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Green-Cities, How to Combine Fire Safety and The Fight Against Global Warming

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Abstract

Vegetative systems are a recent effort to bring greenery into the cities which provides multiple benefits for the people and the environment. These technological systems do not equal to safety and require to be analyzed from a fire safety perspective which is the focus of this research by performing a literature review that reunites multiple documents from a global scale. The aim of developing a *Best Practice Guideline* for the design of fire safety measures on green roofs and walls in any location is achieved after performing an initial research. The study of the three main components, benefits, classifications, installation typologies, system components, and standards provides with a better comprehension of the general functioning of these systems. A fire review of the elements comprising fire spread, standards, tests, experiments, and modelling expands the understanding of the fire behavior and evolving properties of plants. A hazard identification reunites in five categories threats recognized by several documents. Fire safety strategies are analyzed considering inputs from multiple documents that address the hazards previously identified from prescriptive and performance-based methodologies. Revised case studies provide with useful insights from an engineering approach based on specific conditions. Based on these findings, the guideline is developed focusing on the steps for an engineering approach which is more flexible and applicable for complex projects. Three main objectives, prevention of a negative evolution of the system, limiting the extended of fire, and the ability for self-extinguishing, are developed further on multiple proceeding steps. Tools that summarize the previous findings are developed to support key sections. Examples scenarios are provided that illustrate the way to use the tools by identifying hazards, ranking, and addressing them with fire safety strategies. Traditional and innovative solutions are proposed addressing the evolving nature and non-traditional characteristics of vegetative systems present throughout its entire lifespan.

Resumen

Los sistemas vegetativos son un esfuerzo reciente para llevar la vegetación a las ciudades, lo que proporciona múltiples beneficios para las personas y el medio ambiente. Estos sistemas tecnológicos no equivalen a seguridad y requieren ser analizados desde una perspectiva de seguridad contra incendios la cual corresponde al foco de esta investigación mediante la realización de una revisión bibliográfica que reúne múltiples documentos de una escala global. El objetivo de desarrollar una *Guía de Buenas Prácticas* para el diseño en seguridad contra incendios de cubiertas y muros verdes ubicadas en cualquier lugar se logra después de realizar una investigación inicial. El estudio de los tres componentes principales, beneficios, clasificaciones, tipologías de instalación, componentes del sistema y estándares permite comprender mejor el funcionamiento general de estos sistemas. Una revisión de los aspectos relacionados al fuego en los elementos principales de estos sistemas sobre la propagación del fuego, estándares, pruebas, experimentos y el modelado amplía la comprensión acerca del comportamiento bajo fuego y de las propiedades evolutivas de las plantas. Una identificación de riesgos reúne en cinco categorías amenazas reconocidas por varios documentos. Las estrategias de seguridad contra incendios se analizan considerando los aportes de múltiples documentos que abordan los peligros identificados previamente a partir de metodologías basadas en regulaciones prescriptivas y a través del desempeño. Los casos de estudio brindan visiones útiles desde un enfoque del desempeño basados en condiciones específicas. Con base en estos hallazgos, se desarrolla la guía enfocándose en los pasos para soluciones basadas en el desempeño, siendo este acercamiento más flexible y aplicable a proyectos complejos. Tres objetivos principales, la prevención de una evolución negativa del sistema, la limitación de la extensión del fuego y la capacidad de auto extinción, se desarrollan a través de una serie de pasos procedentes. Herramientas que resumen los hallazgos anteriores son elaboradas para respaldar secciones claves. Se proporcionan ejemplos de escenarios que ilustran la forma de utilizar las herramientas al identificar los amenazas, clasificarlas y proveer soluciones con estrategias de seguridad contra incendios. Se proponen estrategias tradicionales e innovadoras que consideran la naturaleza evolutiva y las características no tradicionales de los sistemas vegetativos presentes a lo largo de toda su vida.

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Overview

This document is composed by seven chapters that revises vegetative systems comprising an introduction, a review of the state-of-the-art of vegetative systems, a fire review, an identification of hazards, an analysis of strategies, and a guideline for future installations followed by conclusions. Diagram 1 expose the seven chapters that compose this document and their main sections.

Green-Cities, How to Combine Fire Safety &
The Fight Against Global Warming

Chapter I — Introduction

1.1 Background
1.2 Definitions
1.3 Problem Statement
1.4 Aim
1.5 Objectives
1.6 Methodology
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Chapter II — Vegetative Systems

2.1 General Components
2.2 Benefits
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Chapter III — Fire Review

3.1 Fire Spread
3.2 Fire Standardization
3.3 Fire Tests and Experiments
3.4 Modelling of Vegetation
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Chapter IV — Hazard Identification

4.1 Hazard Review
4.2 Case Studies
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Chapter V — Fire Safety Strategies

5.1 Prescriptive Strategies
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Chapter VI — Best Practice Guideline

6.1 Introduction
6.2 Initial Considerations
6.3 Prescriptive Approach
6.4 Engineering Approach
6.5 Fire Safety Strategies
6.6 Documentation
6.7 Guideline Discussion
6.8 Final Considerations

Chapter VII — Conclusion and Outlook

7.1 Conclusion
7.2 Outlook

Diagram 1. General Overview

The following paragraphs explain the content of each chapter and the sources of the information considered. The research, being a global scale literature review, includes documents from different latitudes. The list of references is cumulative having certain documents also used in the subsequent chapters.

Chapter I, *Introduction*, provides with a general background review and an early definition of the systems analyzed. This section identifies the problem statement based on an initial literature review. The aim and objectives are defined immediately afterwards providing guidance for the rest of the research. The methodology followed by limitations are also explained in this chapter.

Chapters II & III, *Vegetative Systems* and *Fire Review*, considers documents involving vegetative systems in Europe, North America, and Australia. The review of the existing documents provides with an initial understanding of the general components, benefits, classification, installation typologies, system components, and standardization. The following regulations are revised:

- Standard
  - ANSI/SPRI VF-1 (2017). *External Fire Design Standard for Vegetative Roofs*, USA.
  - SIA 312 (2013) *"Végétalisation de toitures"* (Roof Greening), Switzerland.
- Data Sheet from Insurance Company
  - FM DS 1-35 (2020). *Vegetative Roof Systems*, FM Global.
  - ANSI FM Approvals 4477 (2016). *American National Standard for Vegetative Roof Systems*, FM Global.
- Guidelines
  - FLL (2018). *The Landscaping and Landscape Development Research Society. Guidelines for the Planning, Construction and Maintenance of Green Roofing*, Germany.
  - GRO (2011). *GRO Green Roofs Code*, UK.
  - State of Victoria, Department of Environment and Primary Industry (2014). *Growing Green Guide. A guide to green roofs, walls and facades in Melbourne and Victoria, Australia*, Australia.

In addition to the previous regulations, research reports and articles, books, and tests are also considered expanding the knowledge about vegetative systems. The following documents are revised:

- Research Reports
  - Department for Communities and Local Government (2013). *Fire Performance of Green Roofs and Walls*, UK.
  - NASFM (2010). *Bridging the Gap: Fire Safety and Green Buildings. A Fire and Building Safety Guide to Green Construction*, USA.
  - NFPA FPRF (2020). *Fire Safety Challenges of Green Buildings: Final Report*, USA.
  - A. Elias, E. Gunnarsson, D. Håkansson, R. Jansson, J. Lövgren-forslund, and A. Mossberg (2017) "*Green roofs: From a Fire Technical Point of View*", Sweden.
  - J. Burman, A. Granström, I. Bohlin, P.-Å. Gradmark, and C. Lejon, (2016) "*Distribution Models for Fire in Vegetation: Test of models suitable for Swedish conditions*", Sweden.
  - A. Granström, "*Forest Fire: Fire Behavior and Interpretation of Fire Risk Index*", Sweden.
  - E. Alexander and D. Håkansson (2016) "*Herb Sedum Roof: A survey of the fire properties and design of a herb sedum roof with regard to fire*", Sweden.

- Research Articles
    - K. C. Dahanayake and C. L. Chow (2018) "*Moisture Content, Ignitability, and Fire Risk of Vegetation in Vertical Greenery Systems*", Hong Kong.
    - C. L. Chow, S. S. Han, K. C. Dahanayake, and W. K. Cow (2018) "*Fire Hazards with Vertical Greenery Systems*", Hong Kong.
    - K. C. Dahanayake, Y. Yang, Y. Wan, S. Han, and C. L. Chow (2020) *"Study on the fire growth in underground green corridors"*, Hong Kong.
- Books
    - E. Giacomello (2021) "*Green Roofs, Facades, and Vegetative Systems*".
    - G. Pérez, K. Perini (2018) "*Nature Based Strategies for Urban and Building Sustainability*".
- Tests
    - ENV 1187, *Test methods for external fire exposure to roofs*.
    - EN 13501-5, *Fire classification of construction products and building elements-Part5: Classification using data from external fire exposure to roofs tests*.
    - ASTM E 108, *Standard Test Methods for Fire Tests of Roof Coverings*.
    - NFPA 276, *Standard Method of Fire Tests for Determining the Heat Release Rate of Roofing Assemblies with Combustible Above-Deck Roofing Components*.
    - ISO 11925-2, *Ignitability of products subjected to direct impingement of flame - Part 2: Single-flame source test*.
    - EN 13823, *Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item*.

Chapters IV & V, *Hazard Identification* and *Fire Protection Strategies*, identifies the risks that green roofs and walls can pose towards people, buildings, its surroundings, and the fire brigade. The prescriptive sections of these chapters are structured following the five requirements and considerations used in Approved Document B, the British Building Regulations for fire safety. In addition, the Swiss Fire Protection Norm, and some applicable Directives are also considered. Prescriptive strategies to address the identified risks are also suggested based on these documents. The following regulations are considered:

- Approved Document
    - HM Government (2019) *"The Building Regulations 2010: Fire Safety, Approved Document B Volume 2: Buildings Other Than Dwellings"*, UK.
- Norm
    - VKF / AEAI / AICAA (2015) *"Norme de protection incendie 01.01.2015 / 1-15fr,"* (Fire Protection Norm), Switzerland.
- Directives
    - VKF / AEAI / AICAA (2017) *"Matériaux et éléments de construction 01.01.2017 / 13-15fr,"* (Construction Material and Elements), Switzerland.
    - VKF / AEAI / AICAA (2015) *"Utilisation des matériaux de construction 01.01.2017 / 14-15fr,"* (Use of Construction Materials), Switzerland.
    - VKF / AEAI / AICAA (2017) *"Distances de sécurité incendie, systèmes porteurs et compartiments coupe-feu 01.01.2017 / 15-15fr,"* (Fire Security Distances, Load Bearing Systems, and Fire Compartments), Switzerland.

Given the lack of available information regarding green walls, a comparison with wood façades is done. This comparison considers the Swiss document, Lignum 7.1 as a guide to come up with strategies.

- Document
    - Lignum Suisse Economie du Bois (2009) *"Parois extérieures - Constructions et revêtements, Documentation Lignum protection incendie 7.1"* (Document Lignum fire protection 7.1 External walls - Construction and linings), Switzerland.

In addition, regarding green walls, a comparison with double skin façades is also done since it can be one type of installation. This comparison considers the following Swiss document:

- Explicative Note
    - VKF / AEAI / AICAA (2017) *"Bâtiments à façades double-peau 01.01.2017 / 102-15fr,"* (Double Skin Façade Buildings), Switzerland.

Case studies are also analyzed to identify hazards. The cases also revealed strategies that followed a performance-based approach.

- Case Studies
    - N. Lobel and C. Chennell, *"Irrigation Systems For Life Safety ? - Design And Approval Of A 60m Green Wall In An Internal Office Atrium"*, Australia.

Chapter VI, *Best Practice Guideline*, consists of a guide for future fire safety designs on vegetative systems. Since this design is considered to be a parallel process between the general designers and the fire safety engineering team, the tasks that are considered by the designers are mentioned as well the fire safety duties following two possible approaches. This chapter considers the findings from the previous sections of the thesis and its references in addition with international fire safety guidelines:

- Fire Safety Guidelines
    - M. J. Hurley and E. R. Rosenbaum (2015) "*Performance-Based Fire Safety Design"*.
    - SFPE (2007) *"SFPE Engineering Guide to Performance-Based Fire Protection"*.
    - SFPE (2012) "*SFPE Guidelines for Designing Fire Safety in Very Tall Buildings"*.

A discussion of the results of the guideline is included at the end of this chapter.

Chapters II to VI include final remarks of the main points on the last section of each chapter.

Chapter VII, *Conclusion and Outlook*, resumes the main findings of the thesis and suggests future research that can be done related to this thesis.

References and Annexes can be consulted at the end of this document.

Chapter I

Introduction

This chapter introduces the research topic while defining the problem statement, setting out the aim, and providing the main objectives that structure the rest of the research document. The methodology and limitations are also exposed subsequently. Diagram 2 expose the seven sections that compose this chapter and their main contents.

Introduction Overview	
1.1	**Background** History Increased Popularity
1.2	**Definitions** Vegetative Systems Green Roofs Green Walls
1.3	**Problem Statement** Research Purpose
1.4	**Aim** Research Target
1.5	**Objectives** State-of-the-Art of Vegetative Systems Fire Behavior of the Elements Hazard Identification Fire Safety Strategies
1.6	**Methodology** Literature Review
1.7	**Limitations** Document Accessibility Testing and Experiments

Diagram 2. Introduction - Chapter I Overview

1.1 Background

Vegetative systems have been a part of the exterior of buildings for decades and even centuries. The multiple benefits that these systems bring for the environment, people, and the building itself. These, in addition with recent technical advances for the building market have made vegetative systems more popular in many latitudes around the world in the last years. Vegetative systems, also known as living architecture or green systems, are composed by green roofs and green façades.

Green roofs became an element in construction in the 1960s starting in Germany, Switzerland, and Austria [1]. For general installations, these elements have been developed more into detail resulting in standards that apply for specific locations. The most referenced guideline is the German *FLL Green*

Roof Guideline initially published in the 80s making it the benchmark document and the base for many other regulations [2]. Given its popularity for several decades, these elements are more regulated in general terms but not entirely when it comes to fire protection for many locations.

Green walls in the form of climbing walls have been a part of architecture for centuries all over the world in façades. The development of new techniques in recent years have expanded the variety of plants that can be supported on this system [1]. These recent new installation systems increase the possibilities and have resulted in the use of green walls in the interior of buildings and also covering long vertical surfaces. Even though there is a recent advance on these systems, regulations and references addressing fire safety measures are scarce.

New buildings are being designed in recent years to achieve a green building certification. There are different rating systems that evaluate certain aspects of the design and construction that will award the building with a green certificate. These certifications, in addition to the environmental contribution, also promote the market value of the project [3]. Vegetative systems are elements that contribute the certification process by adding credits to green evaluation of the project. These systems also provide public and private benefits like increasing the market value, saving energy, and providing well-being for people.

Fire involving the vegetation in these systems has not been well documented but the risk that they create towards the people and building exists. Documents from different latitudes have been developed to understand their fire reaction and possible strategies to reduce the risk.

1.2 Definitions

Vegetative systems are defined by *Green Roofs, Facades, and Vegetative Systems* [2] as: *"A technological system onto which vegetation is intentionally grown"* [2]. It is also known as: exterior vegetative covering, greenery systems, living architecture, and green elements. It is a system that can be located in the interior or exterior of a building and is comprised by:

- Green Roofs

  This horizontal element is defined by the GRO as: *"A green roof is created when a planting scheme is established on a roof structure. The roof can be at ground level, often with an underground car park beneath, or many storeys higher. Green roofs can be designed as recreational spaces to be enjoyed by people, as visual, sustainable or ecological features to support wildlife or a combination of both"* [4]. It is also known as: Vegetative roof system, living roof, roof garden, or eco-roof.

  Figure 1 (left) shows an example of a green roof located in the California Academy of Science in San Francisco, USA.

- Green Walls

  This vertical element can be located inside or outside of a building and is defined by GRHC as: *"A 'Green Wall', also commonly referred to as a 'Vertical Garden', is a descriptive term that is used to refer to all forms of vegetated wall surfaces. Green wall technologies may be divided into two major categories: Green Facades and Living Walls"* [5]. In general terms, a green wall can also be called: Vertical greenery system (VGS), vegetated wall, green façade, vertical greenery, living wall, or vertical gardens. There are some differences with some of the terms mentioned that are explained in the following chapter.

  Figure 1 (right) expose a green wall located in the façade of the Quai Branly – Jacques Chirac Museum in Paris, France.

Figure 1. Green Roof and Green Wall
Images: Shunji Ishida (left) and Patrick Blanc (right)

1.3 Problem Statement

Vegetative systems are increasing in popularity as part of strategies in new buildings to address global warming, increase market value, and deliver a series of additional public and private benefits. These technological systems do not equal to safety. Most of the current standards or guidelines only address the general concepts to install a vegetative leaving fire safety out of scope. Applications on tall buildings are also not analyzed in most of the documents. An assessment from a fire safety point of view of these green elements is required in order to evaluate the hazards that these systems might pose towards people, the building, its surroundings and the fire service. The evolving nature of the vegetation is a unique quality of these systems that makes it a non-traditional construction element. Due to this evolving property of the vegetation and the complexity of the designs, many of the vegetative systems designed for buildings deviate from prescriptive code requirements. A guideline that stablishes the steps to address the fire hazards on these green elements by applying strategies based on codes or following a performance-based approach will benefit designers and fire safety engineers for the design of future projects.

The FM Global Technical Report *The Influence of Risk Factors On Sustainable Development* [6], concludes that: *"Efforts to improve sustainability solely by increasing energy efficiency (without consideration of risk) have the potential to increase the relevance of risk factors by a factor of 3"* [6]. This remark, despite being general, applies for vegetative systems which confirms and stresses the importance to analyze the risk that these new elements pose.

1.4 Aim

Given the increased recent popularity and lack of studies around vegetative systems and fires, the aim of the research is the development of a *Best Practice Guideline* which functions as a guide for the future design of fire safety measures for vegetative systems installed in buildings. This final guide document will be based on the research performed on the first sections of this thesis. This document is addressed to architects, fire safety engineers and authorities interested in the implementation or evaluation of vegetative systems in buildings. The document will list the variables that are considered by the general designer during the design stage as well as define a process to determine fire protection measures focusing on a performance-based approach. The guideline will be applicable to projects including green roofs and walls with high complexity levels located in any latitude.

1.5 Objectives

In order to achieve the aim of developing a Best Practice Guideline, four main objectives need to be analyzed. These objectives summarize and structure the document as follows:

A revision of the state-of-the-art of vegetative systems regarding the general components is summarized in the section *Vegetative Systems*. The first objective corresponds to:

- Study the general component, benefits, classification, installation typology, system components, and existing standards that conform green roofs and walls.

Specific concerns involving fire and vegetation are revised in the section *Fire Review*. The second objective corresponds to:

- Review the fire spread, standardization, tests, experiments, and modelling of vegetation that exists or apply for green roof and walls involving fire.

An assessment of hazards related to vegetative systems and fires in buildings is exposed in the section *Hazard Identification*. By reviewing different standards and case studies, the third objective is defined:

- Identify the hazards that vegetative systems pose towards people and the building from prescriptive regulations and case studies.

A study of fire strategies applied for vegetative systems using different methodologies and revising standards and case studies is presented in the section *Fire Safety Strategies*. The fourth objective corresponds to:

- Analyze strategies used around the world that provide fire safety on the identified risks following a prescriptive and an engineering approach.

These four objectives are developed as chapters in a step-by-step manner to finally be used as inputs for the development of the *Best Practice Guideline*, the aim of the research.

1.6 Methodology

This research comprises a literature review of multiple documents from a global scale. The thesis research is structured in seven chapters. The Overview, on the previous section, explains each chapter's content and the sources of information considered.

1.7 Limitations

This thesis research concentrates on a literature review analyzing published documents on a global scale. Direct access to certain of the latest or complete versions of the documents was not always possible. Certain documents had to be translated from different languages into English by using electronic tools.

Fire tests or experiments involving vegetation or any other component as well as numerical simulations are out of the scope of this research.

Chapter II

Vegetative Systems

This chapter consists of a review of the state-of-the-art for green roofs and walls. It comprises their general component, benefits, classification, installation typology, system components, and existing standards. Diagram 3 expose the seven sections that compose this chapter and their main subsections.

Vegetative Systems Overview

2.1 General Components
- Vegetation
- Growing Medium
- Other System

2.2 Benefits
- Public Benefits
- Private Benefits

2.3 Classification
- Green Roof
- Green Wall

2.4 Installation Typology
- Green Roof
- Green Wall

2.5 System Components
- Green Roof
- Green Wall

2.6 General Standardization
- Standards
- Insurance Documents
- Guidelines
- Research Reports

2.7 Final Considerations
- Final Remarks

Diagram 3. Vegetative Systems - Chapter II Overview

2.1 General Components

As previously defined in Section 1.2, vegetative systems are composed of green roof and walls. Each system can be classified more into detail but in general, both of them share the same main components and provide with similar benefits. This section corresponds to the three main elements that conform vegetative systems: vegetation, growing medium, and additional components to support the whole installation as can be seen in Figure 2. A study of these elements considering their properties regarding fire is performed in the following sections.

Figure 2. General Components
Vegetation, Growing Medium, and Other Components.
Images: Garry Belinsky (left), Jongkind B.V. (center), FloraFelt (right)

2.1.1 Vegetation

The vegetation that compose the green systems is affected by the intrinsic properties of the plants but also by physical properties of the environment. Plants have properties that evolve through time. The following factors have an impact on the plants behavior when it comes to ignition or fire spread.

- Species Selection. The selection of the vegetation must be based on the objective, plant characteristics, climate, and microclimate [4]. The type of the green roof and wall, on site conditions such as the temperature, wind, and rainfall must be revised before selecting the species for the system [7].
  Species with the potential of weed developing, poisonous, or prone to toxicity, diseases or pest infestation should be avoided [7]. The depth and mixture of the growing medium, weight loading capacity of the structural elements, budget, and maintenance requirements should also be considered when applicable [7].
  Factors that should be considered when selecting plants that may increase their flammability are: high oil or resin content, low moisture content foliage, tendency for accumulation of dead vegetation underneath (litter), dry leathery leaves, peeling bark, very fine leaves, dry and dead leaves or twigs [8], and a fast drying process time [9].
  Plant types are exposed more into detail in Sections 2.5.1 for green roofs and 2.5.2 for green walls.

In addition to the selection of the species, the environmental conditions will have an impact on the plants' reaction to fire, these aspects should be considered:

- Dry Conditions. Low relative humidity will accelerate the drying process of the vegetation. A lack of proper irrigation may also lead to this drying process. Exposure to sun may also affect the plants hydration.
- Moisture Content. As it is exposed by *Dahanayake and Chow* [9], the most critical factor that affects a plant's ignitability is its moisture content. Green elements systems without a correct irrigation system can lead to dry plants. Compared to well-maintained plants, dry vegetation burns faster and generate more heat [10]. Fire spread propensity, total heat release, and smoke toxicity potency hazard increase with a lower moisture content as it is explained in Section 4.2.2.
- Maintenance. The presence of dead and dry vegetation increases the risk fire spread [11]. Also, overgrown vegetation can work as a fuel ladder that promotes fire spread towards upper levels [9]. Planning should be done to address the requirements of the plant and the desired conditions of the elements. It should consider certain specific tasks and the nutrition of the vegetation [7]. A summary chart of important factors to be considered for maintenance is exposed in Tool 1.

2.1.2 Growing Medium

The growing medium is intended for the rooting of the vegetation and to provide them with water and nutrients. It is composed by an engineered combination of inorganic and organic materials designed for the specific plants and system.

- Inorganic Materials. These components are non-combustible and include clays, slates, shales, aggregate, sand, perlite, and vermiculite [12].
- Organic Materials. These components include compost worm castings, coir, peat, and others. High concentrations of these materials can support combustion affecting the fire resistance of the system [12].

The *ANSI SPRI VF-1 External Fire Design Standard for Vegetative Roof* indicates that the mixture of the growing medium should comply with ASTM or FLL performance standards or be tested with specific testing methods [12].

2.1.3 Other System Components

This category reunites the components that commercial system requires for the attachment to the building and the support of the vegetation and growing medium.

- Supportive Components. Support structure and materials to sustain the vegetation are part of any greenery system. If these materials are combustible, additional fire load is included in the system [13]. Depending on the system selected, the following components can be found: layers, containers, wires, panels, fabrics, irrigation and lighting systems. These elements are explained more in detail in Sections 2.5.1 for green roofs and 2.5.2 for green walls.

An additional factor that can be used in specific designs are synthetic components.

- Synthetic Plants Blending & Decoration. When included in a green wall, plant imitation fixtures made out of silk or plastic, increase the fire load of the element. This synthetic replicas can be highly flammable [11]. The VKF AEAI Norm 1-15 *Fire Protection Norm,* on Article 59 *Decorations* states the following: *"The decorations must not lead to an inadmissible increase in the danger of fire. They must not endanger people and not obstruct escape routes"* [14].

Another component that can be associated with vegetative roofs and walls is the use of insulation. This additional component becomes an extra layer in the whole roofing or wall system.

- Insulation. The Swiss document, *Lignum 7.1 Exterior Walls – Construction and linings* [15], indicates as a result of the tests performed to wood façades that combustible exterior insulation can accelerate fire spread in case of a fire. This same effect may also apply for vegetative systems that include a combustible layer of insulation.
  As it is mentioned by *Bridging the Gap: Fire Safety and Green Buildings* [16], insulation in the market is mostly polyurethane or expanded polystyrene foam. Without any special treatments and exposed to high temperatures, this material will burn strongly producing large amounts of smoke and spreading easily towards surrounding combustible materials [16].
- Irrigation. Not all vegetative systems require irrigation but intensive systems will definitely need it. In some cases, the water demand can be high which is why it is recommend to search for non-potable sources and to consider the reuse of it. Irrigation should be considered at the beginning of the project based on the species selected, sources, and budget available [7].

2.2 Benefits

Vegetative systems provided multiple benefits for the people and the environment. Some of these advantages can be categorized in two main groups, public and private benefits.

2.2.1 Public Benefits

- Reduce Urban Heat Island Effect. An increase in the temperature of urban settlements coming from the heat absorption of building and urban infrastructure materials such as concrete, brick, and glass results in the formation of urban heat islands [7]. Green roof and walls can contribute to provide an urban cooling effect.
  Vegetative systems also increase albedo reflection and allow natural cooling by evapotranspiration [1]. These systems reduce the heat that is radiated by buildings towards its surroundings decreasing the ambient temperature [4] and providing with shade on surfaces for people on its surroundings.
- Sustainable Drainage. Green roofs reduce the amount of run-off water to the drainage system decreasing the risk of flood [1][4].
  The Australian guideline *Growing Green Guide* [7], compares a bare roof against one with a green roofs, the results, as can be seen in Figure 3, show that a green roof can manage storm water volume by having a slow onset which results in a decrease in the volume and maximum flow. This is due to the components of the systems where the vegetation, growing medium, and water retention layers avoid the water to go directly into the storm water system.

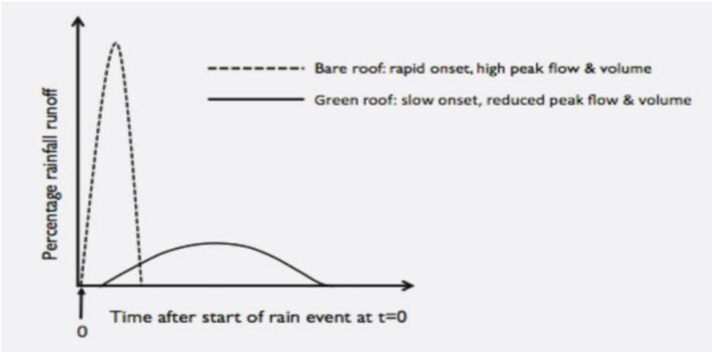

Figure 3. Storm Water Run-Off Comparison
Source: Growing Green Guide [7]

  Additionally, green roofs, can also improve storm water quality by reducing the amount of nitrogen and phosphorus content [7].
  Further test results comparing types of species, depth of the growing medium, and different rainfall amounts on bare roofing systems against green roofs can be revised in the *Growing Green Guide* [7].
- Biodiversity. Vegetative systems promote flora and fauna into the area [1]. This is done by creating or recreating wildlife habitats inside the urban environment. These systems can even create a “green corridor” inside the city promoting wildlife movement [4].
- Human Health and Wellbeing. Vegetative systems provide visual relief and interest for people [17][5]. These systems improve human health and mental well-being by reducing stress, and increasing positive feelings [4][5].
  In locations with high temperatures during summer, green roofs and façades provide shading and help to maintain buildings cooler. This contribute to prevent health related problems associated with extreme heat [7].
  In addition, vegetated spaces have the potential to promote social interaction within the community. These environments are considered to be beneficial for physical and psychological health and wellbeing. Nature provides stress relief in an urban context as well as it improves people’s ability to focus and creativity. It can also reduce antisocial behavior on people [7].
- Improve Exterior Air Quality. An improvement in the urban air quality can be achieved by vegetative systems since the plants leaves will filter noxious gases in the air and capture pollutants on the leaf surface [5]. Also, small particles carried in the air can be stored or degraded in the growing medium. [7].

2.2.2 Private Benefits

- Reduce Energy Consumption. Energy costs of the building can be reduced due to the insulation layer created by a green roof [1]. Shading created by green walls also reduces ambient temperatures [5]. A reduction on the costs for the need of air-conditioning into the building can be achieved which reduce the carbon emissions [4].
  The Australian guideline *Growing Green Guide* [7], indicates that reducing the energy budget of a building is achievable by the inclusion of green roof and walls which reduces the heat gain or loss across the surface where the vegetative system is installed. This document revised experimental data that supports this benefit. Among the reviewed researches, a comparison on the annual energy demand between a room with and without a green roof shows that the amount of energy either to heat or to cool the room is lower when it has a green roof on top of it. Figure 4 shows the results from the experiment done in Melbourne, Australia.

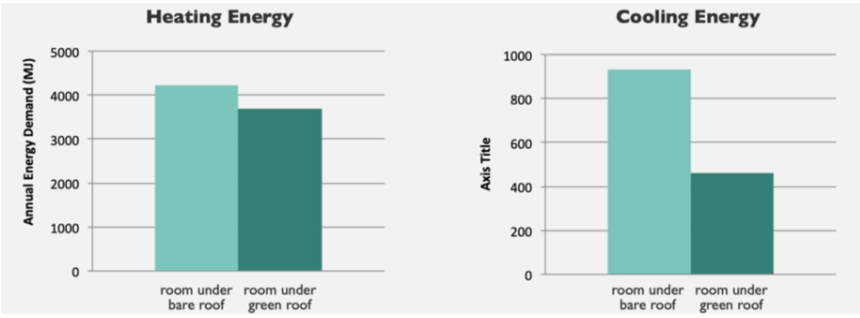

Figure 4. Energy Consumption Comparison
Source: Growing Green Guide [7]

  Additional test results comparing thermal conductivity of certain roofing systems against green roofs as well as different plant species can be revised in the *Growing Green Guide* [7].
- Sound Attenuation. Vegetation creates a sound insulation layer [1]. A vegetative system can help to reduce noise coming from the exterior to the inside of the building.
- Building Protection. Vegetative systems can provide shade protection for the exterior finishes against UV radiation and associated temperature fluctuations [5].
  The Australian guideline *Growing Green Guide* [7], based on experimental studies, mentions that the shading of a green wall can reduce the wall surface temperature in between 5-10°C. Different variables such as the orientation, species selected, and matureness of the plants have an impact on the shade that is produced [7].
- Marketing. Spaces for recreation and improved aesthetics make the buildings more visually attractive for potential clients interested in buying a property [4].
  Research in Canada have found that an accessible green roof can increase in 11% the property value of a building. Additionally, a building with a view towards a green roof have an increase of 4.5% of its property value [7].
- Green Building Rating Schemes Credits. Vegetative systems can contribute in achieving credits for different categories on green rating schemes such as LEED, BREEAM, and others [4][5].
  Annex A summarizes the credits that can be achieved by vegetative systems on LEED scheme. These green rating schemes focus on the usage of certain sustainable techniques like vegetative systems but does not consider in an explicit manner fire safety concerns. In many cases, these rating schemes expect that fire safety requirements are satisfied by building code compliance [3]. The hazard that these systems may create to the buildings is not fully understood.
- Agriculture. Edible plants and herbs can be produced by vegetative systems [9]. The *Growing Green Guide* [7], mentions that urban food production with these systems can be part of private residences but also school and community farms as well as commercial farms [7].

