QUANTIFYING FIRE HAZARDS OF SUSTAINABLE INITIATIVES IN THE BUILT ENVIRONMENT

by

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ABSTRACT

CHRISTINA M. SAUNDERS. Quantifying fire hazards of sustainable initiatives in the built environment. (Under the direction of ASSOCIATE PROF. JEFFERY T. KIMBLE)

We are now challenged with design-oriented goals of sustainability initiatives requiring energy efficiency in the built environment. Stricter energy codes have added more potential fuel load to a structure and its building envelope. However, these sustainability initiatives do not explicitly consider the fire risks and hazards posed by green building designs, significantly affecting the fire protection and life safety of buildings. At present, a quantitative method to compare the relative fire performance of green building materials and the hazards associated with them is not available. The objective of this research is to propose a semi-quantitative fire hazard assessment, assigning values to selected fire hazard variables. The framework to quantify the impact of sustainable initiatives to a model project is provided; the green building facade elements are the focus of the analysis in this research.

A recent hypothetical case study[67] is the model project for this research, used to demonstrate the novel framework for the development of a semi-quantitative method. It compares the relative fire performance of green building initiatives and the hazards associated with them on a high-rise residential building using cross-laminated timber. The approach employs an index method, establishing an order of magnitude, with relative rankings based on engineering judgement and experience. Levels of impact are assigned; relative hazard levels are estimated, as a weighted function of the importance or influence, of the hazard impact on the various green elements; decision-making matrices are

developed and an overall hazard ranking of the building with the designed green building initiatives calculated.

Some features present mild or moderate hazard to the green building, others present high or severe hazards. The greatest concern is from the facade components; these are related to the energy efficiency credits in green building rating programs. A range of potential mitigation measures are suggested, based on synergistic effects, to provide a means of reducing the fire hazards associated with the green building initiatives. Without mitigating strategies, the fire hazards from green building initiatives can increase, life safety can decrease, and/or building performance in comparison with conventional construction can decrease. An alternate fire risk assessment method is used to compare and evaluate the semi-quantitative technique developed.

Quantifying the fire hazards of green building initiatives is critical to the performance of all structures. The sustainable intent for a building design must, therefore, be integrated into the approach to provide fire and life safety protection strategies. This integrated approach to design and construction could improve the building performance, reducing risk and achieving synergies, yielding economic, environmental, and human benefits.

DEDICATION

To my incredibly patient husband,

William

Who encouraged me to take on this task and supported me completely.

Thank-you for your confidence and letting me be me.

You are my light of hope.

To my youngest daughter,

Caitlin

Who lovingly challenged and motivated me to realize my potential.

Your energy and determination are contagious.

I marvel at your courage.

To my youngest son,

Jonathan

Whose passion and enthusiasm during my journey was so inspiring.

Your motivation and commitment are compelling.

I admire your resilience.

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LIST OF ABREVIATIONS

AHJ	Authority Having Jurisdiction
ACM	Aluminum Composite Material
ANSI	American National Standard Institute
ASTM	American Standard Testing Method
BREEAM	Building Research Establishment's Environmental Assessment Method
CLT	Cross Laminated Timber
CO_2	Carbon Dioxide
D/B-V	Drained/Back-Ventilated
DSF	Double Skin Facade
EFFECT	External Facade Fire Evaluation and Comparison Tool
EIFS	Exterior Insulating Finishing Systems
EPS	Expanded Polystyrene
EVF	Externally Venting Flames
FCC	Fire Command Center
FDC	Fire Department Connection
FHI	Fire Hazard Index
FMEA	Failure Modes and Effects Analysis
FPRF	Fire Protection Research Foundation
FRA	Fire Risk Assessment
FSC	Forest Stewardship Council
FSES	Fire Safety Evaluation System

GBRS	Green Building Rating System
GLULAM	Glue Laminated Timber
HHR	Heat Release Rate
IBC	International Building Code
ICC	International Code Council
ICCPC	International Code Council Performance Code
KPI	Key Performance Indicator
LEED	Leadership in Energy and Environmental Design
MCM	Metal Composite Material
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NRC	National Research Council
OEE	Occupant Evacuation Elevators
PAS	Publicly Available Specification
PER	Pressure Equalized
PIR	Polyisocyanurate Foam
PUR	Polyurethane Foam
R-Value	Resistance-Value
SFPE	Society of Fire Protection Engineers
SIPS	Structural Insulation Panel System
UAE	United Arab Emirates
UK	United Kingdom

UL	Underwriters Laboratories
USA	United States of America
USGBC	United States Green Building Council
WRB	Weather-Resistive Barrier
XPS	Extruded Polystyrene

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

We are challenged today with design-oriented goals of sustainability initiatives requiring energy efficiency in the built environment. Stricter energy codes have added more potential fuel load to a structure and its building envelope. Consequently, the fire performance of green (sustainable) designs are extremely critical now. A green material's ability to mitigate the risk caused by fire has become increasingly difficult; the synergistic effect of the various combinations of green design materials increases the potential fire hazard in structures. The potential hazard of the inherent flammability and rapid flame spread upon fire exposure of green building elements is not well characterized. The fire risks and hazards associated with green building materials and systems are not explicitly addressed by the sustainability initiatives.[32] As a result, fire protection and life safety can be significantly affected.

There are not many documented fire incidents involving sustainability initiatives; we need a better understanding of the variations in green technologies that are involved in fires, the ignition details, and the mechanics of the fire spread of these combustible elements and systems. Fire spread in green buildings could have catastrophic consequences, such as the Grenfell Tower fire in 2017, causing 79 deaths.[72] The rapid spread of the fire was attributed to the building's exterior facade system, a system that could be considered a green building design and used worldwide. The behavior of fire with various sustainable initiatives can differ quite significantly. Currently, there is no consensus for a quantitative hazard analysis; qualitative approaches are performed now to understand the fire hazard and risk assessment. Research regarding the risk associated with the fire performance of green building materials is not well-documented.[34] Sutula and Ryder suggest “a need to develop a methodology that can be used to evaluate and compare the potential fire growth risk associated with green materials, as these can result in enhanced heat release rates and pathways of fire spread not typical observed with standard construction materials.”[34] Heat release is a critical fire-reaction property because it is the driving force for fire spread; fire is propagated by heat. The Fire Protection Research Foundation (FPRF) has also highlighted the problem, indicating a hazard characterization and ranking exercise is necessary to analyze the fire risk associated with green building elements.[32] A quantitative method to compare the relative fire performance of green building materials and the hazards associated with them must, therefore, be developed. This research applies a case study approach to demonstrate the novel framework developed to analyze the impact levels of sustainable initiatives with green design facade elements as the focus.

1.2 Background

In recent years, fire has occurred in high-rise buildings involving rapid flame spread upon the building envelope, causing severe damage and loss. The extensive use of green combustible materials was believed to contribute to the uncontrollable fire spread on the facade of these high-rise buildings. Colwell suggests limited combustibility of exterior wall system components could provide acceptable fire safety performance because one potential route for the fire spread through a multistory building is the external wall system of the building.[2] Increased energy efficiency in structures, driven by the global transformation in sustainability, focuses on the improvement in the ‘fabric’ of new buildings.[2] As a result, the changing drivers in construction design must be considered; innovative facade systems are the optimum method to achieve increased building energy performance.[2]

Enhanced thermal performance is now offered in the construction industry as the world embraces sustainable green building designs; the thermal design of the building envelope is the most important parameter for controlling the amount of energy required to ensure thermal comfort throughout the year.[2] The control of this parameter depends primarily on the choice of materials for the walls of the building. Although many combustible materials are now used on green building envelopes, energy performance is improved, water and air infiltration reduced, and flexibility for aesthetic designs is provided.[74] These green exterior wall assemblies incorporate several components including cladding, insulation, and weather-resistive barriers (WRB). The variability of system configurations and components to achieve a green facade design is exponential. This area is subject to rapidly changing designs and materials, so it is important to better understand the parameters impacting the fire-safe design and construction of a green building envelope. The combustibility of green building assembly components directly impacts the fire hazard. As technology has developed in the building envelope area, hybrid systems are increasingly being offered to the market that use a combination of materials, such as metal composite material (MCM) with thermal attachment clips, polyisocyanurate insulation outboard of a stud cavity wall, a fluid-applied WRB over exterior sheathing, and spray foam insulation within the stud cavity wall. Often, several different combinations of these type finishes are applied on a single project contributing to the complexity of the fire performance of a green building facade.

There is a range of insulation materials used on the building envelope and can vary greatly.[2] A combination of insulation products is often designed for a lightweight application; one type is applied to the exterior side of the sheathing board and another type is applied in the stud cavity wall frame as infill to provide better thermal and acoustical performance.[2] The effective thermal performance of the building envelope is also through the use of vapor barriers and breather membranes.[2] Since thermal requirements are extremely different globally, design methodologies and development of a green building envelope has created extremely complex assembly options with combustible green design components in the exterior wall assembly. The fire performance of these green features must be considered. Green building elements may not pose a fire risk applied in isolation. However, the combination of other green features used over a large surface area on multistory buildings can create a dynamic synergy, potentially contributing to intensified fire growth and spread on or through the system.[2]

There are relatively few reported cases involving exterior fire spread on combustible wall claddings and even fewer cases where life safety was compromised.[37] Building codes in many countries limit the use of green combustible materials in the exterior walls to low-rise buildings only; this may be responsible for reducing losses to an insignificant level[37] The infrequency of these fire events, however, does not necessarily indicate fire spread on the facade would not present significant risk to life safety and property protection.[3]

1.3 Fire and the Green Built Environment

1.3.1 Fire

“A striking aspect of the global fire problem is the indifference with which humans confronted the subject; we have become accustomed to the indifference to the fire problem in the built environment.”[5] Until recently, fire safety has been a reactive approach, rather than considering preventive and proactive measures.[5] Designers and their clients were satisfied meeting the minimal safety standards of local building codes, assuming the codes provided complete, adequate measures rather than minimal requirements.[5] This perception has changed and evolved in recent years, encouraging growth and development in life safety practices.

1.3.2 The Green Built Environment

“In the built environment, it is important to consider one aspect of the man environment interaction that tends to be overlooked; the ways in which man acts upon the environment to cause fire is dynamic.”[5] Yet, the fire problem is aggravated by the built environment’s influence on the behavior of man.[5] The modern urban environment can impart a false sense of security about fire. In part, this sense of security is because there has not been a major fire in American cities in more than half a century; the newness of so many buildings also imparts invulnerability of attack by fire.[5] The emerging technology of building certification programs for sustainable principles and practices imparts a sense of security as green building assessments are performed by construction authorities, international organizations, or private consultancy companies. Most people tend to take for granted that those who design and assess green building features always do so with adequate attention to their safety; that assumption can be incorrect. Design teams are expected to consider a range of building components and systems, all harmonized to achieve a seamless performance for both normal daily use as well as after a fire event.[11] However, these expectations are often not realized by design teams.[11]

The built environment consists of vertical and horizontal infrastructure, featuring the places where people live, work and play.[6] The built environment includes buildings such as homes, businesses, transportation, infrastructure and urban spaces. The scope of this research is limited to the building envelope of the vertical infrastructure in the built environment; horizontal infrastructure elements are outside the scope.

1.3.2.1 The Building Envelope

The building envelope is the materials and systems that come between the interior and the exterior environments of a building, see Figure 1.0. The functions of the building envelope can be separated into three main groups: support to resist and transfer mechanical loads; control the flow of matter and energy of all types such as water, heat, air light, noise, and vapor; and the comfortable and serviceable finishes to support human activities on the inside and outside.[14]

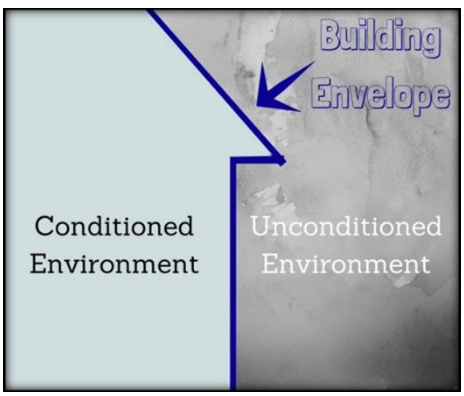


Figure 1.0 The Building Envelope [64]

A typical building envelope can include several component parts such as doors, windows, and exterior walls. These components must control solar and thermal flow, as well as moisture flow in and out of the building.[14]

The indoor air quality, fire, wind, rain, temperature difference, and vapor pressure difference are also controlled;[14] these dynamics of the building envelope are shown in Figure 1.1. Designers considering the building performance of the enclosure must now understand the relationship between the building science and its effect on the fire hazards of the exterior wall assembly. Although the behavior and performance of each component part may be well understood, the inter-relationship between the components of the building envelope is the foundation for the effectiveness and durability of the system as a whole.[6] A component may be specified, designed or constructed to a high standard, however, it must be a part of an effective system, or the performance may be compromised.

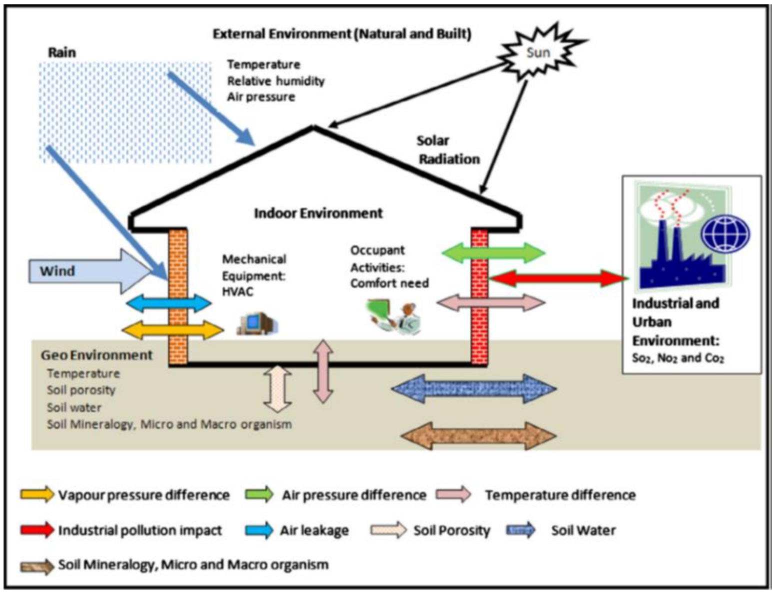


Figure 1.1 The Dynamics of a Building Envelope [14]

In this systems approach, relationships among components are essential, especially regarding fire and fire spread. The material properties, as well as the mechanical behavior of the system, must be considered along with the dynamics of the individual materials in the exterior walls of the building envelope, especially the exterior cladding, insulation, and weather-resistive barriers.

1.4 Sustainability and Green Building Rating Systems

1.4.1 Sustainability

There has been a significant shift towards green and sustainable architecture in the building design industry during the past decade.[6] The U.S. Green Building Council (USGBC) defines sustainability as "the practice of creating structures and applying processes that are environmentally responsible and resource efficient throughout the building's life cycle."[21] Sustainability, then, is an interdisciplinary design process with many professionals working together throughout the life cycle of a project, responsibly linking together the infrastructure and the environment.[16] Sustainable green practices afford citizens in large urban areas healthy indoor and outdoor environments; improving quality and performance of buildings that are constructed and renovated in a cost-effective manner while enhancing the environment.[16]

Human health and the environment are greatly affected by building construction and occupancy use.[16] The construction, renovation, and operation processes of a building employ a vast amount of resources.[16] The production of these resources can negatively impact our environment. An estimated three billion tons of raw materials are used by buildings annually.[15] Residential and commercial buildings in the United States account for 39 percent of energy use[15, 16] and produce more than 136 million tons of construction and demolition waste yearly.[16] Building pollutants released from energy consumption in the U.S. include 38% of all carbon dioxide (CO_2) emitted into the atmosphere[15, 16] and account for 81% of all U.S. greenhouse gas emissions[15] in 2016, see Figure 1.2.

A greenhouse gas absorbs and emits radiant energy within the thermal infrared range. Increased greenhouse gas emissions can cause the greenhouse effect, the process by which radiation from the Earth's atmosphere warms the surface, the lower atmosphere, and

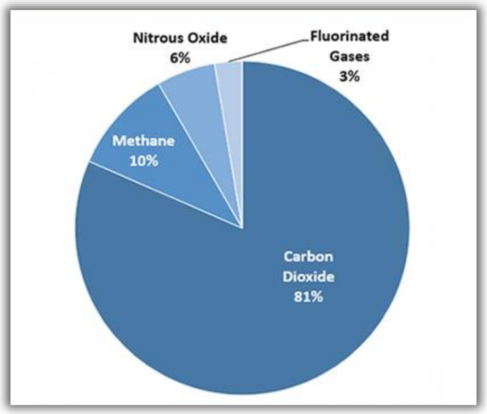


Figure 1.2 U.S.A. Greenhouse Gas Emissions in 2016 [15]

oceans to a higher temperature.[16] As a result, global warming impacts seasonal temperatures; spring and summer temperatures are higher now, bringing earlier spring snow melt. The effects include hotter and drier forests for longer periods of time, creating perfect conditions for wildfires to ignite and spread.

Globally, architects have fostered the effort to decrease the atmosphere's greenhouse gases through high-performance buildings, thereby reducing the carbon footprint of buildings.[16] The carbon footprint is the amount of the volume of CO_2 emitted into the atmosphere to produce and use a material; the footprint concept makes it possible to measure the impact of different materials on the environment. Buildings account for a significant portion of greenhouse gas emissions; environmental impacts of a fire with the discharge of gaseous and particulate products into the atmosphere and the potential contamination of groundwater and land from suppression product run-off can have a negative impact on the carbon footprint.[17, 39] Therefore, prevention of fire can be a significant green design feature. An effective fire protection system could reduce the risk of fire, thereby reducing the carbon emissions over the lifecycle of a building; approximately 14% of carbon emissions can be generated over the lifetime of a facility exposed to extensive fire hazards,[39] as shown in Figure 1.3. Note, the time periods for construction, rebuilding, and demolition have been enlarged to be more legible and is not to scale.

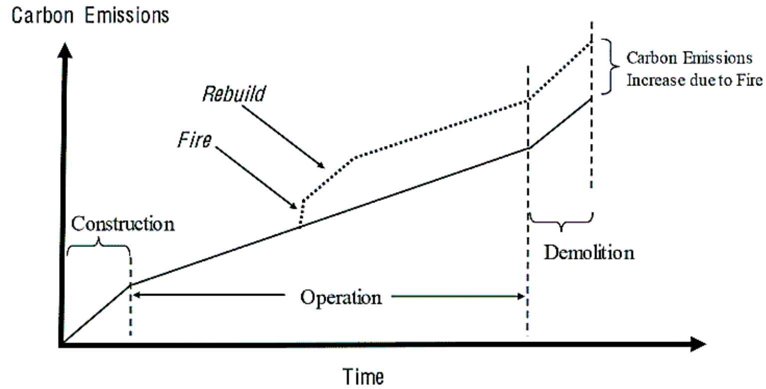


Figure 1.3 Diagram of Contribution of Risk Factors for Lifecycle Carbon Emissions [39]

The environment is widely impacted directly and indirectly by buildings.[20] They use energy, water, and raw materials; waste is generated, emitting potentially harmful atmospheric emissions during their construction, occupancy, renovation, repurposing, and demolition.[20] Development of the built environment, while meeting the needs of the present generation, should not compromise the ability of future generations to meet their needs;[14, 17] the creation of green building rating systems mitigates the impact of buildings on the natural environment, helping to ensure the needs of our future generations.[20]

1.4.2 Green Building Rating Systems

A range of green building rating systems (GBRSs) have been developed as the concept of green buildings has grown over the past two decades; a comprehensive framework assesses and verifies the sustainability and greenness of buildings.[23] A group of explicit performance thresholds that buildings must meet to be certified, as well as guidelines that can help project teams meet or exceed those performance thresholds, are the basis of these rating systems.[23] The sustainable principles and practices implemented on projects are identified by the GBRS, representing the extent green components have been incorporated, and provides the basis for the certification of the design and construction of an environmentally sound building.[23] GBRS are now essential to the development of green building design.[23]

Many countries have established GBRSs to evaluate the sustainability of design and construction, addressing the global concern of climate change and the conservation of natural resources.[15] The push toward sustainable design began in 1990 with the creation of the Building Research Establishment's Environmental Assessment Method (BREEAM), the world's first green building rating scheme for the development of the built environment in the United Kingdom (UK).[20] The USGBC also released criteria directed at improving the environmental performance of buildings through its Leadership in Energy and Environmental Design (LEED) rating system in 1994.[20] LEED is now one of the most popular and widely used GBRS in the world.[23] LEED certified projects in the U.S. increased from 296 certifications in 2006 to approximately 63,000 in 2016; totaling over 80,000 projects globally.[69]

Additional rating systems have been developed by other countries, influenced by these early programs. However, these are modified to address their own national requirements, and several go beyond current standard limitations to address evolving issues.[20] These programs assess the sustainability of different types of built structures (i.e. hotels, schools, data centers, etc.) or in terms of project stages (i.e. design, construction, decoration, and operation). In the 21st century, when growing concerns over global warming and resource depletion became more prominent and supported by research, the number and type of green product standards and certifications grew.[20] GBRS have been well researched and comprehensively described by many, including Spadafora and the FPRF.[16, 23, 32, 44] See Table 1.0 for a summary of 15 prevailing global GBRS's.[23]

Table 1.0 Global Issuers of Green Building Rating Systems [23]

No.	GBRS	Issuer	Country/Region
1.	ASGB	Ministry of Housing and Urban-Rural Development of People's Republic of China	China
2.	BREEAM	Building Research Establishment Ltd.	UK
3.	BEAM	Hong Kong Green Building Council and the BEAM Society Limited	Hong Kong
4.	CASBEE	Ministry of Land, Infrastructure, Transport and Tourism of Japan	Japan
5.	CEPAS	Buildings Department of Hong Kong Special Administrative Region of the People's Republic of China	Hong Kong
6.	CSH	Department for Communities and Local Government	UK
7.	EPRS	Abu Dhabi Urban Planning Council	Abu Dhabi
8.	GBI	GBI Innovation Sdn Bhd	Malaysia
9.	GG	ECD Energy and Environment Canada	Canada
10.	GM	Building and Construction Authority	Singapore
11.	GS	Green Building Council Australia	Australia
12.	GSAS	Gulf Organization for Research & Development	Qatar
13.	ISBT	International Initiative for a Sustainable Built Environment (non-profit organization)	Not Applicable
14.	IGBC	Indian Green Building Council	India
15.	LEED	US Green Building Council	USA

There is now an abundance of standards, rating, and certification programs to help guide and certify sustainable, high-performance building.[20] These green building rating programs in use around the world vary in their approach with many outlining prerequisites and optional credits; the evaluation criteria for these 15-prevailing global GBRS's are outlined in Table 1.1.[20] As a result, the research for this thesis is based on the most widely used green building rating and certification system in the US marketplace and the world, LEED. Among the 29 criteria outlined in Table 1.1, seven key evaluation criteria used by the 15 prevailing GBRS's include: water, material, energy, indoor environment, site, land and outdoor environment, and innovation.[23] The weightings of these seven essential evaluation criteria are presented in Table 1.2. The average weighting of each essential

Table 1.1 Evaluation Criteria of the Prevailing Green Building Rating Systems [23]

No.	Evaluation Criterion	ASGB	BREEAM	CEPAS	CSH	CASBEE	EPRS	GBI	GG	GM	GSAS	GS	BEAM	IGBC	ISBT	LEED	Total
1.	Water	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	15
2.	Material	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	15
3.	Energy	√	√		√	√	√	√	√	√	√	√	√	√	√	√	14
4.	Indoor Environment	√				√	√	√	√		√	√	√	√	√	√	11
5.	Site			√				√	√		√		√	√	√	√	8
6.	Land and outdoor environment	√	√	√	√	√	√					√					7
7.	Innovation	√	√				√	√				√		√		√	7
8.	Waste		√		√			√		√		√					5
9.	Construction Project Management	√	√						√			√					4
10.	Operation Management	√			√						√						3
11.	Health and Wellbeing		√		√					√							3
12.	Transport		√									√				√	3
13.	Integrative process						√									√	2
14.	Quality of service					√									√		2
15.	Loadings			√											√		2
16.	Social, Cultural and Perceptual Aspects										√				√		2
17.	Cost and Economic Aspects										√				√		2
18.	Pollution		√		√												2
19.	Surface water run-off				√												1
20.	Urban Connectivity										√						1
21.	Sustainable architecture and design													√			1
22.	Building Amenities			√													1
23.	Neighborhood Amenities			√													1
24.	Neighborhood Impacts			√													1
25.	Off-site environment					√											1
26.	Climatic Responsive Design									√							1
27.	Advanced Green Efforts									√							1
28.	LEED Accredited Professional															√	1
29.	Regional Priority															√	1

evaluation criterion was also calculated and presented in Table 1.2. A comparison of the key evaluation criteria indicates ‘energy’ is the most important evaluation criterion, with 25% as the highest average weighting.[23] The reduction of energy use at peak loading, energy monitoring and reporting, energy efficient appliances, equipment and systems, and the use of renewable energy are the main evaluation criteria.[23] In addition, Table 1.2 reflects the average weighting of “energy” is much higher at 14.53% than the average weighting for all the identified criteria; the energy weightings in 13 of the 15 GBRSs are also greater than 14.53%.[23] The results suggest “energy” is a critical characteristic in GBRS’s and has been widely used by many GBRSs.[23] It is also noteworthy that among the 14 GBRS having the evaluation criterion of ‘energy’, ten allocated the highest weighting to “energy”, compared to the rest of the evaluation criteria.[23] This result

Table 1.2 Weightings of the Essential Evaluation Criteria of the Prevailing GBRS's [23]

No.	GBRS	Energy	Site	Indoor Environment	Land and Outdoor Environment	Material	Water	Innovation
1.	ASGB	19%	–	14%	17%	14%	16%	9%
2.	BREEAM	19.97%	–	–	7.69%	12.5%	6.73%	10%
3.	CEPAS	–	23.2%	–	11.6%	6.13%	2.04%	–
4.	CSH	36.4%	–	–	12%	7.2%	9%	–
5.	CASBEE	20%	–	20%	15%	12%	3%	–
6.	EPRS	24%	–	8.53%	19.47%	16%	24%	2%
7.	GBI	23%	33%	12%	–	8%	12%	8%
8.	GG	39%	12%	16%	–	13%	11%	–
9.	GM	18%	–	–	–	9.38%	9.38%	–
10.	GSAS	24%	13%	16%	–	10%	16%	–
11.	GS	25%	–	16%	10%	14%	10%	9%
12.	BEAM	35%	25%	20%	–	8%	12%	–
13.	IGBC	28%	14%	12%	–	16%	18%	7%
14.	ISBT	5%	29%	14%	–	2.5%	2.5%	–
15.	LEED	28%	12%	14%	–	16%	9%	4%
Average weighting for each criterion		25%	20%	14.78%	13.25%	10.98%	10.71%	7%
Standard Deviation		9%	8.4%	3.4%	4.1%	4.1%	6.1%	2.9%
Average weighting for all the criteria		14.53%						

validates the assessment that "energy" is the principle evaluation criterion for assessing and certifying green buildings.[23]

1.4.2.1 LEED and Impact Categories

LEED 2009 Green Building Rating System for New Construction is used to evaluate the environmental performance of the case study from a whole-building perspective. Performance standards certify the design and construction of all commercial or institutional buildings and high-rise residential buildings.[21] The LEED rating system certifies products based on life-cycle parameters and is a multi-attribute program. An integrated approach to design and construction is fostered by the LEED program; building performance is improved, risk reduced, and synergies achieved to yield economic, environmental, and human benefits.[31] As a result, the overall impact of the development of a building and the structure on the occupants' health and environment is reduced by the integrated approach.[31]

Design prerequisites and credits are used to address these impacts, organized into seven categories, and includes sustainable site development, water savings, energy efficiency, materials and resources, indoor environmental quality, and innovation in design,[21] see Table 1.3. The weighting scale of the seven categories clearly reflects ‘energy’ as the foremost evaluation criterion for certifying LEED green buildings.

