] "Treasury Board Fire Protection Standard" - http://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=17316 (5August2017)

[25] Bergeron, D.; Desserud, R.J.; Hayson, J.C; "The Origin and development of Canada's objective-based codes concept NRCC - 47034" - CIB 2004 World Building Congress 02 May 2004, Toronto, Ontario, Canada

[26] Hussein, Johari; Armitage, Lynne; Too, Linda; "An historical perspective of the evolution of Australian built heritage and its management" - 20th Annual Pacific-Rim Real Estate Society Conference, 19-22 January 2014, Christchurch, New Zealand

[27] Brightman, Michael; "Is the Conservation of the United Kingdom's Built Heritage Sustainable" - Lancashire Business School, University of Central Lacashire. http://www2.warwick.ac.uk/fac/cross_fac/iatl/reinvention/issues/bcur2012specialissue/brightman/ (5May2015)

[28] National Research Council of Canada, "Scope of Construction Codes" - http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/codes_centre/faq/scope.html (27May2015)

[29] "NFPA's Future in Performance-Based Codes and Standards 0 Report of the NFPA In-House Task Group" P.4-5, © 1995 National Fire Protection Association.

[30] Coté, Ron, and Harrington, Gregory E. "Life Safety Code Handbook 9th Edition" P.36-37, © 2003 National Fire Protection Association

[31] Watts John M. Jr, Kaplan, Marilyn E., "Fire Safe Building Rehabilitation" P. 115, © 2003 National Fire Protection Association Inc.

[32] Cote, Arthur E.; Hall, John R. Jr.; Powell, Pamela A.; Grant, Casey C. "Fire Protection Handbook 19th Edition" © 2003 National Fire Protection Association, Inc. - Puchovsky, Milosh T.; Chapter 13 Section 3 "Performance-Based Codes and Standards for Fire Safety"

[33] Cote, Arthur E.; Hall, John R. Jr.; Powell, Pamela A.; Grant, Casey C. "Fire Protection Handbook 19th Edition" © 2003 National Fire Protection Association, Inc. - Watts, John M. Jr.; Chapter 11 Section 3 "Simplified Fire Risk Calculations"

[34] Potworowski, J. André; Murray-Chourhary, Anne; and Losfeld, Bénédicte; "Making it Happen - The transition to a Sustainable Society Case Study The transformation of the National Building Code of Canada: From prescriptions to objectives" P.4-7, March 2010, http://sites.telfer.uottawa.ca/makingithappen/files/2014/05/Building-Code-Case-Study.pdf

[35] Gallagher, J.; Theriault, M.;"2005 National Construction Codes: Increasing clarity and flexibility for design NRCC-48378" - Construction Canada, 48, 1, pp. 58-60, 62, 64, 2006-01-01 http://nparc.cisti-icist.nrc-cnrc.gc.ca/eng/view/accepted/?id=853630e4-390f-43f6-b2fe-fb2a29078cb3

[36] "Performance-based primer codes and standards preparation - Revision 1.0 21 January 2000" P. 8-10, © National Fire Protection Association 1999

[37] Tavares, Rodrigo Machado; "Prescriptive Codes vs. Performance-based codes: Which one is the best fire safety code for the Brazilian Context?" - Safety Science Monitor Issue 1 2008 Article 3 Volume 12

[38] Meacham, Brian J.; "The Evolution of Performance-Based Codes and Fire Safety Design Methods" P.49-50 NIST-GCR-98-761 Building and Fire Research Laboratory - National Institute of Standards and Technology (NIST) Issued 1998

[39] Alvarez, A., Meacham B.J., Thmoas, J.R.; "A Framework for Risk-Informed Performance-Based Fire Protection Design for the Built Environment", Fire Technology 50, 161-181, 2014

[40] NFPA 551 Guide for the Evaluation of Fire Risk Assessments - 2007 Edition. Copyright 2007 National Fire Protection Association

[41] Meacham, Brian J.; "An Overview of Approaches and Resources for Building Fire Risk Assessment" - Fire Protection Engineering SFPE Magazine, July 1, 2013 http://magazine.sfpe.org/content/overview-approaches-and-resources-building-fire-risk-assessment

[42] Hadjisophocleous, G.V and Fu, Z.; "Literature Review of Fire Risk Assessment Methodologies", International Journal on Engineering Performance-Based Fire Codes Volume 6, Number 1. p28-45, 2004

[43] Hui, Man-Cheung; "How Can a Fire Risk Approach be Applied to Develop a Balanced Fire Protection Strategy", Fire Protection Engineering Magazine 2006-04-01

[44] Bukowski, Richard W.; "An Overview of Fire Hazard And Fire Risk Assessment in Regulation

[45] Buchanan, Andrew H.; "Structural Design for Fire Safety" P. 273-274, John Wiley & Sons Ltd. © 2002 Reprinted June 2008