Given the benefits of green systems to the urban environment and the sustainability, some local authorities are moving toward implementing policies where green roofs are expected to be included in new buildings when it is possible [4]. As it is mentioned in *Green Roofs, Facades, and Vegetative Systems* [2], the Toronto Municipal Code requires green roofs on buildings built after 2010 [2].

2.3 Classification

2.3.1 Green Roof

Based on the depth of the growing medium, green roof can be classified as extensive, semi-intensive, and intensive systems as can be seen in Figure 5. These classifications have different characteristics, support certain types of vegetation, and are intended for specific uses [12][4][18].

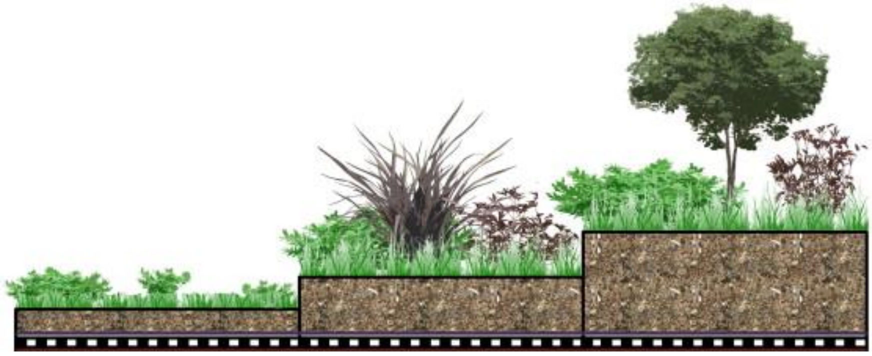

Figure 5. Green Roof Classification
Extensive (left), Semi-intensive (middle), and Intensive (right)
Source: Green roof systems: A study of public attitudes and preferences in southern Spain [19]

2.3.1.1 Extensive Green Roof

This type of system is intended for visual and biodiversity interests. It requires less maintenance, little or no irrigation, and lower nutrient levels. Plants selected for this system can survive on shallow substrate depths. This system presents the least weight and the smaller thickness [4].

2.3.1.2 Semi-Intensive Green Roof

This type of roof comprises characteristics of both extensive and intensive roofs with a depth that is in between these two. It includes similar vegetation to the extensive systems in addition to more plant variety such as shrubs and woody plants. The selection of the plants defines the irrigation and maintenance requirements [4].

2.3.1.3 Intensive Green Roof

Mostly intended for recreational and accessible spaces for people. They can include a big variety of vegetative species including trees and components similar to parks which allows for the inclusion of other installations for the usage of people. These systems present a deeper growing medium that increases the overall weight. Irrigation and maintenance are required with more frequency [4].

Nature Based Strategies for Urban and Building Sustainability [20] provides a summary chart with the main characteristics of the three types of green roofs as can be seen in Table 1. The chart is reproduced including information from GRO [4] and SIA [18] documents. The values may vary between standards.

Characteristics	Green Roof Classification		
	Extensive	Semi-intensive	Intensive
Weight Fully Hydrated	50-150 kg/m^2	120-350 kg/m^2	>350 kg/m^2
Growing Medium Depth	60-200 mm	100-250 mm	>250 mm
Irrigation	Never or periodically	Periodically	Regularly
Maintenance	Low	Moderate	High
Cost	Low	Middle	High
Use	Only for maintenance	Moderate	Pedestrian areas
Plant Typologies	Succulent, herbaceous, mosses, and grasses	Herbaceous grasses, low shrubs, & woody plants	Grasses, perennials, shrubs, and trees

Table 1. Green Roofs Classification and Main Characteristics
Sources: GRO, SIA, and Nature Based Strategies for Urban and Building Sustainability [4][18][20]

Included within the previous classification, another type of system is identified by the GRO [4] called a biodiverse green roof. This type of roof is considered as a system with varying substrate depths that promote diversity for plants that possess deep roots and shallow ones. The aim for this system is to recreate the natural habitat that existed originally before the building construction. The vegetation is composed of a mixture of wildflowers, grasses, and sedums [4].

2.3.2 Green Wall

Green walls can be divided in two main groups: extensive systems or green façades and intensive systems or living walls [20]. Vegetative walls can be applied on the exterior of buildings as part of the façade or as interior elements in atriums, corridors, or major spaces.

2.3.2.1 Extensive Systems or Green Façades

Extensive systems are composed by climbing/green façades [5][21]. This system usually only applies for exterior green walls. This type of green wall system holds climbing plants or cascading groundcovers that cover specially designed structures meant for supporting vegetation. Vines used for this system are usually rooted in the ground at the base of the supporting structures but plants can also be rooted in intermediate or rooftop planters depending on the design. Climbing plants have two main modes of attachment to the vertical element, direct attach to the wall or indirect attachment by additional support as can be seen in Figure 6.

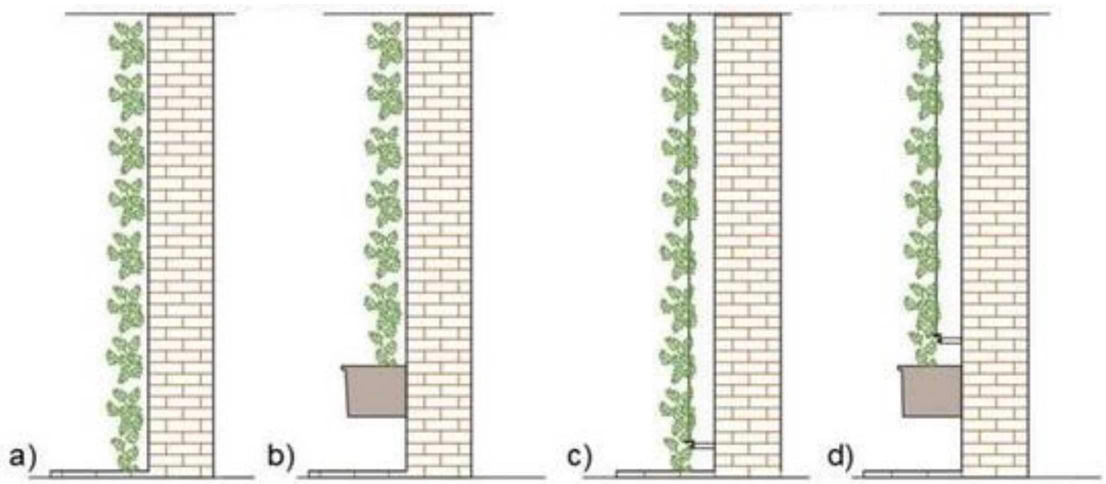

Figure 6. Green Façades Classification
(a)(b): Direct System – (c)(d): Indirect System.
Source: Green Wall systems: Where do we stand? [22]

Direct systems attach themselves to the wall naturally by self-clinging plants. Plants are rooted on the base of the building to the ground and spread towards the upper surface in most cases. This way of attachment may cause damage to the façade depending on the species selected [7].

Indirect systems use twining and tendril climbers that are supported by additional elements so there is no direct contact with the wall. Trellis systems, which can be of two or three-dimensional panels made of galvanized rigid wires, support climbing plants off the façade surface. As an alternative, the climbers can be support by high tensile steel cables that are attached to the vertical surfaces using anchors [7].

2.3.2.2 Intensive Systems or Living Wall

Intensive systems are composed by living walls. This system applies for both exterior and interior green walls. The system, by using textiles or container modules, cover the entire supportive structure or frame installed in the wall with roots in a vertical and horizontal orientation [5]. This system can be subdivided into three categories, cloth, panels, and active systems [20]. A diagram of the systems can be seen in Figure 7.

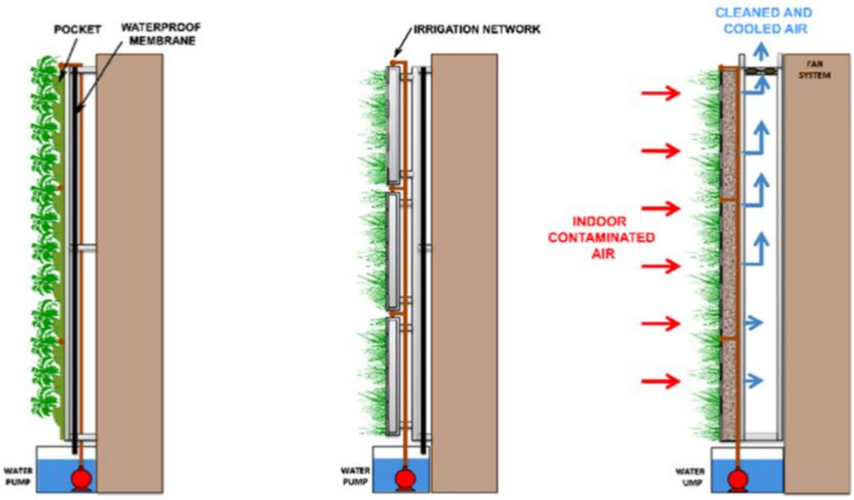

Figure 7. Living Wall Classification
Cloth (left), Modular Panel (center), and Active Systems (right).
Source: Wind tunnel analysis of artificial substrates used in active living walls [23]

Cloth systems are composed by layers of organic or synthetic materials that are supported by frames throughout the façade [5]. The layers can be composed of mesh, geotextiles, fabrics, mineral wool, etc. [13]. The material is folded or cut in a way to create pockets where the roots are hold. This system works in soil-less environments where plants are fed and watered through an irrigation system [5]. Some systems also are available to support small quantities of growing medium in each pocket [20].

Modular panel systems are composed by modular soil containers, boxes, or pots that contain the growing medium and the plants [5]. It also includes an irrigation system for the modules [13]. Some systems may also be hydroponic. The containers may be produced with galvanized steel, polyethylene, and recycled plastic [20].

An additional less common type are active living wall systems. These systems force the air to flow through the living wall filtrating it. Active systems are used in interior spaces and usually are combined with ventilation and air conditioning systems. The filtration process also provides a cooling effect to the air [20].

Nature Based Strategies for Urban and Building Sustainability [20] provides a summary chart with the main characteristics of the multiple types of green walls. This chart is reproduced in Table 2.

Characteristics	Green Wall Classification			
	Extensive System	Intensive System		
	Green Façades	Cloth Systems	Panel Systems	Active Systems
Goals	Aesthetics, passive energy-savings, biodiversity	Aesthetics, passive energy-savings, marketing, biodiversity, agriculture	Aesthetics, passive energy-savings, marketing, biodiversity, agriculture, noise barrier	Air biofiltration, evaporative cooling, active energy saving, marketing, aesthetics
Structure	Cable or wires	Textile	Plastic or galvanized steel	Felt
Location	Exterior	Exterior and interior		Interior
Growing Medium	Organic substrate	Hydroponic cultures or organic substrate		Hydroponic cultures with inorganic substrate
Maintenance	Low	Medium-high		High
Cost	Low	Medium-high		High
Vegetation	Climbing and hanging plants	Epiphytic, lithophytic and bromeliads, ferns, succulent, herbaceous, small shrubs, climbing plants, vegetables		

Table 2. Green Walls Classification and Main Characteristics
Source: Nature Based Strategies for Urban and Building Sustainability [20]

2.4 Installation Typology

2.4.1 Green Roof

Green roofs can be also classified based on their installation typology. Three main types are used, built-in-place, modular, and hybrid systems. Figure 8 exemplifies the three cases.

Figure 8. Green Roof Installation Typology
Built-In-Place System (left), Modular System (center), and Hybrid System (right)
Sources: FM Global Loss Prevention Data Sheet 1-35 & Green Roof Design [24] & [25]

2.4.1.1 Built-In-Place Systems

This system is constructed in site using several different layers over the entire roof surface. Built-in-place systems have a natural function by sharing water, nutrients, and organisms across the entire surface of the green roof through the continuous soil layer. The vegetation can be grown on site, plugged in or rolled as carpet over the growing medium [25].

2.4.1.2 Modular Systems

This system is composed by rectangular containers that are placed over the roof surface. Modular systems are compartmentalized which creates a barrier between modules not allowing them to share water, nutrients and organisms. The vegetation in these systems is usually pre-planted [25]. Modular containers are usually made out of plastic materials which may contribute to the fire load of the system.

2.4.1.3 Hybrid Systems

This system combines the two previous systems by considering their advantages. Hybrid systems uses non-compartmentalized modules where the soil is interconnected between them. This allows moisture, nutrients and organisms to be shared across the modules [25]. The upper part of the modules is exposed so part of the growing medium and the vegetation gets in contact with the ones around it. Again, the modules are usually made out of plastic materials which can contribute to fire load.

2.4.2 Green Wall

Due to the limit information found related to green walls, existing information from wood and double-skin façades are considered since they share certain conditions that can be applied to vertical green systems. An analogy with these construction elements is considered in the next sections. Figure 9 illustrate the three types, non-ventilated walls, ventilated walls, and double-skin façades.

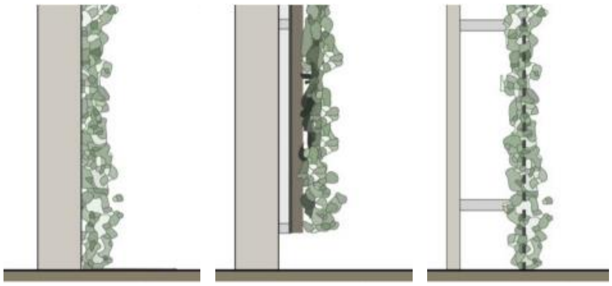

Figure 9. Green Wall Installation Typology
Non-ventilated Wall (left), Ventilated Wall (center), and Double-Skin Façade (right)
Source: Living walls in indoor environments [26]

2.4.2.1 Non-Ventilated Wall

Green wall systems can be directly attached to the walls. The natural properties of certain species allow them to attach themselves directly to the wall. There is no ventilation gap between the vegetation and the wall. Usually this typology corresponds to extensive systems where the plants are rooted on the ground.

2.4.2.2 Ventilated Wall

This type of system corresponds to the green elements that are indirectly attach to the wall by an additional structure. This type of construction results in the inclusion of an air gap that avoid moisture from the green wall to move into the building wall and also prevent roots from getting in contact with the building. This air gap will also reduce the risk of mold growth [7].

The Swiss document, *Lignum 7.1 Exterior Walls – Construction and linings* [15], considers this air gap on wood façades and analyzes it in terms of fire safety. To avoid continuous air circulation behind the wood linings of the façade, certain measure should be installed. This can also be applied for vegetative walls. The safety measures are explained in Chapter 5.

2.4.2.3 Double-Skin Façade

The final type of green wall is explained by the Swiss note, *VKF AEAI Explanatory Note 102-15 Buildings with Double-Skin Façades* [27]. It defines a double-skin façade as an element that has multiple layers and is composed by two levels of façade. The secondary façade is located on the exterior side and is the one facing the environmental conditions. The primary façade is the one on the interior side and it limits the extension of the interior space, it can include windows and insulation. In between these two façades, an intermediate climate zone is located which extends through multiple levels [27].

It is in the secondary façade where the vegetation will be located when it is used as an analogy for green walls. The primary façade and intermediate climate zone remain as previously described with the possibility of different configurations. This system comes with certain fire safety remarks that are explained in Chapter 5.

2.5 System Components

2.5.1 Green Roof

Most built-in place green roof systems are composed by a series of layers that, if installed correctly, accomplish the initials goals and provide the specific benefits for the project. As it was reviewed in multiple standards and other relevant references, the general layers and components are identified and explained in the following paragraphs. Figure 10 illustrates the typical green roof layers.

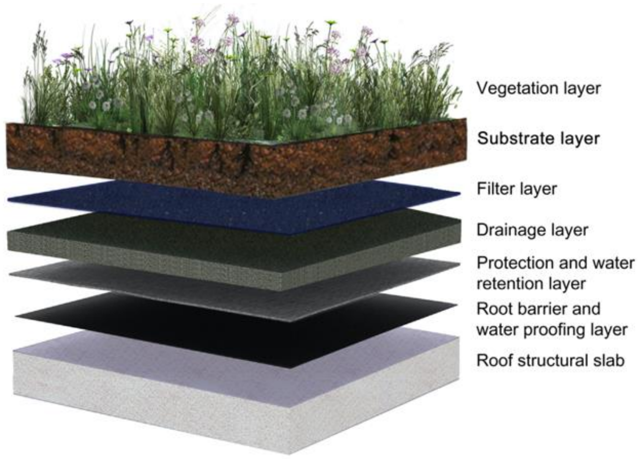

Figure 10. Layer Scheme
Source: Nature Based Strategies for Urban and Building Sustainability [20]

- Vegetation Layer. The selection of the plants and seeds is based on several variables and considerations as it was introduced in Section 2.1.1. It should be based on the objective, plant characteristics, climate, microclimate, and latitude of the project.
  Table 3 reproduces a chart from the German *FLL Guideline* [28] indicating the depth requirements of the growing medium for the type of vegetation.

Depth of the vegetation growing medium			4	6	8	10	12	15	18	20	25	30	35	40	45	50	60	70	80	90	100	125	150	200
Types of greening and vegetation forms	Extensive Greening	Moss-sedum																						
		Sedum-moss-herbaceous plants																						
		Sedum-herbaceous-grass plants																						
		Grass-herbaceous plants																						
	Semi-intensive greening	Grass-herbaceous plants																						
		Wild shrubs, coppices																						
		Coppices and shrubs																						
		Coppices																						
	Intensive Greening	Lawn																						
		Low-lying shrubs and coppices																						
		Med-height shrubs and coppices																						
		Tall shrubs and coppices																						
		Large bushes and small trees																						
		Medium-size trees																						
		Large trees																						

Table 3. Growing Medium Depths for Different Plant Types
Source: FLL Guideline [28]

The Australian *Growing Green Guide* [7], provides a list of type of vegetation that can be used on green roofs based on the same parameter of growing medium depth.

  - Low Growing Succulents. Present a great drought tolerance which can result in minimal or even no irrigation requirements [7].
  - Herbaceous Perennials. These non-woody plants may require high irrigation during dry periods and could present a fire hazard due to its large biomass [7].
  - Annual to Biennial Plants. Annual and ephemeral plants require irrigation in order to be sustained for longer periods. Vegetables also fall under this category which require irrigation and maintenance to avoid weed [7].
  - Turf. Turf may require frequent irrigation, fertilizing, and constant maintenance for mowing to keep it healthy and with a good performance for use [7].
  - Shrubs. Depending on the height of the shrub, deeper growing medium are required which will consume more water as well. Regular maintenance is required to remove excessive biomass [7].
  - Trees. Small trees up to five meters can be installed on green roofs. This type of vegetation require deeper growing mediums of at least one meter [7].

An extensive list of specific species for each type of vegetation for green roofs can be consulted in the Australian guideline *Growing Green Guide* [7]. These lists are suitable for the region of Melbourne, Australia but can serve as a first guide for projects on other locations considering the local conditions. In general, it is recommended to consult with local experts and review local standards or the existing ones from similar latitudes for the selection of species.
When it comes to fire considerations, certain plants perform better than others, this is revised in Chapter 3.

- Growing Medium Layer. This layer is intended for the rooting of plants and to provide them with water and nutrients. Engineered substrates are mostly used nowadays that consider physical and chemical properties. The mixture is composed by organic (usually <20%) and inorganic components. The final mixture composition have an influence in the vegetation that can be installed [7]. Also, the depth and the annual precipitations will impact the growing medium final mixture or plant selection [18]. Organic mulches can create a fire risk in dry and hot temperature locations [7].

The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] request a depth of at least 80mm of growing medium. The proportions of the two components depends on the systems and vegetation [24].

- Moisture Retention Mat. Some standards or guidelines suggest the inclusion of a layer for moisture retention depending on the green roof system to provide moisture to the roots. It can be composed of thermoplastic fabric or polypropylene fibers [24].
- Filter Layer. Maintaining fine particles of the growing medium within it and preventing them to trespass the layers below is the main goal of the filter layer. This will prevent wash-though of the growing medium and clogging of the drainage layer. The water flow rate, growing medium composition and vegetation type should be considered for the selection of the filter fabric. It can be used as a root barrier depending on the product [7]. It can be composed of geotextile fibers [7] or thermoplastic fibers (polypropylene, polyethylene) [24].
- Drainage Layer. This layer is intended for the evacuation of the waters below the growing medium in order to avoid the accumulation of large amounts of water that can affect the building and vegetation. Rock aggregates can be used as a drainage layer but more recent green roof systems use plastic drainage sheets or boards which are lightweight. Water retention can also be achieved in this layer that will be used later by the plants [7]. Measures to evacuate the water in case there is an overflow of rain water should be considered [18]. It is composed by rock aggregate [7] or thermoplastics (polypropylene, polyethylene) [24].
- Protective Layer. Protection for the waterproofing system against damage related to the installation process is done by the use of a layer of mats or boards. This can also increase the water retention of the system and provide certain noise absorption [7]. It can be composed by polyester and polypropylene [7].
- Root Barrier. Protection against root penetration into the waterproofing layer should be considered. Depending on the vegetation type, thicker root barriers are required. The compatibility of this layer and the waterproofing one should be revised regarding material compositions [7]. It can be composed by polyethylene sheets [7] or thermoplastics (PVC, TPO, and again polyethylene) [24].
- Waterproofing Layer. The roofing system requires a treatment to prevent water from getting inside the building. This should be done with materials that are strong and flexible to withstand physical and thermal expansion movements. Depending on the location of the project, this is something commonly done by a specialist. It also requires an independent leak detection specialist to test the system. If the system is not root resistant, this additional layer is required [7]. There are several systems on the market which can be divided in two, liquids or sheets. Liquid applied treatments are composed by bitumen emulsions, polymer cement, polyurethane, and acrylics [7]. Preformed sheets are made out of asphalt-based, thermo-plastic, and thermo-setting [7]. The selected solution must meet the fire classification requirements by the local authorities [12].
- Roof Structure. The roof deck is the layer that carries the loads from all of the other ones on top of it, vegetation and equipment [18]. It redistributes them downwards into the building through the other structural elements. Roof decks are mostly concrete elements but metal sheet can also be used. The use of timber is accepted but it may be difficult to gain an insurance with this material [7].
  As it is mentioned in *Bridging the Gap: Fire Safety and Green Buildings* [16], the roof slope should be considered during the design process since the structure will be exposed to high amounts of water during storms or during firefighting operations. This will add additional loads to the element that need to be considered to be sustained [16].

Projects with high exposure to wind and with high slopes may require additional protective layers.

- Erosion Protection. Measures should be taken in case there is a risk of erosion due to wind or water [18]. A retention system is a solution to avoid materials been blown off the roof. The wind force is stronger on the perimeter, corner, and edges than in the center of the surface, special attention should be placed on these areas where edge treatment should be used. Plant should also be selected considering the areas with higher wind exposure. Additionally, parapet

walls, jute erosion control nets, or wire retaining system can be considered [7]. It can be organic or inorganic, temporary or biodegradable [12].
The *ANSI FM Approvals 4477 American National Standard for Vegetative Roof Systems* [29] considers the use of wind blankets as an element to minimize erosion and to help during stabilizing period of the roots on a new green roofs systems.

- <u>Sliding Protection</u>. Measures should be taken to prevent the sliding of the system layers [18]. Additional protection is usually required when the slope is greater than 15°. Some measurements include anti-erosion jute netting, drainage layer with large cups filled with growing medium, and honeycomb webbing [7].

Other components of green roof systems may include the following elements.

- <u>Thermal Insulation</u>. As previously mentioned in Section 2.1.3, an insulation layer can be part of the roofing system. In a green roof, it can be located below the roof deck but it is preferred to be located above the waterproofing layer since this will protect it [7].
The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] recommends the use of the two layers of insulation when the system has a growing medium over 200mm, above and below membrane. This is in order to protect the waterproofing layer. Combustible materials such as expanded polystyrene or extruded polystyrene can become a fire hazard [24].
- <u>Irrigation</u>. Depending on the type of green roofs and on the species selected, an irrigation system is required. It will ensure the environmental and aesthetic goals. When an irrigation system is used, it should consider additional variables such as climate, species selection, growing medium composition, layout design, water supply, and budget. Different irrigation methods include automatic or manual systems and visible or sub-surface installations [7].

In case where the green roof is not a build-in-place installation it includes an extra component.

- <u>Modular Containers</u>. As introduced in Section 2.4.1.2, green roof that include modular containers have this additional component into their system. This containers mostly allow a growing medium depth of 100mm which reduces the variety of species that can be used [25]. The modules can be composed of plastic or metallic materials [25].

2.5.2 Green Wall

Depending on the systems classification, extensive or intensive, the number of components may increase. There are plenty of systems on the market and others under development that results in multiple elements as can be seen in Figure 11. The components exposed in this section consider the main elements but some systems may not require certain components or include additional ones.

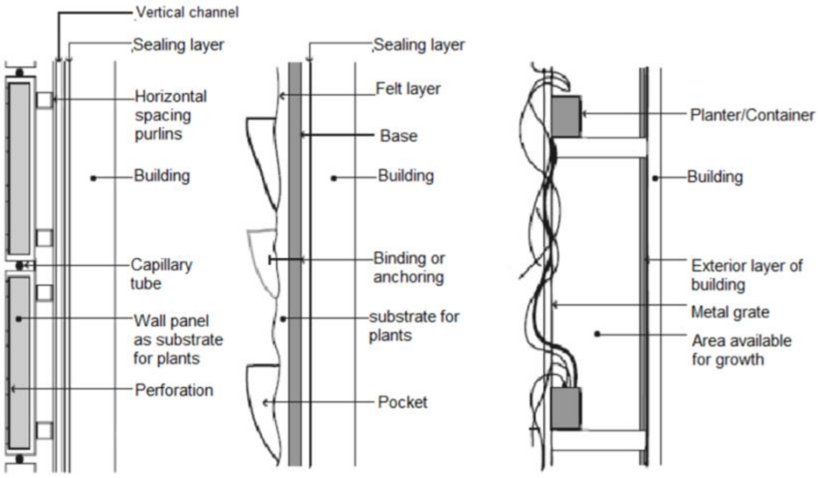

Figure 11. Components on Green Walls
Modular Systems, Felt System, and Indirect Green Façade.
Source: Green Construction in Building Renovation [30]

- Vegetation. The Australian *Growing Green Guide* [7], provides with a list of types of vegetation that can be used on green walls. It is divided into the green façades and living walls. Regarding green façades, the selection of the species depends on the tolerance to light, the wind factor, maintenance, and the screening coverage that is required. The method used by the plants to attach themselves to the structures divides them in two as can be seen in Table 4 (left).
  Living walls require similar considerations for the selection of the species, such as the objective and classification of system that is proposed. In addition, climatic conditions, access to natural or artificial light, shade, sun and wind tolerance should be revised. Also, the location of the species in the wall should consider that borders might have higher wind exposure and lower levels will probably end up with more water from the irrigation system [7]. The vegetation typology suggested in the guide can be seen in Table 4 (right).

Vegetation Typology	
Extensive Systems Green Façades	Intensive System Living Walls
• Self-clinging • Twining and tendrils	• Shrubs • Evergreen herbaceous perennials • Herbaceous ground covers • Ferns • Grass-like foliage forms • Lilies & irises

Table 4. Green Wall Vegetation Typology
Source: Growing Green Guide [7]

  Based on these considerations and the system classification, a detailed list of specific species for green façades and living walls can be consulted in the Australian *Growing Green Guide* [7]. The list is suitable for the region of Melbourne, Australia but it can serve as a first input for projects on other locations considering the local conditions. In general, it is recommended to consult with local experts and to revise local standards or the existing ones from similar latitudes for the selection of species.
- Growing Medium. Living walls can include an inert or a natural engineered growing medium depending on the system and plant requirements. The growing medium should provide the plants with a physical mean for them to attach themselves. It can also act as a water retention sponge for the use of plants but this increase the load of the system. It is composed by inorganic and organic components including horticultural foams [7].
- Waterproofing. A waterproof layer is required depending on the project and system used. Usually, if the air gap between a living wall and the building wall is not big enough waterproofing becomes necessary. Roller-liquid treatments on the building wall can be used for internal and external systems. Also, the building wall can consider this requirement into its material design. Its manufacturing and installation should comply with local regulations [7].
- Air Gap. When a ventilated façade is considered, an air gap is required to protect the building wall as mentioned in Section 2.4.2.2. Air circulation between the vegetation and the building wall becomes possible. This condition should be revised carefully.
- Intermediate Climate Zone. Double-skin façades include an intermediate climate zone as mentioned in Section 2.4.2.3. This large separation between the vegetation and the building should be revised carefully.
- Supportive Components. An independent vertical structure attached to the building façade provides the support required by certain indirect vegetative system to extend on a vertical and horizontal manner covering the desired surface. The structure will require specific elements depending on the choice of the system. Indirect green façades will require for the climbing plants wires or cables usually made out of stainless steel. Living walls require fabrics or modular panels or containers to support the vegetation and growing medium. Usually these components are made out of plastic or metal materials.
- Building Façade. Certain systems are supported directly to the building main façade as is the case for extensive direct green façade systems.

Other components of green wall systems may include the following elements.

- Thermal Insulation. As previously mentioned in Section 2.1.3, an insulation layer can be part of the green wall. The inclusion of this layer is more related to the building itself than to the vegetative system but since the materiality of this layer may be flammable, it should be revised and considered carefully.
- Irrigation. Living walls require irrigation to survive. Inbuilt irrigation systems provide a solution that can also be automated. Irrigation will also provide the nutrients for the plants based on their requirements. Special components to monitor and measure specific values on the system and water may also be included. In the same way, if the water is harvested it may require other special equipment for its correct operation [7].
- Drainage and Drip Trays. Drainage for elevated containers on green façades may be considered to avoid them from getting overfilled with rain water [7]. Drip trays may sometimes be required to collect the excess of water below the panels or containers on both green wall systems [7].
- Lighting. Internal living walls may require artificial lighting to maintain the wall healthy. This requires specific aspects that should be revised by an expert [7].
- Decoration. Decorations such as synthetic plants are sometimes included in green walls to a create visual highlight with colors or species that are not suitable for the specific location. These elements may be fabricated from silk or plastic materials which increase the fuel load.
- Active Systems. Active systems require supplementary electrical and mechanical equipment to provide with their biofiltration capacity.

2.6 General Standardization

The following documents provide guidance for the design of vegetative systems in a general manner. These documents address general requirements such as system classification, wind, plant selection, maintenance, and irrigation, in addition with fire safety measures. All of the documents exposed in this section include fire safety remarks in a general or more specific manner.

A thorough explanation of the main documents is exposed by *E. Giacomello* in *Green Roofs, Facades, and Vegetative Systems* [2]. This book addresses four major concerns related with vegetative systems: fire risk, wind design, irrigation, and maintenance. A total of 25 documents from different latitudes were revised as part of the scope of the research extracting valuable information on these concerns.

- Standards
    - SM 3700:2017 (2017). *Green Roofs-Criteria for the planning, construction, control and maintenance of Green Roofs,* Malta.
    - ASTM E2777 (2014). *Standard Guide for Vegetative (Green) Roof Systems*, USA.
    - ANSI/SPRI VF-1 (2017). *External Fire Design Standard for Vegetative Roofs,* USA.
- Insurance Documents
    - FM DS 1-35 (2020). *Vegetative Roof Systems,* FM Global.
    - ANSI FM Approvals 4477 (2016). *American National Standard for Vegetative Roof Systems*, FM Global.
- Guidelines
    - FLL (2018). *The Landscaping and Landscape Development Research Society. Guidelines for the Planning, Construction and Maintenance of Green Roofing*, Germany.
    - CIBSE KS 11 (2007). *Knowledge Series 11 Green Roofs*, UK.
    - CIBSE (2013). *Guidelines for the Design and Application of Green Roof System*, UK.
    - GRO (2011). *GRO Green Roofs Code*, UK.
    - State of Victoria, Department of Environment and Primary Industry (2014). *Growing Green Guide. A guide to green roofs, walls and facades in Melbourne and Victoria, Australia*, Australia.