Table1.3 LEED Assessment Criteria and Point Values

LEED Assessment Criteria	
Evaluation Criteria	Points
Energy and Atmosphere	35
Sustainable Sites	26
Indoor Environmental Quality	15
Materials and Resources	14
Water Efficiency	10
Innovation and Design	6
Regional Priority	4
Total Possible Points	110

LEED points are awarded on a 110-point scale with a four-level hierarchy scoring system for certification; Certified: 40-49 Points; Silver: 50-59 Points; Gold: 60-79 Points; and Platinum: 80-100 Points.[21] The USGBC developed a LEED certified checklist to provide guidance for options methods to reduce the environmental impact of facility construction and operations on carbon emissions.[39] A tangible measure of the sustainability of the facility is provided through the LEED certification.[39] The model project for this research is recognized as a Gold Certified Building. The LEED 2009 Project Checklist, shown in Appendix A, represents credits applied as the basis for this research.

The USGCB indicates the allocation of points is centered on the potential environmental impacts and human benefits of each credit with respect to a set of impact categories.[21] However, the fire risks and hazards associated with green buildings and building elements are not explicitly considered with the allocation of points.[32] The sustainable intent for the building design must therefore be integrated into the fire safety strategy, harmonizing the functionality and aesthetics of the building. A description outlining the impact categories and associated credits allocated is provided in Appendix C.

1.5 Fire Assessment of Green Building Features

1.5.1 Introduction

Green building practices can have unintended consequences from fire, presenting challenges to life safety and property preservation.[32] As a result, an assessment of the fire safety strategies for green building features is essential.[32] Decisions concerning fire safety is a fire risk decision, regardless of whether it is treated as one or not.[50] In the context of fire safety in the built environment, the term risk is defined by SFPE as “the potential for the realization of unwanted, adverse consequences to human life, health, property, or the environment; it is the chance or probability of injury or property loss.”[50] As a result, the product of probability distribution of events and associated consequences relevant to that building is the established risk.[50] Risk has two essential components, requiring statistical data for frequency and undesired consequences.[50] However, insufficient statistical data precludes a quantitative risk assessment because there are few incidents of fire documented in green buildings.[32] Therefore, green building features in this research are assessed through a semi-quantitative approach, using a fire hazard index.

1.5.2 Fire Hazard

The terms risk and hazard are often used interchangeably, however, they do not have the same meaning.[50] While a hazard is the potential for fire loss, risk is the probability that it is likely to occur. In the context of fire safety in the built environment, the term ‘hazard’ is used to describe something that can “cause damage to people, property, or the environment (the consequence); it has the potential for causing injury to life or damage to property or the environment."[50] Therefore, the method of assessing risk commences with identification of the fire hazards associated with a process or material.[34]

Fire hazards, in general, are a direct result of fuels being exposed to enough heat to cause ignition. Uncontrolled energy can produce a fire hazard, including sparks, open flames, electrical energy, and chemical reactions. A structured approach must be taken to recognize and define the characteristics of the hazard.[50] A hazard assessment includes a hazard evaluation in which judgements are made about the significance and acceptability of the hazard.[50] Therefore, a formal assessment of the fire hazard of green building features is required to quantify the significance and acceptability in the building fire performance, related to life safety and property preservation.

1.5.3 Fire Hazard Assessment

A fire hazard assessment is the process of establishing information regarding acceptable levels of the hazard; they are identified, impact levels evaluated, and appropriate methods to mitigate or control the hazard determined.[51] The assessment characterizes potential ignition sources, fuels, and fire development without consideration of the likelihood of occurrence.[51] A typical procedure for a fire hazard assessment includes an evaluation of the building to identify potential ignition sources, arrangement of fuel packages, the geometry of the building and compartments, and presences of fire safety features.[51] Ignition is assumed and the fire growth, spread, and impact is estimated.[51] To mitigate the hazard analyzed, risk management can then be implemented.[34] The goal of a hazard assessment is to remove or reduce the hazard impact level by adding precautionary or control measures through mitigation strategies.

Fire hazard assessments generally follow one of three approaches: qualitative; semi-quantitative; or qualitative. These approaches are used in the fire safety industry, but quantitative analysis is only possible if there is statistical data. Currently, qualitative assessments are performed for the fire hazard of green building features; “the principal driver is the lack of statistical data on fires in green buildings and elements.”[32] Meacham et al. suggest the number of incidents identified is small and the data needed are not being collected systematically.[32] As there is no statistical data linking all the variables of a combustible facade system on a high rise building with the likelihood or consequences of a fire, a semi-quantitative deterministic fire hazard assessment must be used, assigning values to selected fire hazard variables outlined above, based on professional judgment and past experience.[83] There are a number of tools and methods available for the purpose of fire hazard assessment, including checklists, failure modes and effects analysis (FMEA), and indexing, a numerical grading system.[51] This research uses a fire hazard index method for a deterministic semi-quantitative approach.

1.5.3.1 Fire Hazard Index Method

Watts suggests fire hazard indexing is considered a link between fire science and fire safety.[4] In the literature, reports on the identification and ranking of hazards in fires is documented;[22] noteworthy among these include the Dow Index,[22, 30] Fire Safety Evaluation System (FSES),[22, 30] Mond Index and Toxicity Index,[22, 30] and Gretener.[30] The purpose of fire hazard indexing is to provide a useful tool for decision making.[30] The index is a single number measure of the hazard associated with the green building attribute.[30, 43] Visual observation of the fire performance can help define the related factors regarding the magnitude of the impact of an attribute.[43] Fire hazard indexing, then, is the process of modeling and scoring a hazard and exposure attributes to produce a rapid and simple estimate of relative fire hazards.[30] The concept has gained widespread acceptance as a cost-effective prioritization and screening tool for fire hazard assessment programs.[27]

1.6 Objectives and Scope

A simple, yet consistent decision-making tool is needed to quantify the fire risk of common green building features in the built environment. The objective of this research is to develop a novel, semi-quantitative framework to understand the fire hazard and impact of sustainability initiatives on a structure. The goal is to provide decision makers with a simple method to use during the early design stage of a construction project to consider tolerable levels for fire hazards of green building features. A formal evaluation of risk posed by potential fires must be a rigorous scientific procedure to understand the relationship between the event of fire initiation and the potential outcomes of fire. As a result, this research is intended to lay the foundation for future evaluation of the inter-relationship between fire hazards and green building features.

The scope of this work includes developing an indexing method to estimate and score the fire hazards posed by green building features. A hypothetical case study[67] for a high-rise residential building using cross-laminated timber is the model project used to demonstrate the analysis for the fire hazard of green building features. This study presents a multi-attribute framework for the entire structure of the case study. However, the scope of this research focuses on the facade elements of the energy efficiency category of sustainability initiatives; the professional judgement and past experience in the facades industry by the author, aided by a weighted analysis from recent research data, assigned values to the selected variables representing features of fire safety.

1.7 Organization of the Thesis

There are five chapters in this thesis. The first chapter provides an introduction, including the problem statement and background information necessary for understanding the multi-disciplinary problem under consideration. The built environment, sustainability and green building rating systems, and fire hazard assessments are described, along with the inter-relationship intensifying the problem. The second chapter is a comprehensive literature review which demonstrations the necessity and significance of this research, reviews previous work, and presents the existing knowledge gaps. Chapter three provides a novel framework to quantify fire hazards of sustainable initiatives on a structure. An indexing method is proposed, scoring fire hazards on a hypothetical case study, screening to acquire a global grasp of the issues to set priorities.[30] The fourth chapter introduces the results of the methodology, provides mitigation strategies, and analyzes the results. Finally, the conclusions of the research is presented in Chapter five, along with suggested recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Sustainability and green building design encourages new ideas, technology, materials and approaches to improve a materials performance in the environment.[44] As a result, the design of green building products are dynamic and continues to develop, adapting to the new practices.[44] The market for America's green building construction was estimated to be approximately $30 billion in 2007; the market for green building products and services approximately $12 billion.[16] This growth has brought about concerns regarding conflicts in building design resulting from sustainability objectives and fire-safety objectives; being considered in isolation may have unintended consequences.[44] These could be mitigated and combined to address the dynamics of the two separate objectives.[44] A key factor to aligning the focus and uniting the various efforts of all aspects of the building industry could be a common definition of sustainability in the context of fire-safety building design.[44] Features could include incorporating building features, systems and procedures to benefit multiple building design objectives, and to minimize unintended reductions in building safety, functionality, or introduction of new hazards.[44] Therefore, sustainability in the context of fire-safety building design could be defined as:[44]

"Sustainability within the fire protection industry involves application of fire-safety systems and design measures that support and promote building characteristics that are environmentally friendly during the building's daily use. These systems and designs must reduce the fire risk and impact that such characteristics and uses might contribute to throughout the full life expectancy of the building. Daily use characteristics include

reducing harm to the environment by minimizing energy consumption, water consumption, material consumption, and fire risk."[44]

One aspect of a structure combining the sustainability and fire-safety objectives is the building envelope on high-rise buildings. Energy and material efficiency must be emphasized to achieve sustainable development.[14] An extensive use of exterior facade systems with enhanced insulation products and techniques, including Structural Insulation Panel Systems (SIPS), Exterior Insulating Finishing Systems (EIFS), Aluminum Composite Material (ACM) and Metal Composite Material (MCM) cladding systems, is a common energy efficient building technique.[48] Although these systems may have greater energy-saving performance, ignition could promote intense flame spread, producing an abundance of gaseous toxic products.[48] There have been many indicative recent high-rise building fires around the world, involving external fire spread via the building facade due to externally venting flames (EVF) spilling out of external openings; a list has been provided in Appendix B.[48] In addition, pressure related fire hazards may become more significant in high-rise construction as the rapid shift in construction requirements and practices move towards more air-tight building envelopes.[46]

It is widely recognized that the fire behavior of high-rise buildings is challenging regarding fire safety as there are some additional features compared to "conventional" low-rise buildings,[48] such as the influence of the building envelope on fire pressure.[46] Another potential hazard for a facade fire is the induced pressures driving flows between compartments.[46] Yet, present building energy-saving evaluation methods do not account for the ventilation effect during fires.[47] The fire performance of facades in high-rise buildings can be affected by the amount of air flowing through the building envelope due to pressure difference between the inside and outside environments.[46]

Facade fires represent 1.3‑3.0% of the total number of building fires.[48, 74] The main fire safety aspects of such fire events concern facade heat flux and EVF plume characteristics,[48] fire resistance of the facade assembly for load and non-load bearing structures, and fire spread on the external surface or at the interior of a facade assembly.[48] The heat flux levels are mainly influenced by the fire compartment geometry, heat release rate (HHR), ambient conditions (e.g. temperature, wind speed) and compartment temperature.[48] “In fire events where EVF are studied, external wall claddings are usually ignited, thus increasing the complexity of the observed fire spread mechanisms.”[48] As an example, the Marina Torch Tower fire in 2015,[3] the fire, counter-intuitively, spread downwards along the facade.[48] Several other high-rise building fires have experienced the same phenomenon, highlighting the importance of understanding the mechanisms of fire spread.[48]

2.2 Mechanism of Fire Spread in a Green Facade

Facade fires can have devastating effects on human life, business and property. A fire breaking out an opening from a room on a lower story of a high-rise building has the potential to spread quickly up the external cladding system, re-entering the building through windows in upper stories.[7] This type of fire spread can escalate rapidly, potentially breeching compartmentation within the building; the time available for evacuation can be significantly reduced.[7] Also, individuals on the ground such as fire fighters and evacuating occupants face potential risks from the falling debris of the flaming cladding system because of fire. A key concern then, to assessing risk to people and property, is the performance of cladding on external walls when exposed to fire.[8]

The fire spread from the floor of fire origin to the floors above through exterior walls has been well-documented.[1] Generally, there are three primary fire threats to a building's exterior walls: fire in the building venting through exterior openings in a wall; fires external to the building including stored combustible materials in dumpsters, vehicle fire, and brush fire; and fire in an adjacent building. [37, 74] Of these, the first - a fire within the building and venting through an opening - is more severe and statistically the most significant. [37, 74]

Oleszkiewicz suggests the severity of the exposure from a fire venting through an opening results from the direct impingement of an intense fire plume on the outer face of the facade.[37] The fire exhibits spread mechanisms upwards along the wall but also spread downwards due to the thermal and material properties of the facade components.[1] The spread of fire on the facade is through convection heat, the quickest method of fire spread in buildings. The facade is the interface between the inside and outside environment of a building.[38] Therefore, at the facade, many factors converge that enable the dynamics of fire, including unlimited amount of oxygen, the vertical nature of the facade surface, the pressure difference between inside and outside of the building, and wind.[38] There are several methods that can lead to the spread of fire through the exterior face of a building. However, the most dangerous fire is one that originates in an interior compartment of the building and spreads outward from an opening in the building.[38]

Fire or burning is the combustion of materials and is an exothermic oxidation of a fuel. The critical elements for fire include heat, an oxidizer such as the oxygen in air, and fuel.[8] Heat is necessary to initiate the process, and the reaction produces exothermic heat of combustion,[61] the quantity of heat that can be theoretically released during a fire. Different building materials release different amounts of heat in a fire and play a major role in fire behavior after ignition; however, ignition has no effect on fire severity.[49] From a combustion perspective, a fuel is something that can burn in a fire.[61] The physical and chemical characteristics of fuels and their locations are important to how fire will burn and the time for significant events to occur.[61] Pyrolysis produces volatile gases when a fuel is heated.[61] A flammable mixture is then produced when these gases mix with oxygen from the air within a specific range of proportions.[61] When this mixture reaches a high enough temperature to initiate a chemical reaction, flaming occurs.[61] This reaction releases many combustion products, including light, heat, gases, and soot particles.[61]

There are four consecutive stages of a typical fire development, including: Incipient, Growth, Fully Developed and Decay.[9] The different characteristics of each stage, as well as the fire behavior should not be underestimated.[9] Fires occur in almost any kind of building, workplace and wildland. An environment with a low probability of loss of life and property is often a key objective in the design and construction for fire safety in places with occupants.[8] However, despite providing the latest active control devices, including sprinkler systems and smoke detectors, full fire prevention may not be achieved.[9]

Most research on fire characteristics has concentrated on the “room of fire origin”. The amount of data collected in this type of fire research is significant. However, Kolbrecki suggests the effects of fire beyond the room of origin has not been well-documented.[38] In this respect, one noteworthy characteristic of fire is the spread out of an opening, such as windows in buildings. Unburned gases venting from the room of origin and continued combustion of the gases beyond the opening where an abundance of fresh air exists produces the appearance of flames through windows.[38] One characteristic of a fire that has undergone a transition to flashover and entered a ventilation-controlled state is external flaming from an opening.[26]

When a fire breaks out and spreads in a building, high-temperature jet plumes ejected from windows can cause fire to spread to adjoining floors or neighboring buildings.[10] Research on jet plumes emitting from openings have been well-documented, including the well-known pioneering work of Yokoi [36] who presented theoretical and experimental findings from temperature distributions of jet plumes.[38] The glass in windows is a vulnerable component in the building envelope and can be broken easily when exposed to a fire.[38] Kolbrecki suggests the main cause for glass breaking when subjected to fire is the temperature gradient between the exposed and ambient region of the glass.[38] Hot gases flow out the top portion of the opening once the window glazing breaks.[55] Limited air in the room does not allow a portion of the hot gases to burn (ventilated-controlled). However, once the hot gases move to the exterior, sufficient air entrainment allows the hot fuel gases to burn outside the building.[55] The result is a flame projecting out and upward from the window, extending high above the top of a window opening.[55] Exterior building flames have no restriction to air-entrainment, eventually spreading and growing more hazardous than an interior fire.[73] In high-rise building fires, flames can eject from the window of a room after flash over and then spread to upper floors, leading to catastrophic loss of life and property. The heat flux from the exposure of ejected fire plumes is the most influential parameter, directly determining the damage to the thermal envelope as well as the vertical fire spread along the building facade wall.[12]

The greatest risk of emerging flames and combustion products to the facade of building is greatest during the fully developed stage of the fire.[3] It is during this phase that the temperature both inside the room of the fire origin and outside on the building facade are at their highest. As a result, a secondary fire may occur in either the upper floor levels of the building or on an adjacent structure. The venting plumes provide either direct flame contact or radiant heat transfer.[3] The burning rate of the fuel, affecting the severity of a venting fire plume and its shape, is directly affected by the ventilation conditions within a room.[26] As a plume ejects from a window after the glass is broken, the plume is also affected by the opening shape; the window aspect ratio determines the overall height and width of the venting flames.[26] Once the plume surges out of the opening, contact to the exterior wall is achieved some distance above the opening from the curling flame.[38] It emerges from narrow openings, generally projecting outwards a distance of half of the window height; flames emerging from a wide or square window generally project one and a half times the window's height. Oleszkiewicz showed that a wide window caused the flame to attach to the wall above the opening.[37]

Many factors affect flame spread behavior, including the ambient flow velocity, the oxygen concentration, the pressure, and radiation intensity,[40] see Figure 2.0. The controlling mechanisms of flame spread behavior vary in different external conditions[38] Flame spread and growth are determined by the thermal response of the material to an imposed heat flux distribution; a higher heat flux conducts heat more easily.[34] "Thermal response of a material includes the preheating of material to an ignition temperature, pyrolysis (the decomposition by high temperature), and burning properties of decomposing gases from high heat.[3]

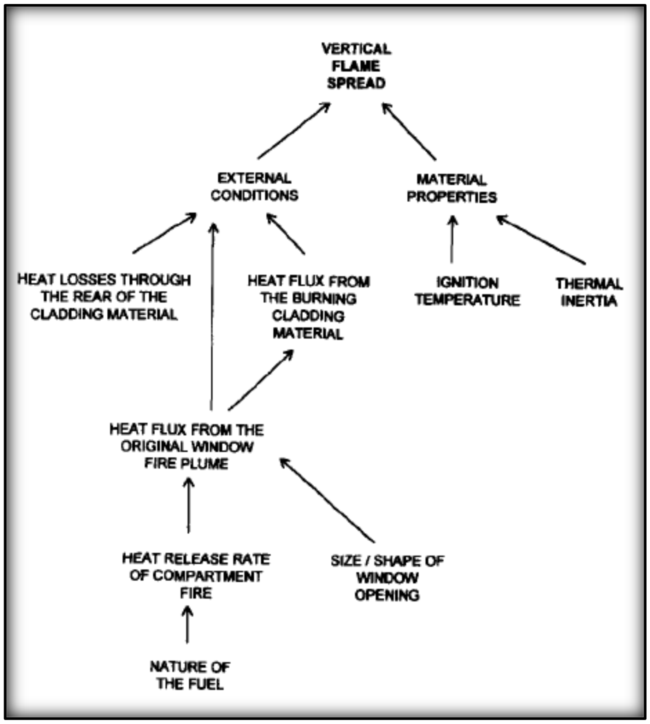


Figure 2.0 Factors Affecting the Rate of Vertical Fire Spread [40]

The severity of an external wall's exposure resulting from a window fire plume varies, depending on the heat release rate of the compartment fire, the geometry of the window opening, and the heat flux from the original window jet plume.[13] An increase in vertical distance above the window decreases the exposure, but grows with the burning rate of the cladding material.[40] Babrauskas suggests a heat flux of 50 kW/m^2 may be reasonable to simulate the heat flux from a window fire plume onto the building facade.[13, 40] Although higher heat fluxes could occur, Babrauskas indicates they would require very large fires and very large openings.[13, 40]

Other contributing factors to vertical flame spread are the material properties of the cladding system and the mechanical behavior of the cladding system under elevated temperatures.[3] As such, fire safety features of exterior wall claddings should be considered very carefully, especially for high-rise buildings. The geometry of the compartments in a cladding system, as well as fire load density, thermal characteristics of the surrounding surfaces, and ventilation within the system, plays a role in the severity of a facade fire.[49] Heat and mass can be trapped by the facade cavity depth, significantly affecting channelized air flow and heat transfer within the facade system.[66] Buoyancy then allows the hot air to move vertically within the channel of the cavity.[66]

The jet plume ejected from an opening onto a building facade creates a special fire phenomenon.[70] As a result, there have been several research efforts focused on the study the fire performance of exterior wall claddings for high-rise buildings,[10] including factors that can affect the opening jet plume behavior such as various combinations of opening and horizontal projection conditions, vertical projections, and buoyancy.[37] The application of horizontal or vertical projections can alter the ejected window plume, [37] see Figure 2.1. The vertical projections simulate a non-combustible spandrel wall with no openings.[3] The horizontal projections can be a canopy or a balcony, installed on the wall directly above the window opening, functioning as a deflector for the flame projecting from a window opening.[3] This type of projection provides considerable protection to the wall above the window and protects the stories above from the intense heat given off by a window fire plume.

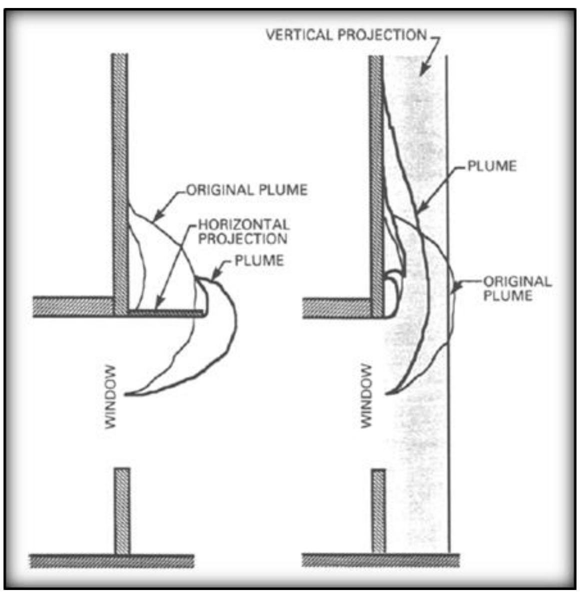


Figure 2.1 Window Fire Plume Directional Change Due to Projections [37]

Large eddy simulations applied to opening jet plumes denote very low heat flux and temperature distributions can be achieved by installing horizontal projections at the top of an opening.[10] The earliest work of this topic was researched by Yokoi;[70] his experimental work discovered a horizontal projection perpendicular to the wall above an opening prevented glass windows above a projection from breaking.[38] The horizontal projection also provided a better performance for fire separation, drawing hot smoke away from the wall.[10] Fire projecting from an opening generally travels vertically unobstructed along the facade without the presence of a horizontal projection such as a balcony.[38] However, the addition of a horizontal projection right above the wide window projects the jet plume away from the facade, impeding the vertical fire spread and reducing radiation to the floors above.[10] Figure 2.2 shows the simulated temperature contours of the opening jet plume without and with a horizontal projection.[10] A horizontal projection decreases the heat flux to the wall above the opening, minimizing the risk of secondary fire at the level beyond the fire compartment.[38] There could be adverse effects of the projection used to prevent the spread of fire; an adjacent building must be protected as the projection can increase the danger of fire spread should it respond as if it was an eave condition.[36]

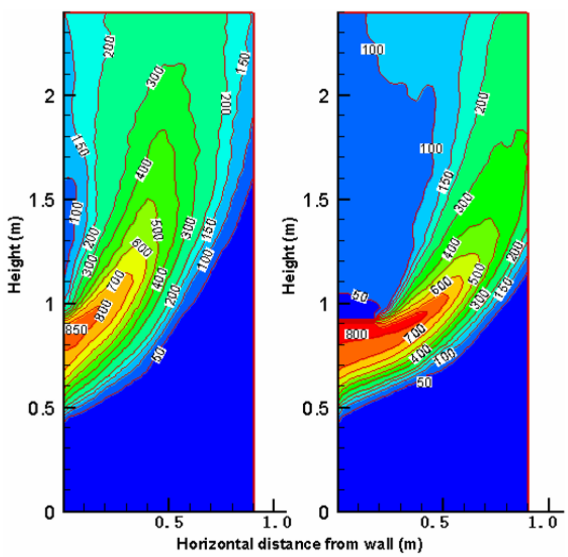


Figure 2.2 Temperature Distribution Contours [10]

Fire performance is dynamic; it is based on constantly changing fire conditions combined with phasing in and phasing out of different components.[61] The key factor linking all of these components is time; conditions producing fast fires rather than slow fires create very different hazards, altering the fire performance.[61] Therefore, a building fire is dynamic as the fire characteristics change constantly.[61] The continuingly changing building environment influences time relationships for hazard characteristics involving occupants and building functions.[61]

2.3 Global Fire Incidents Involving Green Facades

2.3.1 Introduction

Advanced technologies are creating energy-efficient buildings and these technologies employed in sustainable green design are evolving constantly.[16] As a result, architectural innovations of sustainable building designs, construction, and finishing materials have created new challenges regarding hazards and have dramatically increased fire risks in structures.[18] The building envelope should not allow excessive upward fire propagation on exterior wall assemblies and fire should not spread into upper floor levels and reach heights of ineffective or impossible external fire-fighting.[2] Traditionally, this has been achieved by requiring the use of non-combustible materials in the exterior wall assemblies of the building envelope. However, this precludes the use of other materials and composites which may have significant advantages such as energy efficiency and sustainability.

2.3.2 Representative Fire Incidents

There have been several global fire incidents over the last decade involving green facades; a large portion of these have involved the use of a combustible ACM-based rainscreen cladding with predominately accelerated vertical flame spread.[72, 73, 74] The key parameters influencing these fires and their consequences are the spread through the facade system and penetration from the outside to the inside.[72] Although many of these recent global fire incidents are documented in the form of newspaper articles, literature is limited.[74, 41, 32] Very few documents present detailed investigations of the fire incidents, such as fire behavior or mechanisms of spread.[74] A limited list of recent high-rise facade fires is provided in Appendix B [48] and several are highlighted below.

2.3.2.1 Mermoz Tower: Roubaix, France 2012[74]

The Mermoz Tower is an 18-story residential building in Roubaix, France. The building was renovated in 2003 and included the installation of an insulated exterior wall assembly with an MCM cladding system, see Figure 2.3.[74] The balconies were also outfitted with the MCM cladding system. The ground level design included phenolic cladding with MCM cladding on the remaining 17 stories. The material was a composite design with a 3 mm thick polyethylene core sandwiched between two 0.5 mm thick aluminum sheets.[74] On May 14, 2010 a fire started on a 2nd story balcony, resulting in rapid vertical flame spread on the MCM cladding to the top of the building.[74] The fire spread was observed to be enhanced by the vertical “U”-shaped channel profile created by the balconies, with flames moving in-and-out of balconies on each level as the fire spread upwards.[74] Smoke infiltrated the building interior through broken windows. Molten flaming debris from the exterior insulated wall assembly cascaded to the ground. There was 1 fatality and 6 people were injured.

Figure 2.3 Mermoz Tower Fire 2012[74]

2.3.2.2 Tamweel Tower: Dubai, UAE 2012[74]

The Tamweel Tower is a 34-story mixed-use building, including a residential occupancy, located in Jumeirah Lakes, Dubai, UAE. The facade of the tower was clad with an insulated exterior wall assembly, with an MCM cladding system. The material was a composite design with a 3 mm thick polyethylene core sandwiched between two 0.5 mm thick aluminum sheets, see Figure 2.4.[74] On November 18, 2012 at 1:30 in the morning, a fire started near the air conditioning equipment on the roof level. The fire spread quickly, propagating over the exterior of the building and was observed spreading downward. The molten flaming debris from the cladding fall onto lower level balconies, igniting the facade at lower levels.[74] There were no fatalities or injuries reported.

Figure 2.4 Tamweel Tower Fire 2012[74]

2.3.2.3 The Torch: Dubai, UAE 2015 and 2017

On February 21, 2015 and August 4, 2017, fire spread on the facade of The Torch, in Dubai's Marina District. The building is an 86-story high rise and was completed in 2011. The Tower has a concrete column structure, with beam and slab construction with a non-load bearing facade. The first fire in 2015 is thought to have started at about 2 a.m. on the 51st floor; fire spread quickly up to the 79th floor aided by strong winds. The fire also spread downwards, engulfing 193,750 sf of the facade from ground level to the roof, see Figure 2.5.[75, 76] The tower was clad with an insulated wall assembly, including MCM with a PE core. There were no reported deaths or injuries. The second fire in 2017 was thought to be ignited by a cigarette butt; it landed on a plant at a balcony. Although the fire was caused by a minor heat source, it is believed the building's exterior cladding system may also have played a role; rapid vertical flame spread was observed and flaming debris fell on the streets below.