[46] Baril, Paul.; "Fire Prevention Programs for Museums Technical Bulletin 18" - Canadian Heritage Canadian Conservation Institute, Canadian Conservation Institute Department of Canadian Heritage. © Government of Canada 1997. https://www.cci-icc.gc.ca/resources-ressources/publications/downloads/technicalbulletins/eng/TB18-FirePreventionProgramsForMuseums.pdf

[47] Sakenaite, Jurgita; Vaidogas, Egidijus R.; "Fire Risk Indexing and Fire Risk Analysis: A Comparison of Pros and Cons", VGTU leidyklos TECHNIKA 1769-M mokslo literatūros knyga, http://leidykla.vgtu.lt ,ISBN 978-9955-28-592-2 CD, © Vilnius Gediminas Technical University, 2010

[48] Richardson, Ken; Frye, M. John; "The Fire Risk Indices for the application to the rehabilitation and re-use of existing buildings in Manitoba for residential and business and personal services occupancies" P.1-3, - A publication of the City of Winnipeg Planning & Land Use Division,

[49] Wisconsin Administrative Code Industry, Labor and Human Relations - Chapter ILHR 70 Historic Building Code, Register, September 1986 NO. 369

[50] "SFPE Handbook of Fire Protection Engineering Fourth Edition" ©2008 by the Society of Fire Protection Engineers - Watts, John M. Jr.; Section 5 Chapter 10 "Fire Risk Indexing" 5-168 to 5-182.

[51] Wisconsin Administrative Code - Department of Commerce Chapter Comm 70 Historic Buildings Dec 2004 http://dsps.wi.gov/Documents/Industry%20Services/Forms/Commercial%20Buildings/HistoricalCodes/HistoricBldgs%202004%20Dec.pdf (14June2017)

[52] 2013 Act 270 Grandfathered Ordinances http://dsps.wi.gov/Programs/Industry-Services/Industry-Services-Programs/Commercial-Buildings/Act270

[53] Human Resources and Skills Development Canada "Building Code Data Sheet" - http://www.ofntsc.org/sites/default/files/files/Building%2520Code%2520Data%2520Sheet.pdf (5Aug2017)

[54] Coté, Ron, and Harrington, Gregory E. "Life Safety Code Handbook 9th Edition" P. 127-128, © 2003 National Fire Protection Association

[55] National Fire Protection Association (NFPA), "NFPA 14 Standard for the Installation of Standpipe and Hose System 2016 Edition" © 2016 National Fire Protection Association, All Rights Reserved

[56] Gharahdaghi, Mahnaz; Sylvester, David; "Smoke Control How to Obtain Tenable Conditions" - CFAA 2011 presentation by Mahnaz Gharahdaghi and David Sylvester from Morrison Hershfield Consulting Engineers and Managers

[57] Fire Loss in Ontario 2011–2015 – Ministry of Community Safety and Correctional Services http://www.mcscs.jus.gov.on.ca/english/FireMarshal/MediaRelationsandResources/FireStatistics/OntarioFires/FireLossesCausesTrendsIssues/stats_causes.html (February 2017)

[58] Stewart, Deborah, "Agent of Deterioration: Fire" http://canada.pch.gc.ca/eng/1444924750023 31August2016

[59] "Fit-up Standards: Technical Reference Manual" Public Works and Government Services Canada October 17, 2005 Page A6.2-9 http://publications.gc.ca/collections/collection_2009/tpsgc-pwgsc/P26-3-2005E.pdf 6Feb2017

[60] Treasury Board Standard for Fire Safety Planning and Fire Emergency Organization https://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=12562 20September2015

[61] Proulx, G., "Occupant Behaviour and Evacuation NRCC-44983", 9th International Fire Protection Symposium, Munich, May 25-26, 2001, pp. 219-232

[62] "SFPE Handbook of Fire Protection Engineering Fourth Edition" ©2008 by the Society of Fire Protection Engineers - Proulx, Guylene - Section 3 Chapter 12 "Evacuation Time" P3-355 to 3-370

[63] Proulx, Guylene; "Strategies for Ensuring Appropriate Occupant Response to Fire Alarm Signals", NRC Construction Technology Update No. 43

[64] Cote, Arthur and Bugbee Percy, "Principles of Fire Protection" National Fire Protection Association Batterymarch Park Quincy, MA 02269 Copyright 1988 ISBN 0-87765-345-3 P. 44-47

[65] "SFPE Handbook of Fire Protection Engineering Fourth Edition" © 2008 by the Society of Fire Protection Engineers - Walton, William D.; Thomas, Philip H.; SFPE Handbook Section 3 Chapter 6 "Estimating Temperatures in Compartment Fires" page 3-204 to 3-220