- Research Report
    - Department for Communities and Local Government (2013). *Fire Performance of Green Roofs and Walls*, UK.
    - NASFM (2010). *Bridging the Gap: Fire Safety and Green Buildings. A Fire and Building Safety Guide to Green Construction*, USA.
    - NFPA FPRF (2012). *Fire Safety Challenges of Green Buildings: Final Report*, USA.

When it comes to green walls, at the current time, there are no standards developed for these systems [2][11]. The previous documents address green roof regarding general and certain fire safety concerns. Only the Australian *Growing Green Guide*, the British *Fire Performance of Green Roofs and Walls*, and the American *Fire Safety Challenges of Green Buildings: Final Report* guideline and research reports address green walls. The lack of standardization related to green walls is explained by *E. Giacomello* due to the less frequency and recent popularity of these vertical systems. In addition, there are multiple types of green walls and new technologies being developed and tested at the moment. All these factors makes it hard to standardize the system [2].

In general, regarding the green buildings movement, as it is mentioned by *Bridging the Gap: Fire Safety and Green Buildings* [16], it is important that during the development of the standards and rating criteria, considerations from the fire service are being taken into account since this group is the one that has the expertise to identify potential hazards for a future firefighting operation on a building [16].

In the same manner, the inputs from fire safety engineers should also be considered to identify potential hazards during the design, construction and operation stages of a building that includes any of the new green building techniques.

2.7 Final Considerations

The review of the state-of-the-art for vegetative systems provided with an understanding of the importance and general functioning of these systems. The three main components, benefits, classification, installation typologies, system components, and standards provided with a better comprehension of what is on the market nowadays and where are the gaps regarding safety topics. The study indicates the need of performing an in-depth revision of the missing fire safety concerns that are not covered by the standards to analyze the fire behavior of these systems.

In general, vegetative systems are composed by three main elements, vegetation, growing medium, and other components. The vegetation can be considered a non-traditional material for constructions since its properties are affected by the environment and the plants are constantly evolving through time. Species selection, moisture content, environmental conditions, and maintenance have an impact on the conditions of the plants. The growing medium is basically a combination of organic and inorganic components that is designed for each system considering the needs of the plants. Finally, other components mostly comprise supportive elements for the previous two.

Multiple benefits are obtained from the use of vegetative systems in buildings, these can be divided in public and private. Public benefits relate to positive environmental improvements and health for human beings. Private benefits also have a positive impact on the environment but in addition, it brings attractive conditions for the building, its owners, and the tenants. The benefits are promoted without considering in some cases the fire safety impact that these systems may pose.

Green roofs are classified based on the depth of the growing medium as extensive, semi-intensive, and intensive systems. The deeper the system gets, the more plants it can sustain. But this depth also increases the cost, irrigation, and maintenance requirements.

Green walls are basically divided considering how the system is rooted. Extensive systems or green façades are rooted on the ground at base of the wall and the vegetation climbs above it. Their cost and maintenance requirements are low but the number of species that can be sustained is reduced. On the other hand, intensive system or living walls are rooted in small compartments across the entire height and width of the system. It can sustain a wider variety of plants but maintenance and cost increase.

Vegetative roofs can be installed as built-in-place systems with continuous layers covering the entire surface of the roof. Modular systems use containers the are easily placed on the roof but creates a barrier between each module. Finally, hybrid systems combine the easy installation of the modules with the continuity benefits that built-in-place system have.

Vegetative walls can also be installed in three different manners. Non-ventilated systems are directly attached to the walls. Ventilated walls are indirectly attached having an air gap between the system and the building. Double-skin façades have an intermediate climate zone between the two façades that extends through the entire height of the element. Some of these conditions need to be analyzed further in terms of fire safety.

Both systems are composed by multiple elements, each one addressing specific requirements for the wellbeing of the system. The variety and materiality are broad but given the years available on the market, green roofs have general elements that apply for many systems. Green walls, on the other hand, are more recent elements that are still under development and the diversity of systems components is broader and may vary more. In general, the multiple elements work together to achieve the initial goal.

Regarding standards and guidelines available for vegetative systems, there are documents that address the design, classification, wind concerns, plant selection, maintenance, and irrigation. Additionally, the documents mentioned include fire safety remarks in a general or more detailed manner. Most of the exiting documents correspond to green roof, only a guideline and two research reports provide information related to green walls. In general, it is important that the existing and new standards as well as rating schemes that promote vegetative systems are being revised in terms of fire safety.

With the gathered knowledge of the functioning and components of vegetative systems, and understanding that many of the existing standards and rating schemes do not entirely address fire safety concerns, it is required to revise them from a safety perspective. Initial signs of hazards were identified suggesting a study of the fire behavior of these elements.

Chapter III

Fire Review

This chapter corresponds to a review of vegetative systems from a fire safety point of view. Fire spread, standardization, tests, experiments, and modelling of vegetation specifically involving the vegetation as well as the other elements of vegetative systems are addressed in the following sections. Diagram 4 expose the five sections that compose this chapter and their main subsections.

Fire Review Overview

3.1 Fire Spread
- Horizontal Fire Spread
- Vertical Fire Spread

3.2 Fire Standardization
- Vegetative Systems

3.3 Fire Tests and Experiments
- Testing Standards and Fire Classification
- Fire Experiments
- Wood Façade Testing Analogy

3.4 Modelling of Vegetation
- Wildland Fire Report & CFD Process

3.5 Final Considerations
- Final Remarks

Diagram 4. Fire Review - Chapter III Overview

3.1 Fire Spread

Two types of fire spread may be applicable for vegetative systems: horizontal spread for green roofs and vertical spread for green walls as can be seen in Figure 12. The following sections are based on general fire spread considerations but also specific documents involving vegetation and fires.

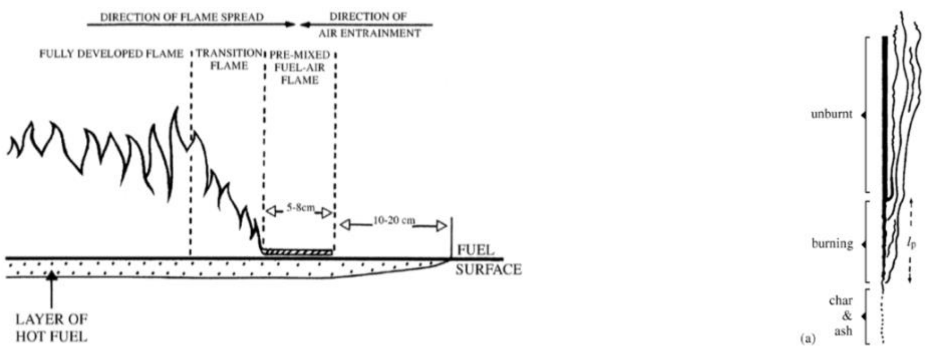

Figure 12. Horizontal and Vertical Fire Spread
Source: An introduction to fire dynamics [31]

3.1.1 Horizontal Fire Spread

When it comes to fire spread in a green roof, given the nature of the system, a horizontal fire spread is analyzed. Due to the similarity between green roof and forest fires by sharing vegetation and growing medium as the fuel, important considerations can be derived from existing research about the last.

The Swedish research report *Green roofs - From a fire technical point of view* [32], analyzes forest fires by considering the report *Forest fire - Fire behavior and interpretation of fire risk index* [33] as well as some experiments performed on herb sedum roofs from the academic report *Herb Sedum Roof - A survey of the fire properties and design of a herb sedum roof with regard to fire* [34].

The following parameters were developed considering Swedish and Canadian forests but the principles can be applicable to other latitudes.

- Burning Time
  Described as the time between the moment the fuel gets ignited until it gets extinguished. The thinner the element is, the faster it burns out [32].
  From the forest fire report, the grass fodder is stated to have a burning time of 20 seconds while for moss fodder it is of 1-2 minutes [33]. The sedum herb roof report found by performing a few tests that the burning point for this type of grass is between 40-50 seconds [34].
- Intensity
  It is defined as the flame's energy development per unit length in the flame front (kW/m). Depending on which part of the flame front is being analyzed, the intensity of the fire may vary. It is affected by the slope of the ground and the direction of the wind [32].
  The following parameters influence in the intensity of the fire:
  - Fuel Mass
    This is described as the amount of fuel. Based on the Swedish research report, tall trees and shorter shrub landscapes have a fuel quantity of 0.7 kg/m^2, fine fuel on land 0.6-1.2 kg/m^2 and grassland of 0.3-1kg/m^2 [32].
  - Energy Content
    Based on the Swedish research report, the energy content will not vary significantly between fuels. For dead fuels the energy content is of about 18 000 kJ/kg of dry weight while for living fuels about 24 000 kJ/kg. A green roof, being a mixture of living and dead fuels is assumed to have an energy content between 18 000 - 24 000 kJ/kg [32].
  - Spreading Rate
    It consists of the speed at which the fire advances in time (m/min). The spreading rate varies depending on the Initial Spread Index ISI, which is combination of the Fine Fuel Moisture Content FFMC, wind speed, and fuel type. High moisture and low wind speed will result in a low ISI while the opposite will result in a high value [32].
    In the case of green roof, the ISI can be used to describe a fire spread rate. The FFMC will be affected by the relative humidity, amount of precipitation, and air temperature. A high fuel moisture content tends to have a lower spreading rate which can be due to a larger amount of energy that is required to dry the vegetation and pyrolyze the material to continue the fire spread [32].
    The Buildup Index BUI estimates the potential amount of energy development in coarser fuels. This can affect the fire intensity and the spread in further stages [32].
    For a forest fire, in order to calculate the fire spread, initially the wind speed and the estimated fine moisture content are considered. Then, the wind direction and the topography are added to get a better result. Finally, the BUI is also considered [32].

Following the basic principles of horizontal fire spread from Drysdale in *An introduction to fire dynamics* [31], as mentioned in the Swedish research report *Green roofs - From a fire technical point of view* [32], the wind speed and direction are important factors affecting the spread. A heating zone right next to the flame front arises where combustion is still not occurring but pyrolysis gases from the fuel are being produced. When the flame temperature is reached the fire spreads moving forward. On the opposite direction of the flame spread, entrainment air brings oxygen to the fire contributing to the combustion process [32].

If the direction of the wind is opposite to the flame spread, this will slow down the spread rate since the air flow from the wind has a cooling effect and it displaces the pyrolysis gases. On the other hand, if both, the flame direction and the wind follow the same direction, an increased fire spread rate result. This is due to the bending of the flame over the unburnt material which intensifies the radiation over the heating zone. An increase on the wind speed can increase the flame spread but only until a certain limit, high speeds can also decrease it. The limit between increasing or decreasing the flame spread is found to be a wind speed between 4-10 m/s [32].

As shown in Figure 13, the flame base presents different patterns depending on the wind speed. Low wind speeds result in a circular flame base. High wind speeds result in an ellipse. The stronger the wind, the narrower the ellipse. This ellipse is characterized as a function of the length/breadth (L/B) [35].

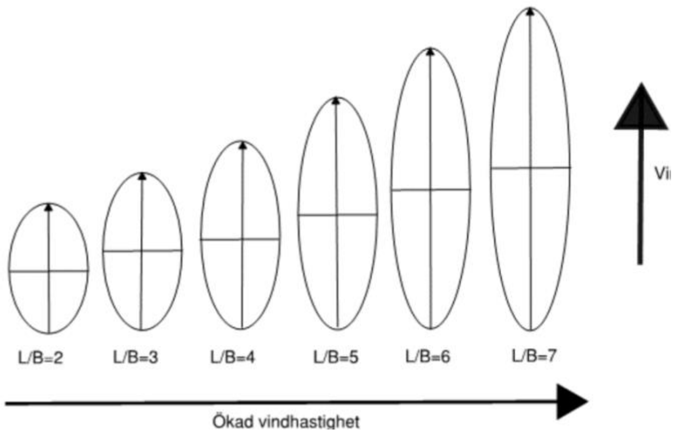

Figure 13. L/B factor and Wind Speed
Source: Green roofs - From a fire technical point of view [32]

The moisture content is another fuel property that can affect the fire. If it is too high, the flame will most likely self-extinguish before spreading itself. From the Swedish academic report, a moisture content below 9 – 20% can result in ignition and fire spread from flying brands. Based on experiments performed in the same report on herb sedum roofs, a healthy moisture content for the plants was found to be at around 40% [34].

Live herbs and grasses possess a high moisture content that prevents the spread of fire. On the other hand, dry and dead specimens can become a flammable fuel under a dry climate [35]. The moisture content of a plant depends on the relative moisture content of the environment. A relative ambient humidity below 30% increase the risk of ignition [33].

The Swedish report also identifies potential fire spread between buildings by three manners, or a combination of them: flying brands, flame contact, and heat transfer.

- Flying Brands
  When combined with radiation, flying brands may become an ignition source. The radiation will start producing volatile gases on the surface which may be ignited by the flying brand [36].
- Flame Contact
  A potential fire spread due to direct flame exposure in a green roof can occur when the distance between the burning surface and the adjacent vegetation is shorter than the length of the flames. The length of the flames is affected by the wind and fire intensity [32].
- Heat Transfer
  Flame spread due to heat transfer can occur in three ways. Conduction is seen as the heating of the growing medium during the fire and heat transfer towards the front of the flame. It is considered a limited heat transfer considered to other ones [34]. Convection, can occur when a stream of hot gases at very high temperatures coming from a close location ignite the vegetation [36]. In forest fires, it is considered as an important type of heat transfer [34]. Finally, radiation is considered as the most common way of fire spread between buildings and can happen in greater distances than the others [36].

Identified in *External Fire Spread To Adjoining Buildings* [36], radiation is considered the main way of heat transfer that can lead to fire spread between buildings. In the experiments performed on an herb sedum green roof [34], different moisture contents of the plants were tested with pilot ignition and without. The final results indicate that for this type of green roof vegetation, at certain levels of moisture contents, ignition at a radiation level of 25 kW/m^2 may occur [34].

3.1.2 Vertical Fire Spread

Regarding green walls, a vertical type of fire spread is analyzed in this section. Specific information about fire spread on vegetative walls is scarce at present time. Due to this lack of available information, general consideration of vertical fire spread from Drysdale *An introduction to fire dynamics* [31] served as a basis for this section. In addition, multiple aspects that were considered on the previous section are also applicable for these systems.

From *An introduction to fire dynamics* [31], orientation is mention to have a predominant effect on fire spread which is faster in an upward direction on a vertical surface. The vertical orientation develops a natural concurrent flow due to buoyancy of the hot gases and the flame which is favorable for the spread of fire in an upward direction. The rate of fire spread is enhanced by the hot gases rising from the burning zone and preheating the unburnt zone above it. On the opposite manner, downward and horizontal fire spread have a natural counter-current spread behavior, resulting in a slower propagation [31]. In the research article *Study on the fire growth in underground green corridors* [37], scaled experiments of a fire in a green wall were performed resulting in a shorter time of fire spread in a vertical manner while a slow spread on a horizontal direction [37].

The thickness of the fuels is also a relevant factor as well as the means of heat transfer. Thin fuels have a slow steady downward spread but an increasing one on the upward direction. For thick fuels conduction may contribute to fire spread on the downward direction. In general terms convection and radiation are the dominant factors for upward fire spread [31].

From the previous section, based on the information related to vegetation, certain aspects are also applicable for green wall systems. Studies about the burning time of vegetation in vertical fires would be relevant as well as tests considering the intensity, fuel mass, energy content, and spreading rates of different species. The moisture content and ambient conditions will also have a significant impact in the ignition and spread of fires for green walls. Finally, fire spread by other buildings by means of flying brands, flame contact, and heat transfer are all pertinent characteristics that should be tested for vegetative walls.

3.2 Fire Standardization

Standards specifically meant for fire safety design of vegetative systems is scarce at the present time. In addition to the American ANSI/SPRI VF-1 External Fire Design Standard for Vegetative Roof, there are general documents for the design of vegetative systems that include a section related to fire safety. Some of these documents that address fire safety concerns are listed in Section 2.6.

As already explained in Section 2.6, the majority of these documents address only green roofs due to its more frequent use, presence for several decades now, and smaller quantity of classifications. Green walls on the other side are only addressed by a few documents but no official standards have been found.

3.3 Fire Tests and Experiments

3.3.1 Testing Standards and Fire Classification

3.3.1.1 Green Roofs

When it comes to testing green roofs systems, two approaches are revised, the European and the American one. The tests analyzed are not specific for vegetative roof but general for roofing systems.

The European market follows the ENV 1187, *Test methods for external fire exposure to roofs*. This test is divided into four methods, depending on the country, a specific test method must be followed.

- Test 1 - with burning brands.
  Classifications: B_{roof}(t1), F_{roof}(t1).
- Test 2 - with burning brands and wind.
  Classifications: B_{roof}(t2), F_{roof}(t2).
- Test 3 - with burning brands, wind and supplementary radiant heat.
  Classifications: B_{roof}(t3), C_{roof}(t3), D_{roof}(t3), F_{roof}(t3).
- Test 4 - with two stages incorporating burning brands, wind and supplementary radiant heat.
  Classifications: B_{roof}(t4), C_{roof}(t4), D_{roof}(t4), E_{roof}(t4), F_{roof}(t4).

The classifications are according to EN 13501-5, *Fire classification of construction products and building elements-Part5: Classification using data from external fire exposure to roofs tests*. In general, a classification B_{roof} for all of the methods indicates that the test result is approved [32].

For the American market, the *ANSI FM Approvals 4477 American National Standard for Vegetative Roof Systems* [29] states the test requirements for vegetative systems and evaluates its performance regarding fire from above and below the structural deck [29].

- Test: ASTM E 108, *Standard Test Methods for Fire Tests of Roof Coverings.*
  Combustibility from above the roof deck.
  This test requires roofing elements to be conditioned for a period of at least 28 days prior to testing. This means that no water will be applied during this period to simulate drought conditions. It requires to be exposed to daily sunlight at a temperature of 22.2C°. The vegetation shall cover at least 90% of the sample and it shall be at a mature stage development [12]. The test method is divided into three subtests that have specific requirements [32].
    - Flame spread test
    - Intermittent flame test
    - Burning brand test

  Classification: Class A, Class B, Class C.
- Test: NFPA 276, *Standard Method of Fire Tests for Determining the Heat Release Rate of Roofing Assemblies with Combustible Above-Deck Roofing Components*.
  Combustibility from below the roof deck.
  Acceptance Criteria: The heat release rate should be below the limits specified at certain times. In addition, no dropping of flames particles or uncontrolled fire should be developed.

The research report *Green roofs - From a fire technical point of view* [32], summarizes in table 1 the fire classification that are indicated by the FLL, GRO, FM Global, ANSI, and Swedish documents. The FLL German guide requires B_{roof} (t1), the GRO British guide solicits B_{roof} (t4), and the Swedish standard requests B_{roof} (t2). The insurance data sheet and the American standard require Class A or Class B [32].

The *Green Roofs, Facades, and Vegetative Systems* [2] document, referring to the Toronto *TGRCS, Supplementary Guideline* mentions that *"Green Roof coverings (including plant material) may not comply with the 'Fire Test of Roof Coverings' standard, particularly if vegetation is dormant. At this point in time, there is no widely accepted testing method developed for Green Roofs"*[2] and "*there is no approved fire testing methodology for green roofs; thus, it is not possible to classify green roofs in terms of fire resistance"* [2]. As mentioned earlier, the tests exposed are general for roofing systems since there are no specific ones for vegetative roofs.

3.3.1.2 Green Walls

Regarding green walls, the research report *Fire Performance of Green Roofs and Walls* [1], considers the following European tests:

- ISO 11925-2, *Ignitability of products subjected to direct impingement of flame - Part 2: Single-flame source test.*
- EN 13823, *Reaction to fire tests for building products. Building products excluding floorings exposed to the thermal attack by a single burning item*.

The classifications is according to EN 13501-5, *Fire classification of construction products and building elements, Part 1 – Classification using data from reaction to fire tests* [32]. Based on the two tests mentioned, the systems can be classified as A2, B, C, D, E, and F. For this case A2 corresponds the highest performance and F being the lowest [1].

Once again, the tests mentioned previously are for general materials since there are no specific tests at the moment for vegetative walls. No examples have been found where vegetative systems were evaluated using a façade test.

3.3.2 Fire Experiments

This section revises experiments that have been performed for vegetative systems. Since there is no specific test when it comes to vegetative systems, the following experiments follow general tests standards or no specific ones. The experiments performed on vegetative systems have as a focus the same three elements explained in Section 2.1, vegetation, growing medium, and additional components.

3.3.2.1 Vegetation

When it comes to green roofs, fire tests were performed to the modular hybrid system *LiveRoof*. The information about the tests found on their website [38] show that the whole system was considered: vegetation, growing medium, and modules but the fire was exposed only from the upper side towards the vegetation. The experiments were performed at UL labs following a typical test protocol for roof coverings [38], not specified.

Figure 14. Fire Test on Green Roof
(a) Flame exposure on vegetation, (b) Inspection of growing medium, (c) Inspection of modules
Source: LifeRoof Global LLC [38]

After exposing the system with fire for ten minutes, the vegetation turned into ashes but there was no ignition of it or fire spread, the growing medium and the modules were not affected by the heat as it can be seen in Figure 14 (b) and (c). The succulent planting and inorganic growing medium prevented the spread of fire to the modules [38]. Proper plant selection and condition, in addition to the selection of the components of the growing medium become important factors to achieve these results.

Regarding green walls, *Dahanayake and Chow* [9] performed a series of fire tests to three commonly used plants in green walls at different levels of moisture content to explore their ignitability and fire risk under radiative heat fluxes.

The moisture content is considered as the most relevant factor that affects the ignitability and fire propagation of vegetation. Three commonly used species in Asia were selected for testing using the cone calorimeter at different moisture contents. The plants selected plants correspond to: *Hedera helix* which can also be found in Europe, *Peperomia obtusifolia* which may be used indoor in Europe, and *Aglaonema commutatum* which is original from tropical latitudes. Figure 15 shows the three species.

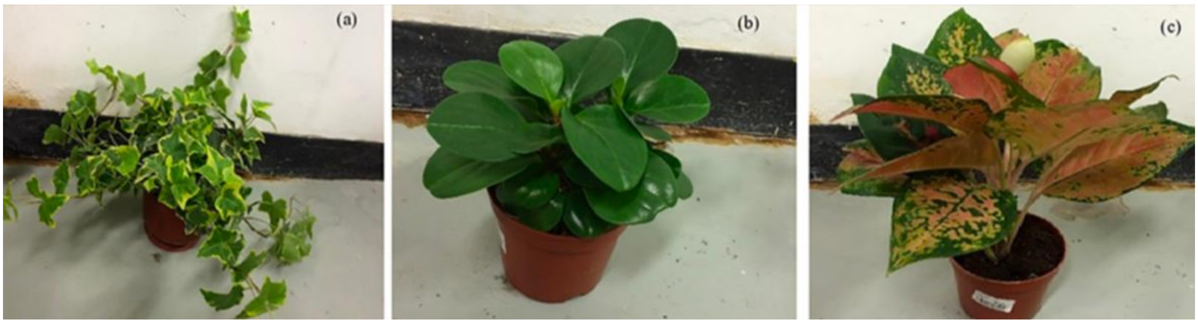

Figure 15. Species Tested
(a) Hedera helix; (b) Peperomia obtusifolia; (c) Aglaonema commutatum
Source: Moisture Content, Ignitability, and Fire Risk of Vegetation in Vertical Greenery Systems [9]

The moisture content is expressed as a percentage and was calculated using Formula 1. It cannot be instantly measured since the dry mass is calculated by oven drying (70° overnight).

$$MC = \frac{M_{fresh} - M_{dry}}{M_{dry}} \times 100\% \qquad (1)$$

For each of the plant species, the moisture content was calculated at the initial fresh stage. Multiple tests were performed for a period of 75 days where the plants were allowed to dry in a natural way at 25 °C and 60 % relative humidity without watering. For each test date, the moisture content was calculated. The decay of the moisture content levels of the plants is shown in Figure 16. A considerable difference of the initial moisture content between the three species can be seen. A quick drop of *Hedera helix* to values below 15% occurred on the first 15 days.

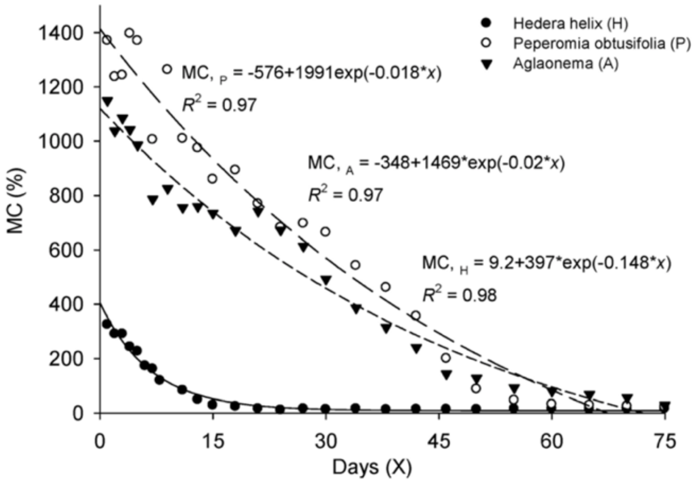

Figure 16. Evolution of the Moisture Content
Drop of the moisture content following natural drying periods.
Source: Study on the fire growth in underground green corridors [37]

The burning tests using the cone calorimeter used heat fluxes at 20, 35, 50, and 60 kW m^{-2}. All these heat fluxes, combined with the multiple levels of moisture content generated different results regarding ignition, burning behavior, and smoke production.

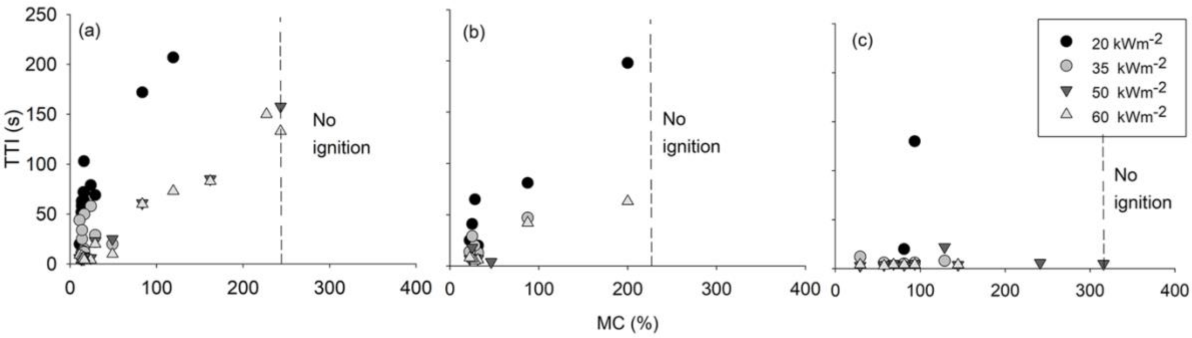

Figure 17. Ignition Time and Heat Flux Level
(a) Hedera helix; (b) Peperomia obtusifolia; (c) Aglaonema commutatum
Source: Moisture Content, Ignitability, and Fire Risk of Vegetation in Vertical Greenery Systems [9]

Ignition of the three plants did not occurred on fresh samples even at high radiative heat fluxes. It only started at certain levels of moisture contents as can be seen in Figure 17. *Hedera helix* started to ignite 4 days after the drying process, *Peperomia obtusifolia* after 46 days, and *Aglaonema commutatum* 38 days after [9].

The experiments and additional literature review from the authors indicate that fresh and live vegetation are difficult to ignite even when high radiative heat fluxes are used. The importance of maintenance and of proper selection of plants which have a slow drying process is remarked by the authors [9].

In general, this study is valuable since it clearly shows the importance of the moisture content of plants, how it evolves, and how it differs between species. This, in combination with four levels of radiative heat fluxes created different results. It suggests the importance of developing a discussion on defining the proper conditions for testing vegetative systems.

As it is mentioned by *Dahanayake and Chow* [10], the fire behavior of vegetative walls has been based on preliminary studies and test standards for general roof and walls. In addition, there are no appropriate fire scenarios for testing the systems. The consequences that burning vegetation have on green walls has not been studied thoroughly. This can be due to the small quantity of fire incidents involving vegetative systems on buildings and that there is no available compilation of them. No matter the small number of incidents, the consequences related to fire spread can be considered as serious [10].

3.3.2.2 Growing Medium

Regarding green roofs, *Fire Performance of Green Roofs and Walls* [1] performed a series of tests with dried growing medium using the cone calorimeter. The goal was to test the fire performance of the growing medium by varying the type and amount of organic and inorganic content used. Three main conclusions can be drawn from the tests results.

Completely dried out standard organic mix did not ignite. When a completely dried out 100% standard organic mix ignited, flame spread could not be sustained since the peak heat release rate was 55 kW/m^2. The use of leaf mould as part of the growing medium mix increases the risk of ignition and fire spread. Ignition of the growing medium happened at concentrations greater than 50%. A sample of 100% dried leaf mould is very flammable but is unlikely to be used for green walls [1].

Large scale tests were also discussed in the same document [1] using different dried growing medium mixtures. The tests followed the DD CEN/TS 1187 standard. Components of the growing medium were considered as well as the depth of it in order to revise if there could be fire spread down through the green roof system into the building.

The tests performed with a growing medium on 80mm thick samples (minimum recommended) resulted in smoking and glowing but no fire penetration at the base of the sample after 60 minutes. The highest temperature measured of all the samples was of 218°C is lower than the one required to ignite polymers, which is commonly used as the material below the growing medium.

Regarding green walls, *Fire Performance of Green Roofs and Walls* [1] performed tests with the cone calorimeter to three dried samples of growing medium composed by a mixture of coir, peat, wood fiber, perlite fertilizer, and insect and wetter control. The samples were dried out at 40°C and tested at 50kW/m^2. No ignition or signs of it was observed.

Large scale tests were also performed by the research report [1] to five entire built-up commercially available green wall systems. The growing medium and the system components (no plants) were tested following the BS EN 13823 *Single Burning Item Test*. The tests were supposed to measure the heat release rate, smoke production, smoke growth rate, and fire growth rate index. These parameters could not be calculated since the tests had to be finished earlier because either the heat release rate exceeded 350 kW or the specimens collapsed over the burner. It is concluded that all of the systems failed [1].

From previous tests (no plants considered) it can be concluded that the growing medium is extremely unlikely to ignite or contribute to the fire spread [1]. The tests exposed on the *Fire Performance of Green Roofs and Walls* [1] provide useful remarks but certain details about the components that were used for the tests are not explained which would be valuable information for future tests and research.

3.3.2.3 Additional Components

Regarding green walls, the large test exposed on the previous section from the British research report [1] indicates that the other components that make up the green wall system can ignite. This can make the whole system collapse as it was the case on two of the samples.

Green Living Technologies INTL created a video [39] where three different materials commonly used to support green walls were exposed to a direct flame to compare their fire reaction. The first material, a blend of synthetic and natural fabrics, ignited quickly and melted. The second element, polypropylene trays, which is highly flammable, spread quickly and burned as a liquid. The last product, made out of aluminum trays which is said to be Class A fire rated, did not burn [39]. Images of the fire exposure can be seen in Figure 18.

Figure 18. Reaction to Fire of Supportive Components
(a) Synthetic & Natural Blend, (b) Polypropylene, & (c) Aluminum.
Source: Green Living Technologies INTL [39]

Even though these experiments do not follow any standardize test procedures, the images exemplify what can happen to certain supportive materials while exposed to direct flames. This illustrates what was mentioned on the first paragraph of this section by the *Fire Performance of Green Roofs and Walls* [1] research report.