Figure 2.5 The Torch Fire 2015 [75, 76]

2.3.2.4 Grenfell Tower: London, England 2017

On June 14, 2017 a fire occurred at 1:00 a.m. on the facade of Grenfell Tower, in London, England. The building was a 221 feet tall, 24-story high-rise building. Renovations to achieve better levels of energy efficiency and improved aesthetics had just been completed in 2016; improvements included a new cladding system consisting of ACM with a PE core and polyisocyanurate (PIR) thermal insulation had been installed.[72] The fire started due to an electrical short in a refrigerator on the 4th floor. The fire breached the window of the room of origin within minutes, setting the surrounding exterior cladding panels on fire. A column of flames spread rapidly up the side of the building. The fire also spread horizontally, with smoke and flames infiltrating multiple residential units, see

Figure 2.6. [77, 78]

Figure 2.6 Grenfell Tower Fire 2017 [77, 78]

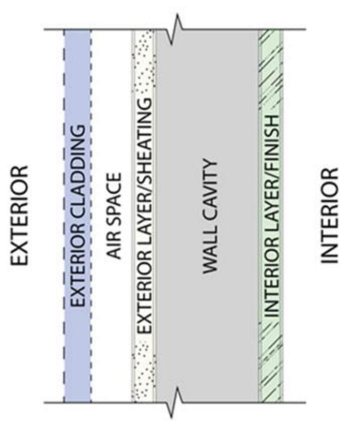
2.4 Documented Research

2.4.1 Fire Safety Challenges of Green Facades

The main characteristic of green construction is the design and construction of the building's façade, significantly impacting a structure's ability to conserve energy.[16] The building envelope can be designed to improve energy performance by reducing air and water infiltration. However, many of these design strategies include combustible materials, and their synergy can increase the complexity of the dynamics and fire hazard in the building envelope. There are numerous sources for descriptions and detailed explanations regarding the construction of exterior walls; several documents address building envelope wall system and curtainwall design concepts.[55] The exterior wall of a building envelope incorporates a variety of materials to create the outermost exterior wall cladding system.[55] A green exterior wall cladding system may include non-combustible or combustible materials. Enhanced insulation products and techniques, high performance glazing, and cladding systems are a few of the shell components that contribute to the sustainability of a structure.[16] Although some have little or no effect on fire safety, others present significant challenges.

2.4.1.1 Cladding Systems

Many of the ‘green’ exterior wall claddings on the market today include combustible foam materials, such as SIP, double skin facades (DSF), EIFS, and ACM insulated wall systems. Lower heat loss rate in a building may be obtained with these new architectural features.[32] However, the thermally insulated facades make it much easier for the onset of flashover in a building because the heat generated in a fire is trapped, creating a rapid rise of the air temperature in the room.[32] Many cladding systems also incorporate the ‘rainscreen’ principle in the horizontal and vertical joinery. The ‘rainscreen’ approach is based upon two separate and distinct leafs (or control layers) on the exterior building wall.[57] The outer leaf sheds and controls, but does not eliminate, the majority of the rain water. The inner leaf performs multiple function, including final moisture barrier, air/vapor barrier, insulation, and building structural wall,[57] see Figure 2.7.



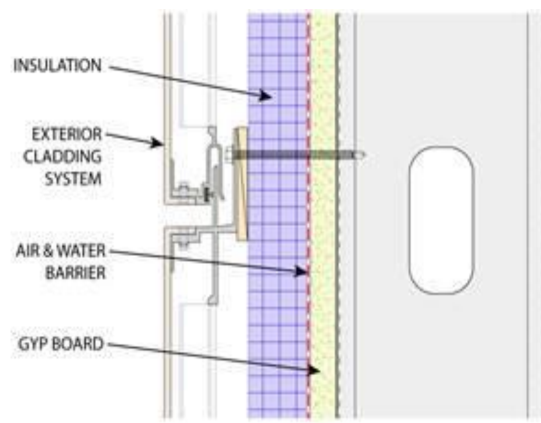
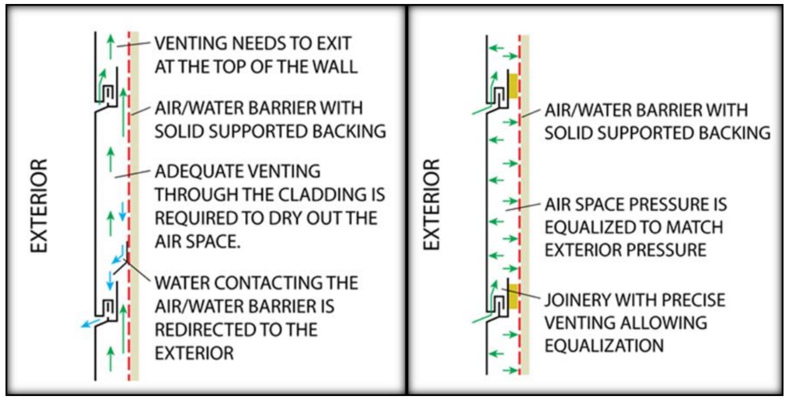


Figure 2.7 Rainscreen Principle Control Layers [59, 58]

The outer leaf allows penetration of water through open joinery. The volume of penetrating water will vary dependent upon design principle. There are two rainscreen system design approaches: drain/back-ventilated (D/B-V) and pressure-equalized (PER), see Figure 2.8.



D/B-V Rainscreen System PER Rainscreen Systems

Figure 2.8 D/B-V and PER Rainscreen System Details [59]

The D/B-V system allows, but controls, water; a ventilation cavity drains residual water and natural venting dries out residual water.[56] The PERS system is compartmentalized to eliminate or reduce the pressure differentials between the exterior cladding and the air space.[56] The air space within the panel system is divided and sealed into separate compartments.[56] This compartmentalization prevents the air within the air space from moving laterally from higher to lower pressure zones.[56] However, this system employs ventilated air gaps, allowing air infiltration, and is dynamic; the pressure differentials and air flow could contribute to potential flame spread concerns in the event of a fire. Combustion and the air flow in the wall cavities may elongate the flames 5-10 times compared to exterior flames.[2] The term ‘rainscreen’ has been generalized and consolidated into one commingled product in specifications combining both systems’ characteristics,[57] magnifying the fire hazard in a rainscreen facade system.

2.4.1.2 Insulation

A reasonable level of fire safety is expected as insulation techniques and products evolve.[16] The common types of insulation shown in Figure 2.9 are categorized in the U.S.A. as either non-combustible or combustible materials, per American Standard Testing

Methods (ASTM) E-136, Standard Test Method for Behavior of Materials in a Vertical Tube Furnace at 750°C. There are two non-combustible options, fiberglass and mineral wool. The combustible options are plastic-based foam. The foam plastic insulating products generally provide better resistance value (R-value) per inch; foam is more efficient and also has an excellent cost benefit. Plastics are classified as thermoplastic or thermosetting plastics. Thermoplastic products soften when heated, melt, and form a pool fire that produce additional burning; facade cladding such as ACM can include this type

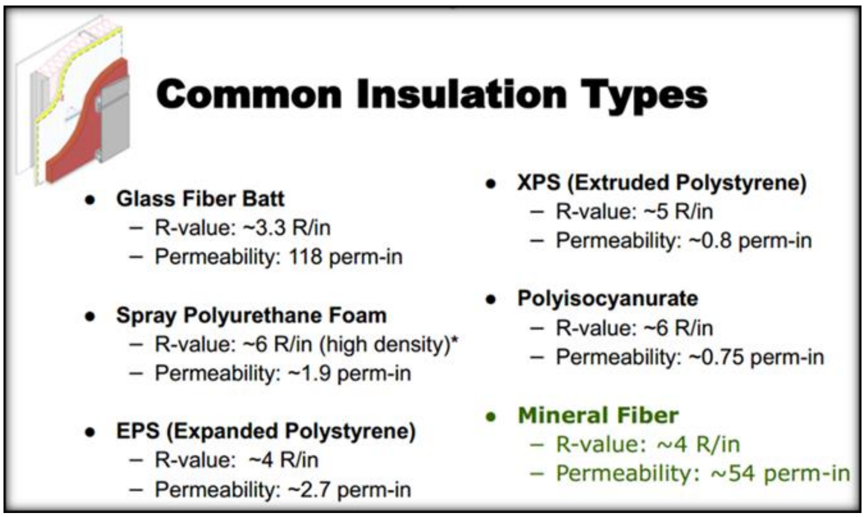


Figure 2.9. Common Types of Insulation Used in the Building Envelope [59]

of thermoplastic core. Many of the foam insulation products on the market are thermoplastic and are either extruded polyurethane (XPS) or expanded polystyrene (EPS), both of which are manufactured from petroleum products.[16] Thermal performance is meet by various sizes and thickness of the foam insulation.[2] Thermosetting plastics do not soften when heated but can burn vigorously when ignited.[61] Polyurethane foam (PUR), polyisocyanurate foam (PIR), and phenolic foams are part of this group, used to provide greater insulation values for external cladding systems,[2] often charring during a fire event. Foam products can burn intensely, producing considerable smoke and spreading fire to other combustibles if unprotected and exposed to elevated temperatures.[16] The fire characteristics of both types of foam are very similar, as they're both a petroleum-based material.[16]

2.4.1.3 High-Performance Glazing

Sustainable buildings thrive on natural lighting to create the interior environment desired and to save on artificial lighting.[16] Therefore, windows become an important issue, because of the potential energy loss resulting from heat transfer between the interior and exterior of the building. The type of glazing, including the number of layers, glass and frame quality is important; glazing is vulnerable to local heating, which results in rapid failure. Glass breakage due to fire is limited with high degrees of uncertainty given the possible configurations and variations in windows and curtainwall construction.[55] Reflective coatings, low "e" (emissivity) glass, and gas-filled cavities are varying components of energy-efficient windows. The primary concern for high performance glazing is the difficult process firefighters incur while ventilating horizontally, as many energy-efficient windows are manufactured with multiple layers of glass.[16]

2.4.2 Fire Hazard Assessment Challenges of Green Facades

The tools and techniques available for fire risk analysis are fairly well-developed, providing various approaches for fire risk assessments.[11, 32] Risk indexing is one common method of fire safety evaluation.[30] Many sources outline these ranking indices, including the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering,[51] SFPE Engineering Guide on Fire Risk Assessment,[65] and literature (e.g. Rosenblum 1989, Larsson 2000, Meacham 2004, Sakenaite 2010, Yau 2014, and Lamont 2018). Five indices most often mentioned in the literature are summarized in Table 2.0.[43] The index provides some idea of the types of variations involved in modeling and quantifying fire hazard.[27, 30] Generally, these indices are not absolute, but relative, used for a comparative basis[50] and provides a useful and valid method for a cost-effective means of risk evaluation.[43] However, fire safety decisions are often made with uncertain and sparse data.[43]

"Fire risk indexing systems is a thorough quantification method that is heuristic, finding an approximate solution when classic methods fail to find any exact solution, rather than fundamentally based."[50] They constitute various processes of analyzing and scoring hazard and other system attributes to produce a rapid and simple estimate to relative fire risk. There are several common features of these methods, including: a defined list of variables (attributes) applied as to specify the input; the calculation of the indices yield a single number which represents the magnitude of the hazard, however, this value is neither frequency nor consequence based; and the calculation can be compared with some tolerable or target value which is different for each index.[43] "It is an axiom of the analysis that zero risk is not an achievable goal; there is no risk-free alternative available."[50]

In addition to a hazard index, another approach is a performance matrix; it compares performance groups (consolidation of use groups with common performance requirements, developed as part of the risk characteristic process) by magnitude of design events (probabilistic or deterministic descriptions of hazard event).[51] Within the performance matrix, there are tolerable levels of impact, reflecting the amount of damage expected for the buildings with different performance groups given specific magnitudes of design events,[51] see Figure 2.10. As the performance group increases from Group I to Group IV, the level of required performance increases, as do the corresponding levels of tolerable impacts, from low to severe.[51] More damage is expected to occur as the impacts

Table 2.0 Representative of Five Fire Indices Most Often Mentioned in Literature[43]

Index	Mathematical expression of the index	Expression of tolerable risk	Reference
Gretener;s index $I_G^{(1)}$	$I_G = \dfrac{P(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) \times A(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)}{N(\mathbf{x}_3) \times S(\mathbf{x}_2) \times F(\mathbf{x}_2)}$	$I_G \leq 1{,}3$	Kaiser (1979)
FRAME index I_{FR}	$I_{FR} = \dfrac{P(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)}{A(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3)\, D(\mathbf{x}_2, \mathbf{x}_3)}$	$I_{FR} \leq 1{,}0$	F.R.A.M.E. (2008)
Dow's fire and explosion index (F&EI) $I_D^{(2)}$	$I_D = x_0 \cdot \sum_{i=1}^{6} x_{i1} \cdot \sum_{i=1}^{12} x_{i2}$	$I_D \leq 96$	Dow (1994)
Fire safety evaluation system (FSES) index $I_F^{(3)}$	$I_F = \prod_{i=1}^{5} x_{i1}$	$I_F \leq \sum_{j=1}^{3}\sum_{i=1}^{12} \mathbf{1}_{jk}(x_{i2}) x_{i2}$	Rasbash *et al.* (2004)
Hierarchical approach (HA)index $I_H^{(4)}$	$I_H = \sum_{i=1}^{n} w_i x_i$	$I_H \leq I_{H,tol}$	Rasbash *et al.* (2004), SFPE (2002)

$^{(1)}$ $A(\cdot)$ is the probability that a fire will start (the risk of activation); $P(\cdot)$ is the possible dangers (the potential risk); $N(\cdot)$ refers to standard measures; $S(\cdot)$ refers to special protection measures and $F(\cdot)$ is the fire resistance factor of the building; the components of the vectors $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are explained in Table 2.

$^{(2)}$ The values 1 to 96 of I_D embrace the categories of the light and moderate hazard (potential damage); intermediate, heavy and severe hazard is represented by the intervals $I_D \in [97, 127]$, $I_D \in [128, 158]$, and $I_D \geq 158$ (Dow 1994) ; the components of the vectors $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are explained in Table 4.

$^{(3)}$ $\mathbf{1}_{jk}(x_{i2})$ = an indicator (zero-one) function related the fire safety parameter x_{i2}; the components of the vectors $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$ are explained in Table 3.

$^{(4)}$ The symbol w_i denotes the weights of normalized attributes x_i; $I_{H,tol}$ is a tolerable value of the index I_H (not specified in the literature).

get larger, unless a higher level of performance is chosen.[51] The levels of impact are, therefore, inversely proportional to the building performance: less impact implies better performance.[51] Since absolute protection is not possible, and some damage, injury, or loss is currently tolerated in structures, especially after a hazard event, the term 'tolerable' is applied rather than 'acceptable'.[51] The SFPE Handbook indicates 'impact' is considered a broad description of loss.[51]

There is a benefit to a performance matrix. It could overlay a risk ranking matrix; a simple engineering approach quantifying the consequences of the most severe events anticipated, coupled with approximate event frequencies (probabilities), see Figure 2.11. The magnitudes of design event in the Performance Matrix can be overlaid with the frequencies of event occurrence of a Risk Ranking Matrix, from high probability at the

		Increasing Level of Building Performance (Performance Groups)			
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV
Magnitude of Design Event (Increasing Magnitude of Event)	Very Large (very rare)	Severe	Severe	High	Moderate
	Large (rare)	Severe	High	Moderate	Mild
	Medium (less frequent)	High	Moderate	Mild	Mild
	Small (frequent)	Moderate	Mild	Low	Low

Figure 2.10 Performance Matrix [51]

		Frequency			
		Beyond Extremely Unlikely	Extremely Unlikely	Unlikely	Anticipated
Consequences	High	Moderate	High	Severe	Severe
	Moderate	Mild	Moderate	High	Severe
	Mild	Mild	Mild	Moderate	High
	Low	Low	Low	Mild	Moderate

Figure 2.11 Risk Ranking Matrix[51]

bottom to low frequency (probability) at the top,[51] see Figure 2.12. For all high or moderate probability events, the allowable magnitude of impact is either mild or moderate, depending on the performance group.[51] For low-probability events, the allowable

		PERFORMANCE GROUP				
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV	
FREQUENCY (Probability)	Beyond Extremely Unlikely $f \leq 10^{-4} yr^{-1}$	Severe 5	Severe 5	High 4	Moderate 3	Very Large (Very Rare)
	Extremely Unlikely $10^{-2} f > 10^{-4} yr^{-1}$	Severe 5	High 4	Moderate 3	Mild 2	Large (Rare)
	Unlikely $10^{-1} f > 10^{-2} yr^{-1}$	High 4	Moderate 3	Mild 2	Mild 2	Medium (Less Frequent)
	Anticipated $f > 10^{-1} yr^{-1}$	Moderate 3	Mild 2	Low 1	Low 1	Small (Frequent)
		High	Moderate	Low	Negligible	MAGNITUDE of DESIGN EVENT
		CONSEQUENCES (Magnitude of Impact)				

Figure 2.12 Overlay of Performance and Risk Matrices

allowable magnitude of impact can be moderate, high, or severe, depending on the performance group. This approach allows for decisions to be made on the required level of building performance to which a building is designated.[51]

"Currently, a gap exists to analyze fire hazards associated with green building features."[32] A fire incident reporting system must be developed in the Unites States to specifically collect and track data from fire incidents in green buildings or from green building features; statistical data for an assessment is currently unavailable.[32] As a result, we do not understand the consequences and frequency (likelihood) of a fire associated with green building features; it is necessary to verify the fire safety with respect to both life safety and property protection. Although sometimes there is a benefit to decoupling the frequency of fire occurrence from the analysis of potential consequences and the likelihood that they will occur, the level of safety must be comparable in a systematic way to identify, analyze, and evaluate the fire hazards of green building features.[11] The use of a modified fire hazard index for the fire hazard assessment would be practical due to the relative simplicity of specifying input data.[43] A fire hazard analysis includes various diverse factors, creating difficulties in a uniform and consistent assessment; although not impossible, the analysis of such complex systems is challenging.[4] A detailed risk assessment can be expensive and a labor-intensive process with a considerable scope for improving the presentation of results.[4] Hazard ranking can provide a cost-effective means of evaluation which is sufficient in both utility and validity.[4] However, specific information, such as the synergistic effect of multiple green building features used together can be 'hidden' in the fire hazard index, making them difficult to apply comprehensive decision-making.[43] There is a need for a new assessment technique to quantify the hazards of green building features in the built environment; a fire hazard index (FHI) ranking method could be an innovative solution.

2.5 Significance of the Literature Review

The concept of sustainable development has evolved greatly since it was introduced by Brundtland Commission in 1987.[14] Energy efficiency has been identified by the International Energy Agency (IEA) as a major sustainable development goal by the year 2040, allowing the world to potentially extract twice as much economic value from energy it uses compared to today.[71] Energy bills for consumers could be reduced by more than

$500 million dollars per year[71] and a key strategy to help deliver this vision includes improving the energy efficiency in buildings further than currently designed.[71] This global effort to deploy the right energy efficiency policies is evident of a renewed effort to incorporate sustainable development in the built environment. Therefore, to incorporate sustainable development concepts into a building envelope design, it is important all stakeholders are involved in the sustainable building envelope design, including fire protection specialists.[14] It is essential that approaches to green building construction elements and the fire protection systems be identified during the early design process.[16] It has been suggested energy is primarily the foremost evaluation criteria for accessing green buildings, representing the potential as the greatest contributor to the fire hazard impact of a green building. As a result, an integrated systems approach is necessary to analyze building components as a total building fire safety system package.[16] The integrated approach encourages a broad analysis of all building features, including fire protection strategies; meeting the minimum requirements of the building code for protecting a structure is inadequate.[16]

Generally, there are no applicable and coherent guidelines to evaluate the fire hazards of green building features for sustainability initiatives and the associated impact to the built environment. A ranking system must be developed that is simple, rapid, and accurate; hazard indexing can accomplish all three of these parameters.[27] The aim of the fire hazard analysis must comprehensively understand and characterize the fire-related risks of green building features to better inform the wide range of decisions that must be made as part of building design, construction and operation.[43]

CHAPTER 3: A NOVEL FRAMEWORK TO QUANTIFY FIRE HAZARDS OF SUSTAINABLE INITIATIVES

3.1 Introduction

In the current paradigm, building fire performance related to life safety might be defined differently than building performance for property preservation.[11] However, the fire performance of the building, with respect to all performance objectives, is the most important.[11] Therefore, a novel framework to quantify fire hazards of sustainability initiatives in the built environment could parallel the general approach of facilitating sustainable building solutions; a multi-disciplinary approach with applied systems or whole-systems considered.[44] This type of approach would consider the green building features and systems holistically, evaluating how they are interconnected, how they best work together to achieve a solution that addresses multiple problems or has multiple layers of benefit while assessing a single structure.[44] The generalized concept includes these steps: identify the main fire hazards, quantify the fire hazards, identify the hazard control options (mitigation strategies),[50] and communicate the fire risk.[22] To illustrate the application of the novel framework, a case study model project is used to demonstrate the calculations for the fire hazards of the green building features of a high-rise residential building with cross laminated timber.

3.2 Brief Description of Hypothetical Case Study Model Project [67]

The model project is a 32-story, 305foot tall tower located in a densely populated financial city, based on the U.S. performance-based design case study for a high-rise residential building using cross-laminated timber at SFPE's 12th International Conference.[67] The target market for the building is members of the gig economy and maximizes transient use. The building incorporates a structural concrete podium design with cross laminated timber (CLT) balloon framing, eliminating hidden voids at the structural connections. There is also an architectural design feature exposing parts of the CLT. There are two carpark levels below grade constructed from precast concrete and a 30-story structure above grade constructed with a CLT engineered wood system to create a wood-concrete concept.[19] A conceptual view of the project structure is shown in Figure 3.0. The model project is designed as a mixed-use structure, including the following occupancy classifications: Assembly, Business, Mercantile, Storage, and Residential. The project footprint is rectangular with exterior dimensions of 131 ft. × 131 ft. with a total footprint of approximately 17,227 ft.^{2} per floor, and a floor-to-floor height of 9.8 ft. A green (sustainable) design is incorporated into the expression of the building; measures such as vegetated open spaces on the roof and proximity to a planned light rail station alleviate many zoning restrictions, including carpark requirements. A central reinforced concrete shear wall core houses and protects one exit stairwell, one service elevator car, and 4 passenger elevator cars. These are Occupant Evacuation Elevators (OEE) and used for emergency situations. The building is centrally located on a rectangular building site with a 6’-6” separation distance to all four adjacent property lines. A complete description of the building characteristics is provided in Appendix F.

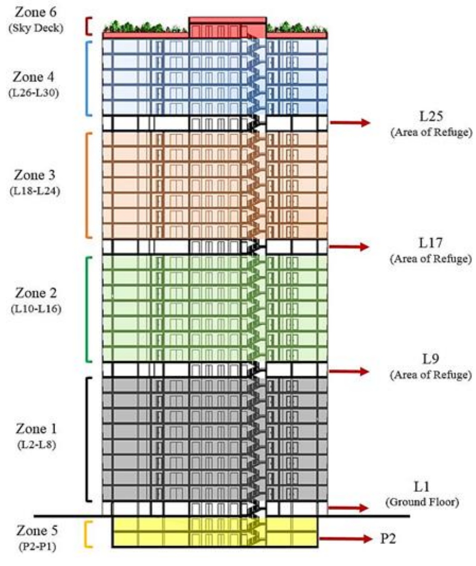


Figure 3.0 Conceptual View of Model Project Structure [67]

3.3 Methodology

3.3.1 Introduction

The foundation of the fire performance evaluation is the gathering of information regarding the building's characteristics influencing the building's fire performance.[61] The initial knowledge base for the analysis is developed from this information.[61] The analytical framework organizes the building's green features into manageable parts that contribute to the fire hazard analysis; the elements maybe combined to describe holistic performance.[61] The comparison of performance and hazards must be considered in a consistent manner by evaluating each building with the same systematic method.[61] Although every fire is different, the process for analyzing the fire hazards of green building features should be consistent, logical, and orderly.[61] The evaluation considers the growth and propagation of fire in green building features, assuming no extinguishment intervention; active fire defenses such as automatic detection and alarm systems, automatic sprinkler systems, or fire department operations are excluded. This analysis of the fire performance of the green features in isolation provides realistic measure in the event of active defense failure; active defense mitigation in this research is considered the safety factor. The tolerable risk levels are assessed to determine the need for hazard control options. Mitigation strategies consider only passive fire defenses, building components that remain fixed whether or not a fire emergency exists. These strategies include features to delay or prevent failure and barriers to prevent extension of the flame-heat or smoke-gas from one space to another.

3.3.2 General Structure of the FHI Method

The general structure of the FHI method is loosely based on several combined principles from the framework of three approaches: Fire Safety Evaluation System (FSES), Risk Indexing, and a Performance Matrix. The concept of the FSES subdivides a building into fire zones for evaluation;[30] the FHI subdivides the sustainable initiatives into separate green building features, evaluating each individually, and collectively as green building credit categories. Also, the FSES determines the relative risk deriving from characteristics of a health care occupancy;[30] the FHI determines the relative hazards derived from the characteristics of fire variables from the green building features on the model project. While the FSES uses five occupancy risk parameters,[30] the FHI uses 16 anecdotal fire hazard parameters; "data points from a database that has not been designed to ensure statistical representativeness and cannot be used to estimate incident rates or probabilities."[53] The concept of risk indexing assigns relative weights based on frequency and consequences; the FHI assigned relative weights based on the professional judgment and experience. There is no documented process for validating these values and there is no historical fire data regarding loss due to green building features. Hall indicates one method for estimating numerical values can be based on the judgment made by a lone user.[54] As a result, the professional judgement and expertise of facades and exterior cladding systems of the author, along with recent data from facade fire testing research from Nishio et al.,[68] provide the basis for the weighting technique of the green building features from the Optimized Energy Performance sub-category. There are 5 Key Performance Indicators (KPI) identified from the data of Nishio et al.; the potential correlation between the KPI's and the fire hazard variables for the green facade materials are considered. The three green building features benefiting from this analysis include the continuous exterior rigid foam insulation, higher insulation values, and area of combustible facade cladding, see Appendix H for the weighting technique.

A Performance Matrix was also implemented in the process to identify relative magnitudes of frequencies and consequences during a fire event, defining the loss related to damage or life safety. In the absence of statistical data, a risk index can be overlaid with a Performance Matrix to provide a perspective to an impact level relative to a ranking.[51] Therefore, the FHI method can calculate the fire hazard of the green building features by a relative scoring system.

The relative score of the 16 anecdotal fire hazard attributes of each green building feature is algebraically summed and the total severity of the impact hazard for each green building feature is obtained; the total severity of the impact hazard for each credit category can also be developed. These values can then be algebraically summed to determine the total level of impact on a structure and can be used for a comparative assessment of design features.

The primary outcome of the methodology identifies the sustainable initiatives considered pertinent to a fire and having the greatest potential impact in the event of loss due to fire; the hierarchical level of the FSES method is implemented for the analysis [45, 30] and structured as follows. First, the overall policy for the index system is formulated; to consider the fire safety performance for a high-rise residential building with cross-laminated timbers. Subsequently, the primary objectives are specified; to provide life safety and property preservation. Fire and life safety during building construction is outside the scope of this work. Goals are then developed to meet the two model project objectives;

performance criteria for tolerable levels of impact, or loss related to damage/life safety, as established by the project stakeholders. Levels of impact are then designed in conjunction with a Performance Group designation in the 2015 International Code Council Performance Code (ICCPC).[62] Next, the main strategy is determined; the focus includes green building features and the associated fire hazards. The attributes of the fire hazard affecting life safety and property preservation are characterized and assessed; the impact of the fire hazards to each green building feature is assigned a numerical value, correlated to the model project objectives. The final step verifies the results. The next decision-making level involves fire safety (mitigation) strategies.[30] Examples of fire safety strategies include ignition prevention, limitation of combustibles, and compartmentation.