[66] "SFPE Handbook of Fire Protection Engineering Fourth Edition" ©2008 by the Society of Fire Protection Engineers - Mowrer, Frederick W. SFPE Handbook Section 3 Chapter 9 "Enclosure Smoke Filling and Fire-Generated Environmental Conditions" page 3-247 to 3-249

[67] NIST Fire Dynamics https://www.nist.gov/%3Cfront%3E/fire-dynamics (7November2016)

[68] Phan, Long T., McAllister, Therese P., Gross, John L. "NIST Technical Note 1681 - Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings" November 2010 National Institute of Standards and Technology P. 186-187

[69] Phan, Long T., McAllister, Therese P., Gross, John L. "NIST Technical Note 1681 - Best Practice Guidelines for Structural Fire Resistance Design of Concrete and Steel Buildings" November 2010 National Institute of Standards and Technology P. 31

[70] Luo, M. and He, Y. 1988 "Fire Growth and Smoke Spread Model for Fire Safety Design: Experimental Verification. AOFST 3" http://www.iafss.org/publications/aofst/3/261/view/aofst_3-261.pdf 28October2016

[71] G. Rein, "Smouldering Combustion Phenomena in Science and Technology", International Review of Chemical Engineering, Vol 1, pp 3-18, Jan 2009. Copy available at https://www.era.lib.ed.ac.uk/bitstream/handle/1842/2678/Rein_SmoulderingReview_IRECHE09.pdf?sequence=1&isAllowed=y

[72] CAN/ULC-S101-07 "Standard Methods of Fire Endurance Tests of Building Construction and Materials" © 2007 Underwriters' Laboratories of Canada

[73] "What is a Standard Fire Test - A Guide to interpreting what those fire endurance ratings really mean" - http://www.concreteconstruction.net/business/management/what-is-a-standard-fire-test_o 15May2016

[74] Thomas, G.C.; Buchanan, A.H.; and Fleischmann, C.M.; "Structural Fire Design: The Role of Time Equivalence" - http://www.iafss.org/publications/fss/5/607/view 20June2016

[75] "Building Control Technical Guidance Leaflet No. 27. Fire Resistance of Floor with Lath and Plaster Ceilings" - http://www.stevenage.gov.uk/content/15953/24595/24598/27-GN-Fire-Resistance-of-Floor-Lathe-and-Plaster-Ceilings-Dec2013.pdf 5May2015

[76] Hoefferle, Joseph Jr., "Fire & Building Safety Code Compliance for Historic Buildings: A Field Guide (2nd Edition)" University of Vermont Graduate Program in Historic Preservation in Cooperation with The Vermont Division for Historic Preservation and The Vermont Department of Public Safety, Division of Fire safety. 2006 P7. https://www.uvm.edu/histpres/307/LifeSafetyFieldGuide.pdf

[77] Wisconsin Department of Safety and Professional Services, "Chapter 9 Fire Protection Systems" http://dsps.wi.gov/sb/docs/sb-educationcbi07chpt9pp.pdf 6August2016

[78] "Wisconsin Department of Industry, Labor & Human Relations Chapter ILHR 50 to 64 Building and Heating Ventilating and Air Conditioning" 52 GENERAL REQUIREMENTS P.66 http://dsps.wi.gov/Documents/Industry%20Services/Forms/Commercial%20Buildings/HistoricalCodes/Bldg_HVAC%201995%2050-64.pdf 28Jan2017

[79] Federal Heritage Buildings Review Office. "Building Report: 85-07 - Sault Ste Marie Canal Buildings Sault Ste Marie, Ontario"

[80] Practice Tips PT.3 Building Code Data Matrix VERSION: 4 http://www.oaa.on.ca/professional+resources/practice+tips+&+regulatory+notices/practice+tips/3

[81] Ohlemiller, T.J. "Smouldering combustion" Chapter 9; Section 2; NFPA HFPE-02; SFPE Handbook of Fire Protection Engineering. 3rd Edition, DiNenno, P. J.; Drysdale, D.; Beyler, C. L.; Walton, W. D., Editor(s), 2/200-210 p., 2002 http://fire.nist.gov/bfrlpubs/fire02/PDF/f02074.pdf

[82] "Collingwood, Ontario Federal Building 44Hurontario Street" - http://www.historicplaces.ca/en/rep-reg/place-lieu.aspx?id=3405 10November2012

[83] FIRE RESISTANT COATING FOR LATH-AND-PLASTER CEILINGS - https://envirograf.com/product/fire-resistant-coating-for-lath-and-plaster-ceilings/

[84] "91-181 Amherstburg, Ontario Hough House Fort Malden" http://www.historicplaces.ca/media/15425/1991-181(e)houghhouse.pdf 5April2017

[85] "Structural Stabilization of Hough House at Fort Malden National Historic Site" https://buyandsell.gc.ca/cds/public/2014/05/27/217303bd70e0c2af24107c166ed2e8bf/specs_-_fort_malden.pdf 10May2017