3.3.3 Wood Façade Testing Analogy

Due to the lack of test information found regarding green walls, an analogy is performed taking as an input existing information regarding wood façades in Switzerland.

The Swiss document, *Lignum 7.1 Exterior Walls – Construction and linings* [15], provides tests that have been done on different scales for wood materials. These tests can be classified by its scale:

- <u>Laboratory Tests.</u> Small samples of different types of woods (0.09x0.23m).
- <u>Real Fire Tests.</u> Real size tests of wall construction of several levels (3.3x8.3m).
- <u>Natural Fire Tests.</u> Tests performed in existing buildings on an exterior environment.

There are different parameters that influence the fire development in a wood façade: Façade type, lining type, lining disposition, construction of the ventilation space, and balconies. For each of the parameters, there are optimal, good, and critical possible compositions that produce different fire behaviors as is shown in Figures 135-1 & 135-2 of the Swiss document [15].

From the results of these wood tests, it can be concluded the following:

- Tests done on big-scale produce better results than what was expected based on the small-scale ones.
- The auto-protection effect of wood by carbonization of the surface stops a fast propagation of fire on a vertical direction. Fire propagation on a horizontal direction was not significant.
- Fire spread through the ventilation layer of the exterior walls is already controllable with simple construction measures.
- Water is effective for extinguishing the fire on the wood façades.
- On the tests performed, there were no collapse of elements that could put in danger people.
- Optimized wood materials against fire protection can produce great resistance against arson fire.
- Combustible exterior insulation can accelerate fire spread in case of a fire.

The previous considerations and test results provide with relevant aspects that are applicable for vegetative walls. Different scale of tests, multiple variables that characterize façades, and the test results are all inputs that should be considered for performing tests on green walls.

3.4 Modelling of Vegetation

Wildland fire reports were revised as an initial input for modeling vegetation and fires. In addition, a research article on green walls explains the process followed to develop the required inputs for numerical simulations performed in CFD (Computational Fluid Dynamics).

The Swedish report *Distribution models for fire in vegetation* [40], defines two types of models: non-spatial and spatial. The non-spatial models use local data and can provide with estimates and rough spreading prediction. Spatial models can provide with a more comprehensive fire spread prediction by considering the fuel, topography and a simulation model that considers spatially varying information [40].

The report revises different fire behavior models and identifies important inputs that should be considered when the vegetation is the main component of the model. The fuel, topography, moisture content, and wind speed are important parameters to be considered. The accuracy of the fire simulation depends more on these inputs than on the model itself. The main outputs consist of the spread over time as well as the fire intensity. Other outputs can be derived from the main ones [40].

Fire behavior models involving vegetation can be divided into three groups:

- <u>Physical Models</u>
  These models are based on mathematical descriptions of chemical and physical processes. Ignition, heat transfer, fuel consumption, and the interaction between flames and the atmosphere are considered [40].
- <u>Semi-Empirical Models</u>
  These models are based on simplified relationships that are correlated with fire tests [40].
- <u>Statistical Models</u>
  These models are based on statistics descriptions from a large number of studied fires. Physical principles are not considered [40].

These types of models present advantages and disadvantages, depending on what is the model used for, one can be more suitable than the others [40].

The report mentions the program WFDS, which is now part of FDS (Fire Dynamics Simulator) developed by NIST, as a physical model that can be used for wildland fires. The goal of it is identified to be the prediction of the fire spread in forests and building [41].

FDS has an extended use for interior fires in buildings, the inclusion of vegetation as a fuel makes it a suitable program for modeling exterior fires in buildings with vegetative systems. The next paragraphs use FDS as the modeling tool for an interior green wall study.

The research article *Study on the fire growth in underground green corridors* [37], considers the results from the experiments explained in Section 3.3.2.1 as inputs for the heat release rate and the development of fire curves. The article analyses fires on green walls located on underground corridors. The reports consider three different green wall species: *Hedera helix*, *Peperomia obtusifolia*, and *Aglaonema commutatum*. The species are analyzed at different levels of moisture content to assess fire and smoke behavior by performing numerical simulations and a validation on a physical scaled model experiment.

For each of the plant species, the moisture content was calculated at the initial fresh stage and after 25, 50 and, 75 days where the plants were allowed to dry in a natural way at 25 °C and 60 % relative humidity without watering. By using the cone calorimeter, tests were performed at day 1, 25, 50 and 75 at 50 kW/m^2. The heat release rate was measured and the fire curves of the three species on these four dates can be seen in Figure 19.

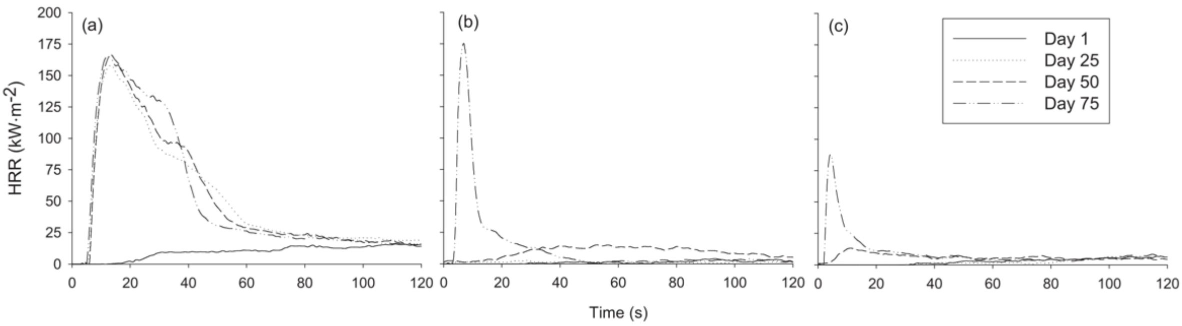

Figure 19. HRR Curves for Vegetation
(a) Hedera helix; (b) Peperomia obtusifolia; (c) Aglaonema commutatum
Source: Study on the fire growth in underground green corridors [37]

Additionally, the emission of carbon dioxide (CO_2, %) and the effective heat of combustion (EHC, MJ/kg) were also measured resulting in different values for the three species as the moisture content decreases.

For the numerical simulations an underground passage was modeled using FDS software. The model consisted of a 3m x 10m x 2.2m room made out of concrete with both sides open and a 1.2m x 2.2m green wall located in the center.

Based on the cone calorimeter tests results, the HRRPUA is defined. A simulation time of 300 seconds was used and after a sensitivity analysis, cell sizes of 2.5cm were implemented. For each plant species, four simulations were performed based on the HRR that was obtained at fresh conditions and after 25, 50, and 75 days of natural drying of the samples.

The results showed that plants with a high moisture content such as the ones tested at fresh conditions do not create a fire hazard. The risk of fire increased as the moisture content decreased as can be seen in Figure 20, where a comparison of the obtained temperatures of the three species and four tests is done.

Hedera helix produced the highest temperature of 850°C at day 75 and became a hazard since day 25. *Peperomia obtusifolia* became a hazard only at day 75 with temperatures reaching 800°C. *Aglaonema commutatum* did not create a fire hazard in any of the cases.

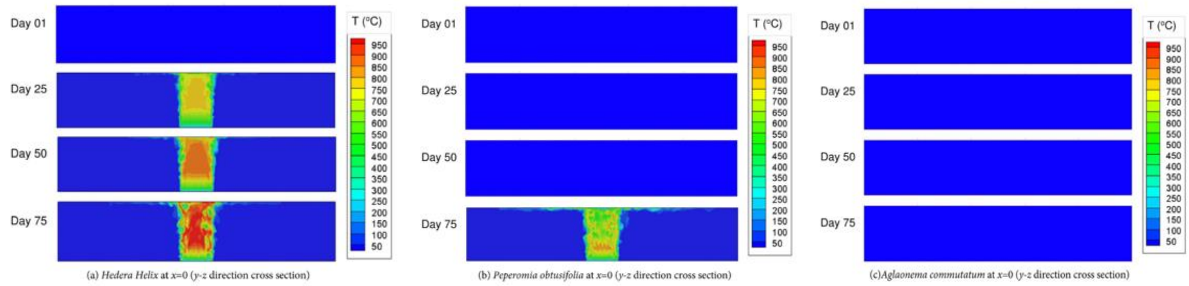

Figure 20. Temperature Results
(a) Hedera helix; (b) Peperomia obtusifolia; (c) Aglaonema commutatum.
Source: Study on the fire growth in underground green corridors [37]

In this case, the model included a device that was set to measure the temperatures at the center of the corridor where passengers will walk by but different devices can be used to measure the performance criteria.

The smoke behavior can be seen with Smoke-View, in these simulations, since the model does not correspond to any specific space, the smoke flow moves towards the ceiling in a natural manner due to buoyancy without any additional important remarks. Visualizing the smoke through this tool can be a useful output for models that include specific details of the space and safety features.

Reduced-scale green corridor experiments were executed to validate the numerical simulations. A scale of 1:10 was used and a 75 day naturally dried *Cynodondactylon* was chosen to represent the vegetation. A propanol pool fire of 20ml was used to ignite the vegetation. The main finding of the experiment is that fire spread in a vertical manner occurred in very short time while on a horizontal direction the spread was slow. An image of the scaled model with a fire at 140 seconds is included in Figure 21.

Figure 21. Scale Model of a Green Corridor
Fire at 140 seconds
Source: Study on the fire growth in underground green corridors [37]

In general, the fire curves used as an input for the numerical simulations were created after a process that involved burning different species at certain moisture contents levels with a cone calorimeter. After the simulations were analyzed, validating them with scaled experiments was the last step. The results show the importance of selecting proper plants that have a lower heat release rate and a slower drying process. This remarks the importance of testing and creating data source for different species that are commonly used on vegetative systems.

3.5 Final Considerations

The review of fire involving vegetative systems delivered useful insights on the existing research regarding these systems. Fire spread, standards, tests, experiments, and modelling provided with a better understanding of its fire behavior and initial considerations regarding hazards and strategies.

When it comes to fire spread, existing researches about wildland fires become a base for understanding how vegetation burns and how it is affected by multiple aspects such as the moisture content, plant type, and environmental aspects such as wind direction and speed and humidity levels. At this moment, there are more reports regarding green roofs than walls. Since the main components of both systems is the same, the vegetation, multiple aspects are applicable for both systems in general. The burning time and intensity, composed by the fuel mass, energy content, and spreading rate are important parameters that influence fires in vegetation. The big difference is the orientation of the systems, resulting in a different behavior between horizontal and vertical fire spread. This is explained in a general manner, additional research regarding ignition and fire spread specifically for vegetative systems is required. Different plants, conditions, and commercial systems should be analyzed, especially for vertical fire spread analysis.

Fire standards specific about fire safety and vegetative systems are scarce at the moment. Many general standards about green roofs include safety remarks about fire. These remarks may be general or more developed depending on the document. Many of the considerations are coming from the German FLL standard. Green walls on the other side are only addressed by a few guides or reports but not standards.

Testing and classifying vegetative system in terms of fire properties follow general tests for construction systems or materials. This is due to the lack of specific tests procedures for green roofs or walls. This requires further analysis since, as seen previously, vegetation evolves over time and its reaction to fire is affected by the multiple factors and also because species can differ a lot in the results under the same conditions. Vegetation is not a traditional material that requires to be analyzed in a different manner when it comes to testing and classifying.

Experiments on vegetative systems have been performed on the past focusing on the three main elements: vegetation, growing medium, and other components. Regarding vegetation the research on the green walls provided with a deeper understanding of the importance of the moisture content of the plants and how it evolves in a very different manner depending on the species. The experiments performed, combining different heat fluxes with decreasing levels of moisture content generated different results regarding ignition, burning behavior, and smoke production. The tests on the growing medium included, even though not explained in detail, provided with the important conclusion that this element is extremely unlikely to ignite or contribute to fire spread. This research also indicated that the other components that support the vegetative system may be ignited and, as seen in the other experiments, the elements may melt and collapse.

In general, more tests at small and large scales are required. Observing the drying process of commonly used plants as well as understanding their properties once ignited is relevant for plant selection. This can be performed by using the cone calorimeter. Large scale tests with all of the elements is also important to understand their reaction to fire and performance of the elements combined. The inclusion at this scale of tests including automated extinguishing systems like sprinklers or irrigation systems on a fire mode, or passive measures such as fire breaks is also relevant to observe their effectiveness. Following the procedures and experiences of testing wood may also provide useful guidance.

When it comes to modelling vegetation, the first step is creating a fire curve. This requires multiple tests of the vegetation at specific moisture content levels. Once the HRR is measured, the fire curves are used as the inputs for the CFD numerical simulations where the geometry of the project is included. This allows a revision of the performance of the vegetative systems during a fire under specific conditions. Finally, validating the results would be the last step of the process.

The fire review performed reveals the changing nature of the fire properties of vegetative systems. It suggests the importance of identifying the hazards that these elements may pose as a non-traditional and evolving construction material towards people and the building itself.

Chapter IV

Hazard Identification

This chapter identifies fire hazards by a revision of existing literature on vegetative systems and fire safety practices from different latitudes and categorizing the hazards under five areas. Also, a revision of a case study is performed considering the approach used to address and rank the risks involved in the inclusion of a green wall in an atrium and after a series of testing vegetation. Diagram 5 expose the three sections that compose this chapter and their main subsections.

Hazard Identification Overview

4.1 Hazard Review

B1. Means of Warning and Escape
B2. Internal Fire Spread (Linings)
B3. Internal Fire Spread (Structure)
B4. External Fire Spread
B5. Access and Facilities for Fire Service

4.2 Case Studies

Interior Green Wall Design
Experimental Approach

4.3 Final Considerations

Final Remarks

Diagram 5. Hazard Identification - Chapter IV Overview

4.1 Hazards Review

The research report *Fire Performance of Green Roofs and Walls* [1], considers certain hazards associated to green roofs and walls. This document considers the possibility that these systems ignite and spread resulting in the affectation of the five requirements that the Building Regulations from the UK considers from Approved Document B [42].

Initially, this section identifies fire hazards following the five areas that *Fire Performance of Green Roofs and Walls* [1] used as a structure. In addition to the hazards already considered in this report, further ones are included considering the revised documents as explained in the Overview.

A summary table of the identified hazards including the strategies that are explained in Chapter 5 can be seen in Annex B.

B1. Means of Warning and Escape

The requirement B1 is defined by Approved Document B [42] as:

"The building shall be designed and constructed so that there are appropriate provisions for the early warning of fire, and appropriate means of escape in case of fire from the building to a place of safety outside the building capable of being safely and effectively used at all material times" [42].

Regarding the means of escape for green roofs, a hazard that involves wind and the capacity of the vegetation and growing medium to remain in place is identified in *Bridging the Gap: Fire Safety and Green Buildings* [16] as follows:

1. **Potential slide of green roof components towards people on the lower levels.**

   Considerations should be given to the possibility that the vegetation, growing medium, and other components might fall on lower levels compromising people's safety [16].

When it comes to green walls, as it is mentioned by *Dahanayake and Chow* [9], the following hazard is identified:

2. **Potential interrupt of the evacuation of tenants due to building's exit and/or egress route obstruction.**

   The collapse of an ignited system may result in the building exit being blocked at the ground level or evacuation routes next to it being affected [9].

B2. Internal Fire Spread (Linings)

The requirement B2 is defined by Approved Document B [42] as:

"To inhibit the spread of fire within the building, the internal linings shall adequately resist the spread of flame over their surfaces; and have, if ignited, either a rate of heat release or a rate of fire growth, which is reasonable in the circumstances" [42].

Regarding green walls and roofs, *Fire Performance of Green Roofs and Walls* [1] identifies the following hazard:

1. **Potential fire spread from a vegetative system into the building and the other way around.**

   When a vegetative system is installed on the exterior of a building, the risk of ignition between the outside and the interior of the building (and vice versa) should be revised.

Considering the use of interior green walls in a building, as it is mentioned in *Fire Performance of Green Roofs and Walls* [1], internal linings should provide evidence that the appropriate classification is meet according to code requirements and location inside the building [1]. This means that these systems must be tested in order to be classified. Nevertheless, with or without testing, it is this researcher belief that the different variables and changing nature of plants can derive into the following hazard:

2. **Potential change in the system classification evolving into a combustible lining.**

   The moisture content of the plants in a green wall may evolve reducing its percentage until the vegetation becomes dry. This may create a change of the initial classification of the system towards undesired levels of fire reaction, smoke production, and the formation of drops.

B3. Internal Fire Spread (Structure)

The requirement B3 is defined by Approved Document B [42] as:

"The building shall be designed and constructed so that, in the event of fire, its stability will be maintained for a reasonable period" [42].

In *Fire Performance of Green Roofs and Walls* [1], a roof is considered an element of structure when it performs the function of a floor. This consideration applies mostly for accessible green roofs like intensive and semi-intensive types. The following hazard is identified for the roof as a structure:

1. **Potential horizontal fire spread over a compartment wall through a green roof between adjacent compartments.**

   To address the identified hazard, adequate provision is required to prevent a fire in the top floor of a building to break through the ceiling into the green roof, spread over the compartment wall in a horizontal manner through the roof and descent back into an adjacent room.

As it is mentioned in *Fire Performance of Green Roofs and Walls* [1], green vertical systems can be attached to walls making them a part of the structure. Based on this, the following hazard is identified:

2. **Potential vertical or horizontal fire spread across a compartment floor or wall through a green wall between adjacent compartments.**

To address the identified hazard, adequate provision is required to prevent a fire in a floor of a building to break across a compartment slab or wall into the compartment on the next level or same by spreading in a vertical or horizontal manner through a green wall.

B4. External Fire Spread

The requirement B4 is defined by Approved Document B [42] as:

"The roof/external walls of the building shall adequately resist the spread of fire over the roof/walls and from one building to another, having regard to the height, use and position of the building" [42].

In *Fire Performance of Green Roofs and Walls* [1], considering the exterior layer of every green roof and wall systems, the following hazard is identified:

1. **Potential ignition and fire spread from adjacent buildings.**

   The green roof and wall shall avoid the spread from one building to another [1].

   This is also identified in the Swedish report *Green roofs - From a fire technical point of view* [32], where three manners, or a combination of them, can result in potential fire spread between buildings: flying brands, flame contact, and heat transfer. Further information about these three ways can be found in Section 3.1.1.

   The *Growing Green Guide* [7] indicates that nearby vegetation can also increase the risk of fire and a source for weed [7]. The site elements around the project should be analyzed to identify hazards.

The different variables and changing nature of green roof or wall systems can derive into the following hazard:

2. **Potential change in the system classification evolving into a combustible lining.**

   The moisture content of the plants in a green roof or exterior wall may evolve reducing its percentage until the vegetation becomes dry. This may create a change of the initial properties of the system towards undesired levels of fire reaction, smoke production, and the formation of drops.

   As mentioned in *Forest fire - Fire behavior and interpretation of fire risk index* [33], the moisture content of vegetative fuels is dependent to the relative ambient humidity. It is identified that the hazard of ignition for vegetative fuels increases when the relative ambient humidity is below 30% [33]. Certain climates or extreme changes in the weather can result in better conditions for ignition or fire spread in vegetative systems.

In *Fire Performance of Green Roofs and Walls* [1], special considerations are taken to prevent the fire spread from the interior or exterior elements to the green roof, the following hazard is identified:

3. **Potential fire spread to a green roof by openings or protruding elements and vice versa.**

   Considerations regarding the protection around openings in roofs and around vertical elements in case of fire should be taken.

In *Fire Performance of Green Roofs and Walls* [1], special considerations are done to prevent a fire in a green roof from spreading across the total surface it comprises, the following hazard is identified:

4. **Potential fire spread of a green roof in a horizontal manner.**

   Considerations regarding the protection to limit the roof into areas to avoid horizontal spread in case of fire should be taken.

Considering wood regulations, the Swiss document, *Lignum 7.1 Exterior Walls – Construction and linings* [15], identifies three different scenarios that should be considered when it comes to fire spread in exterior façades: neighboring building fire, exterior fire, and interior room fire with access to the exterior wall. In addition to the last scenario, as it is mentioned by *Dahanayake and Chow* [10], ignition from a post-flashover fire can become a threat to green walls. Based on the previous considerations, the following hazard is identified:

5. **Potential vertical fire spread of an exterior green wall and ignition from the interior of the building by a window fire plume.**

   It is important to consider a maximum allowed fire spread fire the arrival of the fire service and measures when there is a ventilated green wall. The Swiss document *Lignum 7.1 Exterior Walls – Construction and linings* [15], indicates the following regarding both remarks.

   Independently from the type or material of the exterior walls, the objective defined by the Swiss document is: *"In a fire on the exterior wall, the fire must not spread over more than 2 levels above the floor of the initial fire before the firefighters start to extinguish"* [15]. The document bases in 15 minutes the time of the fire fighter intervention according to Feuerwehr [15].

   When it comes to the wood façade linings where there is a ventilation space between the lining and the building, the Swiss document, requires specific material for certain layers or measures based on the building height since this ventilated space can become a hazard [15]. This may also be applicable to ventilated green walls that present the same air gap behind them.

The use of double skin system requires, in general, additional measures as it is mentioned in *VKF AEAI Explanatory Note 102-15 Buildings with Double-Skin Façades* [27]. When a green wall uses this kind of system, the following hazard is identified:

6. **Potential fire spread in a double-skin green wall system.**

   When a green wall is composed by a double skin system special attention should be given since it can increase the level of external fire spread in the intermediate climatic zone. A non-segmented design can promote horizontal and vertical fire spread. Combustible materials in this in-between space can contribute to a fire [27].

B5. Access and Facilities for Fire Service

The requirement B5 is defined by Approved Document B [42] as:

"The building shall be designed and constructed so as to provide reasonable facilities to assist fire fighters in the protection of life. Reasonable provision shall be made within the site of the building to enable fire appliances to gain access to the building." [42].

In general terms, as it is identified by *Bridging the Gap: Fire Safety and Green Buildings* [16], the green movement, where green roofs and walls belong to, have the potential to modify the work environment for firefighters [16].

In *Fire Performance of Green Roofs and Walls* [1], *Fire Safety Challenges of Green Buildings* [3], and *Bridging the Gap: Fire Safety and Green Buildings* [16], considerations are taken regarding the accesibility of the fire service. The following hazard is identified:

1. **Potential impact on fire service operations and roof access.**

   The building design should provide reasonable facilities to assist the fire service [1]. The Swiss *VKF AEAI Directive 14-15 Use of Building Materials* [43], indicates that when a building with medium height (≤30m) uses combustible materials on the roof, the design must guarantee a mean of access for the fire brigade to the roof .

As it is mentioned by *Dahanayake and Chow* [9], the following hazard is identified:

2. **Potential interrupt of the access of fire-fighters into the building due to an obstruction of the entrance.**

   In case of an ignition, a vegetative wall can interrupt the access of fire-fighters inside the building [9]. The structure with the vegetation may collapse over an entrance blocking the access for the fire fighters.

In *Fire Performance of Green Roofs and Walls* [1], the following hazard is identified:

3. **Potential impact on fire service operations due to the height of the building.**

Fire services have a certain height reach based on their vehicles. The maximum reachable height differs depending on the jurisdiction.

VKF AEAI Explanatory Note 102-15 *Buildings with Double-Skin Façades* [27] indicates that when a double-skin façade is used, it may rise the following hazard:

4. **Potential visual and intervention impact for the fire brigade with a double-skin wall system.**

   A double-skin green wall may affect in a visual way the perception of the fire and people under risk from the exterior. In the same manner, an intervention, means of rescue and attack through the façade is affected by the secondary façade [27].

4.2 Case Studies

This section identifies hazards based on the experience of case studies that had to design the safety measures of a vegetative after analyzing the possible threats that the system may pose to the people and building. The existing number of cases that explain the fire safety consideration of a vegetative system are scarce and only one case of an interior green wall design is found. Additionally, a research study by *Dahanayake and Chow* [9] testing vegetation commonly used on green walls and the impact of the moisture content when studying the associated fire risks is included.

It was also under the intentions of this section to include cases that involved fires involving vegetative systems to gather the lessons learned from the experiences. The incidents found are limited and do not provide with information that could be used to perform a deeper analysis. A data repository, as mentioned in *Fire Safety Challenges of Green Buildings: Final Report* [3], could be established to facilitate a better collection of relevant data on green buildings in the future [3]. Vegetative systems should also be considered to gain a better knowledge of fires involving these systems.

4.2.1 Interior Green Wall Design

This case study corresponds to an assessment done to an interior green wall located in the atrium of an office building in Melbourne, Australia as can be seen it Figure 22. The information presented in this section comes from a paper [44] and poster [45] that were provided by one of the designers of the fire safety features of the project.

Figure 22. Interior Green Wall
Source: Irrigation Systems For Life Safety? [44]

Initially, a review of the building atrium design was conducted addressing the commonly known risks by the use of fire safety features. The inclusion of an internal green wall poses a new risk that is not clearly understood or regulated which required an engineering assessment. A revision of the green wall design was performed [44].

First, the construction of the system of the green element was analyzed. Flexible polyurethane foam panels incased on thick material felt were identified as a significant fuel source that required special attention. An analysis of the wall cavity and immediate surroundings was performed. No electrical or lighting systems were found and other combustibles were located 2m away [44].

The moisture content of the foam is required to be maintained at 30% based on the plants need. An irrigation system provides the required water with specific amounts during daytime (0.4 $l/m^2/hr$) and nighttime (0.1 $l/m^2/hr$). If the detection system or sprinklers are activated, the irrigation system will operate on "fire mode" providing an increased amount of water (3.6 $l/m^2/hr$) [44].

The detection system included high sensitivity detectors in the office levels and a beam detector on the eighth level. Sprinklers dedicated for the green wall were provided at several levels. Exhaust and supply air systems were included for the atrium considering the green location. Both fans were connected to an emergency generator system [44].

Due to the inclusion of the green wall, the approval of this project was revised by the Melbourne Fire Brigade and the Building Appeals Office. A series of updates on the design were performed during the approval stage and tasks to demonstrate the safety of the final design [44].

In order to demonstrate tenability conditions for occupants in the event of fire on a dry wall, a fire and smoke model was performed. Following a request from the authorities, two scenarios were modeled where the complete dry wall was ignited. As it was expected, the results under this extreme condition on the green wall failed to satisfy the goal of life safety. These two scenarios were considered catastrophic and very unlikely to occur which is explained in the next paragraph [44].

A quantitative risk assessment was performed since the previous scenarios demonstrated that occupant tenability was not met. A fault tree was done to demonstrate the likelihood of this extreme scenarios to occur. The fire safety measures were included and the failure of each one considered. The scenario where all safety features fail is too unlikely to be taken under consideration [44].

Sprinklers at each story, beam detection, smoke detection, smoke reservoir, and smoke extraction were some of the traditional fire safety measures used as strategies for the interior green wall located at an atrium [44].

In addition to these well-known safety features, the irrigation System was also used as a life safety measure. The requirement was to maintain the foam on the green panel at a constant moisture content of 30%. In case of a fire, to maintain it saturated with water to avoid it to become a hazard. A redundant system was considered that included a single water tank with water from the town's main and from the bottom of the green wall. Two backed-up pumps with separate piping that was protected with fire rated walls carry the water to the top of the green wall. Specific mechanic and controlling devices for each pipeline that are connected to the Building Management System through the internet and finally to the Fire Indicator Panel are also provided. If the systems detected a failure on the irrigation system, it will provide notifications increasing the number of people being notified as time passes by if the system is still presenting a fault [44].

Additional fire safety measures were used. The total number of strategies applied for this green wall are explained with more detail in Chapter 5.

The overall design required the collaboration of different disciplines to determine the safety design. It is the integration of all the fire safety features included in this project that provide an increased reliability. The use of an old technology such as an irrigation in a new manner as a life safety feature became a key aspect of the design. It is important to maintain the safety system working in an optimal manner, for this, inspections must be provided to the systems [44].

4.2.2 Experimental Approach

As explained in Section 3.3.2.1, after a series of tests that where performed by *Dahanayake and Chow* [9] on three common species used in green walls, the fire risk was also addressed in the study by three parameters: flashover propensity which is obtained dividing the peak heat release rate by the ignition time, total heat release, and smoke toxicity potency hazard using the lethal concentration LC_{50} [9]. The results for these three parameters are summarized and classified in Table 5.

Flashover Propensity (kW m^{-2} s^{-1})														
Hedera helix					*Peperomia obtusifolia*					*Aglaonema commutatum*				
MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})			
(%)	20	35	50	60	(%)	20	35	50	60	(%)	20	35	50	60
51 to 350	L	L	L	L	201 to 1400	L	L	L	L	351 to 1200	L	L	L	L
26 to 50	L	M	M	H	51 to 200	L	L	L	L	151 to 350	L	L	M	H
14 to 25	M	M	H	H	26 to 50	M	M	H	H	29 to 150	M	M	H	H
11 to 13	M	H	H	H	22 to 25	M	H	H	H					
Low: 0.1 to 1.0 Intermediate: 1.0 to 10 High: 10 to 100														
Total Heat Release (MJ m^{-2})														
Hedera helix					*Peperomia obtusifolia*					*Aglaonema commutatum*				
MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})			
(%)	20	35	50	60	(%)	20	35	50	60	(%)	20	35	50	60
250 to 350	VL	L	L	L	1250 to 1400	VL	VL	L	L	800 to 200	VL	VL	L	L
11 to 250	L	L	L	L	700 to 1250	VL	L	L	L	650 to 800	VL	L	L	L
					22 to 700	L	L	L	L	29 to 650	L	L	L	L
Very Low: 0.1 to 1.0 Low: 1.0 to 10 Intermediate: 10 to 100 High: 100 to 1000														
Smoke Toxicity Potency Hazard (m^3 kg^{-1})														
Hedera helix					*Peperomia obtusifolia*					*Aglaonema commutatum*				
MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})				MC	Radiative heat flux (kW m^{-2})			
(%)	20	35	50	60	(%)	20	35	50	60	(%)	20	35	50	60
11 to 350	L	L	L	L	22 to 1400	L	L	L	L	29 to 1200	L	L	L	L
Low: 0.0 to 1.0 Intermediate: 1.0 to 10 High: 10 to 100 Very High: >100														

Table 5. Risk Classification
Flashover Propensity, Total Heat Released, and Smoke Toxicity Potency Hazard
Source: Moisture Content, Ignitability, and Fire Risk of Vegetation in Vertical Greenery Systems [9]

In general, flashover propensity, total heat release, and smoke toxicity potency hazard increased with a lower moisture content. Low levels of radiative heat flux do not represent a high risk but at higher levels, the vegetation creates a higher risk [9].

4.3 Final Considerations

This chapter initially identified fire hazards from the reviewed literature. The five requirements from the Building Regulations of the UK provided categories that reunite the identified hazards under common specific areas that may be threated. This allowed to include hazards already recognized by different documents from multiple jurisdictions in a structured manner.

The first requirement, *Means of Warning and Escape*, identified two fire hazards. The evacuation of the people could get compromised. A revision of certain aspects from green roofs and walls should be performed to avoid these hazards.

The second requirement, *Internal Fire Spread (Linings)*, recognizes two fire hazards. A revision to avoid possible fire spread between the exterior and the interior of the building should be performed. Due to the evolving nature of vegetative systems, an analysis to avoid a negative evolution of the systems intrinsic fire properties should be carefully reviewed.

The third requirement, *Internal Fire Spread (Structure)*, identifies two fire hazards. Compartment rooms should be identified early and revised to avoid any possible fire spread into or out of these spaces.

The fourth requirement, *External Fire Spread*, recognizes six fire hazards. Adjacent buildings, the evolving nature of vegetation, openings or protruding elements from the vegetative surface, horizontal and vertical fire spread, and the use of double-skin façades should be reviewed carefully.

The fifth requirement, *Access and Facilities for Fire Service*, identifies four fire hazards. The operations of the fire service, their accessibility, and visual awareness might be threaded and requires to be revised.