3.3.3 Identifying the Main Fire Hazards of the Case Study Model Project

The process begins with identifying the categories of the LEED certification presenting a fire hazard. The evaluation of the case study model project characterized five categories affecting the fire hazard of the structure, including sustainable site development, water savings, energy efficiency, material and resources, and indoor environmental quality. These categories, including the sustainability design building features, systems, and procedures are outlined in Appendix D. Twenty-two green building features are recognized as potential hazards to the model project and outlined in Table 3.0. The appropriate fire design scenario must then be determined for consistent evaluations; the worst-case scenario should be considered. This research focuses on the fire hazard of green building facade features and, consequently, the worst-case scenario considered is a fire in the building venting through openings in the exterior wall. The thermal insult imparted onto the exterior wall system in terms of heat flux defines the severity of the fire scenario.[73] The fire variables (attributes) contributing to the hazard levels of the green building features are then characterized and identified as performance concerns for the model project, impacting fire, life safety, building and/or fire service performance, although each may not have the same merit. Attempts to establish fire hazard variables of green building features have also been worked out by Meacham, et al.[32] The variables identified for the case study model project are represented in Table 3.1. This is not a representation of a complete list; however, each attribute will rate a degree of importance.[52]

Table 3.0 Green Building Features with Potential Fire Hazards

GREEN BUILDING FEATURES	
Water Savings Category	**Site Selection Category**
Water Conservation: Captured Greywater	Vegetative Roof System
Water Conservation: Captured Rainwater	Battery Storage System
Reduced Water Supply	Electric Vehicle Charging Station
	Increased Building Density
Energy Efficiency Category	**Material Selection Category**
Continuous Exterior Rigid Foam Insulation	Engineered Structural Wood Elements and Connections (CLT)
Area of Combustible Facade Material	Wood Interior Walls
Higher Insulation Values	**Indoor Environmental Quality Category**
Refrigerant Materials	Low-emissivity & Reflective Coating
Onsite Renewable PV Solar Power Energy Roof Panels	Large Areas of Glazing (Daylight and Views)
Vestibules	Glass Interior Walls
Solar Shadings from Perimeter Balconies	Horizontal Semi-open Floor Plans
High-Performance Glazing	More Open Space - Vertical

The model project was designed under Performance Group III, which includes building and facilities with an increased level of societal benefit or importance, requiring increased levels of performance as they house large numbers of people, vulnerable populations, or occupants with other risks.[51] Based on Section 304 and Table 303.3 of the ICCPC, the model project level of impact regarding the magnitude of events for the Performance Group III varies between mild to high,[62] see Appendix G. Since zero risk is not an achievable

Table 3.1 Fire Hazard Attributes of the Green Building Features [32]

LIST OF FIRE HAZARD ATTRIBUTES	
Potential Ignition Hazard	Affects Burning Characteristics
Significant Smoke Production	Potential Shock Hazard
Potential Toxicity Hazard	Presents Flame Spread Concern
Contributes More Fuel Load	May Impact Smoke/Heat Venting
Structural or Stability Issues	May Impact Occupant Evacuation
Changes Thermal Characteristics of Compartment	May Impact Suppression Effectiveness
Readily Ignitable	May Impact Fire Apparatus Access
Burns Readily Once Ignited	May Impact Firefighter Access

3.3.4 Quantifying the Main Fire Hazards of the Model Project

goal and there is no risk-free alternatives, a low (negligible) level of impact is added to the magnitude of events. As a result, there are five categories of impact levels and are described in Table 3.2. Numerical values are then assigned to the five levels of impact and the ranking levels of impact is distributed as shown in Table 3.3. The scaling for the ranking levels is a continuous scale between two points; relative distance is maintained, and equal intervals

Table 3.2 Impact Level Descriptions

IMPACT LEVEL DESCRIPTION	
MAGNITUDE of IMPACT	IMPACT DETAILS
Low	Negligible adverse impact to life safety and property preservation
Mild	Minimal adverse impact to life safety and property preservation
Moderate	Marginal adverse impact to life safety and property preservation
High	Significant adverse impact to life safety and property preservation
Severe	Catastrophic to life safety and property preservation

Table 3.3. Ranking Levels of Impact

LEVEL of IMPACT for FIRE HAZARD	
INDEX RANGE	LEVEL of IMPACT
0 - 1	Low
1.1 - 2	Mild
2.1 - 3	Moderate
3.1 - 4	High
4.1 - 5	Severe

of the scale have the same meaning.[52] As a result, arithmetic-based operations are allowed by this interval scale.[52] Although the validity in terms of measurement could be uncertain due to an error in assuming the equal interval property is not significant, the results can be used to calculate the permutations.[52] The Impact Level is categorized on a scale of 0.1 to 5, where severity of damage is at a maximum value 5 and at a minimum value 0.1 because a fire hazard potential always exists.[65]

In the absence of statistical data, the numerical impact levels are then correlated to the Performance Risk Matrix to further define the loss related to damage or life safety. The acceptability criterion is based on the principle that the greater the severity of the consequences, the less should be the likelihood of occurrence; a high frequency occurrence results in lower consequences while a low frequency occurrence results in higher consequence. The tolerable impact level targeted by the stakeholders for the model project is Moderate and the risk index is overlaid with the Performance Matrix, see Table 3.4.

Table 3.4. Performance Risk Matrix

		PERFORMANCE GROUP					
		Performance Group I	Performance Group II	Performance Group III	Performance Group IV		
FREQUENCY (Probability)	Beyond Extremely Unlikely	Severe **5**	Severe **5**	High **4**	Moderate **3**	Very Large (Very Rare)	MAGNITUDE of DESIGN EVENT
	Extremely Unlikely	Severe **5**	High **4**	Moderate **3**	Mild **2**	Large (Rare)	
	Unlikely	High **4**	Moderate **3**	Mild **2**	Mild **2**	Medium (Less Frequent)	
	Anticipated	Moderate **3**	Mild **2**	Low **1**	Low **1**	Small (Frequent)	
		High	Moderate	Low	Negligible		
		CONSEQUENCES (Magnitude of Impact)					

3.4 Index Computation for the Hypothetical Case Study Model Project

The FHI assigns numerical values to the fire hazard attributes of each green building feature, which represent only negative fire safety features, and the values are then operated on through arithmetic functions to arrive at a single value.[50] Although the mathematical expressions of the index themselves are trivial in terms of computational effort,[43] this process is the basis from which choices between alternate design scenarios can be made.[50] The process to arrive at credible weights with consistent judgement of value for the attributes was carried out to enable an overall assessment.[52] The theoretical process of defining the attribute weights was reduced to a cardinal ranking of the criteria.[4] Weighting (penalty) factors are determined relating to the green building feature. Each feature is given an offsetting weight (of <1.0) and formulae are provided to adjust each of the original index values so giving new, reduced values for each index. The green building features from the Energy and Atmosphere category were weighted the highest as this is primarily the foremost evaluation criterion for assessing and certifying green buildings, potentially providing the greatest fire hazard impact to green buildings.

Once the relative hazard level is estimated, as a weighted function of the influence of the hazard impact on the various green elements,[32] the impact level of the feature is determined. A total possible point value of 80 is established for each green building feature when all 16 hazard variables are valued as a severe impact with 5 points each. Five project Impact Levels are categorized, and the numerical total hazard rankings are distributed equally, as shown in Table 3.5.

The hazard ranking for each green building feature is then carried out and organized into a Matrix; green building features are listed in a left-side vertical column and fire hazard

Table 3.5. Green Building Feature Total Hazard Point Scale

Green Building Feature Total Hazard Scale
Low: 0 - 16 Points
Mild: 16.1 - 32 Points
Moderate: 32.1 - 48 Points
High: 48.1 - 64 Points
Severe: 64.1 - 80 Points

variables listed in a top-side horizontal row, see Table 3.7. The total hazard points from each category can also be algebraically summed to assess the overall impact hazard to the structure. A total possible project point value of 1760 is established if all 22 green building attributes listed in Table 3.0 are valued at the highest impact concern level with 80 points each. The overall Project Impact Level Ranking Points are then distributed equally among the five impact categories, as reflected in Table 3.6.

Table 3.6. Overall Project Total Hazard Point Scale

Overall Model Project Impact Level Ranking
Low: 0 - 352 Points
Mild: 353 - 704 Points
Moderate: 705 - 1056 Points
High: 1057 - 1408 Points
Severe: 1409 - 1760 Points

Once the individual and overall hazard levels are established, decision-makers can compare the outcome of the fire hazard analysis with the tolerable risk level set by the Stakeholders. Control options to reduce any unacceptable fire hazard levels associated with the green building initiatives [29, 32, 40, 41, 42, 90] are then designed and the above quantitative process would be repeated to develop a mitigated Matrix with the reduced impact levels of each green building feature, category, and overall to the structure. This process considers the relationship between materials and ignition sources; best management practice to reduce a fire hazard is to keep adequate separation distance between combustibles and potential ignition sources. Mitigation strategies are also considered based on the synergistic effects to reduce the fire hazards associated with the green building features. A cost-benefit analysis by the stakeholders is then performed to determine which hazard control measures to implement in the design.

Table 3.7 Matrix for Ranking Green Building Fire Hazards

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Site Selection Category																	
Vegetative Roof System																	
Battery Storage System																	
Electric Vehicle Charging Station																	
Increased Building Density																	
Water Savings Category																	
Water Conservation: Captured Greywater																	
Water Conservation: Captured Rainwater																	
Reduced Water Supply																	
Energy Efficiency Category																	
Continuous Exterior Rigid Foam Insulation																	
High-Performance Glazing																	
Area of Combustible Façade Cladding																	
Higher Insulation Values																	
Refrigerant Materials																	
Onsite Renewable PV Solar Power Energy Roof Panels																	
Vestibules																	
Solar Shadings from Perimeter Balconies																	
Material Selection Category																	
Engineered Structural Wood Elements and Connections (CLT)																	
Wood Interior Walls																	
Indoor Enviromental Quality Category																	
Low-emissivity & Reflective Coating																	
Large Areas of Glazing (Daylight and Views)																	
Glass Interior Walls																	
Horizontal Semi-open Floor Plans																	
More Open Space - Vertical																	

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Results

The hazard ranking matrix for the project model is carried out, see Table 4.0. Many green

Table 4.0 Model Project Matrix for Ranking Green Building Fire Hazards

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Site Selection Category																	
Vegetative Roof System	5	1	1	5	4	1	5	5	2	2	4	4	1	1	1	4	46
Battery Storage System	5	5	2	5	1	3	1	1	2	1	1	1	1	1	1	2	33
Electric Vehicle Charging Station	4	5	2	2	1	3	2	1	1	2	1	1	4	2	1	2	34
Increased Building Density	5	1	1	3	1	1	2	2	1	1	4	1	4	2	4	3	36
Water Savings Category																	
Water Conservation: Captured Greywater	2	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	19
Water Conservation: Captured Rainwater	1	1	1	1	1	1	1	1	1	1	1	1	1	4	1	1	19
Reduced Water Supply	1	1	3	3	4	4	4	4	4	4	4	4	4	4	1	1	50
Energy Efficiency Category																	
Continuous Exterior Rigid Foam Insulation	5	1	5	5	2	5	5	5	4	5	4	5	5	3	2	4	65
High-Performance Glazing	2	1	1	1	1	3	2	2	3	1	1	5	3	3	1	4	34
Area of Combustible Façade Cladding	5	1	5	5	3	5	5	5	5	5	5	4	4	4	2	3	66
Higher Insulation Values	5	1	5	5	3	5	5	5	5	5	5	5	5	4	2	5	70
Refrigerant Materials	2	1	3	2	1	2	2	2	2	2	2	2	2	4	1	2	32
Onsite Renewable PV Solar Power Energy Roof Panels	4	5	1	2	4	2	2	2	2	2	2	2	2	2	2	4	40
Vestibules	2	1	1	1	1	3	1	1	3	1	2	3	3	1	1	3	28
Solar Shadings from Perimeter Balconies	2	1	1	2	2	3	1	1	3	1	2	3	2	2	3	4	33
Material Selection Category																	
Engineered Structural Wood Elements and Connections (CLT)	3	1	1	3	5	2	3	3	4	4	3	2	3	3	1	3	44
Wood Interior Walls	4	1	1	3	4	2	3	3	3	3	3	2	2	3	1	4	42
Indoor Enviromental Quality Category																	
Low-emissivity & Reflective Coating	2	1	1	1	1	3	2	2	2	2	2	4	2	2	2	4	33
Large Areas of Glazing (Daylight and Views)	2	1	1	1	2	5	2	2	5	3	5	4	4	4	1	4	46
Glass Interior Walls	2	1	1	2	2	4	3	3	3	2	2	2	3	1	1	2	34
Horizontal Semi-open Floor Plans	5	1	1	1	2	5	2	2	5	4	5	3	4	2	1	3	46
More Open Space - Vertical	2	1	1	1	1	4	2	2	3	2	5	2	3	3	1	3	36

*Note: This is not a ranking in order of importance.

building features present mild or moderate fire hazard to the model project; several present a high or severe hazard. These fire hazards and level of severity for the model project green building features are summarized in Table 4.1.

Table 4.1 Fire Hazards and Level of Impact for the Tower's Green Building Features

Site Selection Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Vegetative Roof System	46	Moderate
Battery Storage System	33	Moderate
Electric Vehicle Charging Station	34	Moderate
Increased Building Density	36	Moderate
Water Savings Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Water Conservation: Captured Greywater	19	Mild
Water Conservation: Captured Rainwater	19	Mild
Reduced Water Supply	50	High
Energy Efficiency Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Continuous Exterior Rigid Foam Insulation	65	Severe
High-Performance Glazing	34	Moderate
Area of Combustible Facade Material	66	Severe
Higher Insulation Values	70	Severe
Refrigerant Materials	32	Mild
Onsite Renewable PV Solar Power Energy Roof Panels	40	Moderate
Vestibule	28	Mild
Solar shading from Perimeter Balconies	33	Moderate
Materials and Resources Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*

Engineered Structural Wood Elements and Connections (CLT)	44	Moderate
Wood Interior Walls	42	Moderate
Indoor Environmental Quality Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Low-emissivity & Reflective Coating	33	Moderate
Large Areas of Glazing (Daylight and Views)	46	Moderate
Glass Interior Walls	34	Moderate
Horizontal Semi-Open Floor Plans	46	Moderate
More Open Space - Vertical	36	Moderate
Overall Project Impact Total Score	886	Moderate

The overall hazard ranking for the model project with the designed green building initiatives is 886 points. Based on the Performance Matrix methodology, the green building initiatives impose a Moderate Impact Level on the model project. However, the impact by the fire initiation or fire growth within the assemblies created by these green material components can result in enhanced heat release rates and pathways of fire spread not typically observed with standard construction materials;[34] a synergistic effect can be created by the combination of the components and can be greater than the sum of its parts. As a result, there can be an increase in the level of hazards and concern, above the overall 886-point value; the magnitude of a fire event can be affected. Mitigation strategies are then considered to understand if and how the fire hazards associated with the green building initiatives could be reduced.

4.1.1 Mitigation Strategies for the Case Study Model Project

Mitigation strategies are considered based on the synergy of the elements to reduce the fire hazards associated with the green building features, see Tables 4.2.1 – 4.2.5.

Table 4.2.1 Mitigation Strategies for Site Selection Category

Material/System/Attribute	Hazard	Potential Mitigation Strategies
Vegetative Roof System [16]	Contributes to fire load and flame spread; Impacts heat and smoke venting; Impacts firefighting and apparatus access; May impact structural stability due to weight	Provide a good roof drainage system to prevent blockage and obstructions by growth media or other materials planted in the roof; Implement an Extensive (low-maintenance and self-sustaining) design tolerant to drought and temperature extremes, using low growing succulents (high moisture content) and similar plants to enhance the roof's fire performance; Plants with high levels of volatile oils or resins should be avoided; Provide a 1 meter tall terrace roof parapet to reduce flame spread to adjacent structures; Adequate access area for the fire department; Manage fire risk of vegetation
Battery Storage System [16]	Ignition, shock, and toxicity hazard; contributes to fuel load; potential shock hazard to fire fighters; potential release of corrosive or toxic materials if damaged; Impacts firefighting access	Compartmentalize the storage area; special suppression system; incipient fire should be extinguished using Class C extinguishing agent (CO_2 or dry chemical); firefighters to use self-contained breathing apparatus (SCBA) and full PPE.
Electric Vehicle Charging Station [16]	Ignition Hazard	Shock protection; deactivate remotely; special suppression system
Increased Building Density	Ignition and flame spread hazard; May impact flame growth; Increase fire spread to adjacent structures; challenges for fire apparatus access	Limit planting and landscaping to reduce potential ignition source and additional avenues of fire spread; Drivable sidewalks for apparatus access; Develop Emergency Plan

Table 4.2.2 Mitigation Strategies for Water Savings Category

Material/System/Attribute	Hazard	Potential Mitigation Strategies
Water Conservation: Captured Greywater	Biological exposure hazard to fire fighters; corrosion of sprinkler piping system	Use for irrigation purposes only [16]
Water Conservation: Harvest Rainwater for Suppression[16]	Availability for suppression; system apparatus issues (hydrants/sprinklers)	Limit volume in water storage tanks- excess used to manage fire hazard of vegetated roof system; use for landscape irrigation and toilet flushing
Reduced Water Supply	Unavailable for fire suppression; May impact fire growth and flame spread;	Water storage tanks provided on 3 floors to meet minimum needs

	Structural stability could be compromised	

Table 4.2.3 Mitigation Strategies for Energy Efficiency Category

Material/System/Attribute	Hazard	Potential Mitigation Strategies
Continuous Exterior Rigid Foam Insulation	Readily ignitable; Expands towards the fire and can be treated as a fast or ultrafast fire; Contributes to fuel load, fire growth, flame spread, heavy, dense smoke and toxic product development; Flashover due to heat buildup and backdraft due to air-tightness potential; Impacts egress and firefighting; potential VOC off-gassing	Limited combustible material (1) includes ASTM E-84 compliant Fire Spread <25 and smoke production <400; NFPA 285 tested assembly; Projections to limit vertical and horizontal spread; Use a fine closed-cell structured material (Phenolic); QA during installation for proper termination conditions; Provide fire resistive thermal barriers; Eliminate fire load near base of the Tower (dumpsters, parking); Sprinklers; Pre-incident Planning; Use PPE & SCBA [16]
High-Performance Glazing	Changes thermal characteristics of burning compartment; may impact fire growth and flame spread; Impacts firefighting and apparatus access	Insert breakout panels to help horizontal ventilation; Protect with fire-resistant glass; Automatic Sprinklers; Adequate fire fighter access; Provide proper heat/smoke ventilation
Area of Combustible Facade Material	Larger area contributes to additional fuel load; may impact fire growth and spread	Limited combustible material (1) includes ASTM E-84 compliant Fire Spread <25 and smoke production <400; NFPA 285 tested assembly; Limit area on elevations; Eliminate combustible facade material at base of Tower; Eliminate facade vertical connectivity; Compartmentalize sections; Add projections to limit vertical and horizontal spread; Add 2.5-meter-wide continuous perimeter balconies; No vegetation or grilling on balconies; Smoking in designated areas only; Implement a backward incline to elevation to reduce impingement
Higher Insulation Values	Alters compartment burning characteristics; additional fuel load; Impacts fire fighter access	Limited combustible material (1); NFPA 285 tested assembly; Projections to limit vertical and horizontal spread; Sprinklers
Refrigerant Materials [16]	Potential ignition and flammability hazard; potential toxicity hazard; Presents flame spread concerns; May impact firefighting suppression efforts	Special emergency response plan (ERP): emergency contact information, site map to include hazardous material locations, fire protection systems locations, Special suppression system
Onsite Renewable PV Solar Power Energy Roof Panels[16]	Ignition hazard; contributes to fuel load and flame spread; potential toxicity and shock hazard to fire fighters; may impact	Use non-combustible roof materials, i.e. concrete for roof deck; provide thermal barrier between roof and PV cells; provide remote solar isolation switching close to solar units and in the FCC for DC disconnects; system

	vertical ventilation; potential glass breakage hazard; impacts fire fighter and apparatus access	automatically shut off power to the buildings electrical system should the inverter lose power from the power company's grid [35]; incipient fire should be extinguished using Class C extinguishing agent (CO_2 or dry chemical); minimize height and inclination of units off roof to reduce flame and heat deflection [29]; pre-incident planning
Vestibule	Impacts fire fighter access	Pre-incident planning
Solar Shading from Perimeter Balconies	May impact ventilation; Firefighting suppression can be impacted	Pre-incident planning

Table 4.2.4 Mitigation Strategies for Materials and Resources Category

Material/System/Attribute	**Hazard**	**Potential Mitigation Strategies**
Engineered Structural Wood Elements and Connections (CLT)	Contributes to Fuel Load; May impact structural stability due to lightweight; May impact egress and fire fighting	Sprinklers; Additional layers for charring; Pre-incident planning; Fire Resistive Barrier; Hidden Connections
Wood Interior Walls	Contribute to flame spread, smoke development, and fuel load	Additional layers for charring; Hidden Connections; Sprinklers; Flame retardant treatment

Table 4.2.5 Mitigation Strategies for Indoor Environmental Quality Category

Material/Systems/Attributes	**Hazard**	**Potential Mitigation Strategies**
Low-emissivity & Reflective Coating	Changes thermal characteristics of burning compartment; Impacts fire fighting	Sprinklers; Adequate fire fighter access; Provide proper heat/smoke ventilation
Large Areas of Glazing (Daylight and Views)	Additional glass breakage for subsequent fire spread; May impact vertical and horizontal ventilation; Impacts firefighting access and egress	Sprinklers; Projections to limit vertical and horizontal spread; design access points between glazing areas; minimize opening sizes
Glass Interior Walls	Inadequate fire barrier, glass breakage hazard; impact fire fighter access	Sprinklers
Horizontal Semi-Open Floor Plans (Open Spaces)	The lack of compartmentation may impact fire growth due to a greater volume of air, contributing to fire and smoke spread; Impact firefighting access	Automatic sprinklers; fire alarm systems; smoke control system; passive fire protection; fire safety and evacuation planning

[1] Limited combustible is defined as: The material, in the form in which it is used, exhibits a potential heat value not exceeding 8141 kJ/kg (3500 Btu/lb.), when tested in accordance with NFPA 259, Standard Test Method for Potential Heat of Building Materials; ***And***, The material shall have a structural base of non-combustible material with a surfacing not exceeding a thickness of 3.2 mm where the surfacing exhibits a flame spread index not greater than 50 when tested in accordance with ASTM E 84, Standard Test Method for Surface Burning Characteristics of Building Materials, or ANSI/UL 723, Standard for Test for Surface Burning Characteristics of Building Materials; ***Or***, the material shall be composed of materials that in the form and thickness used, neither exhibit a flame spread index greater than 25 nor evidence of continued progressive combustion when tested in accordance with ASTM E 84 or ANSI/UL 723 and are of such composition that

all surfaces that would be exposed by cutting through the material on any plane would neither exhibit a flame spread index greater than 25 nor exhibit evidence of continued progressive combustion when tested in accordance with ASTM E 84 or ANSI/UL 723; Or, a material that is classified as A2 by the EN 13501-1 test series [42].

One example of the potential mitigation strategies is the area of combustible facade material. The application of facade insulation and ventilated facades has rapidly increased in the global marketplace and may double in size by 2024.[72] In this growing market, the proportion of ACMs is currently estimated as 25% of the market share for US and the same level for Europe.[72] Proper risk evaluation should parallel the increased global use of ACM cladding.[72] Therefore, the model project includes a robust exterior cladding, a highly combustible ACM system, to demonstrate the value of the application of the quantitative methodology. In addition to the weighting procedure in Appendix H, the limited combustible alternative could have a reduced peak heat release rate. This could also slow the combustion process,[34] reducing the flammability hazard [34] of the initial ACM design. The hazard ranking matrix implementing the mitigated strategies from Tables 4.2.1 – 4.2.5 is provided in Table 4.3.

Table 4.3 Model Project Matrix for Ranking Mitigated Green Building Fire Hazards

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Site Selection Category																	
Vegetative Roof System	2	1	1	3	2	1	3	3	2	2	3	3	1	1	1	3	32
Battery Storage System	3	3	2	3	1	2	1	1	1	1	1	1	1	1	1	2	25
Electric Vehicle Charging Station	3	3	2	1	1	2	2	1	1	2	1	1	3	2	1	2	28
Increased Building Density	3	1	1	2	1	1	2	2	1	1	2	1	3	2	2	2	27
Water Savings Category																	
Water Conservation: Captured Greywater	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Water Conservation: Captured Rainwater	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Reduced Water Supply	2	1	2	2	3	3	3	3	3	3	3	3	3	3	1	1	39
Energy Efficiency Category																	
Continuous Exterior Rigid Foam Insulation	3	1	3	3	1	3	3	3	3	3	3	3	3	2	2	3	42
High-Performance Glazing	2	1	1	1	1	3	2	2	2	1	1	3	2	2	1	2	27
Area of Combustible Façade Material	4	1	3	3	2	3	3	1	3	3	2	2	2	2	2	2	38
Higher Insulation Values	3	1	2	3	2	3	3	3	2	2	3	2	3	2	2	3	39
Refrigerant Materials	2	1	3	2	1	2	2	2	2	2	2	2	2	2	1	2	30
Onsite Renewable PV Solar Power Energy Roof Panels	2	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	30
Vestibules	1	1	1	1	1	2	1	1	2	1	1	2	3	1	1	2	22
Solar Shadings from Perimeter Balconies	1	1	1	2	2	2	1	1	2	1	2	2	1	2	3	3	27
Material Selection Category																	
Engineered Structural Wood Elements and Connections (CLT)	2	1	1	2	2	1	2	2	2	2	2	2	2	2	1	2	28
Wood Interior Walls	2	1	1	2	2	1	2	2	2	2	2	2	2	2	1	2	28
Indoor Enviromental Quality Category																	
Low-emissivity & Reflective Coating	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	27
Large Areas of Glazing (Daylight and Views)	2	1	1	1	2	2	2	2	2	3	2	2	3	3	1	3	32
Glass Interior Walls	2	1	1	2	2	3	3	3	2	2	2	2	2	1	1	2	31
Horizontal Semi-open Floor Plans	3	1	1	1	2	3	2	2	3	3	3	2	3	2	1	2	34
More Open Space - Vertical	1	1	1	1	1	3	2	2	3	2	4	2	3	3	1	2	32

*Note: This is not a ranking in order of importance.

4.2. Analysis

Many mitigation strategies reduced the Impact Levels, altering the fire hazard for the model project. These fire hazards and level of severity for the Tower's green building elements after mitigation are summarized in Table 4.4.

Table 4.4 The Fire Hazards and Level of Impact after Mitigation Strategies

Site Selection Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Vegetative Roof System	32	Mild
Battery Storage System	25	Mild
Electric Vehicle Charging Station	28	Mild
Increased Building Density	27	Mild
Water Savings Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Water Conservation: Captured Greywater	16	Low
Water Conservation: Captured Rainwater	16	Low
Reduced Water Supply	39	Moderate
Energy and Atmosphere Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Continuous Exterior Rigid Foam Insulation	42	Moderate
High-Performance Glazing	27	Mild
Area of Combustible Facade Material	38	Moderate
Higher Insulation Values	39	Moderate
Refrigerant Materials	30	Mild
Onsite Renewable PV Solar Power Energy Roof Panels	30	Mild
Vestibule	22	Mild
Solar shading from Perimeter Balconies	27	Mild
Materials and Resources Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*

Engineered Structural Wood Elements and Connections (CLT)	28	Mild
Wood Interior Walls	28	Mild
Indoor Environmental Quality Category		
Material/System/Attribute	*Hazard Ranking - Total*	*Impact Level*
Low-emissivity & Reflective Coating	27	Mild
Large Areas of Glazing (Daylight and Views)	32	Mild
Glass Interior Walls	31	Mild
Horizontal Semi-Open Floor Plans	34	Moderate
More Open Space - Vertical	32	Mild
Overall Project Impact Total Mitigated Score	650	Moderate

The overall hazard ranking of the Tower, with the mitigated measures, or trial design option,[89] for the designed green building initiatives, reduces to 650 points, imposing a Mild Impact Level on the model project.

Further analysis of each credit category is provided in Tables 4.5 thru 4.9; these reflect a comparison matrix for each credit category. The greatest individual reductions occur in the facade green features in the Optimized Energy Performance sub-category, including the continuous insulation, area of combustible facade material, and higher insulation values. Mitigating the effects of exterior fire exposure on the facade focuses on radiant heat transfer and direct flame contact, see Table 4.10. The synergistic effect of these green building facade initiatives is considered during the analysis and reflected in the Impact Reductions, see table 4.5. Mitigation strategies used in isolation can lead to a disconnect between the measures and the actual expected performance of the building systems.[89] As a result, the facade analysis mitigates fire risks in the context of the overall system performance.[89]

Table 4.5: Comparison Matrix for Energy Efficiency Category

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment for Burning	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Energy Efficiency Category																	
Continuous Exterior Rigid Foam Insulation	5	1	5	5	2	5	5	5	4	5	4	5	5	3	2	4	65
High-Performance Glazing	2	1	1	1	1	3	2	2	3	1	1	5	3	3	1	4	34
Area of Combustible Facade Cladding	5	1	5	5	3	5	5	5	5	5	5	4	4	4	2	3	66
Higher Insulation Values	5	1	5	5	3	5	5	5	5	5	5	5	5	4	2	5	70
Energy Efficiency Category with Mitigated Strategies																	
Continuous Exterior Rigid Foam Insulation	3	1	3	3	1	3	3	3	3	3	3	3	3	2	2	3	42
High-Performance Glazing	2	1	1	1	1	3	2	2	2	1	1	3	2	2	1	2	27
Area of Combustible Façade Material	4	1	3	3	2	3	3	1	3	3	2	2	2	2	2	2	38
Higher Insulation Values	3	1	2	3	2	3	3	3	2	2	3	2	3	2	2	3	39

Table 4.6: Comparison Matrix for Indoor Environmental Quality

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment for Burning	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Indoor Enviromental Quality Category																	
Low-emissivity & Reflective Coating	2	1	1	1	1	3	2	2	2	2	2	4	2	2	2	4	33
Large Areas of Glazing (Daylight and Views)	2	1	1	1	2	5	2	2	5	3	5	4	4	4	1	4	46
Glass Interior Walls	2	1	1	2	2	4	3	3	3	2	2	2	3	1	1	2	34
Horizontal Semi-open Floor Plans	5	1	1	1	2	5	2	2	5	4	5	3	4	2	1	3	46
More Open Space - Vertical	2	1	1	1	1	4	2	2	3	2	5	2	3	3	1	3	36
Indoor Enviromental Quality Category																	
Low-emissivity & Reflective Coating	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	27
Large Areas of Glazing (Daylight and Views)	2	1	1	1	2	2	2	2	2	3	2	2	3	3	1	3	32
Glass Interior Walls	2	1	1	2	2	3	3	3	2	2	2	2	2	1	1	2	31
Horizontal Semi-open Floor Plans	3	1	1	1	2	3	2	2	3	3	3	2	3	2	1	2	34
More Open Space - Vertical	1	1	1	1	1	3	2	2	3	2	4	2	3	3	1	2	32

Table 4.7: Comparison Matrix for Site Selection Category

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment for Burning	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Site Selection Category																	
Vegetative Roof System	5	1	1	5	4	1	5	5	2	2	4	4	1	1	1	4	46
Battery Storage System	5	5	2	5	1	3	1	1	2	1	1	1	1	1	1	2	33
Electric Vehicle Charging Station	4	5	2	2	1	3	2	1	1	2	1	1	4	2	1	2	34
Increased Building Density	5	1	1	3	1	1	2	2	1	1	4	1	4	2	4	3	36
Site Selection Category with Mitigated Strategies																	
Vegetative Roof System	2	1	1	3	2	1	3	3	2	2	3	3	1	1	1	3	32
Battery Storage System	3	3	2	3	1	2	1	1	1	1	1	1	1	1	1	2	25
Electric Vehicle Charging Station	3	3	2	1	1	2	2	1	1	2	1	1	3	2	1	2	28
Increased Building Density	3	1	1	2	1	1	2	2	1	1	2	1	3	2	2	2	27

Table 4.8: Comparison Matrix for Water Savings Category

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment for Burning	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Water Savings Category																	
Water Conservation: Captured Greywater	2	1	1	2	1	1	2	1	1	1	1	1	1	1	1	1	19
Water Conservation: Captured Rainwater	1	1	1	1	1	1	1	1	1	1	1	1	1	4	1	1	19
Reduced Water Supply	1	1	3	3	4	4	4	4	4	4	4	4	4	4	1	1	50
Water Savings Category with Mitigated Strategies																	
Water Conservation: Captured Greywater	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Water Conservation: Captured Rainwater	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	16
Reduced Water Supply	2	1	2	2	3	3	3	3	3	3	3	3	3	3	1	1	39

Table 4.9: Comparison Matrix for Material Selection Category

Green Building Feature	Potential Ignition Hazard	Potential Shock Hazard	Potential Toxicity Hazard	Contributes More Fuel Load	Structural or Stability Issues	Change Thermal Characteristics of Compartment for Burning	Readily Ignitable	Burns Readily Once Ignited	Affects Burning Characteristics	Significant Smoke Production/ Hazard	Presents Flame Spread Concern	May Impact Smoke/Heat Venting	May Impact Occupant Evacuation	May Impact Suppression Effectiveness	May Impact Fire Apparatus Access	May Impact Fire Fighter Access	TOTAL
Material Selection Category																	
Engineered Structural Wood Elements and Connections (CLT)	3	1	1	3	5	2	3	3	4	4	3	2	3	3	1	3	44
Wood Interior Walls	4	1	1	3	4	2	3	3	3	3	3	2	2	3	1	4	42
Material Selection Category with Mitigated Strategies																	
Engineered Structural Wood Elements and Connections (CLT)	2	1	1	2	2	1	2	2	2	2	2	2	2	2	1	2	28
Wood Interior Walls	2	1	1	2	2	1	2	2	2	2	2	2	2	2	1	2	28

Table 4.10 Greatest Impact Reductions after Mitigation Strategies

Site Selection Category		
Material/System/Attribute	*Impact Reduction*	*Reduction Percentage*
Vegetative Roof System	14 Points	30%
Energy and Atmosphere Category		
Material/System/Attribute	*Impact Reduction*	*Reduction Percentage*
Continuous Exterior Rigid Foam Insulation	24 Points	36%
Area of Combustible Facade Material	29 Points	46%
Higher Insulation Values	31 Points	44%
Onsite Renewable PV Solar Power Energy Roof Panels	10 Points	25%
Materials and Resources Category		
Material/System/Attribute	*Impact Reduction*	*Reduction Percentage*
Engineered Structural Wood Elements and Connections (CLT)	16 Points	36%
Wood Interior Walls	14 Points	33%
Indoor Environmental Quality Category		
Material/System/Attribute	*Impact Reduction*	*Reduction Percentage*
Large Areas of Glazing (Daylight and Views)	14 Points	31%

It should be noted that all the calculations made above are purely for the demonstration of the methodology.[33] Once the mitigated strategies are analyzed and the results tabulated, decision-makers can then perform a cost-benefit analysis to choose the control options that best align with the tolerable hazard level of the project.

4.2.1 Validation

"Generally, a fire hazard/risk assessment method can undergo a limited validation; they are applicable to the experimental results they are based on and/or the limited set of scenarios to which the model developers compared the model's output."[60] So, to evaluate the technique developed for this case study, a comparison fire risk assessment (FRA) was performed using the NFPA External Facade Fire Evaluation and Comparison Tool (EFFECT) modeling program. It is qualitative in nature and builds upon the concepts in Publicly Available Specification (PAS) 79 in the context of a fire spreading over multiple stories of a building via a combustible facade system.[41] The PAS 79 approach defines 9

		Likelihood of Fire Hazard		
		Low: Unusually low likelihood of fire as a result of negligible potential sources of ignition	Medium: Normal fire hazard generally subject to appropriate controls	High: Lack of adequate controls applied to one or more significant fire hazard, resulting in significant increase in likelihood of fire
Potential Consequences of Fire Hazard	Slight Harm: Outbreak of fire unlikely to result in serious injury or death of any occupant	Trivial Risk	Tolerable Risk	Moderate Risk
	Moderate Harm: Outbreak of fire could foreseeably result in injury of one or more occupants but unlikely to involve multiple fatalities	Tolerable Risk	Moderate Risk	Substantial Risk
	Extreme Harm: Significant potential for serious injury or death to one or more occupants	Moderate Risk	Substantial Risk	Intolerable Risk

Figure 4.0 PAS 79 Risk Assessment Approach [41]

steps to the qualitative risk assessment, see Figure 4.0. The PAS 79 risk ranking in ascending order include: Trivial, Tolerable, Moderate, Substantial and Intolerable.[41] The process of this risk assessment identifies the hazard(s) and then assess the likelihood and consequence of the hazards occurring.[41] The EFFECT User's guide summarizes the methodology embedded in the FRA modelling program; it was validated against a global portfolio of high-rise buildings.[42]

4.2.1.1 Validation Methodology

The case study building characteristics, prior to the implemented mitigation measures, are entered into the EFFECT program, and included key attributes such as building height, occupancy type, component materials, type of facade system, potential ignition sources, building fire protection systems and evacuation strategies, as outlined in Appendix F. Assumptions include [41]:

- The hypothetical case study is an existing structure
- Maintenance and operation of systems are in proper working condition
- The structural framing system is non-combustible
- Risk during construction of the case study model project is not considered
- The goals considered are life safety and property preservation

The facade fire hazard of the case study model project received an EFFECT Risk Score of “C”, a moderate fire hazard. The likelihood of a fire hazard is medium; normal fire hazards (e.g. potential ignition sources) for this type of occupancy, with fire hazards generally subject to appropriate controls (other than minor shortcomings).[42] The potential consequences of the fire hazard indicate moderate harm; outbreak of fire could foreseeably result in injury (including serious injury) of one or more occupants but unlikely to involve multiple fatalities.[41] According to the EFFECT program, "it is essential that efforts are made to reduce the risk. Risk reduction measures, which should take cost into account, should be implemented within a defined time period. Where moderate risk is associated with consequences that constitute harm, further assessment might be required to establish more precisely the likelihood of harm as a basis for determining the priority for improved control measures,"[42] see Figure 4.1.

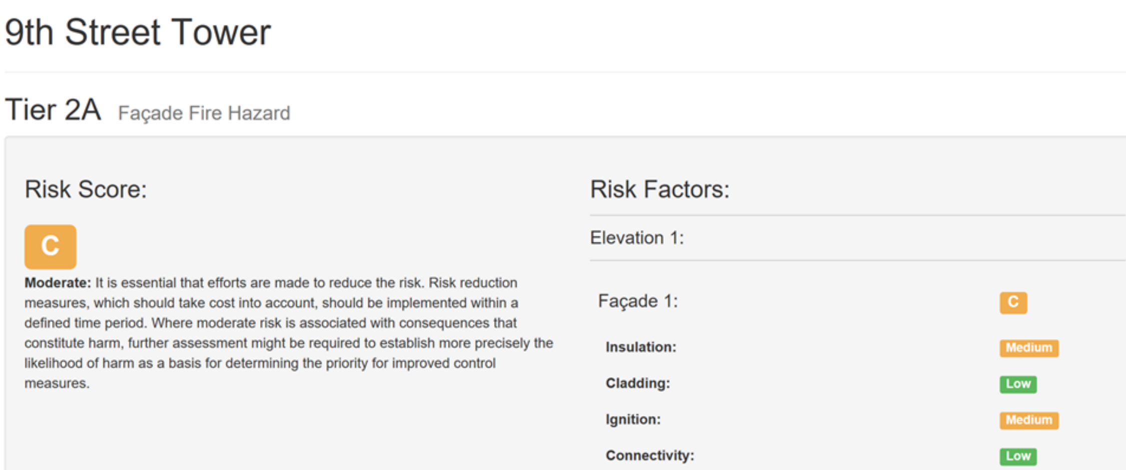


Figure 4.1 EFFECT Model Program Benchmark Facade Fire Risk Score [42]

4.2.1.2 Validation with the Implementation of Mitigation Measures

The case study building characteristics, after the implemented mitigation measures, were entered into the EFFECT program and considered the same assumptions as outlined above. The facade fire hazard with the mitigated measures received an EFFECT Risk Score of "A", a trivial fire hazard. The likelihood of a fire hazard is low; unusually low likelihood of a fire as a result of negligible potential of ignition.[41] The potential consequences of fire hazard indicate slight harm; outbreak of fire unlikely to result in serious injury or death of any occupant (other than the occupant sleeping in a room in which a fire occurs).[41]

According to the EFFECT program, “no action is required, and no details need to be kept,”[42] see Figure 4.2.

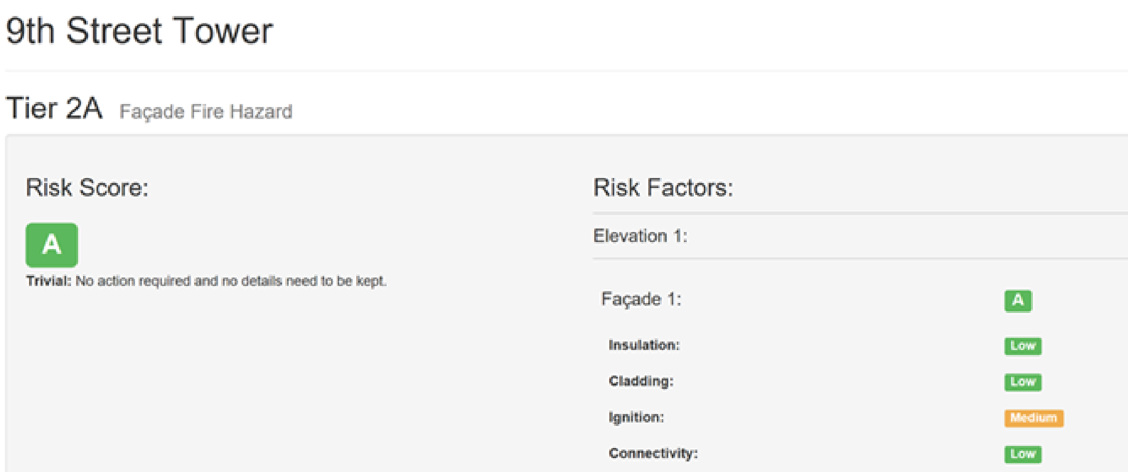


Figure 4.2 EFFECT Model Program Mitigated Facade Fire Risk Score [42]

4.2.1.3 Analysis of Validation

The approach of the validation assessment performs a systematic comparison of the EFFECT model results to the experimental data from the semi-quantitative approach for the facade developed for this case study. The EFFECT model results parallel the outcome of the semi-quantitative technique analysis, developed for this case study, of the fire hazard from the green building initiatives on the facade. It is identified, however, several limitations, including:[41]

- The tool is not applicable to timber frame buildings. The structural frame should be non-combustible, such as steel or concrete.
- The tool is a qualitative technique, the FHI is a semi-quantitative method, assigning numerical values to selected fire hazard variables.
- The tool addresses life safety only. Operations continuity and property preservation are not considered.

- The tool is for use in assessing existing buildings with a possible combustible facade system. It is not a design tool and should not be used for design of new buildings.
- There is limited statistical data on fires involving the exterior facade system. Test data is largely proprietary and therefore, generally not available to inform this study with the exception of test data explicitly cited by this work.
- The tool assesses buildings in their completed state; i.e. it does not assess “temporary risks” that arise from construction work or partially occupied buildings.
- The FRA tool is applicable in any geography but is currently limited to residential (hotel, apartments) or business (office) type occupancies that are over 59 ft. high where height is measured as the vertical distance from fire department access level to the top most occupied floor of the building.
- The tool is distributed by NFPA as a risk assessment tool for use by an Authority Having Jurisdiction (AHJ). While other parties (owners, facilities managers, fire safety engineers, fire risk assessors) may also use the tool, it is developed with the NFPA specified end users in mind.

4.3 Discussion

The sustainable intent for the model project design is integrated into the fire and life safety protection strategy. “Without mitigating strategies, the fire hazards from green building initiatives can increase, life safety can decrease, and/or building performance in comparison with conventional construction can decrease.”[32] A quantitative method to compare the relative fire performance of green materials and the risk associated with them is currently being developed.[32] However, facade fire scenarios cannot be analyzed by the existing quantitative or semi-quantitative fire hazard assessment methods.[41]

The outcome of this research is an enhanced understanding of the way green building features perform in a fire, enabling better decisions regarding risk management or other fire safety engineering projects.[61] The FHI characterizes the variables' hazard levels or mitigation potential and incorporates them into a matrix that allows decision makers to prioritize mitigation.

The FHI has been developed from first principles and is not a precise measure of the scope or range of effect from a future fire hazard.[28] Instead, the FHI sets out to provide a broad ranking for a limited number of potential green building features on a structure. As with other indices, the scale is relative and based on experience, not on an absolute scale. The FHI deliberately adopts a simple methodology, using common factors wherever possible, so it can be used as an additional decision-making tool.[28] Because hazard indexing for fire hazard prioritization simplifies basic hazard assessment principles, hazard indexing can be an effective way to acquire a global grasp of the issues.[27, 30] However, Rosenblum indicates problems could occur from excessive simplicity.[27]

Larsson documents there are significant difficulties in evaluating how well or how poorly an index method performs.[45] A consensus of the fire hazard attributes for green building materials has not been established and are therefore, not measurable in a traditional quantitative sense; specific procedures are not available.[45] Another method to evaluate the fire performance of an external wall assembly is the HHR, a global measurement parameter that could provide an objective and robust evaluation.[73] While professional judgment and expertise in this thesis considered how reduced heat release rates could slow the combustion process for the mitigated facade green materials, identifying heat release rates of green materials could also help to characterize the hazards associated with the flame spread for further indexing of the green materials. Oleszkiewicz documented peak heat release could be an objective technique to distinguish between wall assemblies[73] and this could help to further identify different fire hazard impact levels. Although the proposed index method addresses many important fire hazard attributes, the degree of accuracy is difficult to assess.[45] However, the level of accuracy demanded for a fire hazard analysis is not typically the same as for other engineering purposes; Watts indicates establishing levels of magnitude are appropriate.[30]

The process of risk assessment is to identify the hazards and then assess the likelihood and consequence of the hazard occurring. The likelihood of a fire occurring is linked to the hazards that may cause ignition combined with the presence of fuel and oxygen.[42] The form of materials, their fuel properties, and the thickness and surface roughness impacts the ignition and intensity of a fire. Although ignitability describes the ease of ignition for a material, it does not affect fire severity. Structures with a larger footprint or simply taller have an increased risk of fire as there are more potential ignition sources.[42] The likelihood of a large fire is linked to the fire load available to burn, including construction materials used and whether the fire safety provisions can contain the fire to the room or floor of origin.[42] In the context of buildings with combustible facade systems, active fire protection systems cannot contain fire from spreading over a facade system beyond the reaches of firefighter hose streams.[42]

The analytical framework is universal; geographical locations, jurisdictions writing or enforcing codes and standards, or any fire protection devices or actions intended to make the building perform better does not restrict the structure of the methodology.[61] Although the framework is universal, quantification is local and dependent upon the building design, its location, and all existing features influencing the fire performance.[61] The heat of a fire adversely affects all building materials. Some materials are affected at lower temperatures or at shorter time exposure than others; a materials sensitivity to elevated temperatures is important. Sourcing of the supply chain for product manufacturers is also different, influencing potential variations in the fire performance of similar green building products; different types of cladding can achieve very different levels of performance.[72] As a result, a potential weakness in the method is the risk that the typical product tested and promoted is not the typical product involved in a fire event.[54] This situation is unavoidable, however, the input from fire service personnel would be helpful.[54] Therefore, the mitigated strategies outlined incorporated documented fire service expertise.[16, 35]

Fire protection design and engineering requires a high degree of decision making and because of the unpredictable nature of fire, the engineering demands a high degree of subjectivity, and therefore, uncertainty.[52] It is inherent to any analysis and design, resulting from a lack of complete knowledge or randomness, including how or where fire can start.[61, 76] Although a quantitative analysis includes probabilities with an understanding of uncertainty and how uncertainty is handled [54], there is no model that predicts reality without any error.[33] Results can deviate between the values predicted and those measured in a test or a real fire caused by limitations and simplifications in the model.[33]

Hazard indexing is not a substitute for a detailed quantitative risk analysis, but is a planning tool useful for screening, ranking, and setting priorities. As such, risk management decisions should not be based solely on a risk index or other prioritization system. Risk management should be based on a much deeper analysis of fire risks.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Energy efficient structures are being designed and built today, yet we still face many challenges associated with the current knowledge gaps of the fire hazards of a building's exterior wall assembly with green design features. The global fire behavior is driven predominately by the cladding system;[72] we need to clearly understand how these green materials used in our built environment perform, both as distinct products and as part of increasingly complex systems. The range of green materials used in the built environment continues to change, creating fire performance challenges and opportunities. The current contribution of fire risk factors to sustainable design has the potential of tripling due to the future efforts to enhance sustainability by improving energy efficiency.[39] Therefore, the field of fire engineering must parallel these innovations in the field of architecture, building and material science, and civil engineering. The potential fire hazard of the inherent flammability and subsequent fire spread in a dynamic green building envelope is not well characterized. The practicality of assessing hundreds of green building features with fire hazards is in its infancy, leading to the creation of this simplified hazard index system. A novel framework for an index-performance based approach has been proposed to assess relative fire hazards, determined by the relationship between multi-attribute fire hazards and green building features, and to prioritize any subsequent changes early during the design process to address tolerable risks by decision makers.

The novel methodology is applicable to the evaluation of sustainable design hazard alternatives, considering the requirement to minimize risk induced on a structure, including life safety and property preservation impacts. This research has emphasized the necessity for considering of fire hazards as crucial inputs in determining the impact levels of green building features. The simple Fire Hazard Index described herein incorporates the direct impact of fire on green building features in the built environment; the response is synthetic and is applicable when considering alternatives for different variants of one specific project. In this case, among different possible alternatives, the one that obtains the best index score is the one that minimizes both life safety impact and property preservation impacts. The weights proposed herein are based on an individual's professional judgement, past experience, and a correlation to recent data from research facade fire testing. Estimates from individuals whose expertise has afforded long periods of nonsystematic field observations can be applied in the absence of data from systematic field observations.[53] The index score is not to be considered absolute, as the methodology result is not meaningful as an absolute value, but only as relative (comparative) ranking.[52] Weight values can, therefore, be altered for specific situations, providing the proportions and relationships are not completely changed.[52] The FHI has been tested on a single model project as part of this thesis and the facade results validated, however, its usefulness should be demonstrated by application to a much wider range.

5.2 Significance of Research

Green construction creates sustainable, high-performance structures that integrate and optimize all major high-performance building attributes such as energy efficiency, durability, life cycle performance, and occupant productivity. "This holistic approach to design, construction, and demolition minimizes the building's negative environmental impact; is environmentally responsible; and is resource efficient throughout the building's life cycle, from the site design to construction, operation, maintenance, and deconstruction."[35] As technology changes and new building materials are introduced, it is important to be able to appropriately identify the fire risk that is associated with them.[34] Currently, the process does not consider and integrate the fire hazards associated with green building design. Several studies have been conducted on the fire safety challenges of green buildings, but a gap to analyze fire hazards associated with green building elements was present. A method to identify, assess, and quantify the fire hazards of green building features in the built environment has not been developed.[28] Research was needed to conduct a hazard characterization and ranking exercise to develop a hazard performance level. A method would be advantageous during the selection of appropriate materials for a new design, a review of an existing design, or a modification to a design.[28] Implementing such an assessment could help determine appropriate fire safety protection features on a project. For certain applications, it is valuable to have a general-purpose method for comparing green building features in the built environment.

This research was a limited study focused on developing a simple semi-quantitative method to characterize the fire hazards of green building features. Findings of this study indicate the index rating tool is generally accurate in the prediction process of the potential fire hazard of facades with green building features. This methodology could be extended to other green building features and program categories. In addition, a whole building hazard characterization could be developed, ultimately leading to increased life safety and property preservation in the built environment. The special ability of FHI to not only rank an individual green building fire hazard in terms of severity but also to forecast an overall level of impact from green credit categories, as well as all green features on a structure, makes it valuable as a management tool in choosing between potential green building features or credit categories when designing sustainable infrastructure. The FHI is a valuable screening tool that can also be used in conjunction with other analyses to help determine the relative fire hazards of green building features in the built environment. An important outcome of using this technique is to raise questions concerning fire hazard potential at an early stage in the design process to identify ways to lessen the severity and resultant losses.[34]

5.3 Recommendations for Future Research

There are several areas which need additional research and development to facilitate use of the novel framework for fire hazard assessment of green building features. The weights proposed herein are based on literature evidence and expert knowledge of the author. Doubt and skepticism could arise in the FHI because it is based on a static model and one expert opinion.[51] A single authority recognized by the peer group as an expert, could be appropriate.[63] However, fire safety engineering may be too complex for the opinion of a single expert.[63] Therefore, several groups of experts from an appropriate panel,[63] such as Delphi surveys where biases can be balanced,[54] could estimate the values of the weights and grades. Several multi-disciplinary Delphi panels could divide the scope into smaller assessment groups, such as green building features by specialties, as the process can be unstable when there are more than 6 or 7 factors ranked.[30] The synergistic effects of these materials used as a system could adjust the FHI further, providing a greater degree of validity and confidence. The SFPE Handbook suggests both broad and deep expertise,[54] gathered in a consensus from industry professionals, including members of the fire service, insurance companies, general contractors, various industry specialists, architects, fire protection engineers, and code officials, providing insight into green practices and laying the foundation to formulate effective strategies for life safety and property preservation in the built environment.

Further consideration of the green facade cladding material should be undertaken. The fire test data of the combustible exterior wall materials from Nishio et al. was taken in isolation. While this is important to understand the individual performance of a material or product, these green building materials have a synergistic effect when combined into a system. Additional testing should be investigated to determine how the fire hazard variables are altered as these materials perform together as a system during a fire event; identical experimental facilities, test procedures and details of the facade systems would include combining the insulation and ACM cladding to correlate the results from the differences of Nishio's data in isolation. Heat release rates and total heat release data from isolation and system testing could also be used to enhance the methodology. Gas analysis could further define smoke impact of the effluents regarding potential toxicity, significant smoke production, smoke/heat venting and occupant evacuation hazards. The results could further characterize the fire hazard variables of the three green building facade features as a system on a structure.

Another recommendation would be an analysis of the effects from the LEED Optimized Energy Performance; it is the most important parameter for controlling a structure's energy use through optimization of thermal insulation and is therefore, potentially the major contributor for the impacts of fire hazards of facade green building materials and systems. As a result, the hazard analysis for the features of the Energy Optimized Performance credit category would benefit from a whole building energy simulation. This is a requirement by the LEED green building rating system for the point assignments and was not performed in this research. The percentage of improvement in the model project building energy performance rating compared to a baseline building energy performance rating is necessary to assess the higher insulation values needed to achieve the additional point values, ranging from 1-19 points, in the rating program. The baseline building energy performance would be calculated according to Appendix G of ANSI/ASHRAE/INESNA Standard 90.1-2007, using a computer simulation model for the whole building project. The energy analysis would include all the energy costs associated with the model project and is outlined further in EA Credit 1: Optimized Energy Performance section, on page 35 of the USGBC LEED 2009 New Construction and Major Renovation Handbook. Understanding how much additional combustible insulation is required per GBRP point on the model project could provide a more in-depth comparative analysis for the fire hazard impact of the higher insulation values on a project. An equivalency between the energy efficiency savings and insulation values could then provide a better weighting scheme for the fire hazard attributes of the higher insulation green feature.

Additional research is also needed to identify a methodology for collecting statistical data of green building features involved in fires. Currently, there is no system in place to categorize the green materials/products and systems after a fire event. The National Fire Incident Reporting System (NFIRS) collects data from a variety of sources to provide information and analysis on the status and scope of the fire problem in the U.S.[53] The data is used to highlight current and emerging trends in fires, including what causes fires, where they occur, and who is impacted the most by fire.[53] The lack of data from green building features involved in fires or as the cause of fires, could alter the perception of the current and emerging trends in fires.[53] Existing processes and document collection methods have knowledge gaps and would benefit from an industry study to highlight the data needed to help assess the hazards and risks of green building features in the built environment further.