The case studies available that analyze fire safety design and hazard identification involving vegetative systems are scarce at the moment. In the same way, cases of fire incidents on existing green elements are also limited. This prevents to gain a knowledge from previous experiences and lessons learned.

The interior green wall design case study in Melbourne, Australia, addressed the inclusion of this not so clearly understood or regulated system in an atrium by an engineering assessment. Flammable components in the system were identified and a scenario with a dried vegetation was considered. A series of safety measures were included and a quantitative risk assessment was performed to demonstrate that the likelihood of failure of all the added features was too unlikely to be considered any further. The use of irrigation and inclusion of a fire safety mode was a key aspect of the design to avoid a dry vegetation.

The experimental approach where three commonly used species were tested show in a clear manner how a decreasing moisture content increases the risk of fire for flashover propensity, total heat release, and smoke toxicity potency hazard.

Hazards towards people and the building itself can be created by vegetative system but also as a result of the combination with the building general design. The hazard created may be categorized in five different areas. An analysis of each specific project and the likelihood of the identified risks is important as it was performed in the case study to avoid an overdesign. Hazard identification is only one step in the process. The hazards identified in this section require of an analysis of fire safety strategies to address them.

Chapter V

Fire Safety Strategies

This chapter addresses the hazards identified in the previous chapter by analyzing fire strategies from a prescriptive and an engineering approach. Prescriptive measures are coming from standards, codes and the revised literature, these features are reunited following the same five categories previously used. Engineering strategies are formulated from a revision of case studies and certain inputs from standards. Finally, an analysis of certain code requirements that result in an exclusion of the use of vegetation is exposed promoting the use of a performance-based approach. Diagram 6 expose the four sections that compose this chapter and their main subsections.

Fire Safety Strategies Overview

5.1 Prescriptive Strategies
B1. Means of Warning and Escape
B2. Internal Fire Spread (Linings)
B3. Internal Fire Spread (Structure)
B4. External Fire Spread
B5. Access and Facilities for Fire Service

5.2 Engineering Strategies
Interior Green Wall
Experimental Approach
Additional Strategies

5.3 Approaches Considerations
Non-Compliance

5.4 Final Considerations
Final Remarks

Diagram 6. Fire Safety Strategies - Chapter V Overview

5.1 Prescriptive Strategies

Based on the hazards identified in the Section 4.1, several strategies are analyzed from standards, codes, and research documents to address the threats. The same five building requirements continue to structure and categorize this section. Each of the hazards present the strategies addressing it immediately as bullets.

A summary table of the hazards identified in Chapter 4 including the associated strategies analyzed in the following sections can be seen in Annex B.

B1. Means of Warning and Escape

1. Potential slide of green roof components towards people on the lower levels.

- <u>Perimeter Parapet Walls</u>
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] request to provide a perimeter parapet wall with specific dimensions depending on the building height. This

addresses the fire service concern to avoid growing medium falling down during adverse weather as it is mentioned in *Bridging The Gap – Fire Safety and Green Buildings* [16].

- For a roof height up to 46 m, a parapet height of 150 mm is requested.
- For a roof height above 46 m, a parapet height of 760 mm is requested.

A border zone of 0.9m wide should be included in the interior of the parapet wall.

2. Potential interrupt of the evacuation of tenants due to building's exit and/or egress route obstruction.

- Exit Protection
  Considering measures from wood façades, the Swiss document *Lignum 7.1 External Walls* [15] suggests the following protective features:
  - Exit door located forward or back from the façade axis.
  - Inclusion of an eave the size of the door with one meter of additional protrusion.

When it comes to interior green walls that may be located next to an evacuation route, the prescriptive strategies require materials with certain fire classification.

- Material Selection
  The Swiss directive *VKF AEAI Directive 14-15 Use of Building Materials* [43], indicates that buildings with medium height (≤30m) and high buildings (>30m) must use RF1 (A1, A2-s1d0) materials on the interior wall coverings of horizontal evacuation routes.

When the green wall system is composed by a double-skin and the intermediate climatic zone is located close to an evacuation route, *VKF AEAI Explanatory Note 102-15 Buildings with Double-Skin Façades* [27] indicates that the evacuation routes must comply with special requirements against fire. The following consideration should be revised:

- Fire Resistance
  Depending on the height, the use of the building, and the type of the mean of egress, the fire resistance solicited increases as it is indicated in *VKF AEAI Directive 15-15 Fire Safety Distances, Load-Bearing Systems and Fire Compartments* [46].

The Swiss document *Lignum 7.1 External Walls* [15] presents certain considerations for evacuation routes that are adjoining exterior wood walls.

When it comes to staircases, these elements can include exterior walls with wood linings. For buildings of 4 floors or higher, constructive measures should be taken in order to avoid the fall of parts of the linings in the door entrance, the previous considerations regarding "Exit Protection" also are applicable. In addition, the ventilation zone must be stopped [15]. Different techniques are explained in the next sections coming from the Swiss document.

Corridors may be arraigned along exterior walls with wood linings. Horizontal measures as well as the determination of the fire resistance of the wall should be done in accordance with the recommendations from the Swiss document [15].

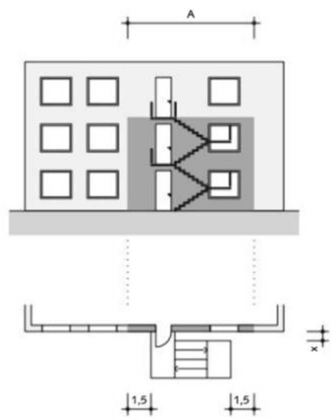

Figure 23. Wood Façade with Exterior Staircases
Source: Lignum 7.1 External Walls [15]

When the building includes exterior stairs, the façade must be of a non-combustible material without openings [15]. Figure 23 shows that the area next to exterior staircases must comply with the specific material requirements.

Exterior passageways and escape balconies can only have non-combustible exterior layer. The floor should not have any openings with a resistance of EI 60. If the building is of 3 floors or smaller, it can be EI 30 [15].

B2. Internal Fire Spread (Linings)

1. Potential fire spread from a vegetative system into the building and the other way around.

- <u>Internal Linings Compliance</u>
  The internal linings should resist fire spread and have a reasonable rate of fire growth [1]. The selection of the linings for the ceiling, walls and internal structure should meet the requirements of the local codes based on their location and use of the space.

2. Potential change in the system classification evolving into a combustible lining.

- <u>Species Selection</u>
  As it is presented in *Green Roofs, Facades, and Vegetative* Systems [2], the CIBSE Green Roof Guideline indicates that *"certain plants should be avoided for safety reasons, such as plants that are highly flammable, develop large root systems and thus high biomass or are excessively thirsty"* [2]. The selection of plants is important since certain species have a faster rate of drying.
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] recommends the use of drought resistant species which have a good as fire resistance. The inclusion of moss and grass is to be avoided [24].
- <u>Growing Medium Composition</u>
  The *Growing Green Guide* [7] indicates that the growing substrate may also become a fire hazard in hot dry conditions [7]. The composition and thickness of it should be considered to avoid an increase in the fire hazard of the system. Specific details about its composition are mentioned in Section B4-3.
- <u>Testing</u>
  Test results of an internal green wall systems at an specific stage can demonstrate the fire classification [1].
- <u>Irrigation</u>
  The ANSI/SPRI VF-1 External Fire Design Standard for Vegetative Roofs [12], identifies irrigation as an important way to prevent fires. It will vary depending on the location, climate, and plants selected [12].
- <u>Maintenance</u>
  The *VKF AEAI Norm 1-15 Fire Protection Norm* [14], on Article 20 *Maintenance Duty*, states the following: *"The owners and operators of buildings and other structures must maintain fire protection and fire protection equipment as well as technical installations, in accordance with the regulations, and ensure their operation at all times"* [14]. Following this article, maintenance becomes a duty in order to keep an approved safety level. In an internal green wall, this means that the moisture content of the vegetation must be keep at the designed level for plant survival and fire safety.
  The Swedish research report *Green roofs - From a fire technical point of view* [32], summarizes the required frequency of inspections and maintenance that are solicited by the FLL, GRO, FM Global, and ANSI green roof standards. For all of these standards, the minimum is two visits annually [32].

B3. Internal Fire Spread (Structure)

1. Potential horizontal fire spread over a compartment wall through a green roof between adjacent compartments.

- Fire Stop
  The common wall should resist the fire spread between two compartments with the usage of suitable materials. The materials selected for the structural base of the roof can also lower the risk of fire spread. Special attention should be put on the junction between the compartment wall and the roof where compartment walls must meet the underside of the roof. Fire stopping must be provided when required [1]. This can be seen in Figure 24 (a).
- Fire Break
  A fire break on the green roof above the compartment wall should be applied. This breaks should be 1500mm wide on both sides of the wall and should be of a material of limited combustibility [1]. This can be seen in Figure 24 (a).
- Wall Extension
  The compartment wall can also be continued 375mm above the top surface of the green roof [1] as can be seen in Figure 24 (b).

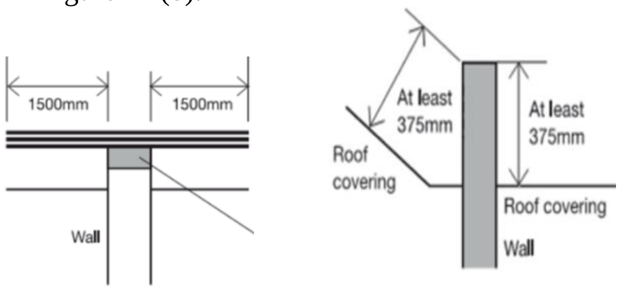

Figure 24.Horizontal Fire Safety Measures
Fire Stop and Fire Break (a) & Wall Extension (b).
Source: Fire Performance of Green Roofs and Walls [1]

- Protective Layer
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] recommends to consider fire and thermal properties of this layer to protect the other ones that might be combustible [24].

As part of the roofing system, when a layer of insulation is included, it should follow certain considerations if the material is combustible.

- "Fire Break" on Insulation Layer
  The Swiss *VKF AEAI Directive 14-15 Use of Building Materials* [43], indicates that depending on the structure type of the roof, thermal insulation surface that are composed with combustible materials must be limited to 600m^2 or 1200m^2 based on the structure type, and include at least a 2m wide strip of a RF1 (A1, A2-s1d0) insulation material. This is not authorized for high buildings (>30m).

2. Potential vertical or horizontal fire spread across a compartment floor or wall through a green wall between adjacent compartments.

- Fire Stopping
  If a green wall is attached to a wall where compartment floors are located, fire stopping must be provided between the compartment floor and the external wall as it is mentioned in *Fire Performance of Green Roofs and Walls* [1]. When a compartment walls meets the external green wall, fire stopping should also be applied.

  The Swiss *VKF AEAI Directive 15-15 Fire Safety Distances, Load-Bearing Systems and Fire Compartments* [46], present different general details of how to solve the connection between an exterior wall and a compartment wall or slab to avoid fire and smoke spread. Several variants can be seen in section 3.3.3 paragraph 2 were mineral wool and other materials are applied.

In a similar manner, the Swiss document *Lignum 7.1 External Walls* [15] presents several details on Chapter 5 regarding the connection of a wood façades and a compartment wall or slab made out of wood. The document considers that if there is a penetration of the wood compartment wall/slab into the wood façade there is no additional measures required on the inside of the wall. If there is no penetration of the wood compartment wall or slab into the wood façade, then the details are solved using mineral wool or additional wood pieces. The external measures, on the outside of the wall, can be seen in the next Section B4.

As part of the exterior wall system, when a layer of insulation is included, it should follow certain considerations if the material is combustible.

- "Fire Break" on Insulation Layer
  The Swiss *VKF AEAI Directive 14-15 Use of Building Materials* [43] directive, indicates that when a building with medium height (≤30m) uses combustible materials for peripheric insulation, the design must comply with one of the recognized systems of the VKF AEAI, or include in every floor a RF1 (A1, A2-s1d0) strip of at least 20cm height. Figure 25 show the location of the strips in the façade in image (a) and the incombustible strip indicated in blue in image (b).

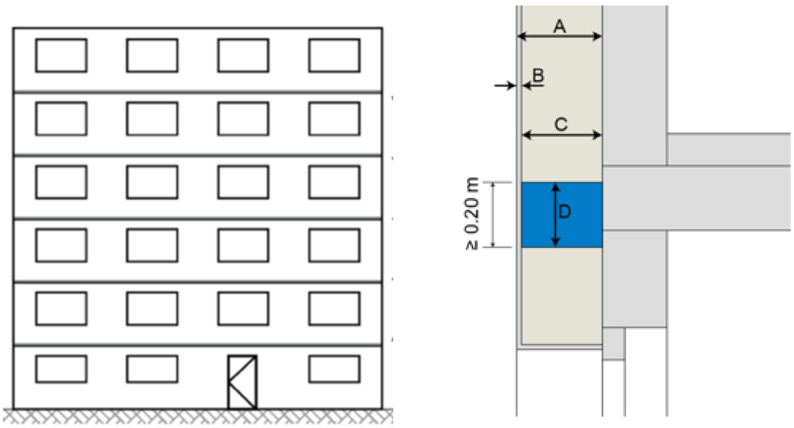

Figure 25. Wall Insulation "Fire Breaks"
(a) Front view and (b) Section view.
Source: VKF AEAI Directive 14-15 Use of Building Materials [43]

B4. External Fire Spread

1. Potential ignition and fire spread from adjacent buildings.

- Separation Distance and Material Classification

  Regarding green roofs, based on the classification of the roof covering, its size and use, a separation distance between the roof and the relevant boundary help to reduce the hazard of fire spreading across different buildings [1]. This separation distance between buildings is given by the local codes as well as the applicable test standard that needs to be followed.

  Regarding green walls, in order to avoid this hazard, a combination of the height, distance to the relevant boundary, and purpose of the building should be considered. According to *Approved Document B* [42], a building with a height lower than 18m, and with a separation distance of 1m o more, green walls can be used. If the previous conditions are not meet, the green wall system must be tested and based on the results, should comply with the requirements of Approved Document B.

  Continuing with green walls, the Swiss *VKF AEAI Directive 15-15 Fire Safety Distances, Load-Bearing Systems and Fire Compartments* [46], indicates the following distances between buildings:

    - 5m between buildings with a RF1 (A1, A2-s1d0) exterior layer.
    - 7.5m between a building with a RF1 (A1, A2-s1d0) exterior layer and a building with a combustible exterior layer.
    - 10m between buildings with a combustible exterior layer.

  This distance can be reduced when the buildings are individual houses, buildings with low height or buildings with medium height but with walls that possess a fire resistance of 30 minutes [46]. If the required distances cannot be achieved, the structures of the exterior walls must comply with higher fire requirements [46].

- <u>System Classification</u>
  Regarding resistance towards flying brands and radiation from other buildings, the German *FLL Guideline* [28] considers intensive roofs that are well maintained as *"hard roof"* and resistant to this fire hazard. Extensive roof can also be considered resistant if they comply with certain requirements established on the document regarding mixture of growing medium, thickness of the vegetation, and specific measures at certain locations [28].
- <u>Extinguishing Systems</u>
  The Swedish research report *Green roofs - From a fire technical point of view* [32], indicates that the extension of combustibles surfaces can be limited by the use of automated fire extinguishing systems [32].
  As mentioned in *Green Roofs, Facades, and Vegetative Systems* [2], the Maltese Green Roof Standard considers emergency sprinklers as a first measure to suppress fires [2].

2. Potential change in the system classification evolving into a combustible lining.

- <u>Species Selection</u>
- <u>Growing Medium Composition</u>
- <u>Testing</u>
- <u>Irrigation</u>
- <u>Maintenance</u>

The previous five strategies are explained in Section B2-2. The same measures can be applied for external vegetative systems.

3. Potential fire spread to a green roof by openings or protruding elements and vice versa.

- <u>Fire Breaks</u>
  Fire breaks around openings and vertical elements is recommended for all types of green roofs. The use of non-vegetated strips of pebbles or concrete paving is advised [1].
  The *GRO Code* [4] indicates that these strips should have a width of 500mm and the dimension of the stones should be between 20 and 40mm.
  The *ANSI SPRI VF-1 External Fire Design Standard for Vegetative Roof* [12], indicate the need to provide a *Border Zone* where a green roof abut a non-combustible rooftop structure, joint or encounter a penetration. The *Boarder Zone* consist of a 1m wide continuous border free of vegetation or growing media [12].
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] indicates the following widths:
    - Surrounding non-combustible rooftop structures, adjacent non-combustible walls and equipment, penetrations, skylights, solar panels, antenna supports, expansion joints, roof area dividers, and interior parapet walls: 0.9m width.
    - Surrounding combustible rooftop structures, equipment, and features: 4m width.
    - At abutting combustible vertical surfaces or at fire barriers *Fire Breaks* must have a width of: 1.8m width.
- <u>Growing Medium Requirements</u>
  To prevent the fire spread over the roof into the building, it is recommended that the growing medium has a minimum depth and a maximum percentage of the organic content.
  In *Fire Performance of Green Roofs and Walls* [1] it is recommended a depth of at least 80mm and an organic content of the mixture of not exceeding 50% [1].

The *GRO Code* [4] indicates a minimum depth of 80mm and that the organic composition of it does not exceed 20% for extensive roofs [4].

4. **Potential fire spread of a green roof in a horizontal manner.**

- Fire Breaks
  To prevent fire spread throughout the vegetation and growing medium, fire breaks should also be used to subdivide large areas in a green roof.
  The *GRO Code* [4] indicates that the fire break strips should have a width of 1m every 40m across the roof.
  The *ANSI SPRI VF-1 External Fire Design Standard for Vegetative Roof* [12], indicate the need to provide an *Area Divider* in order to divide the green roof into sections with an area not larger than 1 450 m^2 and where each sections does not exceed 39m. The break must be composed of a Class A or non-combustible material. The width of the are divider should be 1.8 m.
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] indicates an area free of vegetation and growing medium with a minimum wide of 4 m every 1 450 m^2 and where each sections does not exceed 39m.
  As mentioned in *Green Roofs, Facades, and Vegetative Systems* [2], the Maltese Green Roof Standard *SM 3700:2017*, considers certain species as good fire breakers. As an example, the document mentions *Jacobaea maritima* [2].

5. **Potential vertical fire spread of an exterior green wall and ignition from the interior of the building by a window fire plume.**

- Horizontal Measures
  When it comes to ventilated green walls an analogy with wood façades is performed. *Lignum 7.1 Exterior Walls – Construction and linings* [15] indicates that for four story buildings until high buildings (>30m) details and requirements for building with this height that present external wood finishes are accepted if, by taking measures, there is no contribution to fire spread towards upper levels. The ventilation space should be interrupted by the use of the following options that are illustrated in Figure 26.
  - Apron. The material of this can be metallic, mineral panel, or wood. Further information can be consulted in section 4.1.4 of the Swiss document [15].
  - Upper Obturation. The materials of this element can be metallic, wood lath, or mineral wool.
  - Non-Ventilation. The construction detail can prevent ventilation in the void space by removing the empty space, in the case of green walls direct attachment to the building prevents this air gap.

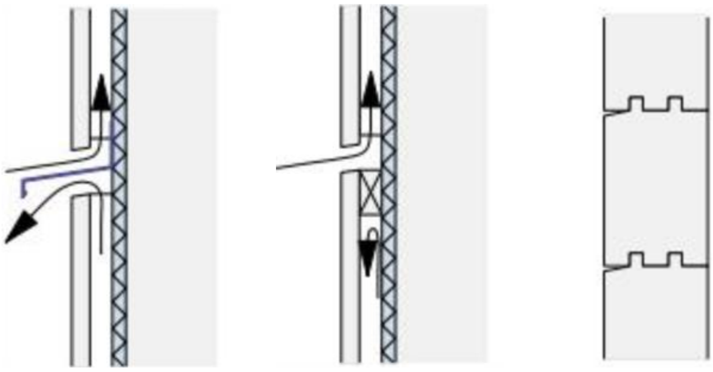

Figure 26. Horizontal Measures
Apron, Upper Obturation, Non-Ventilation.
Source: Lignum 7.1 Exterior Walls [15]

For three story buildings or lower height, the use of wood is admitted depending on the building type and security distances. When it comes to high buildings (>30m), materials must be of a classification RF1 or 6.3 (incombustible). This leaves wood out of this type of buildings. If the access for the fire-fighters is not possible, then combustible materials should be excluded [15].

In the same way, as it is mentioned in *Fire Performance of Green Roofs and Walls* [1], specifically for external green walls that are attached to a wall with a cavity between both elements, this cavity size must be limited by vertical and horizontal barriers [1].

6. Potential fire spread in a double-skin green wall system.

Depending on the type of double-system selected, the following considerations from the *VKF AEAI Explanatory Note 102-15 Buildings with Double-Skin Façades* [27] are relevant strategies:

- Segmentation
  Type A - Fire resistance segmentations. Compartment floor must extend their protection in the intermediate climatic zone with a segmentation EI30. The segmentation must be tightly connected to the secondary façade or continue to the exterior of it.
  In addition, there should be a fire resistance separation between the intermediate climatic zone and the ventilated spaces of the roof [27].
- Extinguishing System
  Type B - Without fire resistance segmentations. When there is not a fire resistance segmentation in the intermediate zone, the building must provide an extinguishing system. Detection is required depending on the use of the building. Opening windows are not allowed in buildings for people where they sleep.
- Material Selection
  Type C - Primary façade fire resistant. The primary façade must have at least a fire resistance of E30. Resistance can become stricter depending on the distance with other buildings.

The inclusion of extinguishing systems covering the intermediate climate zone may allow materials in the secondary façade and the insulation in the primary one to be of a lower classification [20].

B5. Access and Facilities for Fire Service

1. Potential impact on fire service operations and roof access.

- Dry Rising Main Outlets
  When the roof is considered as a floor accessible for tenants and is located at a height above the entrance level of 18m, it should include sufficient dry rising main outlets to meet the hose laying distance of 45m [1]. A building with this height must have a fire shaft as defined by *Approved Document B* [42].
- Fire Hydrants
  The *ANSI SPRI VF-1 External Fire Design Standard for Vegetative Roof* [12], indicate the need to provide Fire Hydrants or stand pipes.
- Border Zone
  The *FM Global Loss Prevention Data Sheet 1-35 – Green Roof Systems* [24] request to provide perimeter parapet walls with specific dimensions depending on the building height where a border zone of 0.9m wide should be included in the interior of the parapet wall [24].
  Bridging the Gap: Fire Safety and Green Buildings [16] identifies the requirement of enough space around the perimeter of the green roof for the fire service personnel and their equipment. Also pathways for the firefighters to access to the roof equipment and skylights should be considered for vertical ventilation operations [16].
- Fire Breaks
  These elements are included for multiple reasons as can be seen in sections B3-1 & B4-3,4. The breaks are also useful for the accessibility of the fire service and maintenance. The elements also help to prevent wind uplift.

2. Potential interrupt of the access of fire-fighters into the building due to an obstruction of the entrance.

- Exit Protection
  Considering measures from wood façades, the Swiss document *Lignum 7.1 External Walls* [15] suggests the following protective features:

- Exit door located forward or back from the façade axis.
- Inclusion of an eave the size of the door with one meter of additional protrusion.

3. **Potential impact on fire service operations due to the height of the building.**

- Height and Material Classification
  The building height is also a parameter that is considered when an exterior wall is selected. As it is mentioned on the previous Section B4-1, *Approved Document B* [42] stablishes a maximum height of 18m. Above this height, and depending on other variables, certain materials cannot be used [42].
  The Swiss *VKF AEAI Directive 14-15 Use of Building Materials* [43], indicates that when a building with medium height (≤30m) uses combustible materials on the external walls or thermal insulation, the design must consider the accessibility of the fire fighters in case of an ignition. The fire should also not spread more than two floors above before the arrival of the fire brigade. If the building is considered to be high (>30m), then the exterior walls and their finishes must be of the category RF1 (A1 or A2-s1, d0) [43].
  Lignum 7.1 bases in 15 minutes the time of the fire fighter intervention in Switzerland according to *Feuerwehr* [15]. This document also indicates that when the construction is made out of wood, due to this additional fire load, the exterior wood finishes should only be used where it is possible for the fire fighters to access it. The use for high buildings is excluded [15].
- Extinguishing Systems
  This measure already explained in Section B4.1, might function as a possible a solution.

4. **Potential visual and intervention impact for the fire brigade with a double-skin wall system.**

- Segmentation
- Extinguishing System
- Material Selection

The same considerations previously explained from the *VKF AEAI Explanatory Note 102-15 Buildings with Double-Skin Façades* [27] in Section B4-6 are also applied in this case.

The Swiss documents previously allowed other possibilities to be applied such as the inclusion of pressurized stairwell for the fire brigade and the inclusion of two windows for each floor that can be open in the façade. These strategies are no longer on the code and should be analyzed specifically for each project.

5.2 Engineering Strategies

Based on the case studies from Chapter 4 and a revision of Swedish research reports, several strategies are analyzed from these inputs to address vegetative systems that have a higher level of complexity or address specific safety aspects.

5.2.1.1 Interior Green Wall Design

The following fire safety features are taken form the final design from the interior green wall project located at an atrium in an office building in Melbourne, Australia. The case study, was already revised Section 4.2.1 regarding a hazard analysis. The safety features provide the required safety level when the systems work combined together. The final design received the approval from the local authorities.

- Fuel Exclusion Zone
  Combustible materials could only be located 2m away around the green wall. The bottom 4m of the vertical surface does not include the green wall limiting the accessibility of intentional fires [44].
- Fire Walls
  Concrete fire walls that also function as the support structure of the green wall were provided to separate the atrium from the adjacent space and inhibit fire spread into the wall cavity. No

electrical motors or pumps were installed inside this cavity [44]. The pipelines located behind the green wall were protected by fire rated walls [44].

- Smoke & Heat Control System
  Extraction and supply air fans were calculated to provide a smoke control system inside the atrium. In addition, a smoke reservoir was designed at the top level of the atrium [44].
- Detection System
  General smoke detection is included in the building and a beam detector at a specific level [44].
- Suppression System
  Vertical side wall sprinklers at each story of the green wall were included during the design process. It is mentioned that even though the performance of this sprinklers will not be as good as on glass, the elements will provide water to prevent and slow fire spread [44].
- Irrigation System and "Fire Mode"
  An irrigation system provides the required water with specific amounts during daytime (0.4 $l/m^2/hr.$) and nighttime (0.1 $l/m^2/hr.$). If the detection system or sprinklers are activated, the irrigation system will operate on "fire mode" providing an increased amount of water (3.6 $l/m^2/hr.$) [44].
  The moisture content of the foam is required to be maintained at 30% based on the plants need. The irrigation system is an important element since the foam was identified as a combustible material. By constantly supplying it with water, the hazards was reduced [44].
- Notification System for Irrigation
  In case the irrigation system presents a fault, an automated notification system will inform specific stakeholders of the operation of the building in an escalating manner. If the fault persists after certain amount of time, the system will create an alarm increasing its coverage as time passes by [44].
- Reliability
  The irrigation system included a redundant design that comprises two pumps, each one piped independently that include individual mechanical and operation accessories. This redundancy increased the reliability and maintainability of the system [44].
  The exhaust and supply air fans are connected to an emergency generator [44].
- Inspections
  Ongoing inspections by a registered fire safety engineer every certain amount of time were defined during the design stage in order to get the final approval [44].

5.2.1.2 Experimental Approach

The research article *Study on the fire growth in underground green corridors* [37], as explained in Section 4.2.2, analyses a fire on a green wall located on an corridor and identifies specific hazards on the project. For this type of elements under specific conditions, a performance-based approach is considered the most suitable one where experiments and numerical simulations can demonstrate the fire and smoke behavior of the vegetation [37]. The process for the development of the fire curves, numerical simulations, and result analysis can be seen in Section 3.4. The strategies followed are part of the entire performance-based design process.

- Testing
  This should be done ahead by considering the plants at specific levels of moisture content after experiencing a natural drying process as performed. Further explanations can be seen in Section 3.3.2.1.
- Species Selection
  The research indicates that certain species retain higher values of moisture content after been exposed to several days of natural dryness. These species are considered more suitable to have a lower fire risk [37].
- Maintenance
  It is concluded on the report that for the three species tested, the plants did not represent a fire hazard when the moisture content is high and the plants are well hydrated and maintained [37].

5.2.1.3 Additional Strategies

The Swedish research report *Green roofs - From a fire technical point of view* [32], indicates that local regulations allows to deviate from the general guidelines if it can be demonstrated that the functional requirement is achieved [32]. The research report mentions the following strategies.

- Radiation Levels & Fire Scenarios
  Based on the local codes, in order to protect against the spread of fire between buildings, the radiation levels should be analyzed based on a series of scenarios. The maximum radiation level should not exceed the acceptable limits on each scenario. The scenarios should be identified and justified as probable worst cases [32].
- Safety Distance Calculation
  The research report proposes the following method for calculating fire impact on green roofs. Radiation, as the main mean of heat transfer in addition with direct flame contact is considered. Certain assumptions have to be done with this method. This suggests the inclusion of a sensitivity and uncertainty analyses [32].
  The goal is to determine a safety distance of separation in order to avoid fire spread due to radiation [32] but this procedure can also be used to calculate certain specific characteristics of the flame. It is explained in the following six steps:
  1. Calculate the area of the flame.
     - Calculate the spreading speed.
     - Calculate depth of the flame.
     - Calculate the width of the flame.
     - Calculate the intensity of the fire.
     - Calculate the height of the flame.
  2. Calculate the incident radiation.
  3. Calculate critical incident radiation.
  4. Calculate the protective distance to the receiving surface.
  5. Calculate the deflection of the flame.
  6. Correct the protective distance in regard to the deflection of the flame.

  Further explanations about each step and an example of this calculation procedure are provided in the Swedish research report [32].

Projects that under a performance-based approach have as a goal environmental protection, can consider the following general measure.

- Sprinkler System
  The FM Global Technical Report *Environmental Impact of Automatic Fire Sprinklers* [47], concludes that: "*In the event of a fire, the use of sprinklers reduces water usage between 50% and 91%*" [47], this is in comparison with manual fire suppression form fire fighters. In addition, *"The total air emissions generated during the sprinklered test were significantly lower than the total air emissions generated during the non-sprinklered test"* [47]. The importance of fire safety measures not only contribute towards life and property safety but also has a positive impact for the environment which is the main goal of the green movement.

5.3 Approaches Considerations

Based on the specific requirements and design of the project, in addition with the local fire safety regulations, two approaches may be followed. A prescriptive or an engineering approach may become more suitable depending on the scale and the level of complexity of the project. A combination of both may also be used when the project follows a prescriptive approach but for deviations from it an engineering approach is applied.

Figure 27, based on *INSTA 950* [48], presents the basic process for the selection of the fire safety approach to be used in a project. The original diagram was modified to illustrate the process for selecting an approach on vegetative systems. Basically, two questions should be asked, if there are standards already existing that are applicable for the project and if the requirements are satisfied. As the following paragraphs explain, vegetative systems, as recent and non-traditional construction elements, may deviate from the code requirements.