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APPENDIX A: LEED 2009 Project Checklist [67]

LEED 2009 for New Construction and Major Renovations

Project Checklist

High-Rise CLT Tower- Charlotte

Y	?	N			
24			**Sustainable Sites**		Possible Points: 26
Y			Prereq 1	Construction Activity Pollution Prevention	
1			Credit 1	Site Selection	1
5			Credit 2	Development Density and Community Connectivity	5
1			Credit 3	Brownfield Redevelopment	1
6			Credit 4.1	Alternative Transportation—Public Transportation Access	6
1			Credit 4.2	Alternative Transportation—Bicycle Storage and Changing Rooms	1
3			Credit 4.3	Alternative Transportation—Low-Emitting and Fuel-Efficient Vehicles	3
2			Credit 4.4	Alternative Transportation—Parking Capacity	2
		x	Credit 5.1	Site Development—Protect or Restore Habitat	1
1			Credit 5.2	Site Development—Maximize Open Space	1
1			Credit 6.1	Stormwater Design—Quantity Control	1
1			Credit 6.2	Stormwater Design—Quality Control	1
1			Credit 7.1	Heat Island Effect—Non-roof	1
1			Credit 7.2	Heat Island Effect—Roof	1
		x	Credit 8	Light Pollution Reduction	1
4			**Water Efficiency**		Possible Points: 10
Y			Prereq 1	Water Use Reduction—20% Reduction	
2			Credit 1	Water Efficient Landscaping	2 to 4
		x	Credit 2	Innovative Wastewater Technologies	2
2			Credit 3	Water Use Reduction	2 to 4
9			**Energy and Atmosphere**		Possible Points: 35
Y			Prereq 1	Fundamental Commissioning of Building Energy Systems	
Y			Prereq 2	Minimum Energy Performance	
Y			Prereq 3	Fundamental Refrigerant Management	
3			Credit 1	Optimize Energy Performance	1 to 19
2			Credit 2	On-Site Renewable Energy	1 to 7
		x	Credit 3	Enhanced Commissioning	2
2			Credit 4	Enhanced Refrigerant Management	2
		x	Credit 5	Measurement and Verification	3
2			Credit 6	Green Power	2
9			**Materials and Resources**		Possible Points: 14
Y			Prereq 1	Storage and Collection of Recyclables	
		x	Credit 1.1	Building Reuse—Maintain Existing Walls, Floors, and Roof	1 to 3
		x	Credit 1.2	Building Reuse—Maintain 50% of Interior Non-Structural Elements	1
2			Credit 2	Construction Waste Management	1 to 2
1			Credit 3	Materials Reuse	1 to 2
			Materials and Resources, Continued		
2			Credit 4	Recycled Content	1 to 2
2			Credit 5	Regional Materials	1 to 2
1			Credit 6	Rapidly Renewable Materials	1
1			Credit 7	Certified Wood	1
12			**Indoor Environmental Quality**		Possible Points: 15
Y			Prereq 1	Minimum Indoor Air Quality Performance	
Y			Prereq 2	Environmental Tobacco Smoke (ETS) Control	
1			Credit 1	Outdoor Air Delivery Monitoring	1
		x	Credit 2	Increased Ventilation	1
1			Credit 3.1	Construction IAQ Management Plan—During Construction	1
1			Credit 3.2	Construction IAQ Management Plan—Before Occupancy	1
1			Credit 4.1	Low-Emitting Materials—Adhesives and Sealants	1
1			Credit 4.2	Low-Emitting Materials—Paints and Coatings	1
1			Credit 4.3	Low-Emitting Materials—Flooring Systems	1
		x	Credit 4.4	Low-Emitting Materials—Composite Wood and Agrifiber Products	1
		x	Credit 5	Indoor Chemical and Pollutant Source Control	1
1			Credit 6.1	Controllability of Systems—Lighting	1
1			Credit 6.2	Controllability of Systems—Thermal Comfort	1
1			Credit 7.1	Thermal Comfort—Design	1
1			Credit 7.2	Thermal Comfort—Verification	1
1			Credit 8.1	Daylight and Views—Daylight	1
1			Credit 8.2	Daylight and Views—Views	1
2			**Innovation and Design Process**		Possible Points: 6
1			Credit 1.1	Innovation in Design: Specific Title	1
		x	Credit 1.2	Innovation in Design: Specific Title	1
		x	Credit 1.3	Innovation in Design: Specific Title	1
		x	Credit 1.4	Innovation in Design: Specific Title	1
		x	Credit 1.5	Innovation in Design: Specific Title	1
1			Credit 2	LEED Accredited Professional	1
			Regional Priority Credits		Possible Points: 4
		x	Credit 1.1	Regional Priority: Specific Credit	1
		x	Credit 1.2	Regional Priority: Specific Credit	1
		x	Credit 1.3	Regional Priority: Specific Credit	1
		x	Credit 1.4	Regional Priority: Specific Credit	1
60			**Total**		Possible Points: 110

Certified 40 to 49 points Silver 50 to 59 points Gold 60 to 79 points Platinum 80 to 110

Figure A.1 Project Checklist for LEED 2009 Gold Certification

APPENDIX B: Indicative Cases of Recent High-Rise Fires [48]

Table B.1 Indicative Cases of Recent High-Rise Fires

Building	Location	Year	Type of façade system	Details
Ajman One residential cluster	Ajman, United Arab Emirates (UAE)	2016	Highly combustible plastic filled ACP	The fire erupted at a building in the Ajman One residential cluster of 12 towers and spread to at least one other tower, 1 injury, external fire spread [7]
Address Hotel	Dubai, UAE	2016	Highly combustible plastic filled ACP	Fire started on the 20th floor of the building and only affected the exterior of the structure, 16 injuries, external fire spread [8]
Docklands Apartment Tower	Melbourne, Australia	2015	ACP	Fire started from an unextinguished cigarette on the sixth-floor balcony, no deaths or injuries, external fire spread [9]
Marina Torch Tower	Dubai, UAE	2015	Highly combustible plastic filled ACP	Fire started in the middle of the tower before spreading downwards, no deaths or injuries, external fire spread [3]
Residential Building	Grosny, Russia	2013	Ventilated façade	Fire started from a short circuit in an air-condition, no deaths or injuries, external fire spread [10]
Polat Tower	Istanbul, Turkey	2012	Ventilated façade	Fire burned through the building's external insulation, no deaths or injuries, external fire spread [10]
Al Baker Tower 4	Sharjah, UAE	2012	Highly combustible plastic filled ACP	Fire started at by a lit cigarette thrown on a balcony, no deaths or injuries, external fire spread [11]
Mermoz Tower	Roubaix, France	2012	Ventilated façade	Fire initiated at the second floor and spread rapidly upwards, 1 fatality, 10 injuries, external fire spread [10]
Wanxin Complex Fire	Shenyang, China	2011	ACP	Fire caused from explosive fireworks, external fire spread [12]
Residential Building	Dijon, France	2010	ETICS (EPS insulation, mineral wool fire barriers)	Arson fire started at the basis of the building from waste containers, 7 fatalities [10]
Residential Building	Shanghai, China	2010	ETICS (under construction)	Fire during renovation for installing exterior wall insulations, 58 fatalities, 71 injuries, external fire spread [12]
Television Cultural Centre (CCTV)	Beijing, China	2009	Ventilated façade (polystyrene insulation)	Fire caused from highly explosive fireworks at construction site on the roof - fire spread, 1 fatality, 7 injuries, external fire spread [2]

APPENDIX C: LEED 2009 Project Requirements and Credits[67]

The LEED 2009 Minimum Program Requirements for the Model Project are:[21]

- Compliance with all applicable federal, state, and local building-related environmental laws and regulations
- A complete, permanent building designed for, constructed on, and operated on already existing land
- Use of a reasonable site boundary
- A minimum of 1,000-ft.^{2} (9-m^2) of gross floor area
- Serves 1 or more *Full Time Equivalent* (FTE) occupant(s)
- Sharing whole-building energy and water usage data
- Gross floor area must be no less than 2% of the gross land area within the LEED project boundary

The following are the sustainability design building features, systems and procedures, listed in terms of sustainability design aspects allocated to the Model Project. All credits denoted with an asterisk (*) present moderate to high fire hazards while considering the performance-based design for the Tower.

"Sustainable Sites

SS Prerequisite 1: Construction Activity Pollution Prevention [21]

Required

Intent: Create and implement an erosion and sedimentation control plan for all construction activities associated with the project

SS Credit 1: Site Selection (1 Point) [21]

To avoid the development of inappropriate sites and reduce the environmental impact from the location of a building on a site.

***SS Credit 2: Development Density and Community Connectivity (5 Points)** [21]

Intent: To channel development to urban areas with existing infrastructure, protect Greenfields, and preserve habitat and natural resources.

Requirements

OPTION 1. Development Density

Construct or renovate a building on a previously developed site AND in a community with a minimum density of

60,000 ft.^{2} per acre net. The density calculation is based on a typical two-story downtown development and includes the area of the project being built.

Potential Technologies & Strategies

During the site selection process, give preference to urban sites with pedestrian access to a variety of services.

SS Credit 3: Brownfield Redevelopment (1 Point) [21]

Intent: To rehabilitate damaged sites where development is complicated by environmental contamination and to reduce pressure on undeveloped land.

Requirements

OPTION 2

Develop on a site defined as a brownfield by a local, state, or federal government agency

SS Credit 4.1: Alternative Transportation: Public Transportation Access (6 Points) [21]

Intent: To reduce pollution and land development impacts from automobile use.

Requirements

OPTION 1. Rail Station Proximity

Locate the project within 1/2-mile walking distance (measured from a main building entrance) of an existing or planned and funded commuter rail, light rail or subway station.

SS Credit 4.2: Alternative Transportation—Bicycle Storage (1 Point) [21]

Intent: To reduce pollution and land development impacts from automobile use.

Requirements

CASE 2. Residential Projects: Provide covered storage facilities for securing bicycles for 15% or more of building occupants.

SS Credit 4.3: Alternative Transportation—Low-Emitting and Fuel-Efficient [21]

Vehicles (3 Points)

Intent: To reduce pollution and land development impacts from automobile use.

Requirements

OPTION 1

Provide preferred parking for low-emitting and fuel-efficient vehicles for 5% of the total vehicle parking capacity of the site. Providing a discounted parking rate is an acceptable substitute for preferred parking for low-emitting/ fuel-efficient vehicles. To establish a meaningful incentive in all potential markets, the parking rate must be discounted at least 20%. The discounted rate must be available to all customers (i.e., not limited to the number of customers equal to 5% of the vehicle parking capacity), publicly posted at the entrance of the parking area and available for a minimum of 2 years.

Potential Technologies & Strategies

Provide transportation amenities such as alternative-fuel refueling stations. The costs and benefits of refueling stations will be shared with neighbors

SS Credit 4.4: Alternative Transportation—Parking Capacity (2 Points) [21]

Intent: To reduce pollution and land development impacts from automobile use.

CASE 2. Residential Projects

OPTION 1

Size parking capacity to meet but not exceed minimum local zoning requirements

Provide infrastructure and support programs to facilitate shared vehicle use such as carpool drop-off areas, designated parking for vanpools, car-share services, ride boards and shuttle services to mass transit.

Potential Technologies & Strategies

The parking lot/garage size is minimum; adjacent buildings with parking facilities will be utilized. Consider alternatives that will limit the use of single occupancy vehicles.

***SS Credit 5.2: Site Development—Maximize Open Space (1 Point)** [21]

Intent: To promote biodiversity by providing a high ratio of open space to development footprint.

Requirements

CASE 3. Sites with Zoning Ordinances but No Open Space Requirements

<u>Provide vegetated open space equal to 20% of the project site area.</u>

<u>For projects in urban areas that earn SS Credit 2: Development Density and Community Connectivity, vegetated roof areas can contribute to credit compliance</u>.

Potential Technologies & Strategies

Strategies include stacking the building program, tuck-under parking and sharing parking facilities with neighbors to maximize the amount of open space on the site.

***SS Credit 6.1: Stormwater Design—Quantity Control (1 Point)** [21]

Intent: To limit disruption of natural hydrology by reducing impervious cover, increasing on-site infiltration, reducing or eliminating pollution from stormwater runoff and eliminating contaminants.

Requirements

CASE 2. Sites with Existing Imperviousness Greater Than 50%

Implement a stormwater management plan that results in a 25% decrease in the volume of stormwater runoff from the 2-year 24-hour design storm.

Potential Technologies & Strategies

Specify vegetated roofs (but not pervious ground surfaces as they cannot handle the weight of fire trucks) and other measures to minimize impervious surfaces. Reuse stormwater for non-potable uses such as landscape irrigation, toilet and urinal flushing, and custodial uses.

***SS Credit 6.2: Stormwater Design—Quality Control (1 Point)** [21]

Intent: To limit disruption and pollution of natural water flows by managing stormwater runoff.

Requirements

Implement a stormwater management plan that reduces impervious cover, promotes infiltration and captures and treats the stormwater runoff from 90% of the average annual rainfall1 using acceptable best management practices

(BMPs). Runoff must remove 80% of the average annual post development total suspended solids (TSS) load based on existing monitoring reports. BMPs are considered to meet these criteria if they are designed in accordance with standards and specifications from a state or local program that has adopted these performance standards.

Potential Technologies & Strategies

Use alternative surfaces (vegetated roofs and grid pavers) and nonstructural techniques (rain gardens and rainwater recycling) to reduce imperviousness and promote infiltration and thereby reduce pollutant loadings.

***SS Credit 7.1: Heat Island Effect—Non-roof (1 Point)** [21]

Intent: To reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impacts on microclimates and human and wildlife habitats.

Requirements

OPTION 2

Place a minimum of 50% of parking spaces under cover (parking underground, under deck, under roof, or under a building). <u>Any roof used to shade or cover parking must have an SRI of at least 29, be a vegetated green roof or be covered by solar panels that produce energy used to offset some nonrenewable resource use.</u>

Potential Technologies & Strategies

Employ strategies, materials and landscaping techniques that reduce the heat absorption of exterior materials. Use new coatings and integral colorants for asphalt to achieve light-colored surfaces instead of blacktop. Replace constructed surfaces (e.g., roof, roads, sidewalks, etc.) with vegetated surfaces such as vegetated roofs and open grid paving or specify high-albedo materials, such as concrete, to reduce heat absorption.

***SS Credit 7.2: Heat Island Effect—Roof (1 Point)** [21]

Intent: To reduce heat islands to minimize impacts on microclimates and human and wildlife habitats.

Requirements

OPTION 2

<u>Install a vegetated roof that covers at least 50% of the roof area.</u>

Water Efficiency

WE Prerequisite 1: Water Use Reduction

Required

Intent: To increase water efficiency within buildings to reduce the burden on municipal water supply and wastewater systems.

Requirements

Employ strategies that in aggregate use 20% less water based on estimated occupant usage and must include only the following fixtures and fixture fittings: water closets, urinals, lavatory faucets, showers, kitchen sink faucets.

Potential Technologies & Strategies

WaterSense-certified fixtures and fixture fittings should be used where available. Use high-efficiency fixtures (e.g., water closets and urinals) and dry fixtures, such as toilets attached to composting systems, to reduce potable water demand. Consider using alternative on-site sources of water (e.g., rainwater, stormwater, and air conditioner condensate) and graywater for non-potable applications such as custodial uses and toilet and urinal flushing.

WE Credit 1: Water Efficient Landscaping (2 Points) [21]

Intent: To limit the use of potable water or other natural surface or subsurface water resources available on or near the project site for landscape irrigation.

Requirements

OPTION 1. Reduce by 50% (2 points)

Reduce potable water consumption for irrigation by 50% from a calculated midsummer baseline case.

Reductions must be attributed to any combination of the following items:

- Plant species, density and microclimate factor
- Irrigation efficiency
- Use of captured rainwater
- Use of recycled wastewater

Potential Technologies & Strategies

Perform a soil/climate analysis to determine appropriate plant material and design the landscape with native or adapted plants to reduce or eliminate irrigation requirements. Where irrigation is required, use high-efficiency equipment and/or climate-based controllers.

WE Credit 3: Water Use Reduction (2 Points) [21]

Intent: To further increase water efficiency within buildings to reduce the burden on municipal water supply and wastewater systems.

Requirements

Employ strategies that in aggregate use 30% less water than the water use baseline calculated for the building (not including irrigation).

Energy and Atmosphere

EA Prerequisite 1: Fundamental Commissioning of Building Energy Systems

Required

Intent: To verify that the project's energy-related systems are installed and calibrated to perform according to the owner's project requirements, basis of design and construction documents.

***EA Prerequisite 2: Minimum Energy Performance** [21]

Required

Intent: To establish the minimum level of energy efficiency for the proposed building and systems to reduce environmental and economic impacts associated with excessive energy use.

OPTION 1. Whole Building Energy Simulation

Demonstrate a 10% improvement in the proposed building performance rating for new buildings compared with the baseline building performance rating. Calculate the baseline building performance rating according to the building performance rating method in Appendix G of ANSI/ASHRAE/IESNA Standard 90.1-2007 (with errata but without addenda1) using a computer simulation model for the whole building project. Appendix G of Standard 90.1-2007 requires that the energy analysis done for the building performance rating method include all energy costs associated with the building project.

To achieve points using this credit, the proposed design must meet the following criteria:

- Comply with the mandatory provisions (Sections 5.4, 6.4, 7.4, 8.4, 9.4 and 10.4) in Standard 90.1-2007 (with errata but without addenda).
- Include all energy costs associated with the building project.
- Compare against a baseline building that complies with Appendix G of Standard 90.1-2007 (with errata but without addenda1). The default process energy cost is 25% of the total energy cost for the baseline building. If the building's process energy cost is less than 25% of the baseline building energy cost, the LEED submittal must include documentation substantiating that process energy inputs are appropriate.

For this analysis, process energy is considered to include, but is not limited to, office and general miscellaneous equipment, computers, elevators and escalators, kitchen cooking and refrigeration, laundry washing and drying, lighting exempt from the lighting power allowance (e.g., lighting integral to medical equipment) and other (e.g., waterfall pumps).

Regulated (non-process) energy includes lighting (for the interior, parking garage, surface parking, facade, or building grounds, etc. except as noted above), heating, ventilation and air conditioning (HVAC) (for space heating, space cooling, fans, pumps, toilet exhaust, parking garage ventilation, kitchen hood exhaust, etc.), and service water heating for domestic or space heating purposes.

Process loads must be identical for both the baseline building performance rating and the proposed building performance rating. However, project teams may follow the exceptional calculation method (ANSI/ASHRAE/IESNA Standard 90.1-2007 G2.5) to document measures that reduce process loads. Documentation of process load energy savings must include a list of the assumptions made for both the base and the proposed design, and theoretical or empirical information supporting these assumptions.

EA Prerequisite 3: Fundamental Refrigerant Management [21]

Required

Intent: To reduce stratospheric ozone depletion.

Requirements

Zero use of chlorofluorocarbon (CFC)-based refrigerants in new base building heating, ventilating, air conditioning, and refrigeration (HVAC&R) systems.

***EA Credit 1: Optimize Energy Performance (3 Points)** [21]

Intent: To achieve increasing levels of energy performance beyond the prerequisite standard to reduce environmental and economic impacts associated with excessive energy use.

OPTION 1. Whole Building Energy Simulation

Demonstrate 16% improvement in the proposed building performance rating compared with the baseline building performance rating. Baseline building performance calculated according to Appendix G of ANSI/ASHRAE/IESNA Standard 90.1-2007 (with errata but without addenda1) using a computer simulation model for the whole building project. Appendix G of Standard 90.1-2007 requires that the energy analysis done for the building performance rating method include all the energy costs associated with the building project.

To achieve points under this credit, the proposed design must meet the following criteria:

- Compliance with the mandatory provisions (Sections 5.4, 6.4, 7.4, 8.4, 9.4 and 10.4) in Standard 90.1-2007 (with errata but without addenda).

- Inclusion of all the energy costs within and associated with the building project.
- Comparison against a baseline building that complies with Appendix G of Standard 90.1-2007 (with errata but without addenda). The default process energy cost is 25% of the total energy cost for the baseline building. If the building's process energy cost is less than 25% of the baseline building energy cost, the LEED submittal must include documentation substantiating that process energy inputs are appropriate.

For this analysis, process energy is considered to include, but is not limited to, office and general miscellaneous equipment, computers, elevators and escalators, kitchen cooking and refrigeration, laundry washing and drying, lighting exempt from the lighting power allowance (e.g., lighting integral to medical equipment) and other (e.g., waterfall pumps).

Regulated (non-process) energy includes lighting (e.g., for the interior, parking garage, surface parking, facade, or building grounds, etc. except as noted above), heating, ventilating, and air conditioning (HVAC) (e.g., for space heating, space cooling, fans, pumps, toilet exhaust, parking garage ventilation, kitchen hood exhaust, etc.), and service water heating for domestic or space heating purposes.

For this credit, process loads must be identical for both the baseline building performance rating and the proposed building performance rating. However, project teams may follow the exceptional calculation method ANSI/ASHRAE/IESNA Standard 90.1-2007 G2.5) to document measures that reduce process loads. Documentation of process load energy savings must include a list of the assumptions made for both the base and proposed design, and theoretical or empirical information supporting these assumptions.

Potential Technologies & Strategies

Design the building envelope and systems to maximize energy performance. Use a computer simulation model to assess the energy performance and identify the most cost-effective energy efficiency measures. Quantify energy performance compared with a baseline building. If local code has demonstrated quantitative and textual equivalence following, at a minimum, the U.S. Department of Energy (DOE) standard process for commercial energy code determination, the results of that analysis may be used to correlate local code performance with ANSI/ASHRAE/IESNA Standard 90.1-2007.

***EA Credit 2: On-Site Renewable Energy (2 Point)** [21]

Intent: To encourage and recognize increasing levels of on-site renewable energy self-supply to reduce environmental and economic impacts associated with fossil fuel energy use.

Requirements

Use on-site renewable energy systems to offset building energy costs. Calculate project performance by expressing the energy produced by the renewable solar power system as 3% of the building's annual energy cost. Use the building annual energy cost calculated in EA Credit 1: Optimize Energy Performance or the U.S. Department of Energy's Commercial Buildings Energy Consumption Survey database to determine the estimated electricity use.

Potential Technologies & Strategies

Assess the project for nonpolluting and renewable energy potential including solar, wind, geothermal, low-impact hydro, biomass, and bio-gas strategies.

EA Credit 4: Enhanced Refrigerant Management (2 Points) [21]

Intent: To reduce ozone depletion and support early compliance with the Montreal Protocol while minimizing direct contributions to climate change.

Requirements

OPTION 2

Select refrigerants and heating, ventilation, air conditioning and refrigeration (HVAC&R) equipment that minimize or eliminate the emission of compounds that contribute to ozone depletion and climate change. The base building HVAC&R equipment must comply with the following formula, which sets a maximum threshold for the combined contributions to ozone depletion and global warming potential.

Small HVAC units (defined as containing less than 0.5 pounds of refrigerant) and other equipment, such as standard refrigerators, small water coolers and any other cooling equipment that contains less than 0.5 pounds of refrigerant, are not considered part of the base building system and are not subject to the requirements of this credit. Do not operate or install fire suppression systems that contain ozone-depleting substances such as CFCs, hydrochlorofluorocarbons (HCFCs) or halons.

EA Credit 6: Green Power (2 Points) [21]

Intent: To encourage the development and use of grid-source, renewable energy technologies on a net zero pollution basis.

Requirements

Engage in at least a 2-year renewable energy contract to provide at least 35% of the building's electricity from renewable sources, as defined by the Center for Resource Solutions' Green-e Energy product certification requirements. All purchases of green power shall be based on the quantity of energy consumed, not the cost.

OPTION 1. Determine Baseline Electricity Use

Use the annual electricity consumption from the results of EA Credit 1: Optimize Energy Performance

Potential Technologies & Strategies

Determine the energy needs of the building and investigate opportunities to engage in a green power contract. Green power is derived from solar, wind, geothermal, biomass or low-impact hydro sources. Visit http://www.green-e.org/energy for details about the Green-e Energy program. The green power product purchased to comply with credit requirements need not be Green-e Energy certified. Other sources of green power are eligible if they satisfy the Green-e Energy program's technical requirements. Renewable energy certificates (RECs), tradable renewable certificates (TRCs), green tags and other forms of green power that comply with the technical requirements of the Green-e Energy program may be used to document compliance with this credit.

Materials and Resources

***MR Prerequisite 1: Storage and Collection of Recyclables** [21]

Required

Intent: To facilitate the reduction of waste generated by building occupants that is hauled to and disposed of in landfills.

Requirements

Provide an easily-accessible dedicated area or areas for the collection and storage of materials for recycling for the entire building. Materials must include, at a minimum: paper, corrugated cardboard, glass, plastics and metals.

***MR Credit 2: Construction Waste Management (2 Points)** [21]

Intent: To divert construction and demolition debris from disposal in landfills and incineration facilities. Redirect recyclable recovered resources back to the manufacturing process and reusable materials to appropriate sites.

Requirements

Recycle and/or salvage nonhazardous construction and demolition debris. Develop and implement a construction waste management plan that, at a minimum, identifies the materials to be diverted from disposal and whether the materials will be sorted on-site or comingled. Excavated soil and land-clearing debris do not contribute to this credit. The minimum percentage debris to be recycled or salvaged is 75%.

Potential Technologies & Strategies

Diversion from disposal in landfills and incineration facilities; adopt a construction waste management plan. Recycle all cardboard, metal, brick, mineral fiber panel, concrete, plastic, clean wood, glass, gypsum wallboard, carpet and insulation. Construction debris processed into a recycled content commodity that has an open market value (e.g., wood derived fuel [WDF], alternative daily cover material, etc.) may be applied to the construction waste calculation. Designated area on the construction site is provided for segregated or comingled collection of recyclable materials but must be considered as a fire hazard during the construction phase.

MR Credit 3: Materials Reuse (1 Point) [21]

Intent: To reuse building materials and products to reduce demand for virgin materials and reduce waste, thereby lessening impacts associated with the extraction and processing of virgin resources.

Requirements

Use salvaged, refurbished or reused materials, the sum of which constitutes at least 5%, based on cost, of the total value of materials on the project. Mechanical, electrical and plumbing components and specialty items such as elevators and equipment cannot be included in this calculation. Only materials permanently installed in the project are used. Furniture is included as it is included consistently in MR Credit 3: Materials Reuse through MR Credit 7: Certified Wood.

Potential Technologies & Strategies

Consider salvaged materials such as doors and frames, cabinetry and furniture, and decorative items.

MR Credit 4: Recycled Content (2 Points) [21]

Intent: To increase demand for building products that incorporate recycled content materials, thereby reducing impacts resulting from extraction and processing of virgin materials.

Requirements

Use materials with recycled content such that the sum of postconsumer recycled content plus 1/2 of the Pre-consumer content constitutes at least 20%, based on cost, of the total value of the materials in the project. Mechanical, electrical and plumbing components and specialty items such as elevators cannot be included in this calculation, only materials permanently installed in the project can be used. Furniture is included as it is included consistently in MR Credit 3: Materials Reuse through MR Credit 7: Certified Wood.

MR Credit 5: Regional Materials (2 Points) [21]

Intent: To increase demand for building materials and products that are extracted and manufactured within the region, thereby supporting the use of indigenous resources and reducing the environmental impacts resulting from transportation.

Requirements

Use building materials or products that have been extracted, harvested or recovered, as well as manufactured, within 500 miles of the project site for a minimum of 20%, based on cost, of the total materials value. Mechanical, electrical and plumbing components and specialty items such as elevators and equipment are not included in this calculation, only materials permanently installed in the project are used. Furniture is included as it is included consistently in MR Credit 3: Materials Reuse through MR Credit 7: Certified Wood.

MR Credit 6: Rapidly Renewable Materials (1 Point) [21]

Intent: To reduce the use and depletion of finite raw materials and long-cycle renewable materials by replacing them with rapidly renewable materials.

Requirements

Use rapidly renewable building materials and products for 2.5% of the total value of all building materials and products used in the project, based on cost. Rapidly renewable building materials and products are made from plants that are typically harvested within a 10-year or shorter cycle.

MR Credit 7: Certified Wood (1 Point) [21]

Intent: To encourage environmentally responsible forest management.

Requirements

Use a minimum of 50% (based on cost) of wood-based materials and products that are certified in accordance with the Forest Stewardship Council’s principles and criteria, for wood building components. These components include at a minimum, structural framing and general dimensional framing, flooring, sub-flooring, wood doors and finishes.

Include only materials permanently installed in the project. Wood products purchased for temporary use on the project (e.g., formwork, bracing, scaffolding, sidewalk protection, and guard rails) may be included in the calculation. If any such materials are included, all such materials must be included in the calculation.

Potential Technologies & Strategies

Establish a project goal for FSC-certified wood products and identify suppliers that can achieve this goal.

Indoor Environmental Quality

***IEQ Prerequisite 1: Minimum Indoor Air Quality Performance** [21]

Required

Intent: To establish minimum indoor air quality (IAQ) performance to enhance indoor air quality in buildings, thus contributing to the comfort and well-being of the occupants.

Requirements

Meet the minimum requirements of Sections 4 through 7 of ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality AND:

CASE 1. Mechanically Ventilated Spaces

Mechanical ventilation systems must be designed using the ventilation rate procedure or the applicable local code, whichever is more stringent.

***IEQ Prerequisite 2: Environmental Tobacco Smoke (ETS) Control** [21]

Required

Intent: To prevent or minimize exposure of building occupants, indoor surfaces and ventilation air distribution systems to environmental tobacco smoke (ETS).

Requirements

CASE 1. All Projects

OPTION 1

Prohibit smoking in the building.

Prohibit on-property smoking within 25-ft. of entries, outdoor air intakes and operable windows. Provide signage to prohibit smoking on the entire property.

IEQ Credit 1: Outdoor Air Delivery Monitoring (1 Point) [21]

Intent: To provide capacity for ventilation system monitoring to help promote occupant comfort and well-being.

Requirements

Install permanent monitoring systems to ensure that ventilation systems maintain design minimum requirements.

Configure all monitoring equipment to generate an alarm when airflow values or carbon dioxide (CO_2) levels vary by 10% or more from the design values via either a building automation system alarm to the building operator or a visual or audible alert to the building occupants AND:

CASE 1. Mechanically Ventilated Spaces

Monitor CO2 concentrations within all densely occupied spaces (those with a design occupant density of 25 people or more per 1,000-ft.^{2}). CO2 monitors must be between 3 and 6-ft. above the floor.

Provide a direct outdoor airflow measurement device capable of measuring the minimum outdoor air intake flow with an accuracy of plus or minus 15% of the design minimum outdoor air rate, as defined by ASHRAE Standard 62.1-2007 for mechanical ventilation systems where 20% or more of the design supply airflow serves non-densely occupied spaces.

IEQ Credit 4.1: Low-Emitting Materials—Adhesives and Sealants (1 Point) [21]

Intent: To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.

Requirements

All adhesives and sealants used on the interior of the building (i.e., inside of the weatherproofing system and applied on-site) must comply.

IEQ Credit 4.2: Low-Emitting Materials—Paints and Coatings (1 Point) [21]

Intent: To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.

Requirements

Paints and coatings used on the interior of the building (i.e., inside of the weatherproofing system and applied onsite) must comply.

IEQ Credit 4.3: Low-Emitting Materials—Flooring Systems (1 Point) [21]

Intent: To reduce the quantity of indoor air contaminants that are odorous, irritating and/or harmful to the comfort and well-being of installers and occupants.

OPTION 2

All flooring elements installed in the building interior must meet the testing and product requirements of the

California Department of Health Services Standard Practice for the Testing of Volatile Organic Emissions from

Various Sources Using Small-Scale Environmental Chambers, including 2004 Addenda.

IEQ Credit 6.1: Controllability of Systems—Lighting (1 Point) [21]

Intent: To provide a high level of lighting system control by individual occupants or groups in multi-occupant spaces (e.g., classrooms and conference areas) and promote their productivity, comfort and well-being.

Requirements

Provide individual lighting controls for 90% (minimum) of the building occupants to enable adjustments to suit individual task needs and preferences. Provide lighting system controls for all shared multi-occupant spaces to enable adjustments that meet group needs and preferences.

Potential Technologies & Strategies

Design the building with occupant controls for lighting. Strategies to consider include lighting controls and task lighting. Integrate lighting systems controllability into the overall lighting design, providing ambient and task lighting while managing the overall energy use of the building.

IEQ Credit 6.2: Controllability of Systems—Thermal Comfort (1 Point) [21]

Intent: To provide a high level of thermal comfort system control by individual occupants or groups in multi-occupant spaces (e.g., classrooms or conference areas) and promote their productivity, comfort and well-being.

Requirements

Provide individual comfort controls for 50% (minimum) of the building occupants to enable adjustments to meet individual needs and preferences. Operable windows may be used in lieu of controls for occupants located 20-ft. inside and 10-ft. to either side of the operable part of a window. The areas of operable window must meet the requirements of ASHRAE Standard 62.1-2007 paragraph 5.1 Natural Ventilation (with errata but without addenda2). Provide comfort system controls for all shared multi-occupant spaces to enable adjustments that meet group needs and preferences. Conditions for thermal comfort are described in ASHRAE Standard 55-2004 (with errata but without addenda2) and include the primary factors of air temperature, radiant temperature, air speed and humidity.

Potential Technologies & Strategies

Design the building and systems with comfort controls to allow adjustments to suit individual needs. Individual adjustments may involve individual thermostat controls, local diffusers at floor, desk or overhead levels, control of individual radiant panels or other means integrated into the overall building, thermal comfort systems and energy systems design. Designers should evaluate the closely tied interactions between thermal comfort and acceptable indoor air quality.

IEQ Credit 7.1: Thermal Comfort—Design (1 Point) [21]

Intent: To provide a comfortable thermal environment that promotes occupant productivity and well-being.

Requirements

Design heating, ventilating and air conditioning (HVAC) systems and the building envelope to meet the requirements of ASHRAE Standard 55-2004, Thermal Comfort Conditions for Human Occupancy.

Potential Technologies & Strategies

Design the building envelope and systems with the capability to meet the comfort criteria under expected environmental and use conditions. Evaluate air temperature, radiant temperature, air speed and relative humidity in an integrated fashion, and coordinate these criteria with IEQ Prerequisite 1: Minimum IAQ Performance, IEQ Credit 1: Outdoor Air Delivery Monitoring, and IEQ Credit 2: Increased Ventilation.

IEQ Credit 7.2: Thermal Comfort—Verification (1 point AND IEQ credit 7.1) [21]

Intent: To provide for the assessment of building occupant thermal comfort over time.

Requirements

Achieve IEQ Credit 7.1: Thermal Comfort—Design. Provide a permanent monitoring system to ensure that building performance meets the desired comfort criteria as determined by IEQ Credit 7.1: Thermal Comfort—Design.

***IEQ Credit 8.1: Daylight and Views—Daylight (1 Point)** [21]

Intent: To provide building occupants with a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building.

OPTION 2. Prescriptive

Use side-lighting to achieve a total daylighting zone (the floor area meeting the following requirements) that is at least 75% of all the regularly occupied spaces.

- Achieve a value, calculated as the product of the visible light transmittance (VLT) and window-to-floor area ratio (WFR) of daylight zone between 0.150 and 0.180. The window area included in the calculation must be at least 30 inches above the floor.
- The ceiling must not obstruct a line in section that joins the window-head to a line on the floor that is parallel to the plane of the window; is twice the

height of the window-head above the floor in, distance from the plane of the glass as measured perpendicular to the plane of the glass.

- Provide sunlight redirection and/or glare control devices to ensure daylight effectiveness.

Potential Technologies & Strategies

Design the building to maximize interior daylighting. Strategies to consider include building orientation, shallow floor plates, increased building perimeter, exterior and interior permanent shading devices, high-performance glazing, high-ceiling reflectance values; automatic photocell-based controls can help to reduce energy use.

***IEQ Credit 8.2: Daylight and Views—Views (1 Point)** [21]

Intent: To provide building occupants a connection to the outdoors through the introduction of daylight and views into the regularly occupied areas of the building.

Requirements

Achieve a direct line of sight to the outdoor environment via vision glazing between 30 inches and 90 inches above the finish floor for building occupants in 90% of all regularly occupied areas. Determine the area with a direct line of sight by totaling the regularly occupied square footage that meets the following criteria:

- In plan view, the area is within sight lines drawn from perimeter vision glazing.
- In section view, a direct sight line can be drawn from the area to perimeter vision glazing.

The line of sight may be drawn through interior glazing. For private offices, the entire square footage of the office may be counted if 75% or more of the area has a direct line of sight to perimeter vision glazing. For multi-occupant spaces, the actual square footage with a direct line of sight to perimeter vision glazing is counted.

Potential Technologies & Strategies

Design the space to maximize daylighting and view opportunities. Strategies to consider include lower partitions, interior shading devices, interior glazing and automatic photocell-based controls.

Innovative Design

ID Credit 1: Innovation in Design (1 Point) [21]

Intent: To provide design teams and projects the opportunity to achieve exceptional performance above the requirements set by the LEED Green Building Rating System and/or innovative performance in Green Building categories not specifically addressed by the LEED Green Building Rating System.

Requirements

PATH 1. Innovation in Design (1 point)

Achieve significant, measurable environmental performance using a strategy not addressed in the LEED 2009 for

New Construction and Major Renovations Rating System.

ID Credit 2: LEED Accredited Professional (1 Point) [21]

Intent: To support and encourage the design integration required by LEED to streamline the application and certification process.

Requirements

At least 1 principal participant of the project team shall be a LEED Accredited Professional (AP)."[21]

APPENDIX D: LEED 2009 Categories and Credits Effecting the Fire Hazard[67]

The following are the sustainability design building features, systems and procedures, listed in terms of sustainability design aspects with potential fire hazards to the Model Project.

D.1: Sustainable Site Development

Credit 2 Development Density

Credit 4.3 Alternative Transportation-Low-Emitting and Fuel-Efficient Vehicles

Credit 5.2 Site Development – Maximum Open Space

Credit 6.1 Stormwater Design – Quality Control

Credit 6.2 Stormwater Design – Quality Control

Credit 7.1 Heat Island Effect – Non-Roof

Credit 7.2 Heat Island Effect – Roof

D.2 Water Savings

Credit 1 Water Efficient Landscaping

Credit 3 Water Use Reduction

D.3 Energy Efficiency

Prereq. 2 Minimum Energy Performance

Prereq. 3 Fundamental Refrigerant Management

Credit 1 Optimize Energy Performance

Credit 2 On-Sire Renewable Energy

Credit 4 Enhanced Refrigerant Management

D.4 Material and Resources

Prereq. 1 Storage and Collection of Recyclables

Credit 2 Construction Waste Management

Credit 6 Rapidly Renewable Materials

D.5 Indoor Environmental Quality

Credit 8.1 Daylight and Views – Daylight

Credit 8.2 Daylight and Views - Views

The following green building elements are featured on the model project, with potential fire and life safety concerns:

I. Sustainable Site Concerns

- Increased building density: separation distance – 2 meters from adjacent property lines
- Electric vehicle charging station
- Battery storage system
- Open Space – vegetative roof system
- Stormwater design – promote infiltration through vegetative roof system; reuse stormwater
- Heat Island Effect – vegetative roof system; solar panels to offset non-renewable energy source

6 Water Savings Concerns

- Water efficient landscaping – use of captured rainwater and recycled wastewater
- Reduced water supply

7 Energy Efficiency Concerns

- Optimize energy performance - includes several architectural features:
  - Continuous exterior rigid foam insulation
  - High performance glazing
  - Area of combustible facade material
  - Higher insulation values
  - Vestibules
  - Solar shading from perimeter balconies
- Fundamental refrigerate management – use suppression system that does not contain HCFC's or halons
- Onsite renewable energy – PV solar power energy roof panels

8 Materials and Resources Concerns

- Storage and collection of recyclables – trash/recycle chutes on each floor connected to a central basement location
- Construction waste management – Fire and life safety during building construction (This is outside the scope of the thesis work)
- Rapidly renewable materials - engineered structural wood elements and connections (CLT)
- Exposed CLT interior wall feature

9 Indoor Environmental Quality Concerns

- Daylight and Views – includes several architectural features:
  - Low-emissivity and reflective coating
  - Open floor plans (horizontal open compartment)
  - Large areas of glazing on exterior walls; see Appendix E for Daylight requirements

- Glass interior walls; see Appendix E for Views requirements

APPENDIX E: LEED 2009 Project Daylight and Views Calculation Summary [67]

Summary for New Construction, Core and Shell, Retail: New Construction, Commercial Interiors, and Retail: Commercial Interiors

Note: All information on this tab is READ-ONLY. To edit, see the previous tabs.

IEQ Credit 8.1: Daylight and Views - Daylight

Option 1. Simulation

Total simulation daylighted area (sq ft)	0.00

Option 2. Prescriptive

Total prescriptive daylighted area (sq ft)	13,470.00

Option 3. Measurement

Total measurement daylighted area (sq ft)	0.00

Total daylighted area (sq ft)	13,470.00
Total regularly occupied area (sq ft)	13,470.00
Percentage of regularly occupied area that is daylighted (%)	**100.00%**

IEQc8.2: Daylight and Views - Views

Total regularly occupied area with access to views (sq ft)	12,130.00
Total regularly occupied area (sq ft)	13,470.00
Percentage of regularly occupied area with access to views (%)	**90.05%**

For projects attempting exemplary performance

	Measure 1	Measure 2	Measure 3	Measure 4
Total regularly occupied area with access to views (sq ft)	0.00	0.00	0.00	0.00
Percentage of regularly occupied area with access to exemplary performance views (%)	**0.00%**	**0.00%**	**0.00%**	**0.00%**

APPENDIX F: Project Building Characteristics [67]

F.1 Architectural Features

a. Area and geometry of the compartments
    i. Building is 40 m × 40 m
        1. 51,200 m^2 total building area, including central core, residential units, amenity floor areas/Refuge Areas, retail area, and carparks,
    ii. 27 Residential floors with 1,251 m^2 living area each
    iii. Each residential floor has 10 open-plan condominium apartment units
    iv. 3 building amenity floors include the closed-plan Area of Refuge and the open-plan fitness areas/other amenities
    v. Closed-plan retail areas are located along the perimeter of the Ground floor
    vi. Two carpark levels have an open-plan design
b. Floor-to-ceiling height: 3m
c. Ceiling configuration: Exposed CLT, flat
d. Interior finish flammability
    i. Ceilings:
        1. Exposed CLT with a 2-hr fire rating
        2. Lightweight concrete at the three amenity floors
    ii. Interior walls:
        1. Exposed CLT: Bedrooms and Living Rooms
        2. Unexposed CLT (encapsulated with gypsum for a 3-hr fire rating): Kitchens
    iii. Floors:
        1. CLT covered with 55mm lightweight concrete
        2. Lightweight concrete at the three amenity floors
e. Construction materials
    i. Carpark construction: Precast concrete
    ii. Columns and beams: Glulam
    iii. Floors/Ceilings: CLT
    iv. Interior walls: encapsulated CLT
    v. Central core: reinforced concrete shear walls
    vi. Exterior walls:
        1. Separation distance: 2m to adjacent properties
        2. Window walls with spectrally selective coated glazing
            a. Window wall facade does not carry any structural load from the building, other than its own dead weight (non-load bearing)

b. Generally designed with extruded aluminum framing members typically infilled with glass, providing excellent daylighting, with spandrel infill panels at the floor levels to conceal the framing connections

3. Exterior wall assembly infill area includes:
   a. Aluminum composite material (ACM) panel system
      i. PE core
   b. Foam Insulation
      i. Extruded polyurethane (XPS)
      ii. R-13.0 + Ci R-3.8 minimum requirement
   c. Wall assembly non-compliant with:
      i. NFPA 285
      ii. ASTM E84 FS > 25, SD > 450

f. Properties of walls, partitions, floors, and ceilings
   i. 1-hr. fire-resistance rated smoke barrier elevator lobby

g. Position, size, and quantity of door/window openings
   i. Vestibule entrance area at Ground Floor:
      1. Floor-to-ceiling glass doors and windows × 10m long
   ii. Ancillary ground floor exits
      1. Floor-to-ceiling glass doors and windows × 1m long
   iii. Remaining Ground Floor perimeter:
      1. Floor-to-ceiling glass windows
   iv. Residential Floor Units:
      1. Unit 1 and Unit 10 window area, 762 mm (2'-6") above floor × 1,828 mm (6'-0") high
         a. $39m^2$ each unit per floor
         b. 52 total units required
      2. Unit 2 and Unit 9 window area
         a. $26m^2$ each unit per floor
         b. 52 total units required
      3. Unit 3 and Unit 8 window area
         a. $46m^2$ each unit per floor
         b. 52 total units required
      4. Unit 4, Unit 5, Unit 6, and Unit 7 window area
         a. $27m^2$ each unit per floor
         b. 104 total units required
   v. Building Amenity Floors
      1. Area of Refuge
         a. No window areas
      2. Amenity Floor Areas
         a. Floor-to-ceiling glass windows along perimeter of building
   vi. Carpark levels

1. L1 level
    a. No exterior windows or doors
2. L2 level
    a. No exterior windows
    b. One each floor-to-ceiling entrance and exit openings

h. Configuration and location of hidden voids
    i. Balloon framing eliminates hidden voids in structural connections
    ii. Trash/recycle chutes connected to the basement for disposal are designed on each level

i. 93m tall mixed-use building
    i. Number of stories above grade: 30
        1. Includes access to Open Space Roof Area
    ii. Number of stories below grade: 2

j. Location of the building on the site relative to property lines: 2m each side

k. Interconnections between compartments:
    i. Each residential unit is separated by a 3-hr rated demising wall
    ii. Residential units are separated from the corridor areas by a 3-hr rated demising wall
    iii. Retail areas on the ground floor are separated by a 3-hr fire rated demising wall
    iv. The Area of Refuge is separated from the corridor area on the Building Amenity floors by a 3-hr fire rated demising wall

l. Relationship of hazards to vulnerable points

F.2 Structural Components

a. Location, size, and construction material of load-bearing elements:
    i. Precast concrete carpark structure
    ii. Columns and beams: Glulam
        1. Column sizes:
            a. 3rd floor – 12th floor: 610 mm × 610 mm (24” × 24”)
            b. 13th floor - 22nd floor: 356 mm × 457 mm (14” x× 18”)
            c. 23rd floor – 32nd floor: 241 mm × 305 mm (9.5” × 12”)
    iii. Floors and ceilings:
        1. CLT - Not exposed
            a. 3rd floor – 12th floor (except 9th floor): 254 mm (10”) thick
            b. 13th floor - 22nd floor (except 17th floor): 203 mm (8”) thick
            c. 23rd floor – 32nd floor (except 25th floor): 140 mm (5.5”) thick
    iv. Floor and ceilings:
        1. Concrete – exposed

a. 9th, 17th, 25th floors: 152.5 mm (6") thick

v. Roof Panels: CLT

1. Not exposed CLT

a. 5 plies: 2.5m × 10m × 95mm thick

vi. Central core: reinforced concrete shear walls

1. 3rd floor – 12th floor: 508 mm (20") thick
2. 13th floor - 22nd floor: 406 (16") thick
3. 23rd floor – 32nd floor: 305 (12") thick

F.3 Fire Load

a. Retail Area
   i. Furnishings
   ii. Office supplies
   iii. Displays
   iv. Wall linings
   v. Carpeting
b. Residential Area
   i. Wall linings
   ii. Furnishings
   iii. Cooking equipment
   iv. Laundry – dryer lint
   v. Carpeting
c. Amenity Floor Area
   i. Equipment (floor mats, treadmill tracks)
   ii. Paper towels, etc.

F.4 Egress Components

a. The main entrance to the building is located on the Ground floor
b. Ground floor is assigned as the exit discharge level
c. Retail areas have direct access to the outside
d. Evacuation strategy is based on self-evacuation using 4 elevators
e. One service elevator to be used by firefighters during an emergency
f. One exit stairwell, connecting all levels, to discharge on the Ground level

F.5 Fire Protection Systems

a. Communication systems
   i. Emergency voice/alarm communication system in elevator groups, exit stairway, each floor, and areas of refuge
   ii. Elevators and areas of refuge are equipped with two-way communication systems
b. Alarm system:
   i. Manual fire alarm boxes at entrance to each exit, red in color
c. Detection systems

        i. Smoke detectors in mechanical/electrical rooms, elevator lobbies, main exhaust and return of air ventilation, and each connection to a vertical duct

d. Notification systems
    i. Visible
        1. Strobes in public and common areas, e.g. floors 1, 9, 17, and 25
    ii. Audible
        2. Horns in every occupied space within the building
e. Smoke control:
    i. HVAC systems designed separately for each floor to minimize smoke migration
    ii. Pressurized stairwell to prevent the stack effect
f. Suppression systems
    i. Automatic sprinkler system
        1. All patios with CLT ceilings are protected by a sprinkler system installed through concealed, internal raceways
    ii. Portable fire extinguishers placed throughout the floor corridors and in each unit
g. Gas supply shut-off
h. Emergency lighting

F.6 Building Services and Processes

a. Location, capacity, and characteristics of ventilation equipment
    i. Mechanical ventilation
        1. Zoned and Located on 9th and 24th Floor levels
        2. Continually operating
    ii. Summer/ Winter differences
        3. Summer Cooling: 22°C (72°F) with 45% humidity
        4. Winter Heating: 20°C (68°F) with 35% humidity

F.7 Operational Characteristics

a. Expected occupancy times
    i. Retail Areas
        1. Sundays: 1:00 p.m. – 6:00 p.m.
        2. Mondays: Closed
        3. Tuesdays – Thursdays: 10:00 a.m. – 6:00 p.m.
        4. Fridays – Saturdays: 10:00 a.m. – 8:00 p.m.
    ii. Residential Units
        1. Permanent Occupants
            a. Sundays: 7:00 p.m. – 9:00 a.m.
            b. Mondays - Fridays: 6:00 p.m. – 7:00 a.m.
            c. Saturdays: 1:00 a.m. – 11:00 a.m., and 3:00 p.m. – 8:00 p.m.

2. Transient Occupants
    a. Sundays: 7:00 p.m. – 1:30 p.m.
    b. Mondays - Fridays: 9:00 p.m. – 7:00 a.m.
    c. Saturdays: 1:00 a.m. – 11:00 a.m., and 3:00 p.m. – 8:00 p.m.

iii. Amenity Areas
1. Sundays: 11:00 a.m. – 6:00 p.m.
2. Mondays – Fridays: 5:00 a.m. – 10:00 p.m.
3. Saturdays: 7:00 a.m. – 7:00 p.m.

F.8 Fire Department Response Characteristics

a. Response time of fire fighters
    i. Charlotte Fire Station 04 is located 2 blocks away
    ii. Fire Response Area includes 2.77 km^2 (685 acres) with a perimeter of 15,232 m (49,973')
b. Accessibility for fire appliances
    i. Emergency vehicles:
        1. Clear access on West and South building elevations respectively
    ii. Fire hydrate is located directly in front on North College Street
        1. Connected to pubic water main
        2. 227.125 -238.26 m^2 (1000-1049 GPM) available flow
        3. 3.45-8.27 bar (50-120 psi) hydrant pressure
    iii. Vestibule area provided at entrance for easier fire hose access to the building
c. Fire fighter access within the building
    i. Vestibule area provided at entrance rather than revolving door
d. Equipment
    i. Fire Department Connection (FDC) located on the South elevation of building
    ii. Standpipe located in the stairwell with access at each floor level

F.9 Environmental Factors

a. Tower located in Charlotte, North Carolina, USA
    i. Climate Zone 3: ASHRAE 90.1 [24] Prescriptive Requirements, see Table F.0 below.
b. Elevation 221m (725') above sea level with a humid, sub-tropic climate
    i. Exterior Ambient temperature and humidity ranges
        1. Average low temperature: 9.5°C (49°F)
            a. Annual Heating Degree Days (HDD): 3341
                i. A climate change indicator: A measurement designed to quantify the demand for energy needed to heat a building. It is the number of degrees that a day's average temperature is

below 65°F, which is generally the temperature below which buildings need to be heated.

Table F.0 Building Envelope Requirements for Climate Zone 3 (A, B, C)*

Opaque Elements	***Nonresidential*** Assembly Maximum	Insulation Min. *R-Value*	***Residential*** Assembly Maximum	Insulation Min. *R-Value*	**Semiheated** Assembly Maximum	Insulation Min. *R-Value*
Roofs						
Insulation entirely above deck	U-0.039	R-25 c.i.	U-0.039	R-25 c.i.	U-0.119	R-7.6 c.i.
Metal building[a]	U-0.041	R-10 + R-19 FC	U-0.041	R-10 + R-19 FC	U-0.096	R-16
Attic and other	U-0.027	R-38	U-0.027	R-38	U-0.053	R-19
Walls, above Grade						
Mass	U-0.123	R-7.6 c.i.	U-0.104	R-9.5 c.i.	U-0.580	NR
Metal building	U-0.094	R-0 + R-9.8 c.i.	U-0.072	R-0 + R-13 c.i.	U-0.162	R-13
Steel-framed	U-0.077	R-13 + R-5 c.i.	U-0.064	R-13 + R-7.5 c.i.	U-0.124	R-13
Wood-framed and other	U-0.089	R-13	U-0.064	R-13 + R-3.8 c.i. or R-20	U-0.089	R-13
Wall, below Grade						
Below-grade wall	C-1.140	NR	C-1.140	NR	C-1.140	NR
Floors						
Mass	U-0.074	R-10 c.i.	U-0.074	R-10 c.i.	U-0.137	R-4.2 c.i.
Steel joist	U-0.038	R-30	U-0.038	R-30	U-0.052	R-19
Wood-framed and other	U-0.033	R-30	U-0.033	R-30	U-0.051	R-19
Slab-on-Grade Floors						
Unheated	F-0.730	NR	F-0.540	R-10 for 24 in.	F-0.730	NR
Heated	F-0.860	R-15 for 24 in.	F-0.860	R-15 for 24 in.	F-1.020	R-7.5 for 12 in.
Opaque Doors						
Swinging	U-0.370		U-0.370		U-0.370	
Nonswinging	U-0.310		U-0.310		U-0.360	

Fenestration	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*	Assembly Max. U	Assembly Max. *SHGC*	Assembly Min. *VT/SHGC*
Vertical Fenestration, 0% to 40% of Wall		(for all frame types)			(for all frame types)			(for all frame types)	
Nonmetal framing, all	0.33	0.25	1.10	0.35	0.25	1.10	0.87	NR	NR
Metal framing, fixed	0.45			0.49			1.20		
Metal framing, operable	0.60			0.60			1.20		
Metal framing, entrance door	0.77			0.68			0.77		
Skylight, 0% to 3% of Roof									
All types	0.55	0.35	NR	0.55	0.35	NR	1.70	NR	NR

* The following definitions apply: c.i. = *continuous insulation* (see Section 3.2), FC = filled cavity (see Section A2.3.2.5), NR = no (insulation) requirement.
a. When using the *R-value* compliance method for *metal building roofs*, a thermal spacer block is required (see Section A2.3.2).