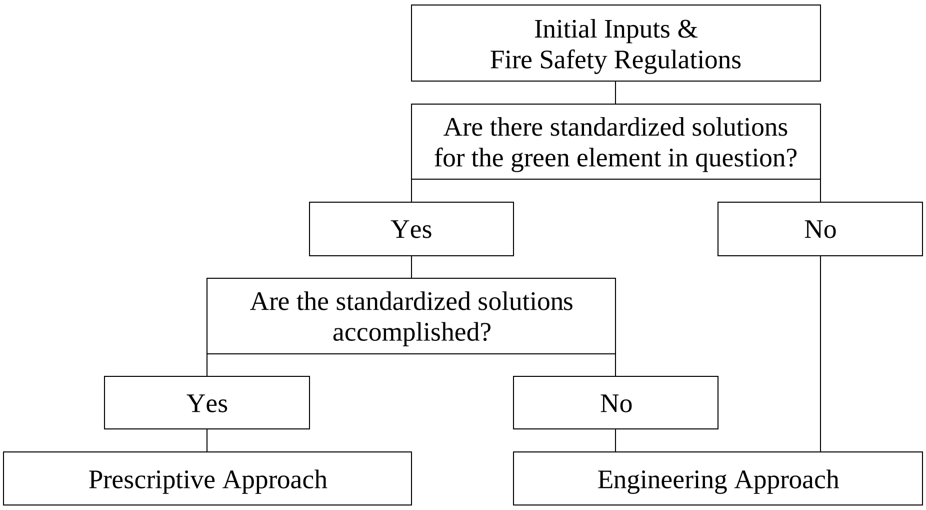

Figure 27. Approach Selection

The prescriptive strategies in Section 5.1 for fire risks identified in Section 4.1 are coming from regulations mostly from the UK, Germany, Switzerland, US, and FM Global. In some cases, the strategies restrict the use of vegetative systems in specific scenarios. Noncompliance with the prescriptive regulations can be a result of the following reasons:

- <u>Building Height</u>. If the location or extension of the green element is beyond the reach of the fire service, regulations specify materials with specific fire ratings requiring then for a fire test on the green system. This maximum height varies according to the legislation, it can be stablished at a certain height or as a combination between the distance to boundary and the use of the building.
- <u>Building Location</u>. If the building is closer than what the local code requires to the limiting boundary or to another building, then the materials to be used should comply with a specific fire rating classification. This requires again testing on the green system. The distance can be defined based on the exterior linings of the buildings or as a combination of the building height and use of the building.
- <u>Means of Egress</u>. The use of specific materials on means of egress such as corridors or stairs is also restricted by certain fire requirements. Again, testing the green system is required to compare the classification against the regulations.
- <u>Testing & Material Compliance</u>. Testing the green system is required in order to know its contribution and behavior exposed to fire and to classify it. The majority of the system are not tested. Based on few experiments, results suggested that the classification will not fall as an incombustible material leaving vegetative systems out of use for several applications.
- <u>Negative Evolution</u>. Even if the green system is tested and the result comply with the requirements, the nature of these elements can evolve in negative way. The green element can decrease its moisture content to levels where it becomes a serious fire hazard.

The Swedish research report *Green roofs - From a fire technical point of view* [32], identifies that certain basic green roof designs meet the solutions proposed on the local codes. But, in order to achieve higher levels on green building certifications, the green roof type selected do not meet the guidelines. Also, architectural interests can result in the selection of a green roof system that do not meet the prescriptive requirements [32]. A different approach to provide a solution to more complex green roofs designs is required.

The research report [32], indicates that, based on the local codes, combustible roofing including green roofs, can only be used over a non-combustible substrate of class A2-s1, d0. The flammable roofing must be class B_{ROOF} (t2) and the building should be 8m away from other buildings. The report mentions that only a few green roof systems can be found on the market that meet the required class B_{ROOF} (t2) classification. However, these products only include certain low vegetation types that is not always the desired one. In order to use the desired vegetation or a non-compliant system, the functional requirement of the code must be proved that is met [32]. The way that the functional requirement is met is subjective and can vary from project to project depending on who revises it. A clearer interpretation of the requirements should be adopted in order to avoid any subjectivity [32].

As it is mentioned in the *SFPE Performance-Based Fire Safety Design* [49], prescriptive codes have a couple of disadvantages.

- The code requirements only protect against events that have occurred in the past [49]. Fires involving vegetative systems are scarce and not well documented.
- The standards can hold back innovation [49]. Vegetative systems are recent technological systems that may be excluded leaving out their benefits.

Many prescriptive-based regulations allow alternative means to comply with the intendent prescribed provision [49]. When a vegetative system is not complying with the local prescriptive regulations, the next step is to consider an engineering approach to evaluate with more detail the design, context, and other specific variables. This will provide a better understanding of the performance of the vegetative systems and the building in case of a fire. Defining a fire safety solution to the green element by a performance-based approach requires a set of steps and tools that are addressed in the Section 6.4 of the guideline.

5.4 Final Considerations

After the identification of hazards performed previously, this chapter revises strategies that have been developed for prescriptive code compliance or after following a performance-based design. The strategies following each of the two approaches are explained with final considerations of the applicability of both.

Initiating with the prescriptive approach, the same five categories that addressed the 20 hazards identified previously were used to compile the strategies found in standards, codes, and research documents

Requirement B1, *Means of Warning and Escape*, identified two fire hazards and reunite four strategies to address them. The measures identified consist of passive elements.

Requirement B2, *Internal Fire Spread (Linings)*, recognizes two fire hazards and address them with six strategies. Interior vegetative systems should acknowledge the changing properties of the vegetation and use measures to keep the system under safety conditions.

Requirement B3, *Internal Fire Spread (Structure)*, identifies two fire hazards and seven measures to manage them. For both, vertical or horizontal fire spread, passive fire measures can be applied.

Requirement B4, *External Fire Spread*, recognizes six fire hazards and exposes fifteen strategies. Some of these measures can be used to address more than one hazard. Active fire protection systems are also considered with passive measures. The changing properties of the vegetation are also addressed by multiple elements to maintain the system well hydrated and with a low risk of ignition.

Requirement B5, *Access and Facilities for Fire Service*, identifies four fire hazards and nine measures are considered to address them. Previsions and considerations for the fire department were analyzed.

Some strategies may be useful for more than one hazard and applied for multiple categories. Regarding green roofs, in some cases, the strategies suggested by the documents are the same but with small changes of the measurements depending on the jurisdiction. This can be explained because most of the codes reference to the German FLL guideline, which is considered the initial and most complete document for green roof design. Green walls, on the other hand, are not so widely addressed which required an analogy by revising wood and double-skin façades measures. In general, measures addressing the evolving properties of the vegetation can be applied for both systems. These preventive measures are considered of major importance.

The engineering strategies section reunites measures taken from case studies on the design of an interior wall and testing on the vegetation and developing numerical simulations. The hazards of each of these two studies were explained in the previous chapter. Additional inputs from documents that address fire safety calculations on vegetative systems were also revised.

The interior green wall case study resulted in a series of general strategies for the atrium but also provided with interesting and new measures such as the inclusion of a notification system to inform about a possible failure on the watering system which would avoid the vegetation to become dry. Also, the irrigation system included a "fire mode" which by delivering additional water once activated can reduce the spread of fire. This last feature is a smart measure since it exploits the already required need for irrigation and its related infrastructure.

The experiments explained in previous sections performed by *Dahanayake and Chow* on vegetation provided with a view of the importance of the moisture content and how its evolution differs between species. Measures like species selection, testing, and maintenance became logic after these experiments.

Additional features such as the safety distance calculation from the Swedish document provide with a way to calculate the required distance as an alternative to a fixed number by the codes. The inclusion of sprinklers may have strong environmental benefits in case of fire which go by hand with the main goals of vegetative systems on the first place.

Prescriptive and engineering approaches may be employed for the design of the fire safety measures. A prescriptive approach may be more suitable for small and low-complexity projects since, as explained in the previous section, codes may demand certain conditions, such as materiality, fire resistance, height, and location of the system, which would result in a non-compliance of the requirements. This may hold back innovation and not achieve specific goals that are wanted from the vegetative systems. As an alternative, prescriptive-based design provides with a custom-made solution for these deviations.

Multiple strategies may be applied for vegetative system but also for the building general design to achieve safety levels. The measures vary between active and passive features with an origin from standards or engineering assessments. These features, in general, prevent fires, limit their spread, or extinguish it. The analyzed strategies will be used as inputs for the guideline. The steps needed for a complete fire safety design are indicated in this final best practice document.

Chapter VI

Best Practice Guideline

This chapter provides the steps for the design of fire safety measures on vegetative systems. It considers a prescriptive and an engineering approach focusing on the last one by providing tools and examples to implement it. Diagram 7 expose the eight sections that compose this chapter and their main subsections.

Best Practice Guideline Overview

6.1 Introduction
- Scope
- Purpose
- Audience
- Lifecycle

6.2 Initial Considerations
- Inputs
- Fire Safety Approach

6.3 Prescriptive Approach
- Code Compliance

6.4 Engineering Approach
- Scope
- Goal
- Objective
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6.5 Fire Safety Strategies
- Control Combustion Process
- Suppress Fire
- Control Fire by Construction

6.6 Documentation
- Design-Brief
- Performance-Based Design Report
- Specifications and Drawings
- Operations and Maintenance Manual

6.7 Guideline Discussion
- Results

6.8 Final Considerations
- Final Remarks

Diagram 7. Best Practice Guideline - Chapter VI Overview

6.1 Introduction

A specific introduction to the Best Practice Guideline is developed to explain the scope, purpose, audience and lifecycle of the document. This document is the result of the research performed on the previous chapter presented as a series of steps supported by tools and scenario examples specifically developed for vegetative systems.

6.1.1 Scope

This guideline addresses fire safety concerns on buildings that include a vegetative system. The guide may be applied for green roofs and exterior or interior green walls with a low to high complexity level.

The document is developed considering the particular aspects of vegetative systems. These systems present non-traditional characteristics when considered as construction elements in buildings due the continuous evolving nature of its intrinsic properties.

This guide reunites considerations from different latitudes based on the previous research exposed in the preceding chapters but is not attached to any specific region and may be applied without any location constraint. National regulations should be considered above this document.

6.1.2 Purpose

The purpose of this document is to provide with steps for designing fire safety solutions specifically for vegetative systems. Two methodologies may be followed, a prescriptive or an engineering approach.

The process on a prescriptive approach is straight forward. It requires less steps but, in many cases, provides with rigid solutions. It is mostly applicable for projects with a low level of complexity. Depending on the location of the project, different measures are requested by the corresponding authorities. This guideline provides with a series of strategies that were included based on a review of multiple standards, some of these measures may be in line with the local requirements but some others may not. The goal with this approach is established by the local regulations.

As an alternative solution for projects with a higher level of complexity, an engineering approach is developed as the focus of this guide. The process is explained through a series of steps, tools, and examples that illustrate the use of the guideline. The goal with this approach is established based on the requirements of the project. Specific objectives that cover most of the needs regarding fire safety when this approach is followed are established and developed further throughout the entire process.

6.1.3 Audience

This guideline comprises different sections that may refer to previous chapters of this research. Depending on the approach to be followed different audience may find certain sections valuable.

In general, this document can be useful for fire safety engineers, architects, authorities, researchers, and developers when a project includes a vegetative system. Certain section may be of interest for the maintenance workers, building managers, contractors, and manufacturers.

When a performance-based design approach is used, many of the steps described in the process are mostly of interest for fire safety engineers and professionals who can apply scientific and engineering principles with knowledge on fire dynamics and risk assessment.

6.1.4 Lifecycle

In general, a building lifecycle can be divided into three main stages: Design, Build, and Operate. The tasks of a vegetative system are multiple according to according to the *Growing Green Guide* [7] and expand throughout the three main stages of a building lifecycle. This goes by hand with the fire safety duties that follow the green system requirements addressing each task that is performed.

At the design stage, *site analysis* and *design & planning* [7] are tasks performed by the designers of the vegetative system. The resulting initial considerations become an input for the fire safety engineer who revises them and provides a fire safety solution following a prescriptive or an engineering approach.

During the build stage, *building and installation* [7] of the vegetative system and specified fire safety features take place. Inspection and system commissioning are important duties that the fire safety engineer performs to make sure the element is built as designed.

The final stage, operate, includes *operation*, *maintenance*, *establishment*, and *renewal/demolition* [7] tasks which are part of the vegetative system lifecycle. These is addressed by the fire safety engineer through the operation & maintenance manual.

It is important to stress that design and build stages are both projects that have a starting and finishing date. Operate stage, on the other hand, is an ongoing phase which can last for decades. As concluded from the previous sections, vegetative systems are non-traditional constructions elements that have an evolving nature. It is important to acknowledge and address these changing properties since it can result in a hazard above what was originally analyzed or designed for.

Figure 28 resumes the lifecycle of a vegetative systems considering the building stages, vegetative system tasks, and fire safety duties prior, during, and after construction.

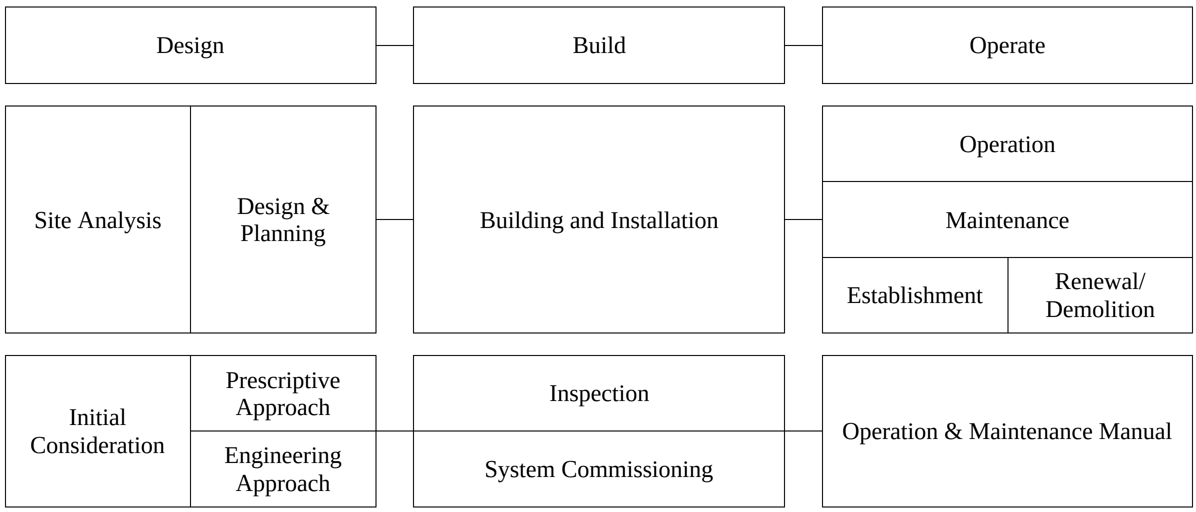


Figure 28. Building Lifecycle
Building Stages (top), Vegetative System Tasks (middle), and Fire Safety Duties (bottom)

6.2 Initial Considerations

At the initial stage of the fire safety design process, the general design of the vegetative system design and considerations should be revised. These initial aspects are considered as inputs for the fire safety engineer which by analyzing them, together with the local regulations may selected the most suitable design approach.

6.2.1 Inputs

The general goals, characteristics and components of the vegetative system are defined by the architect together with the client, and design team. The initial considerations are provided to the fire safety engineer and used as an input for the development of the required safety measures. The initial contact between the general designers and the fire safety team should be at an early stage and a parallel work.

A summary chart of these inputs is provided in Tool 1, which is based on the findings of Chapter 2 in combination with the *Growing Green Guide* [7]. Further and detailed information on these factors can be revised in the sections of this chapter and in the Australian document. The general considerations done at this initial phase are divided into four tasks: Site Analysis which provides an understanding of the characteristics of the area, Design and Planning reunites key considerations of the system, Building and Installation exposes the system components, and Maintenance aspects which should be planned ahead [7]. The tool is divided by categories and indicates its applicability for green roof and walls including general remarks.

Stage	Category		Aspect	Green Roof Ext	Green Wall Ext	Green Wall Int	Remarks
Site Analysis	Seasonal Considerations and Climate		Wind	X	X		Understanding the climatic factors on site will have an influence on the selection of plant species. The aspects mentioned on this section suggest the conditions that the plants will be exposed to.
			Rainfall	X	X		
			Solar radiation	X	X		
			Temperature	X	X	X	
			Microclimate	X	X	X	
	Irrigation		Storage opportunities	X	X		The water requirements of the plants need to be considered as well as the source of it.
			Water demand analysis	X	X	X	
	Weight Loading		Dead load	X	X	X	Calculations on the different loads that the plants will be exposed to need to be analyzed. The weight of the mature system shall be considered.
			Live load	X			
			Transient load	X	X	X	
	Drainage		Primary drains	X	X	X	The amount and length of rainfall should be considered for designing the drainage system. The slope, speed, and capacity of the system should also be revised.
			Secondary drains	X	X	X	
	Existing Structure		Dimensions	X	X	X	Installing a vegetative system on an existing building requires the revision of certain aspects.
			Protection from vegetation required		X	X	
			Waterproofing	X			
			Roof slope	X			
			Water storage	X	X	X	
	Access		Temporary construction	X	X	X	Accessibility during the construction and afterwards should be considered. Providing access for the maintenance of plants and installations is required. Certain vegetative systems will also require to grant access for people to get in touch with the vegetation.
			People and maintenance	X	X	X	
			Installations	X	X	X	
	Local Environment		Biodiversity	X	X		Nearby vegetation shall be considered when a biodiversity habitat is desired. The local plants might be a source of weed, insects, and a fire hazard.
			Weed	X	X		
Design and Planning	Design Objectives		Environmental	X	X		The reason for the inclusion of a vegetative system needs to be defined as well as the requirement of the client and stakeholders. The system can have multiple goals that need to be fulfilled by the design.
			Recreation	X			
			Low maintenance	X	X	X	
			Cooling and insulation	X	X		
			Biodiversity	X	X		
			Food production	X	X		
			Coverage		X		
			Aesthetics	X	X	X	
			Cost	X	X	X	
			Lifespan	X	X	X	
			Easy installation	X	X	X	
			Screening		X		
	Planning for Drainage and Irrigation		Drainage	X	X	X	A good drainage system will not affect the structural integrity as well as the building and the plants. The demand of water needs to be calculated of the irrigation system.
			Irrigation	X	X	X	
	Designing for Maintenance		Maintenance objectives	X	X	X	The maintenance requirements need to be understood by the building owners and managers at this stage. The objectives and future costs should be defined.
			Cost of maintenance	X	X	X	
	Sourcing Skills, Expertise and Information		Project manager	X	X	X	Experts on multiple specific areas are often part of the design of a vegetative system. The more complex the proposal is, the more coordination between different fields is required. Various professionals will need to work together to deliver a quality system.
			Principal contractor	X	X	X	
			Architect	X	X	X	
			Landscape architect	X	X	X	
			Structural engineer	X	X	X	
			Building system engineers	X	X	X	
			Fire safety engineer	X	X	X	
			Builder	X	X	X	
			Building surveyor	X	X	X	
			Waterproofing contractor	X	X	X	
			Leak detection specialist	X	X	X	
			Horticulturalist	X	X	X	
			Green system provider	X	X	X	
			Irrigation consultant	X	X	X	
			Maintenance manager	X	X	X	
	Cost Considerations		Construction	X	X	X	The budget for the construction of the project and its maintenance should be considered since the beginning. A contingency for design and construction should be considered for unexpected problems.
			Maintenance	X	X	X	
			Contingency	X	X	X	
	Planning, Regulations and Local Laws		Planning permit	X	X	X	Local permits should be revised to comply with the regulations and laws applicable where the vegetative system will be installed. This may include heights regulations and management of vegetation.
			Building permit	X	X	X	
			Local laws	X	X	X	
	Building Rating Schemes		Green building certificates	X	X	X	Vegetative systems can contribute into earning credits in building rating schemes.
	Selecting Plants	Green Roof	Low growing succulents	X			The selection of the vegetation must be based on the objective, plant characteristics, climate, and microclimate. The type of the green roof and wall, on site conditions such as the temperature, wind, and rainfall must be revised before selecting the species for the system. Species with the potential of weed developing, poisonous, or prone to toxicity, diseases or pest infestation should be avoided. Depth and mixture of the growing medium should also be considered when part of the system as well as the weight loading capacity of the structural elements, budget, and maintenance requirements.
			Herbaceous perennials	X			
			Annual or biennial plants	X			
			Turfs	X			
			Shrubs	X			
			Trees	X			
		Green Wall	Self-clinging plants		X	X	
			Twining and tendrils plants		X	X	
			Shrubs		X	X	
			Evergreen herbaceous perennials		X	X	
			Herbaceous ground covers		X	X	
			Ferns		X	X	
			Grass-like foliage forms		X	X	
			Lilies & irises		X	X	
	Designing for Plant Establishment		Quality planting stock	X	X	X	At the design stage, several factors need to be considered for a good plant health and establishment as well as the performance of the system.
			Quality growing medium	X	X	X	
			Seasonal conditions	X	X		
			Establishment irrigation	X	X	X	
			Weed control	X	X	X	
Building and Installation	System Components	Green Roof	Vegetation	X			Multiple layers are used depending on the green roof system and building and environment characteristics.
			Growing medium	X			
			Moisture retention mat	X			
			Filter layer	X			
			Drainage layer	X			
			Protective layer	X			
			Root barrier	X			
			Waterproofing layer	X			
			Roof structure	X			
			Erosion protection	X			
			Siding protection	X			
			Thermal insulation	X			
			Irrigation	X			
			Modular containers	X			
		Green Wall	Vegetation		X	X	Multiple components are used depending on the typology selected of the green wall system.
			Growing medium		X	X	
			Waterproofing		X	X	
			Air gap		X	X	
			Intermediate climate zone		X		
			Supportive components		X	X	
			Building façade		X		
			Thermal insulation		X		
			Irrigation		X	X	
			Drainage and drip trays		X	X	
			Lighting system			X	
Maintenance	Planning		Objectives	X	X	X	A maintenance plan should consider several factors based on the requirements of the system and the available resources.
			Performance targets	X	X	X	
			Responsibilities	X	X	X	
			Training required	X	X	X	
			Resources available	X	X	X	
			Risk management	X	X	X	
	Tasks		Establishment maintenance	X	X	X	Each system has its own requirements when it comes to maintenance. There are different types of maintenance that are performed at different stages of the timeline of the vegetation or when there are unexpected conditions or failures on the system.
			Routine maintenance	X	X	X	
			Cyclic maintenance	X	X	X	
			Reactive maintenance	X	X	X	
			Preventative maintenance	X	X	X	
			Renovation maintenance	X	X	X	
	Plant Nutrition		Controlled release fertilizers	X	X	X	Plants on every vegetative system require to receive proper nutrition for their development and well-being.
			Soil testing	X	X	X	

Tool 1. General Considerations

6.2.2 Fire Safety Approach

Based on the inputs provided to the fire safety engineer in combination with a revision of the local fire safety regulations, a prescriptive or an engineering approach may be followed. Depending on the level of complexity of the project, one may become more suitable then the other.

Section 5.3 from the previous chapter explains typical reasons of noncompliance with the standards. Some of the reasons might be due to materiality, fire resistance properties, height, and location of the system. Basically, two questions should be asked, if there are available standards applicable for the project and if the requirements are satisfied. Vegetative systems, as recent and non-traditional construction elements, may deviate from the code requirements for projects with high complexity levels. If the element does not comply with the code requirements, an engineering approach can be followed.

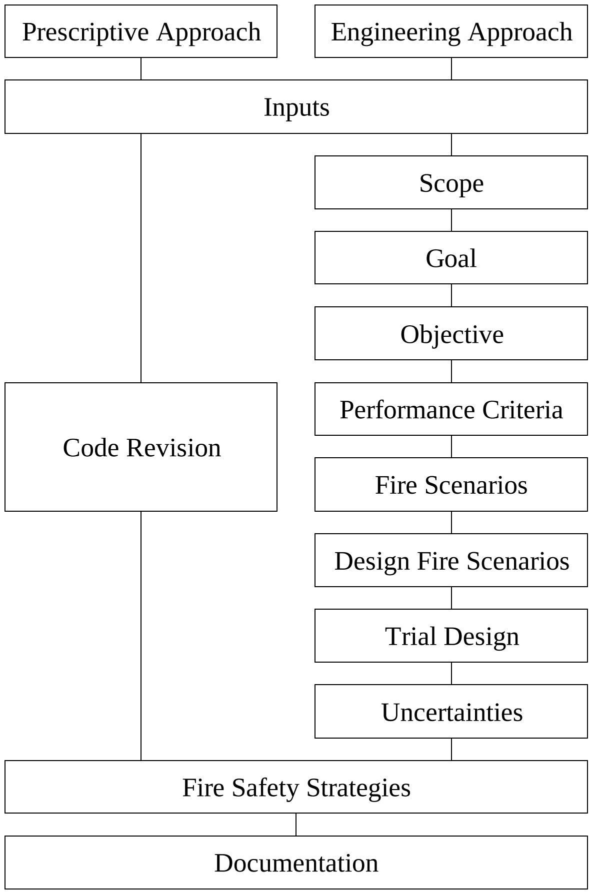


Figure 29. Prescriptive & Engineering Approaches

6.3 Prescriptive Approach

Prescriptive fire safety solutions are be provided by local codes and standards. The measures specified on this approach are based on the experience of previous projects. The solutions can be rigid but applicable for common types of projects with a low complexity. Prescriptive solutions are not suitable for innovative buildings or buildings with a vegetative system with high complexity.

A prescriptive fire safety design depends on the local codes that are applicable for the location of the project. In general terms, as can be seen in Figure 29, the process is straight forward. It starts with a review of the inputs provided to the fire safety engineer about the vegetative system and building where it is going to be installed. The proposed design of the green element is revised against the applicable code and standards and modified until there is compliance in every requirement. The fire safety strategies are defined by the codes, Section 6.5 of this guideline summarizes possible measures for passive and active fire protection, these strategies have been found in regulations and literature as can be seen in Chapter 5. Finally, documentation is the last stage which includes specifications and drawings and the operations and maintenance manual which are explained in Section 6.6.

This approach might be considered for certain green roofs projects since, depending of the location, the applicable standards might provide with adequate solution for the design. Green walls, on the other hand, do not have this advantage since at the time the standards related to these vertical systems are not so well developed.

6.4 Engineering Approach

An engineering approach has the advantage to address the unique features of the building. Specifically, green elements with a high complexity level of design are solved with this approach. It can also provide with non-standard and innovative solutions. An engineering approach will provide a better understanding of how the vegetative systems performs in the case of a fire.

Performance-based design is an approach for fire safety solutions that is based on the achievement of the agreed upon goals. Multiple steps are followed on this process as can be seen in Figure 29. A series of scenarios are tested including the safety features. Once the design demonstrates that the fire safety goals are achieved, it is considered acceptable.

The following sections expose the steps to do a performance-based design considering the inclusion of a vegetative system. The *SFPE Engineering Guide to Performance-Based Fire Protection* [50] provided with the general structure as well as common explanations of the tasks. Specific considerations for vegetative systems are develop for each section.

6.4.1 Scope

The project scope identifies and limits the areas of the building that are going to be considered for the design. The applicable regulations and the stakeholders are also identified in this section.

Regarding vegetative systems, it should be defined if the element is being analyzed alone or as part of the building and which levels or sections are being considered. The boundaries of the exterior or interior green elements should be defined. The desired features of the building and the green element are considered as well as their characteristics.

Additional inputs identified in Section 6.2.1, should also be considered at this stage if relevant.

6.4.2 Goal

The goal is defined by the *SFPE Engineering Guide to Performance-Based Fire Protection* [50] as the *"desired overall fire safety outcome expressed in qualitative terms"*. The guide also identifies four fundamental goals that are applicable for vegetative systems:

- Life Safety
- Property Protection
- Mission Continuity
- Environmental Protection

Certain codes identify goals that should be considered [49]. A revision of the local standards while following a performance-based approach should be carried out. The final design should also demonstrate that it achieves the goals that the local code requests.

6.4.3 Objective

Objectives are defined by the *SFPE Engineering Guide to Performance-Based Fire Protection* [50] as the *"requirement of the fire, building, system, or occupants that needs to be fulfilled in order to achieve a fire safety goal"*. Objectives are divided in two, stakeholder and design objectives.

Stakeholder objectives provide further details than the fire protection goal addressing the tolerable losses. These are described as the maximum allowable levels of damage or injury, risk ranking, downtime, or monetary expenses in case of a fire [50][49].

Design objectives are developed by the engineer based on the agreed upon stakeholder objectives. The previously defined objectives are translated into quantifiable values which can be in deterministic or probabilistic terms. This process should focus on targets, which can be the occupants, building, space, process, or green element that are protected in order to meet the stakeholder objective [50].

Certain codes provide with objectives that should be considered [49]. A revision of the local standards while following a performance-based approach should be carried out.

Regarding vegetative systems, three specific objectives are formulated. These three considerations are escalating in terms of hazards. These objectives can be applicable for many scenarios and are developed further in the following sections.

Based on the previous research, the *potential change in the system properties evolving into a combustible lining* is an identified hazard in Sections B2.2 and B4.2. The importance of knowing the system's properties and maintaining optimal and safe levels formulate the next objective:

A. Prevention of a negative change in the system's intrinsic safety properties.

   Keeping the vegetation well hydrated and free of combustible elements such as excessive biomass, overgrown vegetation or dead or dying material will maintain the risk of ignition and fire spread low.

The *SFPE Guidelines for Designing Fire Safety in Very Tall Buildings* [51], mentions as a fire risk consideration and measurement an applicable objective which can also be used for projects involving vegetative systems:

B. Maximum allowed extend of fire spread.

   Limiting the fire spread to a certain area or number of floors before the arrival of the fire service is a way to maintain property protection and life safety goals. The arrival time of the fire service should be known for the project location.

Based on the difficult accessibility derived from the height, location, or design of a vegetative system, another objective for the vegetative systems is:

C. Self-extinguishing capacity of the green element.

   Elements that are beyond the reach of the fire service need to be able to suppress a fire by its own intrinsic properties or by active or passive means.

6.4.4 Performance Criteria

Performance criteria is defined by the *SFPE Engineering Guide to Performance-Based Fire Protection* [50] as the *"criteria that are stated in engineering terms, against which the adequacy of any developed trial designs will be judged"*. The values correspond to a margin, that if becomes exceeded, the conditions are no longer acceptable. The selected values should be able to be calculated by models. The criteria are divided in two groups, life safety and non-life safety criteria [49].

Life safety criteria considers the survivability of people during a fire. Parameters identified by *the SFPE Guide* include: thermal effects on human beings, toxicity, and visibility [50][49].

Non-life safety criteria considers damage to the property and the other goals [49]. Parameters identified by the *SFPE Guide* include: thermal effects on structures, fire spread, smoke damage, firer barrier damage and structural integrity, damage to exposed properties, and damage to the environment [50].

Certain codes provide with performance criteria that should be considered [49]. A revision of the local standards while following a performance-based approach should be carried out.

For the previously identified objectives applicable for vegetative systems, the following considerations are suggested to develop the criteria and evaluate the achievement of the fire safety design.

A. <u>Prevention of a negative change in the system's intrinsic safety properties.</u>
   To evaluate the dryness of the system, establishing a minimum acceptable moisture content level of the plants, growing medium, or other components that the plants use to collect the water may be helpful. A limit should be defined as the way to measure it. Sensors that measure these conditions should be considered.
B. <u>Maximum allowed extend of fire spread.</u>
   To evaluate the maximum allowed fire spread, a certain area or number of floors above the origin of the fire should be defined considering the time of arrival of the fire service and that accessibility is possible.
C. <u>Self-extinguishing capacity of the green element</u>.
   To evaluate self-extinguishing capabilities of a system, a maximum amount of time should be established within which the fire should be completely suppressed and no new ignition occur. Another way this can be measured is by also limiting the fire spread to a certain distance from the ignition point.

6.4.5 Fire Scenarios

Fire scenarios are defined as the description of a sequence of events and conditions during the development of a fire in a building [50]. Initially, all possible fire scenarios that affect the building or an element of it are considered. Secondly, a reduction of the number of fire scenarios into manageable design fire scenarios is performed. The latter ones are the ones that will be evaluated as the trial designs [49]. Issues of noncompliance with the standards may be used for the developing or grouping of fire scenarios [49].

Certain codes provide with scenarios that should be considered [49]. A revision of the local standards while following a performance-based approach should be carried out.

6.4.5.1 Elements

Three main elements comprise both, fire scenarios and design fire scenarios, fire characteristics, building characteristics, and occupant characteristics.

6.4.5.1.1 <u>Fire Characteristics</u>

Fire characteristics consider fuel packages and ignition sources in the building. A description of the evolution of a fire is performed considering the stages, ignition, growth, flashover, full development, and decay as applicable. Additionally, extinction, location and duration are considered [50].