2. Average high temperature: 22°C (71°F)
    a. Annual Cooling Degree Days (CDD): 1582
        i. A climate change indicator: A measurement designed to quantify the demand for energy needed to cool a building. It is the number of degrees that a day's average temperature is above 65°F, which is generally the temperature above which buildings need to be cooled.
3. Charlotte average relative humidity: 69%
4. Charlotte average clear days per year: 109
5. Charlotte average partly-cloudy days per year: 105
6. Charlotte average cloudy days per year: 151
7. Average annual precipitation: 1,056.6 mm (41.6")

ii. Interior ambient temperature and humidity ranges
1. Summer: 22°C (72°F) with 45% humidity
2. Winter: 20°C (68°F) with 35% humidity

iii. Ambient Sound levels
1. Normal: Emergency announcements should be audible within the building

iv. Expected wind conditions:
2. Average hourly wind speed in Charlotte experiences mild seasonal variation over the course of the year
    a. Windier time of year: November-May
        i. Average wind speed of 9.65 km/hr. (6mph)
        ii. Highest wind speed: 11.59 km/hr. (7.2 mph)
        iii. Wind direction:
            1. November-December wind from the north
            2. December-February wind is from the west
            3. February to March wind from the north
            4. March-May wind from the south
    b. Calmer time of year: May-November
        iv. Calmest wind speed: 7.4 km/hr. (4.6 mph)
        v. Wind direction:
            1. May to August wind from the West
            2. August-November wind is from the north

APPENDIX G: Impact Levels for Performance Group III [62]

Magnitude of Design Event (*Increasing*)		Level of Impact	*Performance Group III* Impact Details	Impact/ Hazard Type
	Very Large (Very Rare)	High	▪ Significant, yet no large falling debris ▪ Repair is possible	Structural Damage
			▪ Significant damage, inoperable ▪ Light debris in egress routes	Non-Structural Systems
			▪ Locally significant with high risk to life, yet generally moderate in numbers and in nature ▪ Moderate likelihood of single life loss vs. low probability of multiple life loss ▪ Higher expected level of injuries in fire hazards in localized areas	Occupant Hazards
			▪ Locally total and generally significant ▪ Higher expected level of injuries in fire hazards in localized areas	Overall Extent of Damage
			▪ Release to environment ▪ Immediate need for localized relocation for building and facilities	Hazardous Materials
	Large (Rare)	Moderate	Repairable damage, some delay in re-occupancy	Structural Damage
			▪ Fully operational, minor cleanup and repair ▪ Emergency systems are fully operational	Non-Structural Systems
			▪ Locally significant, but generally moderate in number and nature ▪ Higher expected level of injuries in fire hazards in localized areas	Occupant Hazards
			▪ Locally significant, generally moderate in extent and cost ▪ Higher expected level of injuries in fire hazards in localized areas	Overall Extent of Damage
			▪ Some release to environment, minimal risk to community ▪ No need for emergency relocation	Hazardous Materials
	Medium (Less Frequent)	Mild	Property is safe to occupy	Structural Damage
			Fully operational	Non-Structural Systems
	Small (Frequent)		▪ Minimal in number and minor in nature	Occupant Hazards

			▪ Low likelihood of single/multiple life loss ▪ Higher expected level of injuries in fire hazards in localized areas	
			Minimal in extent and minor in cost	Overall Extent of Damage
			Minimal amount release to environment	Hazardous Materials

APPENDIX H: Weighting Technique for the Facade Insulation and ACM Cladding

Professional judgement and experience in facades and exterior cladding systems of the author, along with facade fire testing data from Nishio et al.,[68] provided the basis for the weighting of the fire hazard impact levels for three green facade building features from the Optimized Energy Performance sub-category. The facade fire research by Nishio et al. was initiated to verify flame propagation on combustible facades installed on the exterior side of fire-resistant loadbearing walls.[68] The fire test method, the revised JIS A 1310: 2015, "Test Method for Fire Propagation over Building Facades", used 900-kW output constantly for 20 minutes within the combustion chamber. Heat flux on the facade surface in this test were compared by Nishio to other facade-type fire test methods; results indicate the heat flux on the facade surfaces from JIS A 1310 with 900 kW are no less severe than NFPA 285, "Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Loadbearing Wall Assemblies Containing Combustible Components".[68] NFPA 285 is a test method for examining how fire spreads on external wall cladding with flat surfaces; the evaluation criteria for vertical fire spread to an upper floor is based on a maximum peak facade surface temperature less than 538°C (1000°F) measured 10'-0" above an opening with a total time duration of 30 minutes and is the standard test method for the IBC in the USA.

The experimental facilities, test procedures, and details of the facade systems researched by Nishio et al. are fully documented [68]. Various types of combustible facade specimens were tested, including several different EIFS specimens composed of various EPS thicknesses and two ACM specimens, each 4mm thick with either a PE or FR core, see Table H.0. A fire-retardant facade was also benchmarked for calibration. The methodology employed a fire-retardant support system, eliminating any influence onto the facade fire performance. This is noteworthy, as the measured performance of each facade material in isolation allows for a relative comparison to the non-combustible calibrated

Table H.0 Details of Facade Specimens

Specimen	Category	Core	Thickness	Density	Protection Details
Blank	Calibration	Ceramic Fiber Blanket	25 mm	15 kg/m³	No
No. 2	EIFS	EPS	4"	15 kg/m³	Yes*
No. 4	EIFS	EPS	8"	15 kg/m³	Yes*
No. 10	ACM	PE	4mm	-	No
No. 11	ACM	FR	4mm	-	No

**The protection detail at the opening edges for specimen No. 2 and 4 includes back-wrapping with a glass-fiber mesh which is embedded underneath the finish coat and above the EPS boards, for the purpose of strengthening the specimen edges at the opening against the fire from below.*

facade; a correlation can then be assessed for weighting the fire hazard variables of the green building facade features for the case study model project.

The focus for Nishio et al. is vertical fire spreading along combustible facades and horizontal fire spreading to an adjacent building. The tentative temperature boundary limit is 500°C (932°F), the temperature causing glass to break at an upper floor's window by a fire plume ejected from the opening on the floor where the fire originated.[68] Although a number of studies have been conducted on the breakage of glazing under heat stress, no conclusive results have been recorded as the heat flux range for breakage/fallout varies between 23 kW/m^2 and 43 kW/m^2.[55] As a result, the vertical fire spread to the upper floor considered is based on the time to reach 500°C (932°F) and the duration time exceeding 500°C (932°F) on the test facade surface,[68] see Table H.1. The peak facade surface temperature, in particular at the top of the test specimen at TC5, is also an important

Table H.1 Time to Reach 932°F and Duration Time Exceeding 932°F

	Time to Reach 500°C (932°F)			Duration Time Exceeding 500°C (932°F)		
Specimen	TC 3	TC 4	TC 5	TC 3	TC 4	TC5
No. 2 4” EPS Protected	1.2 Minutes	2.1 Minutes	2.4 Minutes	18.8 Minutes	8.1 Minutes	0.6 Minutes
No. 4 8” EPS Protected	1.3 Minutes	1.5 Minutes	4.2 Minutes	18.7 Minutes	6.8 Minutes	3.1 Minutes
No. 10 ACM PE Core	2.7 Minutes	3 Minutes	3 Minutes	9.7 Minutes	6.3 Minutes	5.7 Minutes
No. 11 ACM FR Core	4.2 Minutes	Not over 932°F		13.3 Minutes	Not over 932°F	
	TC 3 @ 5'-0" Above Opening		TC 4 @ 6'-6" Above Opening		TC 5 @ 8'-2" Above Opening	

indicator for evaluating a vertical fire spread, see Table H.2. Aging variations of the EPS

Table H.2 Peak Facade Surface Temperature

Peak Facade Surface Temperature					
Specimen	TC 1	TC 2	TC 3	TC 4	TC 5
Calibration Blank	840°C (1544°F)	670°C (1238°F)	415°C (779°F)	401°C (755°F)	344°C (651°F)
No. 2 (4” EPS Protected)	984°C (1803°F)	923°C (1693°F)	785°C (1445°F)	563°C (1045°F)	558°C (1036°F)
No. 4 (8” EPS Protected)	902°C (1656°F)	893°C (1640°F)	878°C (1612°F)	725°C (1337°F)	561°C (1042°F)
No.10 (ACM PE Core)	1076°C (1969°F)	1018°C (1864°F)	918°C (1686°F)	801°C (1474°F)	832°C (1530°F)
No.11 (ACM FR Core)	887°C (1629°F)	745°C (1373°F)	576°C (1069°F)	383°C (721°F)	329°C (624°F)

and ACM facade temperatures is provided for comparison to the benchmark calibration material, corelating the vertical fire spread of the green facade features to the benchmarked calibrated material, see Figure H.1. The peak surface temperature of 1530°F at TC5 for the ACM PE specimen occurs at approximately 6 minutes, where the maximum heat release is experienced. Lower peak surface temperatures of the calibrated and ACM FR specimens correlate to much lower heat release rates throughout the duration of the test. The peak surface heat flux at the facade can help to determine the impact flames have on the exterior surface; peak heat flux increases with an increase in the HHR.[73] The heat flux of the calibration and ACM FR core specimens are not significant compared to the heat flux of the ACM PE core specimen, see Table H.3. This would correspond with the results from the aging variations, including rapid growth and high heat release values, where fire intensity observed was high. The critical heat flux can also be related to ignition temperature,[34] and as a reference, piloted ignition to ignite wood is about 12 kW/m^2.[55] Generally, the greater the heat flux, the shorter the time to ignition.

The horizontal fire spread to an adjacent building for Nishio et al. is based on a fire exposure to an opposite surface 6’-6” from the tested facade specimen surface; the intensity of heat radiation transferred to combustible materials on the exterior of a distant building is related to horizontal flame spread to adjacent buildings.[55, 74] For buildings with combustible wall surfaces, the entire wall can act as the radiator.[55] Basic principles of radiation transfer from a flame front (radiator) is considered;[55] in all the combustible facades tested by Nishio et al., higher heat flux on the opposite surfaces were measured at positions closer to the opening in the test wall, see OHF1 measurements in Table H.4. This indicates a horizontal fire spread to an adjacent building would mainly happen near the opening because of the ejected flame’s influence.[68] In the case of the ACM with a PE core, fire propagation occurred 3 minutes after the ignition of the burner, and many parts of the specimen were burned out 8 min after the ignition of the burner. Conversely, limited degradation was observed in the ACM specimen with a FR core, and just a slight ignition occurred on the specimen, see Figure H.0. The ACM specimen with a FR core performed well in terms of restricting the vertical fire propagation and the amount of heat generated by the specimens during the tests; fire propagation was limited to only near the ignition area. Specimens with a thermal insulation system (Nos. 2 & 4) showed a longer duration of the temperature exceeding 932°F. Specimens with relatively more EPS (No. 4) had a longer duration of the temperature exceeding 932°F. It should be noted; key assumptions include no wind with constant temperature due to indoor testing and all tests were only performed once.

Table H.2 Peak Surface Heat Flux at 9'-3" Above Opening at HF6

Peak Surface Heat Flux at HF6	
Specimen	Peak Heat Flux
Calibration Blank	12 kW/m²
No. 2 (4" EPS)	20 kW/m²
No. 4 (8" EPS)	27 kW/m²
No.10 (ACM PE)	72 kW/m²
No.11 (ACM FR)	10 kW/m²

Table H3. Peak Opposite-Surface Incident Heat Flux After 10 Minutes

Peak Opposite-Surface Incident Heat Flux (After 10 minutes)				
Specimen	OHF 1	OHF 3	OHF 4	OHF 5
Calibration Blank	15 kW/m²	10 kW/m²	6 kW/m²	4 kW/m²
No. 2 (4" EPS Protected)	20 kW/m²	16 kW/m²	10 kW/m²	5 kW/m²
No. 4 (8" EPS Protected)	16 kW/m²	13 kW/m²	9 kW/m²	6 kW/m²
No.10 (ACM PE Core)	21 kW/m²	21 kW/m²	17 kW/m²	16 kW/m²
No.11 (ACM FR Core)	16 kW/m²	10 kW/m²	6 kW/m²	4 kW/m²

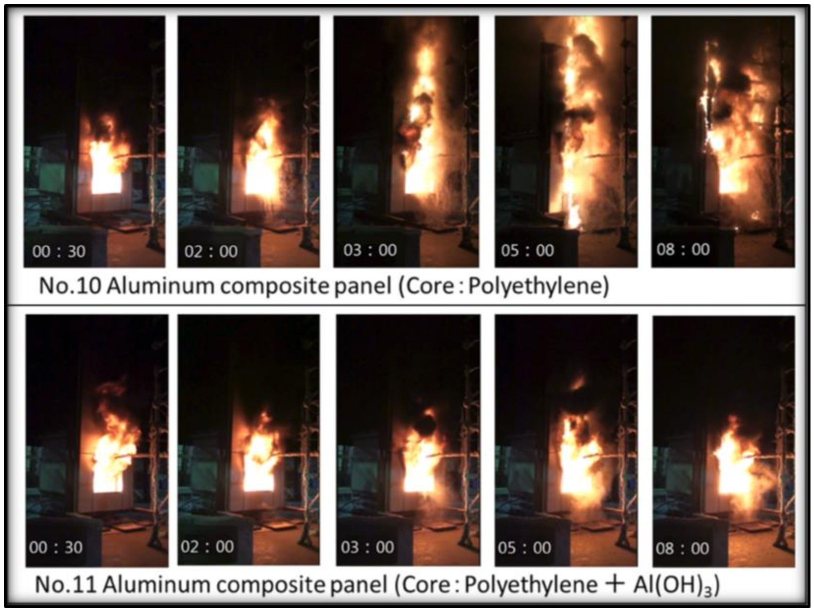
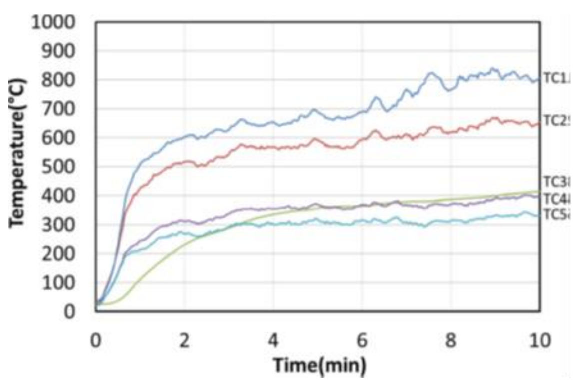
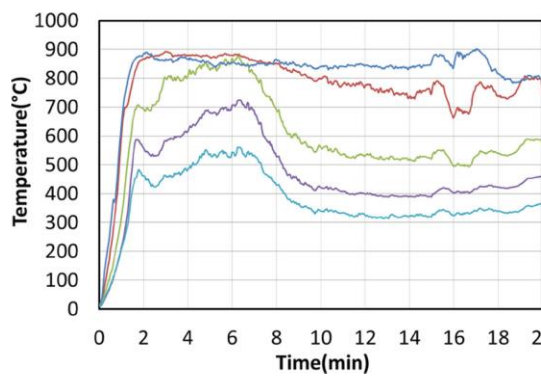


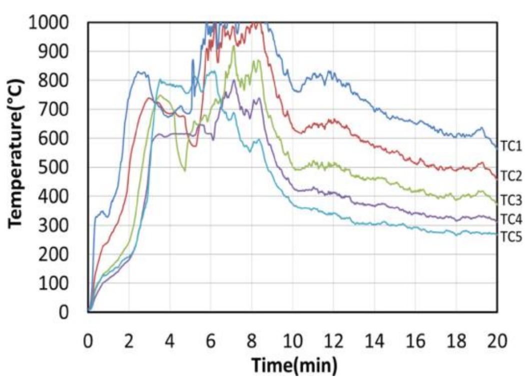
Figure H.0 Fire Propagation Behavior of ACM PE and ACM FR Specimens



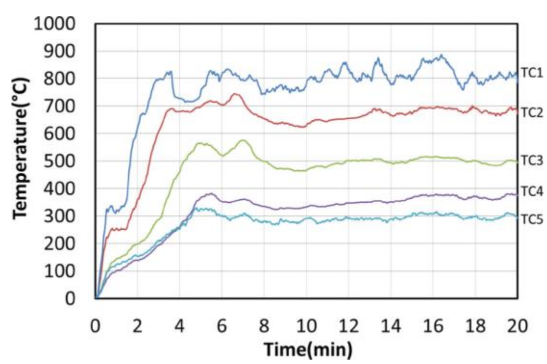
Aging Variation for Benchmark Calibration



Aging Variation for Specimen No. 4



Aging Variation for Specimen No. 10



Aging Variation for Specimen No. 11

Figure H.1 Aging Variations of Facade Surface Temperatures

There are 5 Key Performance Indicators (KPI) identified from the data of Nishio et al.; the KPI's have received equal weighting for this research and include:

1. The time for TC5 to reach 932°F
2. The duration of time after TC5 exceeds 932°F on the test facade surface
3. Peak opposite-surface heat flux at OHF1
4. Peak surface temperature at TC5
5. Peak heat flux at HF6

The potential correlation between the KPI's and the fire hazard variables are considered:

Potential Ignition Source: Peak Opposite-Surface Heat Flux at OHF1

Contributes more Fuel Load: Peak Heat Flux at HF6; Peak Surface Temp at TC5

*Change Thermal Characteristics: Peak Surface Temp at TC5; Time for TC5 to Reach 932°F

Readily Ignitable: Peak Surface Temp at TC5; Peak Heat Flux at HF6

Burns Readily Once Ignited: Time for TC5 to Reach 932°F

**Affects Burning Characteristics: Peak Surface Temp at TC5; Time for TC5 to Reach 932°F; Duration Exceeding 932°F

Presents Flame Spread Concern: Peak Opposite-Surface Heat Flux at OHF1; Duration Exceeding 932°F; Time to Reach 932°F; Peak Surface Temp. at TC5

**Thermal Characteristics include: thermal conductivity (heat transfer occurs at a low rate in materials with low thermal conductivity; transfer at a high rate with high thermal conductivity), thermal resistance (property where an object resists heat flow); thermal inertia (the degree of slowness a material approaches that of its surrounding dependent upon: absorptivity, specific heat, and thermal conductivity) $I=(kpc)^{1/2}$: k=thermal conductivity; p=density; c=heat capacity. The role of thermal inertia is also critical to the energy performance in a structure; high thermal inertia equates to a higher heat capacity.*

***Burning Characteristics include: flame height, flaming duration, smoke production*

The impact levels for the peak facade surface temperatures are outlined in Table H.5. A severe impact temperature of 932°F is chosen, based on the evaluation criteria for vertical fire spread to an upper floor, located 9'-0' above the opening, per the JIS A 1310 revised test. This could also align with results from an NFPA 285 test, where the maximum peak facade surface temperature is less than 1000°F at 10'-0" above the opening. The remaining four impact levels equally distribute the temperature values below 932°F. The impact levels for the peak heat flux of the facade surface are shown in Table H.6. A moderate impact level is assigned to the calibration facade specimen, based on the peak surface temperature impact level from the calibrated facade specimen. The remaining four impact levels equally distribute the heat flux values. The opposite-surface peak incident heat flux is listed in Table H.7. A moderate impact level is also assigned to the calibration facade specimen, mirroring the peak surface temperature impact level. The remaining four impact levels equally distribute the opposite-surface peak heat flux values.

Table H.5 Impact Level of Peak Facade Surface Temperature

Impact Level of Peak Facade Surface Temperature at TC5
Low Impact: 0 - 232°F
Mild Impact = 233°F - 465°F
Moderate Impact = 466°F - 699°F
High Impact = 700°F - 931°F
Severe Impact ≥ 932°F

Table H.6 Impact Level of Peak Heat Flux of Facade Surface

Impact Level of Peak Heat Flux of Facade Surface at HF 6
Low Impact: 0 - 4 kW/m²
Mild Impact = 5 kW/m² - 8 kW/m²
Moderate Impact = 9 kW/m² - 12 kW/m²
High Impact = 13 kW/m² - 16 kW/m²
Severe Impact ≥ 17 kW/m²

Table H.7 Impact Level of Opposite-Surface Peak Incident Heat Flux at OHF 1

Impact Level of Opposite-Surface Peak Incident Heat Flux at OHF 1
Low Impact: 0 - 5 kW/m²
Mild Impact = 6 kW/m² - 10 kW/m²
Moderate Impact = 11 kW/m² - 15 kW/m²
High Impact = 16 kW/m² - 20 kW/m²
Severe Impact ≥ 21 kW/m²

The impact level of the time for TC5 to reach 932°F from Nishio et al. is listed in Table H.8. The calibration facade specimen peak facade surface temperature did not reach 932°F during the 10-minute test, therefore, the range was equally distributed based on the outcome from the 19 specimens tested by Nishio et al. The impact level for the calibration specimen was considered low for the analysis.

Table H.8 Impact Level of Time for TC5 to Reach 932°F

Impact Level of Time for TC5 to Reach 932°F
Low Impact: ≥ 7.1 Minutes
Mild Impact: 5.9 – 7 Minutes
Moderate Impact: 4.5 – 5.8 Minutes
High Impact: 3.1 – 4.4 Minutes
Severe Impact: ≤ 3 Minutes

The impact level of the duration exceeding 932°F at TC5 from Nishio et al. is listed in Table H.9. The calibration facade specimen peak facade surface temperature did not reach 932°F during the 10-minute test, therefore, the range was equally distributed based on the outcome from the 19 specimens tested by Nishio et al. The impact level for the calibration specimen was considered low for the analysis.

Table H.9 Impact Level of Duration Exceeding 932°F at TC5

Impact Level of Duration Exceeding 932°F at TC5
Low Impact: ≤ 1.2 Minutes
Mild Impact: 1.2 – 2.4 Minutes
Moderate Impact: 2.5 – 3.7 Minutes
High Impact: 3.8 – 4.9 Minutes
Severe Impact: ≥ 5 Minutes

Numerical values are assigned to the impact levels for a Hazard Scale, as described in Methodology Section 3.3 and included in Table H.10.

Table H.10 Impact Level Hazard Scale

Impact Level Hazard Scale
Low Impact: 0-1 Point
Mild Impact = 1.1-2 Points
Moderate Impact = 2.1-3 Points
High Impact = 3.1-4 Points
Severe Impact = 4.1-5 Points

The impacts are based on the correlation between several of the fire hazard attributes from the facade green features and the KPI's. Numerical values are assigned to the impact levels of the key performance indicators for each fire hazard attribute and algebraically summed. Since the KPI's are equally weighted, the overall impact level is determined simply from dividing the total KPI impact level point value by the number of KPI's considered for each fire hazard attribute impact level, see Equation 1.

$w_i = \left(\sum_{i=1}^{n} v_i \right)/n$ ……………...…………………….………………….(Equation 1)

Where:

w = Fire Hazard Attribute Impact Level
v = Key Performance Indicator Impact Level
n = number of Key Performance Indicators

Although the mathematical expressions of the index themselves are trivial in terms of computational effort, this process is the basis from which choices between alternate design scenarios for the green facade features can be made. The three green building features benefiting from this analysis include the continuous exterior rigid foam insulation, higher insulation values, and area of combustible facade cladding.

Specimen No. 10: ACM PE

Potential Ignition Source: Peak OHF1= 21 kW/m^2 (severe); Peak HF6 = 72 kW/m^2 (Severe) (5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Contributes More Fuel Load: Peak HF6 = 72 kW/m^2 (Severe); Peak Surface Temp at TC5=1530°F (Severe)
(5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Change Thermal Characteristics: Peak Surface Temp at TC5 = 1530°F (Severe)
(5 points; Severe Overall Impact)

Readily Ignitable: Peak surface Temp = 1530°F (Severe); Peak HF6 = 72 kW/m^2 (Severe)
(5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Burns Readily Once Ignited: Time for TC5 to Reach 932°F = 3 minutes (Severe)
(5 points; Severe Overall Impact)

Affects Burning Characteristics: Peak Temp at TC5 = 1530°F (Severe); Time for TC5 to Reach 932°F = 3 minutes (Severe); Duration Time Exceeding 932°F = 5.7 minutes (Severe)
(5 points + 5 points + 5 points = 15 points/3 = 5 points; Severe Overall Impact)

Presents Flame Spread Concern: Peak OHF1 = 21 kW/m^2 (Severe); Duration Exceeding 932°F = 5.7 minutes (Severe); Time to reach 932°F = 3 minutes (Severe); Peak Surface Temp at TC = 1530°F (Severe)
(5 points + 5 points + 5 points + 5 points = 20 points/4 = 5 points; Severe Overall Impact)

Specimen No. 11: ACM PE

Potential Ignition Source: Peak OHF1= 16 kW/m^2 (High); Peak HF6 = 10 kW/m^2 (Moderate)
(4 points + 3 points = 7 points/2 = 3.5 points; High Overall Impact)

Contributes More Fuel Load: Peak HF6 = 10 kW/m^2 ((Moderate); Peak Surface Temp at TC5 = 624°F (Moderate)
(3 points + 3 points = 6 points/2 = 3 points; Moderate Overall Impact)

Change Thermal Characteristics: Peak Surface Temp at TC5 = 624°F (Moderate)
(3 points; Moderate Overall Impact)

Readily Ignitable: Peak Surface Temp. = 624°F (Moderate); Peak HF6 = 10 kW/m^2 (Moderate)
(3 points + 3 points = 6 points/2 = 3 points; Moderate Overall Impact)

Burns Readily Once Ignited: Time for TC5 to reach 932°F = 0 minutes (Low)
(1 point; Low Overall Impact)

Affects Burning Characteristics: Peak Surface Temp at TC5 = 624°F (Moderate); Time for TC5 to Reach 932°F = Never (Low); Duration Time Exceeding 932°F = Never (Low)
(3 points + 1 point + 1 point = 5 points/3 = 1.7 points; Mild Overall Impact)

Presents Flame Spread Concern: Peak OHF1 = 16 kW/m^2 (High); Duration Time Exceeding 932°F = Never (Low); Time to reach 932°F = Never (Low); Peak Surface Temp at TC = 624°F (Moderate)
(4 points + 1 point + 1 point + 3points = 9 points/4 = 2.25 points; Moderate Overall Impact)

Specimen No. 2: 4” Thick EPS

Potential Ignition Source: Peak OHF1= 20 kW/m^2 (High); Peak HF6 = 20 kW/m^2 (Severe)
(4 points + 5 points = 9 points/2 = 4.5 points; Severe Overall Impact)

Contributes More Fuel Load: Peak HF6 = 20 kW/m^2 (Severe); Peak Surface Temp at TC5=1036°F (Severe)
(5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Change Thermal Characteristics: Peak Surface Temp at TC5 = 1036°F (Severe)
(5 points; Severe Overall Impact)

Readily Ignitable: Peak surface Temp. 1036°F (Severe); Peak HF6 = 20 kW/m^2 (High)
(5 points + 4 points = 9 points/2 = 4.5 points; Severe Overall Impact)

Burns Readily Once Ignited: Time for TC5 to reach 932°F = 2.4 minutes (Severe)
(5 points; Severe Overall Impact)

Affects Burning Characteristics: Peak Temp at TC5 = 1036°F (Severe); Time for TC5 to reach 932°F = 2.4 minutes (Severe); Duration Time Exceeding 932°F = 0.6 minutes (Low)
(5 points + 5 points + 1 point = 11 points/3 = 3.7 points; High Overall Impact)

Presents Flame Spread Concern: Peak OHF1 = 20 kW/m^2 (Severe); Duration Exceeding 932°F = 0.6 minutes (Low); Time to reach 932°F = 2.4 minutes (Severe); Peak surface Temp at TC = 1036°F (Severe)
(5 points + 1 point + 5 points + 5 points = 16 points/4 = 4 points; High Overall Impact)

Specimen No. 4: 8" Thick EPS

Potential Ignition Source: Peak OHF1= 16 kW/m^2 (High); Peak HF6 = 27 kW/m^2 (Severe)
(4 points + 5 points = 9 points/2 = 4.5 points; Severe Overall Impact)

Contributes More Fuel Load: Peak HF6 = 27 kW/m^2 (Severe); Peak Surface Temp at TC5=1042°F (Severe)
(5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Change Thermal Characteristics: Peak Surface Temp at TC5 = 1042°F (Severe)
(5 points; Severe Overall Impact)

Readily Ignitable: Peak surface Temp = 1042°F (Severe); Peak HF6 = 27 kW/m^2 (Severe)
(5 points + 5 points = 10 points/2 = 5 points; Severe Overall Impact)

Burns Readily Once Ignited: Time for TC5 to reach 932°F = 4.2 minutes (Severe)
(5 points; Severe Overall Impact)

Affects Burning Characteristics: Peak Temp at TC5 = 1042°F (Severe); Time for TC5 to reach 932°F = 4.2 minutes (High;) Duration Time Exceeding 932°F = 3.1 minutes (High)
(5 points + 4 points + 4 points = 13 points/3 = 4.4 points; Severe Overall Impact)

Presents Flame Spread Concern: Peak OHF1 = 16 kW/m^2 (High); Duration Exceeding 932°F = 3.1 minutes (High); Time to reach 932°F = 4.2 minutes (Severe); Peak surface Temp at TC = 1042°F (Severe)
(4 points + 4 points + 5 points + 5 points = 18 points/4 = 4.5 points; Severe Overall Impact)

The results from the four-specimen analysis above are used to assess the continuous exterior rigid foam insulation and ACM cladding. Specimen no. 10 was used to assess the area of combustible facade cladding while specimen no.11 was compared to specimen no. 10 to assess the mitigation measures for the facade cladding. Higher insulation values are assessed by comparing the results from specimen no. 2 and no. 4. The overall numerical values are then incorporated into the Hazard Ranking Matrix for the Model Project, see Table 4.0 and the Mitigated Hazard Ranking Matrix for the Model Project, see Table 4.3., both in the Methodology Section.