Regarding vegetative systems, the selected vegetation needs to be considered as well as the growing medium and the other components of the system since all of these elements conform a fuel package. The moisture content of the plants is an important aspect as it has been explained in previous chapters. Fuel packages close to the green elements should also be considered as a possible way of fire spread. Ignition sources that can affect green roofs or walls should also be analyzed carefully.

Tool 2 comprise a checklist for hazard identification that was developed for vegetative systems. It points out a list of aspects that should be revised focusing on the vegetation as the most relevant fuel package as well as the growing medium and the other elements that compose these systems.

These fire characteristics are of major importance when evaluating the first objective of maintaining the safety intrinsic properties of the vegetation and avoiding a negative evolution of it.

6.4.5.1.2 Building Characteristics

Identified by the *SFPE Engineering Guide to Performance-Based Fire Protection* [50], building characteristics include architectural features, structural components, fire protection systems, building services and processes, building operations, characteristics of emergency responder response, and environmental factors [50].

When it comes to vegetative system, the location of the element is an important consideration to see how it can affect the rest of the building in case of a fire. Exterior or interior elements have different impacts on the building and the occupants and may affect evacuation routes. In addition, if fire protection systems have already been included, all of these elements should be listed. The time and accessibility capacities of the fire service should be identified. The environmental factors are also important since humidity and temperature can decrease the moisture content of the plants increasing the risk level.

The checklist developed for hazard identification in Tool 2 also points out relevant aspects that should be considered about the building characteristics that are related with vegetative systems.

When evaluating the second or third objectives, maximum allowed fire spread or self-extinguishing capacities, building characteristics are important to limit the fire and achieve the suppression of it.

6.4.5.1.3 Occupant Characteristics

Occupant characteristics are considered to understand the ability of occupants to react during a fire. Important characteristics are summarized by *Performance-Based Fire Safety Design* into: number and distribution of occupants and occupants health and response characteristics [49].

Projects where the goal is set for life safety or the green elements can be accessed by people require to consider the occupants characteristics of response in case the green element is on fire and evacuation is required. Inoccupancy of the building is an important aspect as it indicates that the green elements may be unattended and a possible unhealthy state of the plants may not be identified or addressed by tenants.

These characteristics are specific for each project, the checklist developed for identifying hazards related with vegetative systems in Tool 2 mentions basic and general aspects. The occupant's characteristics are independent of the use of vegetative systems.

6.4.5.2 Tools

The *SFPE Engineering Guide to Performance-Based Fire Protection* [50] expose tools that can be used to identify fire scenarios. The tools can follow a qualitative, semi-quantitative, or quantitative approach:

- Preliminary Hazard Analysis (PHA)
- Failure Modes and Effects Analysis (FMEA)
- "What if?" Analysis
- Hazards and Operability studies (HAZOPS)
- Historical Data, Manuals, and Checklists
- Relevant Statistical Data
- Engineering Checklists
- Hazard Indices
- Fault Tree Analysis (FTA)
- Event Tree Analysis (ETA)
- Cause Consequence Analysis
- Reliability Analysis
- Risk Matrix
- Input from Stakeholders

As part of this guideline, a checklist for hazard identification specifically for vegetative system is developed and exposed in Tool 2. A generic event tree considering the three identified objectives related to vegetative systems is included in Tool 3.

6.4.5.3 Approaches

The *SFPE Engineering Guide to Performance-Based Fire Protection* [50] expose two approaches for the development and consideration of fire scenarios. A large number of fire scenarios can result using the previous tools, these two approaches can also reduce the number of fire scenarios into design fire scenarios that will be used for trial designs. A hazard or a risk-based approach can be implemented.

6.4.5.3.1 Hazard Approach

A hazard analysis, or deterministic analysis, identifies possible scenarios and their associated consequences. Probabilities are not explicitly considered. Based on the *SFPE Engineering Guide to Fire Risk Assessment* [52], hazard is defined as "*a condition or physical situation with a potential for harm*" [52].

This approach is based on correlations to predict the outcome of a fire. The results are then compared with the defined performance-based criteria. The scenario selection should be diverse and representative of all the potential worst credible fires that can occur [50]. Each of the design fires is evaluated in an individual way, with this approach, a combination of them is not possible [50].

The checklist for hazard identification in Tool 2 highlights aspects that increase the potential of fire hazard related to the use of these green elements.

6.4.5.3.2 Risk-Based Approach

A risk-based analysis, also known as probabilistic or quantitative risk assessment, identifies risk scenarios considering their consequences and probabilities. It basically asks three questions: *What can happen? How likely it is?* and *What are the consequences?* Based on *SFPE Engineering Guide to Fire Risk Assessment* [52], risk is defined as "*The potential for realization of unwanted adverse consequences, considering scenarios and their associated frequencies or probabilities and associated consequences*" [52].

Hazard identification is the first step on a probabilistic approach, in addition, the probabilities of it to happen need to be measured. A numerical value can be defined based on data from fire statistics, history, and fire frequency. When the scenarios include the use of passive or active fire protection systems, their availability and reliability should also be considered [50]. To determine the risk of a scenario, the product of the consequences an its frequency is calculated for each specific scenario. The total risk is the sum of all the values from each scenario [50].

When it comes to vegetative systems, since these elements have recently been included into buildings, a good source of data has not been found. When the source of data is scarce, probabilities and consequences can be divided into groups with arbitrary values. This would not represent a full quantitative approach but a semi-quantitative one.

The checklist on Tool 2 is an initial input for identifying hazards that can be developed further including consequences and likelihood in a quantitative manner.

6.4.5.4 Hazard Identification Checklist

Based on the considerations from the previous chapters, a checklist for hazard identification considering fire, building, and occupant characteristics is presented in Tool 2. The checklist is not intended to be exhaustive but to work as a guide for identifying possible hazards related to vegetative systems.

As mentioned in Section 6.4.3, evaluating the objective of maintaining the safety intrinsic properties of the vegetation focusses mostly in fire characteristics with the inclusion of building services and operational characteristics. Evaluating the objectives of maximum allowed fire spread or self-extinguishing capacities require a revision of building characteristics. Occupant characteristics are not related with the inclusion of green elements. For each project, its future tenants should be revised into detail.

In general, the three characteristics should be considered when developing a fire scenario. Three fire scenarios that apply this checklist were developed as examples and can be seen in Section 6.4.5.6.

Element	Category	Issue	Fire Hazard	Green Roof	Green Wall		Building Safety Requirements					Hazard Remarks
				Ext	Ext	Int	B1	B2	B3	B4	B5	
Fire Characteristics	Fuel Packages	Vegetation	Tendency to quick dryness	X	X	X		2		2		The vegetation characteristics should be evaluated of each of the species used in the green element or for the predominant ones.
			Low moisture content	X	X	X		2		2		
			High resin content	X	X	X		2		2		
			High volatile oil content	X	X	X		2		2		
			Heterogeneous selection of species	X	X	X		2		2		
		Growing Medium	Organic components >20%	X	X	X		2		2		The growing medium is defined based on the plant requirements. It should also consider safety issue related to its composition and volume.
			Mulch content	X	X	X		2		2		
			Depth <8cm	X				2		2		
		Other System Components	Flammable components	X	X	X		2		2		The components or layers of the green system may include combustible materials.
			Flammable insulation	X	X				1-2			
			Flammable layers	X	X	X		2		2		
			Flammable decoration	X	X	X		2		2		
		Surface Geometry	Horizontal coverage > 1450 m2	X						4		Green elements covering extensive surfaces require additional considerations to avoid fire spread.
			Horizontal length > 39m	X						4		
			Vertical coverage > 2 floors		X	X				5		
		Installation Typology	Ventilated façade		X	X				5		Certain typologies for green walls include space for ventilation which require to be revised to avoid the spread of smoke or fire.
			Double-skin façade		X					6	4	
		Fire Classification	Combustible system	X	X	X		2		2		Most of the systems available in the market have not been tested or may not comply with the highest material requirements.
			Not tested	X	X	X		2		2		
	Ignition Sources	Arson	Element susceptible to arson	X	X	X		1		1		Certain elements can be more susceptible to arson.
		Electric Systems	Electrical systems inside cavity	X	X	X		1		1		Certain vegetative systems include electric systems inside their cavities or exposed. This elements will be exposed to water and maintenance.
			Lighting part of the vegetation	X	X	X		1		1		
Building Characteristics	Architectural Features	Flammable Interior Finishes	Element located in the interior of the building			X		2				Flammable linings in the interior of the building adjacent to the green element may increase the risk of fire spread.
			Adjacent linings of walls or ceilings are flammable	X	X	X		1				
		Openings	Protruding elements from the green surface	X	X	X				3		A green element that includes openings on its surface increases the risk of fire spread between one side and the other inside or outside of the building.
			Holes or penetrations into the green surface	X	X	X				3		
			Windows		X	X				5		
			Balconies		X					5		
		Voids	Element located in an atrium			X		2				Interior green walls in an atrium require additional safety measures.
		Location	Neighboring buildings located >maximum distance	X	X					1		Distance and conditions of neighboring buildings may increase the risk of fire spread between the two elements.
			Neighboring buildings with exterior combustible linings	X	X					1		
		Proximity of Hazards	Adjacent rooms store fuels	X	X	X		1		1		Other fuel packages adjacent to the green element may be a possible ignition source and increase the risk of fire spread.
			Machinery close	X	X					3		
			Solar panels	X						3		
	Structural Components	Load-Bearing Element	Intensive green roofs	X					1	1		Certain vegetative systems may be considered as an additional layer of an structural element like a roof or wall. Combustible structural elements require special attention.
			Green wall as part of a structural wall		X				2			
			Combustible load-bearing elements	X	X	X			1-2			
	Fuel Load	Fluctuating Design	Temporary green element	X	X			1		1		Temporary green elements may expose combustible layers when removed.
		Building Fuel Load	Buildings with significant fuel loads adjacent to the element					1				High fuel loads contents next to the green element increase the risk of fire spread.
	Egress Components	Location	Entrance door at same axis of green wall	X	X		2				2	Vegetative systems installed in evacuation routes require special considerations. The main entrance should not be blocked by falling objects from above.
			Adjacent exterior stairs		X		2					
			Adjacent passageways		X		2					
			Green element on a evacuation route		X		2					
	Fire Protection Systems	Detection Systems	No detection systems considered			X		1				Green elements without any fire protection system part of it or of the space require special attention and may end up including certain features.
		Notification Systems	No notification system considered			X		1				
		Suppression Systems	No suppression systems	X	X	X		1		1		
		Smoke Control	No smoke and heat control systems for interior green walls			X		1				
		Smoke Barriers	No smoke barriers for interior green walls			X		1				
		Compartmentation	Adjacent compartment wall	X	X	X			1-2			Adjacent compartments require to be identified and special considerations should be given to the joint details to avoid the failure of the compartment element.
			Adjacent compartment floor		X	X			2			
	Building Services & Processes	Irrigation System	No irrigation system	X	X	X		2		2		Vegetative systems without a irrigation system have a higher risk of getting dry.
	Operational Characteristics	Occupancy	Building unoccupied and unattended	X	X	X		2		2		Vegetation becoming too dry will not be noticed in empty spaces increasing its risk.
		Maintenance	Low maintenance expected	X	X	X		2		2		None or scarce maintenance increase the risk of higher flammable content.
	Fire Department Response Characteristics	Response Time	Arrival time of fire service >15 min	X	X	X				5		Allowed fire spread should be measured considering the response time of the fire service.
		Accessibility	Roof with difficult accessibility	X							1	Green elements at a height above the maximum reachable capacity of the fire service are considered a hazard. Space for the fire service operations need to be considered.
			Green element located >maximum height	X	X						3	
	Environmental Characteristics	Conditions	Area susceptible to dry seasons (relative humidity >30%)	X	X					2		Certain areas or specific seasons have conditions that increase the risk of ignition or fire spread in exterior green elements.
			Element susceptible to high wind speeds exposure	X	X		1					
		Location	Nearby vegetation	X	X					1		Nearby vegetation can increase the risk of fires to the vegetative system.
			Area susceptible to wildfires	X	X					2		Certain areas are identified as susceptible to wildfires increasing the risk of fire spread.
Occupants Characteristics	Number & Distribution	Occupancy	Building unoccupied for long periods	X	X	X						Certain occupant characteristics increase the risk of not achieving life safety goals. These characteristics are specific of each project and independent of the use of vegetative systems.
			Building occupied at full capacity	X	X	X						
	Health Characteristics	Mobility	Occupants present a low travel speed	X	X	X						
		Breathing Requirements	Occupants are more susceptible to breathing concerns	X	X	X						
	Response Characteristics	Alertness	Occupants can be asleep	X	X	X						
		Reaction Time	Occupants reaction time is delayed	X	X	X						

Tool 2. Hazard Checklist

6.4.5.5 Event Tree

An example of an event tree is presented which consists of a generic vegetative system can be seen in Tool 3. This tool, with certain modifications, can be applied to a green roof or wall in a specific building. The event tree considers the three objectives specific for vegetative systems identified in Section 6.4.3.

For the first objective of maintaining the intrinsic safety properties of the vegetation, columns B and C in the event tree, regarding the irrigation system and the moisture content level, are important aspects.

The second objective, corresponding to limiting the fire spread considers, in addition to the previous aspects, features as detection and automatic suppression systems as well as the timely arrival and accessibility of the fire service are all relevant aspects. These considerations correspond to columns D, E, F, and G in the event tree since the intention is to identify a fire at early stages, to control it, and to be accessible and extinguished by the fire service before certain established boundary is exceeded.

The third objective, regarding self-extinguishing capacities, consider the previous aspects, in special the availability of the automatic suppression systems which is relevant in this case not only for controlling the fire but to extinguish it. This would be, in many cases, the strategy when the element is known to be out of the reach of the fire service.

The columns are flexible in the sense that, since it is intended to be a generic tool, certain columns may be removed or additional ones added. Column D, regarding the availability of a detection system, applies for interior vegetative systems but, in a few cases, might also be considered for exterior systems that can include a flame UV-IR detector.

Consequences and likelihood are divided into arbitrary groups, a value between 1 to 5 is given for each aspect of each scenario as follows:

- <u>Consequences</u>: Minimal 1, Minor 2, Major 3, Serious 4, & Catastrophic 5.
- <u>Likelihood</u>: Very Unlikely 1, Unlikely 2, Neutral 3, Likely 4, & Very Likely 5.

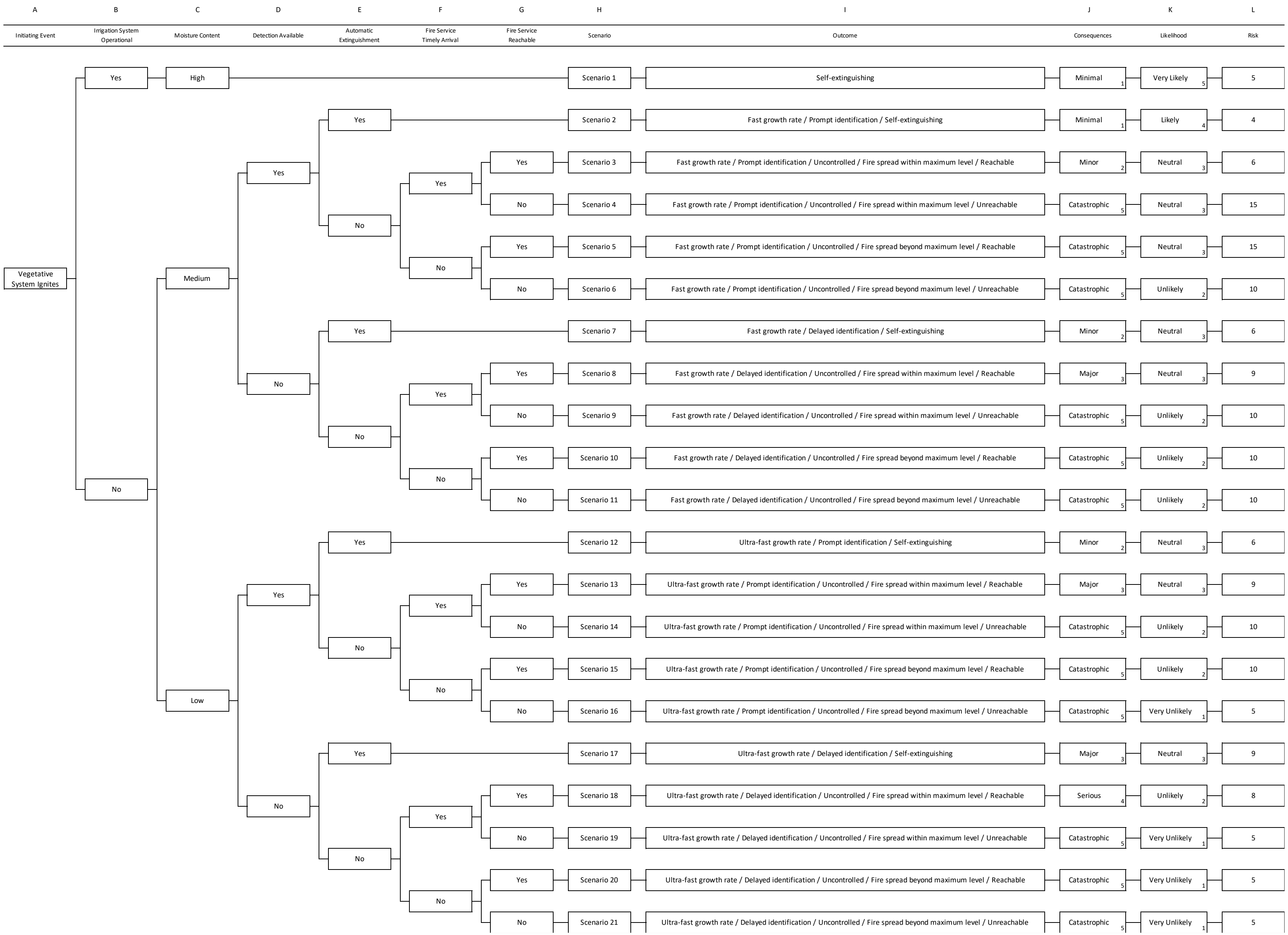
For the consequences, the score for each scenario was assigned considering the “No” answers on the event tree. Each negative response subtracts 1 point. A high moisture content remains the same while a medium one also deducts 1 point and a low one takes away 2 points. Columns F and G subtract 3 points on each negative reply due to the high impact that this would represent. The final scores of the 21 scenarios were distributed among the five groups previously mentioned. The lowest scores correspond to group 5 “Catastrophic”.

The grading for the likelihood focused on the “Yes” answers on the event tree. Each positive reply adds 1 point just like the columns without an answer. A high moisture content provides with 2 points, a medium one adds 1 point and a low one remains the same. The final scores of all the scenario were distributed in the five groups previously exposed. The highest scores correspond to group 5 “Very Likely”.

Regarding the likelihood, in a general way, it is important to explain that vegetative systems are designed to operate at healthy conditions, so high levels of moisture content are expected which resulted in “very likely” on the event tree. On the other hand, low levels of moisture content are not intended which results in “very unlikely”. This is why more weight was assigned in column C.

Once all the scenarios were ranked for consequences and likelihood, the risk was calculated as the product of these two values on each scenario. These rankings were assigned to provide an example of the process and considerations that are taken. The values may be modified or used differently as required. In case a risk-based approach wants to be followed, numerical values need to included and substitute the arbitrary groups for the consequences and the likelihood.

Based on this event tree, three fire scenarios were developed as examples. The scenarios consider the three objectives and represent three different levels of moisture content as well as a green roof, and an internal and external green wall. The developed fire scenarios and be seen in Section 6.4.5.6.



Tool 3. Event Tree

6.4.5.6 Fire Scenarios Examples

Based on the Hazards Identification Checklist, Tool 2 and the Event Tree, Tool 3, three scenarios were selected and developed considering the three main objectives identified in Section 6.4.3. Each scenario identifies the general goal for a green roof and an interior and exterior green wall. This allows to consider possible modifications on certain aspects such as the species selection or forbids it. The fire safety goal is also kept in mind on each scenario as well as the objective. Fire, building, and occupants' characteristics are developed further. The three scenarios consider high, medium, or low moisture contents of the plants. Additionally, specific considerations were assumed to formulate realistic and complex situations. The robustness of certain scenarios is considered by disabling some fire safety systems.

6.4.5.6.1 Fire Scenario 1 – Interior Green Wall Fire

Vegetative System Goal: Marketing and occupants wellbeing.

Fire Safety Goal: Property Protection and Life Safety.

Fire Safety Objective: Prevention of a negative change in the system's intrinsic safety properties and ASET > RSET.

Fire Characteristics:

- Vegetation. Multiple species were selected for visual pleasure. The correct functioning of the irrigation system combined with proper maintenance has kept a high moisture content of the plants.
- Other System Components. Flammable decoration (fake plants). Only 2% of the total surface.
- Surface Geometry. Vertical green coverage of three floors.
- Ignition Source. Element susceptible to arson.
- Fire Classification. Not tested.
- Fire Development. An arson attempt ignites the fake plants of an interior green wall in a small atrium.

Building Characteristics:

- Void. Element located at an atrium.
- Detection System. Included.
- Suppression System. Disabled (robustness consideration).
- Smoke and Heat Control Systems. Included
- Automatic Irrigation System. Operative.
- Maintenance. System well maintained.

Occupant Characteristics:

- Reaction Time. Occupants reaction time is delayed.

Event Tree Outcome: Self-extinguishing.

Consequences: Minimal (1).

Likelihood: Very likely (5).

Risk: 5

This scenario illustrates what could happen when the vegetative system has a high moisture content. The system is well maintained and include an automatic irrigation system. The natural properties of the plants resulted in self-extinguishment of the fire. The outcome related to the consequences was minimal but the likelihood is very likely since it is expected for the system to operate with a high moisture content.

6.4.5.6.2 Fire Scenario 4 – Neighboring Spread Green Roof Fire

Vegetative System Goal: LEED credits.

Fire Safety Goal: Property Protection.

Fire Safety Objective: Self-extinguishing capacity of the green element.

Fire Characteristics:

- Vegetation. Species selected were meant for an extensive green roof. The system works without irrigation and very low maintenance is required. The lack of surveillance and accessibility to the roof combined with dry conditions resulted in a medium moisture content of the plants.
- Growing Medium. Depth below 800mm.
- Other System Components. Combustible insulation layer.
- Surface Geometry. Horizontal green coverage of 2000m^2.
- Fire Classification. Not tested.
- Fire Development. Fire occurs in a neighboring building, radiation combined with burning brands ignites the green roof located above the 10th floor. A medium fire growth is developed also igniting the combustible insulation layer.

Building Characteristics:

- Location. Neighboring buildings with exterior combustible linings.
- Detection System. Included (flame detection).
- Suppression System. Not included.
- Irrigation System. Not required.
- Occupancy. Rooftop unoccupied.
- Maintenance. Low maintenance.
- Fire Service Accessibility. The height is beyond the reach of the fire service.
- Environmental Conditions. Dry season with relative humidity levels below 30%.

Occupant Characteristics:

- Occupancy. Rooftop unoccupied without access.

Event Tree Outcome: Fast growth rate / Prompt identification / Uncontrolled / Fire spread within maximum level / Unreachable.

Consequences: Catastrophic (5).

Likelihood: Neutral (3).

Risk: 15

This scenario explores the risk of ignition from a neighboring building and self-extinguishing capacities. An extensive green roof which typically does not require irrigation due to the use of drought-resistant vegetation decreased its moisture content to a medium level due to environmental conditions. The closeness to the other building results in ignition of the green roof and fire spread across it. Since the green roof does not have any suppression systems and the element is beyond the reach of the fire service, the consequences are catastrophic. The scenario has a neutral likelihood since the moisture content is still at a medium level. The combination of consequences and likelihood resulted in the highest risk score in the event tree.

This scenario will be analyzed further in the trial design section to reduce its risk and improve it final outcome.

6.4.5.6.3 Fire Scenario 15 – Exterior Green Wall Fire

Vegetative System Goal: Reduce energy consumption.

Fire Safety Goal: Property Protection and Life Safety.

Fire Safety Objective: Maximum allowed extend of fire spread of two floors above the origin of the fire and ASET > RSET.

Fire Characteristics:

- Vegetation. The selected species tend to quick dryness. An extended irrigation failure combined with lack of surveillance has led to a low moisture content of the plants.
- Other System Components. Combustible components.
- Surface Geometry. Vertical green coverage of five floors.
- Installation Typology. Ventilated façade.
- Fire Classification. Not tested.
- Fire Development. A window fire plume ignites the exterior green wall of a building, the fire spreads through the ventilation cavity between the vegetation and the façade to the upper levels and breaks into a compartment adjacent room. An ultra-fast growth rate is developed.

Building Characteristics:

- Flammable Interior Finishes. Adjacent floor includes flammable linings.
- Openings. Windows have direct connection between the building interior and the green wall.
- Detection System. Included.
- Suppression System. Disabled (robustness consideration).
- Compartmentation. Adjacent to compartment room.
- Automatic Irrigation System. Extended failure (robustness consideration).
- Maintenance. Infrequent.
- Arrival Time. Fire service arrival after 15 minutes.

Occupant Characteristics:

Mobility. Occupants present a low travel speed.

Event Tree Outcome: Ultra-fast growth rate / Prompt identification / Uncontrolled / Fire spread beyond maximum level / Reachable.

Consequences: Catastrophic (5).

Likelihood: Unlikely (2).

Risk: 10.

This scenario analyzes the objective of limiting the fire spread to a certain area. The fire starts in a room and ignites a dry green wall that has in addition a ventilation gap that allows smoke to circulate across it. Fire spreads into another compartment room. Even though the element is within the reach of the fire service, its late arrival resulted in an exceed of the fire spread limits. This excess created catastrophic consequences. The likelihood of dry plants with a low moisture content for an extended period of time is not a common situation which results in an unlikely ranking. This ended up reducing the risk score of the scenario.

6.4.6 Design Fire Scenarios

Deterministic and risk-based approaches can be used to identify the design fire scenarios. The selected fire scenarios will be developed further into design fire scenarios. The identified aspects are quantified with more detail. Data and resources are often limited to find detailed information about every aspect. Only the most relevant aspects should be quantified further. Design fire scenarios are the base for trial design development and testing. The same three elements already explained in Section 6.4.5.1, fire, building, and occupant characteristics are developed further with measurable data.

Regarding vegetative systems, the fire characteristics are the focus of this guide and will be explained further. The building and occupant characteristics are specific to every project and a general engineering approach can be followed. Further information about these two elements can be revised in the *SFPE Engineering Guide to Performance-Based Fire Protection* [50].

6.4.6.1 Fire Characteristics

Quantification of the fire require a fire curve. This is developed by a series of stages that apply for general fires as well as for fires involving vegetation. Source of the data that is required to produce the curve is also explained in this section.

The main stages of a fire curve involving vegetation are explained as follows:

- Ignition
  Is considered as the beginning of the design fire curve. Combustion in a self-sustained manner initiates at this point by a defined ignition source and is express as the relationship of the heat release rate ($\dot{Q}$) versus time (t).
- Growth Stage
  When it comes to flaming fire, the three general components of a vegetative system can be considered as part of the fuel package development. The vegetation 2.1.1 is considered in this guide as the initial fuel. The growing medium 2.1.2 and other components 2.1.3 can be considered as part of the initial fuel package, as secondary fuels, or not considered at all depending on their properties, conditions, and the scenario selected.
    - Initial fuels
      While analyzing vegetative systems as the fuel package, the vegetation is considered as the initial fuel. It is important to consider the following aspects of the vegetation:
        - Type and Quantity of Fuel. The green element can be a uniform system or a heterogeneous one composed by different species. The properties of the species may be similar or differentiate a lot.
        - Fuel State. The moisture content of the plants as well as the presence of the dead vegetation have an impact on the heat release rate. The moisture content for the scenario being developed should be defined.
        - Fuel Configuration. A vertical or horizontal configuration of the vegetation will have a different impact in the fire behavior. Additionally, the classification 2.3 and typology 2.4 of the system also need to be considered.
        - Fuel Location. The accessibility to oxygen as well as the exposure to wind should be analyzed for exterior or interior vegetative systems.
        - Rate of Heat Release. The amount of heat that is released per a unit of time.
        - Rate of Fire Growth. The rate of the fire growth can be affected by the three first aspects. Highly combustible plants with a low moisture contents for a green wall will have a higher growth rate due to the fuel's type, state and configuration.
        - Species Production. A heterogeneous selection of vegetation needs to consider the species production of each type of vegetation since this may vary among plants. Different levels of moisture content will result in different species production.

      The growing medium can be considered as a fuel package if the organic components of it are high. The mixture previously defined by the designers should be revised.

      Other components can include flammable containers, layers, synthetic plants or decoration, and insulation. The properties of these elements should be revised to consider its inclusion as a fuel package.
    - Secondary fuels
      Adjacent fuel packages can get ignited by heat transfer. This can occur in the form of conduction, convection, or radiation. In addition to the previous factors, the following aspects should also be considered: Proximity, amount, and distribution.
    - Extension Potential
      Potential fire spread across the green surface and into other elements, the building itself or adjacent buildings should be considered. Wind strength and direction as well as the configuration of the green system have an impact on the fire spread.

  If a smoldering fire is considered, special attention should be taken at this stage for the development of the fire curve.

- <u>Flashover</u>
  When the green element is located in the interior of a building, the fire in the enclosure where the green element is burning can evolve into flashover. For this type of interior elements, as identified in the *SFPE Engineering Guide to Performance-Based Fire Protection* [50], the following factors affect the development of flashover: surface area, enclosure openings and height, heat release rate, ventilation conditions, thermal properties of the boundary materials. Except for the heat release rate, the rest of the factors depend on the building characteristics that are specific for each building or scenario.
  This stage does not apply for green elements located on the exterior of buildings.
- <u>Fully Developed</u>
  At this stage, a peak or steady state of the heat release rate is reached. The fire at this stage is either ventilation or fuel controlled inside a compartment. The heat release rate should be calculated based on one of this two mechanisms.
  Exterior fires on green elements will be fuel controlled since the access to oxygen is unlimited.
- <u>Decay and extinction</u>
  At some point, the fire will decay due to the lack of oxygen, depletion of fuel, or by extinguishing systems.

Developing a fire curve requires data about the heat release rate of the fuel packages. The combustion products are also important data that needs to be known. The *SFPE Engineering Guide to Performance-Based Fire Protection* [50], identifies three sources of data: technical literature, testing, and theoretical methods. These three sources are applicable for vegetative systems.

Technical literature from data collected from experiments and registered in documents may be a source for the heat release rate and combustion products. Data about commonly used vegetation and portions of a complete vegetative system including growing medium and other components is hard to find at the moment.

Another alternative for getting the data is by testing the vegetation or a sample of a complete system. Considerations should be done about the moisture content level that wants to be tested. It is recommended to test the same vegetation at different levels based on the scenarios selected. Testing the elements only at normal and healthy conditions for the plants might result in conservative values since the risk of drying is always present.

Section 3.3 provides with additional information testing and experiments related to vegetative systems. Testing the vegetation can be done with the cone calorimeter. With the resulting HRR and combustion yields, a fire curve can be produced as was performed in the case exposed in Section 3.4.

Theoretical methods may be employed when there is no available data and no resources for testing. Empirical correlations from WUI fires may be considered to find the heat release rates and species production. A t^2 *fire* behavior can be used for the growth stage. It is important to consider if the green element is located at the interior or exterior of the building since this may differ from what has been tested originally. The results using this method are approximations and should be used carefully. Safety factors should be employed to compensate for the uncertainties.

6.4.6.2 Building Characteristics

In general terms, the same characteristics identified for fire scenarios are quantified and developed further into detail. Dimensions, positions, properties, capacities, characteristics, and response or activation time for materials, equipment, systems, services, and processes need to be measured and defined. Additionally, temperature, humidity, and wind conditions should also be quantified.

As it is explained in the *SFPE Engineering Guide to Performance-Based Fire Protection* [50], for a subsystem level of design only the factors that are involved with the specific element should be included. This can be applicable while working with vegetative systems. Depending on the goal and objectives, not every aspect of the building characteristics needs to be developed further.

6.4.6.3 Occupant Characteristics

Occupant characteristics are also specific to each project and have the same variable impact when the fire involves a vegetation. As it is explained in the *SFPE Engineering Guide to Performance-Based Fire Protection* [50], the aspects that are developed into further detail involve: human behavior, response characteristics, occupants load, evacuation time predictions, and egress flow. Quantifying these aspects involve defining speeds of movement, survivability capacities, and the time required for the multiple stages that involve the evacuation.

These aspects become more relevant when the goal of the fire protection design is life safety and specially when the green element is included in the interior of a building.

6.4.7 Trial Designs

Trial designs consist of the evaluation against the design fire of the selected safety features that are expected to achieve the stablished goals by satisfying the performance criteria. Fire and life safety features are characterized during this stage [50].

Trial designs are divided in two section, development and evaluation.

6.4.7.1 Development

A table with a list of applicable fire safety strategies was developed as part of this guide in Tool 4, it is divided in three main sections based on the *NFPA 550: Guide to the Fire Safety Concepts Tree* [53] diagram on management of fires. This diagram is related to the three identified main objectives for vegetative systems. From the NFPA diagram, control combustion process, suppress fire, and control fire by construction correspond to the objectives of prevention of a negative change in the system's intrinsic safety properties, self-extinguishing capabilities, and maximum allowed extended of fire respectively. This is explained with further detail in Section 6.5 where Tool 4 can be consulted. Cost, maintenance, reliability, and capabilities should be considered when selecting design features.

The *SFPE Engineering Guide to Performance-Based Fire Protection* [50], proposes a series of subsystems that can be used for the development of the trial designs. Based on the three specific objectives for vegetative systems, the following subsystems are considered in this guide:

A. <u>Prevention of a negative change in the system's intrinsic safety properties.</u>

- Prevention of Ignition.
  The intent is to reduce the likelihood of ignition. The following concepts may be used:
    - Control Source. Removing or isolating ignition sources from the vegetation.
    - Control Materials. Selecting plant species that have better properties when it comes to propensity for dryness.
    - Fire Safety Management. Maintenance is a key practice to prevent fires in vegetative systems. This combined with a proper irrigation system will maintain the plants healthy and reduced their propensity for being ignited.

B. <u>Maximum allowed extend of fire spread.</u>

- Control of Fire Development.
  The intent is to reduce the fire spread. The following concepts may be applicable:
    - Content Selection. The concepts from the previous subsystem are also applicable. Certain plants have better properties than others, also well-maintained vegetation will spread slower.
    - Adjacent Linings Selection. The finishes surrounding the green element should be selected to reduce fire spread.
    - Construction. Certain construction features part of the design of the green element will affected fire spread.
- Limiting Fire Spread through Passive Means.
  The intent is limiting the spread of fire to a certain area. The following concepts may be applicable:

    - Compartmentation. The roof or wall structure can be considered as a compartment.
    - Fire Barriers. Vertical and horizontal barriers protect against fire spread.
    - Protection of Openings. Protecting the openings and surroundings of them reduce the chances of fire spread.
    - External Spread. Green roof and façades should employ means to reduce the spread of fire across their surface.
    - Controlling Fire. Suppression systems or irrigation systems in fire mode can control the fire and reduce further spread.
- Detection.
  The intent is to identify a fire in a timely manner to be able to notify it or activate another system. Early detection will allow for rapid response and reduce the fire spread.
    - Manual Detection. A fire in certain green elements may be identified by people in a timely manner. Considerations about the building occupancy are important.
    - Automatic Detection. Different types of detectors may be used for green elements. this becomes harder for systems on the exterior. An alternative that can function for certain projects is the use of UV-IR flame detectors.
- Notification.
  The intent is to notify the occupants and fire service about a fire in the building and its location.
    - Occupants Notification. Important for life safety goal.
    - Fire Service Notification. A rapid notification will provide a fast response of the service which will reduce the spread of fire.
- Fire Suppression.
    - Automatic Fire Suppression Systems (Control Fire). The intent for this objective is to control the fire. The activation of the system will affect the design fire curve. The activation time needs to be considered.
    - Manual Fire Fighting Operations. The intent is to extinguish the fire.
        - Notification. The response forces require to be notified for a timely arrival.
        - Accessibility. The fire must be at a reachable height for the local fire service.

      The local fire department capacity of response needs to be known. The possible delays also need to be considered while defining the maximum acceptable fire spread.

C. <u>Self-extinguishing capacity of the green element.</u>

- Automatic Fire Suppression Systems (Extinguish Fire).
  The intent for this objective is to extinguish the fire without human interaction. This may be activated be a detection systems or work as a stand-alone system. Sprinklers is the most likely system to be applied for vegetative systems. The activation time needs to be considered depending on the design.

These subsystems should be selected based on the project objective and the performance criteria that has already been defined. The subsystems should be analyzed independently but also in a combined way at the same time.

6.4.7.2 Evaluation

The *SFPE Engineering Guide to Performance-Based Fire Protection* [50], states that evaluation is the process where the design is tested and determined if it meets the performance criteria. It identifies three levels of evaluation: subsystem, system, and whole building. For vegetative systems, this guide considers the first two as follows:

- Subsystem Level. Consists of an analysis of a single component or subsystem in order to satisfy the defined goals and objectives of the project.
- System Level. Consists of an analysis of the defined goals and objectives of the project involving more than one fire protection features that interact between each other.

These two levels of evaluation may also be used as a comparison between the proposed features and the ones requested by the codes if applicable. Since there are not so many specific guides for fire protection in vegetative systems, an approach that considers the defined goals and objectives is the one considered in this guide. Depending on the design, the three specific objectives identified for vegetative systems in Section 6.4.3 can be used in a subsystem or system level depending in the number of features being used to protect the green element and the interactions between these safety measures.

Two techniques may be applicable for carrying the evaluations; deterministic or probabilistic approaches, this are explained in more detail the *SFPE Engineering Guide to Performance-Based Fire Protection* [50]. Depending on the requirements of the project, both may be used for vegetative systems although finding data related to vegetative systems and fires may be scarce at the moment. Appropriate tools such as models or computer software should be used to evaluate the trial designs. Section 3.4 includes an example of a research paper where, after testing certain vegetation, a fire curve was developed and numerical simulations were performed in FDS for a green wall in a corridor.

6.4.7.3 Trial Design Example – Fire Scenario 4

Based on the fire scenarios developed in Section 6.4.5.6, Fire Scenario 4 - *Neighboring Spread Green Roof Fire* is considered further at this stage. This scenario was selected based on its risk outcome of 15, the highest among the event tree scenarios. The consequences were considered catastrophic (5) since the fire was not reached by the fire service. The likelihood resulted in neutral (3) since a medium level of moisture content it's not so rare but not planned for. This scenario can be considered as a plausible worst-case scenario.

The scenario should be quantified in terms of fire, building, and occupant characteristics. For this example, since it corresponds to a fictitious case without specific details, further quantification was not developed. Development and evaluation of the trial design should be done as explained previously. Again, the fictitious case without specific details does not allow this to be fully addressed. The focus of this section is to explain the process of analyzing the current outcome and to bring Fire Scenario 4 to an acceptable safety level.

The improvement to the outcome is done by the inclusion of fire safety measures. Tool 4, regarding Fire Safety Strategies, was developed in a way that it addresses the three objectives for vegetative systems. The table was applied to address the areas where Fire Scenario 4 presented weaknesses.

Regarding the consequences, a review of the hazards was performed following the Hazard Identification Checklist Tool 2. Low depth of the growing medium (B4.2-3), combustible insulation layer (B3.1), extended coverage area (B4.4), untested system (B4.2), unreachable height location (B5.3), neighboring buildings with combustible linings (B4.1), unoccupied area (B4.2), no irrigation (B4.2), low maintenance (B4.2), and dry environmental conditions (B4.2) were all hazards identified by the checklist. Following the columns about the *Building Safety Requirement* (B1 to B5), each hazard is associated with measures on the Fire Safety Strategy Tool 4.

An improvement of these hazards can be done by the referred strategies on the Fire Safety Strategy Tool 4. Some of these measures are: growing medium composition and depth increase (B4.2-3), "fire break" on the insulation (B3.1), fire break (B4.4), testing systems (B4.2), extinguishing systems (B5.3 & B4.1), separation (B4.1), irrigation and maintenance (B4.2). The selection of the strategies depends on cost, maintenance, reliability, and capacity aspects.

The specific goal of self-extinguishing capacity of the green roof is kept in mind and the subsystem to address it as explain in the development section is applied. Automatic Fire Suppression Systems (Extinguish Fire) subsystem requires the inclusion of an extinguishing system.

Addressing the identified hazards by the inclusion of these fire safety strategies will have an impact on reducing the consequences of this scenario.

Regarding the likelihood, if it wants to be addressed, the first objective, prevention of a negative change in the system's intrinsic safety properties, suggests strategies to maintain the system with a high moisture content as part of the *Control Physical Properties of the Environment* section. This would result in an increase of the likelihood which is directly related with a decrease of the consequences.

Applying the same evaluation of the event tree to the modified Fire Scenario 4 that includes now proper fire safety strategies resulted in a better outcome that corresponds to scenario 2 in the event tree. This outcome score can be considered as appropriate.

Event Tree Outcome: Fast growth rate / Prompt identification / Self-extinguishing.

Consequences: Minimal (1).

Likelihood: Likely (4).

Risk: 4

6.4.8 Uncertainties

The *SFPE Engineering Guide to Performance-Based Fire Protection* [50] defines uncertainty as *"the amount by which an observed or calculated value might differ from the true value"* [50]. It is divided in two, epistemic and aleatory.

Epistemic uncertainty is related to the lack of (complete) knowledge, it can be reduced by gaining a better understating or additional information. Aleatory uncertainty is caused by random variations, no additional information will reduce this uncertainty [49].

A list of general sources of uncertainties in performance-based design is described in *Performance-Based Fire Safety Design* [49]. This general list is also applicable for vegetative systems. Specific sources of uncertainty involving green elements include:

- Data Source for Vegetation. Data regarding plants and vegetative systems in general is scarce at the moment. As explained in section 6.4.6.1, technical literature, testing, and theoretical methods may be employed yet in many situations the values may not be fully representative of a specific scenario.
- Moisture Content. Measuring the moisture content of a plant requires testing for long periods to know how it evolves as time passes by. It may also be affected by the environmental conditions. Plants evolve in a different way which may add uncertainty if a heterogeneous system is used.
- Environmental Conditions. Humidity may affect the drying process of the plants. Below a certain level, it may make vegetation more easily ignited. Environmental conditions can be defined for a scenario but even in regions with well stablished seasons, the conditions could drop below expected.
- Modelling Vegetation. The use of models requires input data that as seen on the three previous aspects is not easy to define. Heterogeneous systems that have multiple plant species require to be simplified into one fuel package.
- Fuel Intensity. The amount of fuel present on the system may be able to sustain a fire leading to catastrophic consequences or it might burn instantly without serious consequences. Further testing is required to understand this in order to avoid an expensive overdesign.

Compensating for the expected uncertainties is a common practice that also need to be applied for vegetative systems. *Performance-Based Fire Safety Design* [49] established certain methods that can be used in general terms:

- Safety Factor.
- Analysis Margin.
- Importance Analysis.
- Sensitivity Analysis.
- Switchover Analysis.
- Classical Uncertainty Analysis.

6.5 Fire Safety Strategies

Following either a prescriptive or an engineering approach, the result of the fire safety analysis includes the selection of the fire safety features and the design of them. In a prescriptive approach, the features are already identified by the codes and the details about their installation are also specified. An engineering approach follows a series of steps and is open for more than one solution.

Based on the fire safety strategies that were revised on codes, literature review and case studies in Chapter 5, and considering the diagram of management of fires in *NFPA 550: Guide to the Fire Safety Concepts Tree* [53], Tool 4 was developed including a list of suggested fire safety strategies that are recommended or have been used specifically for vegetative systems.

The table addresses the hazards that were identified on Chapter 4 by following the five building safety requirements category. It comprises active and passive fire protection features and also indicates the applicability for green roofs and exterior or interior green walls.

The three main branches of the NFPA Concepts Tree [53] consist of, *control combustion process, suppress fire*, and *control fire by construction*. These three branches are applicable to the three specific objectives identified in Section 6.4.3 for vegetative systems.

- <u>Control Combustion Process</u>. The first branch of the NFPA Concept Tree [53] corresponds to the "prevention of a negative change in the system's intrinsic safety properties" objective. In this section, the goal is to select suitable species, understand their properties, and to provide maintenance to keep them healthy with a high moisture content.
  An active fire safety measure specific for green roofs and walls to *control combustion process* of the vegetation is the use of an irrigation system. This will maintain the moisture content of the plants high with low risk of ignition and fire spread. Additional active safety features to reduce the risk of failure of the irrigation system comprise a detection system that will verify the levels of humidity of the growing medium. A level under the established requirements will activate the notification system to inform the building manager about a failure of the system affecting the plants and its safety moisture content.
- <u>Suppress Fire</u>. The second branch of the NFPA Concept Tree [53], is related to the "self-extinguishing capacities" objective. The goal is to detect, notify, and provide with suppression methods that will be able to extinguish the fire.
  An active fire safety measure applicable for green roofs and walls to *suppress fire* involving vegetation is including a "fire mode" on the irrigation system. Once a fire is detected, the irrigation system will function in a "fire mode" delivering more water than the one normally required. This will result in no further fire spread and the fire will self-extinguish once the ignited vegetation is consumed. If considered necessary, a sprinkler system may be used in combination to extinguish the fire.
- <u>Control Fire by Construction</u>. The third branch of the NFPA Concept Tree [53], addresses the "maximum allowed extended of fire" objective. Containing the fire to a certain area before the arrival of the fire service is the main goal. Multiple passive options may be applied. Active measures can also control the fire extending the time before the arrival of the fire service, for this, the previous branch can be applied.
  Two passive fire safety features to *control fire by construction* are fire breaks for green roofs and horizontal measures or segmentation for green walls. These passive elements will limit the spread of fire to a specific area for a period of time before the arrival of the fire service. The use of incombustible materials strips of a specific wide and deep every certain length or around specific elements will contain fires in green roofs. In the case of the ventilated or double-skin green walls, obstructions of the air flow in the void created between the green wall and the façade will prevent hot smoke and flames to spread to higher levels for a period of time.

Requirements related to code, cost, maintenance, lifetime, reliability, and capacities should be considered when selecting the design features.

Approach	Category	Issue	Fire Protection Strategy	Green Roof	Green Wall		Building Safety Requirements					Measures		Strategy Remarks
				Ext	Ext	Int	B1	B2	B3	B4	B5	Active	Passive	
Control Combustion Process	Control Fuel	Control Fuel Properties	Testing	X	X	X		2		2			X	Testing the system or the species provides an understanding of the fuel content.
			Material selection	X	X	X	2			6	4		X	Sometimes certain modifications can be done to the materials in order to have a higher fire resistance.
			Fire resistance	X	X	X	2						X	
			Species selection	X	X	X		2		2			X	Sometimes it is possible to modify the selection of the species and the growing medium to provide with
			Growing medium components	X	X	X		2		2-3			X	better properties when it comes to fire.
			Reduction of stem enlargement		X								X	Reducing the fuel growth or stem enlargement of woody species by limiting an extensive development.
			System selection	X	X	X				2-5-6			X	Certain classifications of green roofs and walls may reduce the hazard of fire.
		Control Fuel Distribution	Height of the green element	X	X						3		X	The location of the green element may be modified.
			Fire resistance species as fire breaks	X						4			X	Certain plant species are considered as good fire breakers due to its properties.
	Control Environment	Control Physical Properties of the Environment	Maintenance	X	X	X		2		2			X	Maintaining the environment at low risk require a proper irrigation system to keep the plants well hydrated.
			Inspections	X	X	X		2		2			X	Maintenance should also be done regularly to remove death elements from the green system and inspections
			Irrigation system	X	X	X		2		2		X		to revise the general system.
			Low moisture content notification system	X	X	X						X		Notifying low moisture contents and a failure of the irrigation system informs about an increased in the risk
			Irrigation failure notification system	X	X	X						X		levels of a green element.
			Water supply	X								X		A water supply is sometimes require for irrigation. It can include a safety factor in case of fire.
			Water storage	X									X	Water can be designed to be stored in certain layers of a green roof system.
Suppress Fire	Automatic/Manual Suppress	Detect Fire	Exterior detection system	X	X							X		Beam and smoke detectors can be applied for interior green walls. Flame detectors can be used on certain
			Interior detection system			X						X		exterior elements that can have a front view of the vegetated surface.
		Communicate Signal	Fire notification	X	X	X						X		Notification to the building manager, fire service, and/or occupants can reduce consequences.
		Suppress Fire	Manual extinguishing systems			X						X		Availability of manual extinguishing can reduce consequences when the element is reachable.
			Automatic extinguishing system	X	X	X				1-6	3-4	X		Extinguishing systems for areas with difficult accessibility will reduce the fire spread.
			Fire mode irrigation system	X	X	X						X		A fire mode on the irrigation system will deliver more water delaying the fire spread.
			Dry rising main outlets	X							1	X		Water supply options for the fire service is a requirement in order to carry their operation of suppressing fires
			Fire hydrants	X							1	X		in green roofs.
			Smoke and heat control system			X						X		Fires in interior spaces with green walls may be controlled with smoke management system.
			Redundancy	X	X	X						X		Robustness of the systems should be considered to prevent failure of any of the features.
Control Fire by Construction	Control Movement of Fire	Confine/Contain Fire	Perimeter parapet walls	X			1				1		X	Measure to prevent the falling of the vegetation or growing medium to lower areas.
			Border zone	X							1		X	Measure to increase the accessibility for the operation of the fire service in a green roofs.
			Exit protection	X	X		2				2		X	Protecting the exit/entrance of building against the collapse and blockage o green elements.
			Fire stop	X	X	X			1-2				X	Adjacent compartment elements must include proper fire stop measures.
			Fire break	X					1	3-4	1		X	Incombustible strips at certain areas or surrounding specific elements reduces fire spread.
			Wall extension	X					1				X	Extending compartment walls over green roofs also reduces the risk of fire spreading.
			"Fire break" on insulation layer	X	X				1-2				X	The use of combustible insulation can be limited to certain areas by incombustible materials.
			Separation distance	X	X					1			X	Calculating separation distance with other buildings avoids fire spread from this buildings.
			Horizontal measures		X	X				5			X	Measures to avoid fire spread in ventilated green walls.
			Segmentation		X					6	4		X	Double-skin green walls measures to avoid fire spread.
			Building linings compliance	X	X	X		1					X	The adjacent linings of the building should also be revised to avoid further spread.
			Fuel exclusion zone		X	X							X	Limiting the contact and closeness of green elements towards other fuels or arson.
			Fire walls		X	X							X	Compartmentation of green walls may reduce fire spread towards the interior or other spaces.

Tool 4. Fire Safety Strategies

6.6 Documentation

Either a prescriptive or a performance-based approach requires documentation about the final fire safety design and the process or considerations followed. Three primary purposes for documentation are identified in *Performance-Based Fire Safety Design* [49]: to present it to the stakeholders, to communicate the design to those involved in its execution, and to record it for future modifications or forensic analysis.

The following sections should be included: design brief, performance-based design report, specifications and drawings, and operations and maintenance manual. Some of these sections may not be applicable for a prescriptive design approach.

6.6.1 Design Brief

Regarding an engineering approach, the fire protection engineering design brief comprises the qualitative portion of the design. Its goal is to establish an agreement between the stakeholders and can be used as a communication tool to ensure understanding. Further information can be revised in the *SFPE Engineering Guide to Performance-Based Fire Protection* [50]. In general terms, it includes the project scope, goals, objectives, performance criteria, fire scenarios, and trial design development.

Regarding vegetative systems, it is important that all stakeholder understand the evolving nature of these system and what this represents in terms of defining scenario and system conditions. These are unique characteristics of vegetative systems which have a big impact on the hazard they represent and the outcome of the analysis.

Once the design brief has been agreed by the stakeholders, the detailed engineering analysis, or quantitative portion is performed which includes the quantification of the design fire scenarios, trial design evaluation, and further documentation.

For a prescriptive approach, an introduction about the fire safety design is recommended explaining the project scope, goals, and objectives of the project.

6.6.2 Performance-Based Design Report

This section corresponds to performance-based designs, it comprises the quantitative portion of the design which includes: model and calculations used, input data with the source of it, and the methods used to compensate for uncertainty.

6.6.3 Specifications and Drawings

Specifications and drawings are used in prescriptive or performance-based designs to communicate the final measures and the safety design. These deliverables will inform the contractors how to implement the design and also present the final design to authorities and other stakeholders for their approval.

During the construction stage, inspections should be specified including their scope, frequency and at which stages of the project they should be done. It should be specified if the systems need to be tested after their installation, the protocol, stage at which it should be done, and pass/fail criteria.

6.6.4 Operations and Maintenance Manual

A manual that specifies operation and maintenance requirements during the lifetime of the system should be prepared by the fire safety engineer. This is applicable for prescriptive and performance-based solutions since in both cases the green system requires specific attention. The manual should be prepared in an easy way to be read by building managers or people without a background in engineering.

Category	Element	Inspection Item	Frequency	Conformance			Comments
				Yes	No	N/A	
Building Design and Context	Plan Layout	Layout in conformance with approved plans					
		Accessibility for fire service remains adequate					
		Evacuation for tenants remains adequate					
		Adjacent spaces free from modifications					
		Fuel exclusion zones respected					
	Location	Neighboring areas free from vegetation invasion					
		Neighboring buildings free from modifications					
		Neighboring vegetation zones free from posing a hazard					
		Seasonal conditions expected to be within regular records					
General Components	Vegetation	Planting layout in conformance with approved plans					
		Species selection in conformance with approved details					
		Moisture content within established levels					
		Vegetation within established sizes					
		Death vegetation presence controlled					
		Weed presence controlled					
		Unwanted foreign vegetation presence controlled					
		Biomass presence controlled					
	Growing Medium	Depth in conformance with approved details					
		Mixture in conformance with approved details					
		Medium free from unsafe components					
		Medium free from erosion threat					
	Other Components	Components firmly attached					
		Underlying flammable layers remain covered					
		Decoration within admissible amounts					
		Irrigation system operates according to plans					
		Valves, joints, driplines in optimal state					
		Components remain clean free from dirt deposits					
		Seasonal shutdown scheduled					
		Seasonal reactivation scheduled					
		Adequate water supply before dry season confirmed					
		Water supply within established levels					
Fire Safety Strategies	Active Measures	Detection system at optimal state					
		Notification system at optima state					
		Suppression system at optimal state					
		Smoke and heat control system at optimal state					
		Systems remain clean free from dirt deposits					
	Passive Measures	Load-bearing elements remain stable					
		Fire breaks free from vegetation or combustible materials					
		Border zones free from vegetation or combustible materials					
		Compartments remain in conformance with approved details					
		Horizontal measures in conformance with approved details					
Hazards	Threats	Existing fire hazards controlled					
		System free from new fire threats					

Tool 5. Inspection Checklist

A performance-based solution can be more sensitive to modifications so the limitations of the design need to be identified. The manual shall specify the allowed and non-allowed changes that can be done to the building. Modifications in the conditions and contents of the building may affect the design.

Regarding vegetative systems, a specific maintenance plan for the vegetation should be prepared. The frequency and scope should be specified. The revision and operation of active systems and passive measures should be included. Important considerations should be done to temporary vegetative systems since the removal of it may expose flammable layers or components.

The maintenance, according to the *Growing Green Guide* [7], can be of different types. Establishment, routine, cyclic, reactive and preventative, and renovation are mentioned in the document. Preventive maintenance is important to keep the system continuously at a safety level.

An Inspection Checklist was developed on this section which can be seen in Tool 5. It is included as a guide of key aspects that should be revised at the operation stage of the building lifecycle. The tool is flexible so it can be modified as required and applied to projects at any location.

6.7 Guideline Discussion

This section discusses the guideline steps explaining the process to perform a fire safety design for vegetative systems following a prescriptive or an engineering approach. The procedure for a performance-based design, the focus of this guideline, is supported by five tools that were developed specifically for these green elements. The five tools can be examined in the original Excel files as part of Annex C. The fire scenarios developed to exemplify the process are also analyzed.

The steps were based the ones that SFPE recommends for performance-based design. Each of the steps exposes specific remarks related to vegetative systems. The process, even though extensive, is considered a complete and well-structured series of steps.

Three main objectives, prevention of a negative change in the system's intrinsic safety properties, maximum allowed extended of fire, and self-extinguishing capacities, were kept in mind while addressing the subsequent steps and the development of the tools.

The General Considerations Tool 1 summarize general information from Chapter 2 about considerations taken by the designers of the general system. These general remarks are intended to inform the fire safety engineer about relevant decisions that might have been taken by the designers. Knowing what was considered helps to understand what can be modified and what cannot when performing the fire safety analysis.

The Hazard Identification Checklist Tool 2 covers in a summarized manner a great portion of the wide literature review performed in Chapter 4. The condensed information is structured in a way that is useful for the section it belongs to by following the existing categories of fire, building, and occupant characteristics. The subcategories allow to group similar hazards by a similar topic. The applicability with green roof and external and internal green walls is also provided as well as general remarks for each hazard subcategory. The reference with the Building Safety Requirement columns can be used to look for further information in Chapter 4 but also to find related strategies from the Fire Safety Strategies Tool 4.

The Event Tree in Tool 3 provides with a general representation of the development of a fire including key aspects in its columns based on the three main objectives. A total of 21 scenarios is the result with different outcomes. Consequences and likelihood are also evaluated for all of the scenarios based on arbitrary groups of five levels. A final risk score is assignment as the product of consequences and likelihood.

The Fire Safety Strategies Tool 4 reunites multiple strategies analyzed in Chapter 5 and groups them in three useful categories, *control combustion process*, *suppress fire*, and *control fire by construction*, that relate to the three main objectives. The applicability with green roof and external and internal green walls and type of safety measure, active or passive, is also provided as well as general remarks for common strategy subcategories. The reference with the Building Safety Requirement columns can be used to look for further information in Chapter 5 but also to find the hazard origin from the Hazard Identification Checklist Tool 2 and Chapter 4.

The Inspection Checklist Tool 5, as part of the operation and maintenance manual, provides a useful list of safety considerations that should be revised to maintain the system healthy and with a low level of risk.

The tools are also intended to be flexible so that they can be modified and applied for specific requirements. Developing these generic tools excludes certain specific details. Fire and building characteristics are broad and occupant characteristic are not considered into detail.

As part of this guideline and to exemplify the process, three fire scenarios were developed based on the Event Tree Tool 3 and the Hazard Identification Checklist Tool 2. The scenarios were applied to a green roof and an exterior and interior green wall. Each scenario follows one of the main objectives and corresponds to a high, medium, and low level of moisture content. Scenarios 1, 4, and 15 from the event tree exemplify all these conditions with the additional information subtracted from the General Considerations Tool 1 and the Hazard Identification Checklist Tool 2 regarding the fire, building, and occupants' characteristics. Fire Scenario 4 was developed further as a trial design due to its high risk score. By using the Fire Safety Strategies Tool 4, certain strategies were analyzed and the risk score was reduced.

The lack of detail from the generic tools does not allow to perform certain steps such as the quantification of the elements in Design Fire Scenarios or a detailed development and evaluation of the Trial Designs. Nevertheless, the process and usage of the tools is explained and an improvement of the risk is achieved for the fictitious scenario.

The next step is to test the guideline by performing an analysis on real projects. Finding alternative solutions to already built systems and comparing the safety levels and costs would provide useful feedback to measure the benefits of the guide and to update the tools and steps including improvements.

6.8 Final Considerations

Based on the research performed on the previous chapters, a guideline for fire safety design on vegetative systems was developed. It comprises a series of sections that expose the required steps for the design process. Specific tools that consider vegetative systems were developed to provide additional support on key sections as well as scenario examples.

An introduction to the guideline exposes the scope and purpose of the document, green roofs and walls are included and their fire safety design can be addressed by a prescriptive or an engineering approach. The audience of the guideline is presented which may vary depending on the content of each section. The building lifecycle stages combined with the tasks of the general design of vegetative systems and the related duties of the fire safety engineer are presented. It is important to stress that special attention should be given to the operate stage and the related tasks and duties since this is an ongoing stage that may last for decades. This becomes relevant since, given the evolving nature and non-traditional characteristics of vegetation systems, the hazard level of the system may increase over time without the correct maintenance.

Starting a fire safety design requires from the inputs of the general designers of the vegetative system. Tool 1 summarizes general considerations that the designers may contemplate. It is provided to inform the fire safety engineer about the reasoning of certain design decisions. With the general overview of the project design and considering local regulations, a fire safety design approach can be selected.

A prescriptive approach, for projects with a low level of complexity, provide a straight forward process bounded to the local regulations. In general, solutions may be rigid and hold back innovation. Due to the recent trend of the inclusion of vegetative systems in buildings, some of the modern and more complex designs may not comply with the code requirements resulting in the need of a different approach.

An engineering approach addresses the unique features of the building being a suitable design approach for vegetative systems. It will also provide a better understanding of its performance in case of a fire. This approach is divided into multiple steps: scope, goal, objective, performance criteria, fire scenarios, design fire scenarios, trial designs, and uncertainties.

The scope and the boundaries of the design of the vegetative system are be defined at this early stage as well as an identification of the applicable regulations and the stakeholders.

The goals need to be defined for which the four general ones mentioned by the SFPE guide are also applicable for a fire safety design on vegetative systems.

Three main objectives are identified specifically for vegetative systems, prevention of a negative change in the system's intrinsic safety properties, maximum allowed extended of fire, and self-extinguishing capacities. These objectives intent to cover the main requirements of a fire safety design on these systems. The objectives are explained further in the next sections and were considered for the development of the tools.

Measuring the three objectives is required to evaluate their accomplishment or failure. This is addressed in the performance criteria section by establishing the minimum moisture content level, limiting the maximum area or number of floors of fire spread, and setting the maximum time for self-extinguishment.

The development of fire scenarios requires the study of three main elements, fire, building, and occupant characteristics. A Hazard Identification Checklist Tool 2 was developed in order to point out hazards that are related to these three elements and that should be addressed. An Event Tree Tool 3 was also developed in a generic way so that it becomes a flexible tool that can be modified for specific requirements. The three main objectives are considered in the columns of the event tool. Consequences and likelihood of the final 21 scenarios were ranked based on arbitrary groups resulting in a risk score.

Based on these two tools, three fire scenarios examples were developed considering the three main objectives, a high, medium, and low moisture content, and applied for a green roof and an interior and exterior green wall. The Hazard Identification Checklist Tool 2 allowed to identify and include relevant dangerous aspects that the design might include. The Event Tree Tool 3 suggested key considerations in the development of a fire event that should be revised.

Design fire scenarios developed in a further way the selected fire scenarios. Quantification of the fire, building, and occupant characteristics is done at this stage. The focus of this guide, fire characteristics, explains the steps for developing a fire curve focusing on the use of vegetation. Technical literature, testing, and theoretical methods are sources of data that are explained. Technical literature is scarce at the moment suggesting the use of test or correlations that might increase in uncertainties. Further studies are required.

The development of trial designs is done keeping the main objective in mind. Several subsystems are exposed by NFPA at this stage which can be grouped under one of the three main objectives for a fire safety design including vegetative systems. The subsystems revealed certain general measures that can be used. After the inclusion of the safety features the design the evaluation of trial designs take place by testing the system and revising it against the performance criteria.

Fire Scenario 4, from the previous three examples, was analyzed further due to its high risk score. The focus was on explaining the process of analyzing the initial outcome and to bring it to an acceptable safety level by the inclusion of measure suggested in the developed Fire Safety Strategies Tool 4. The link with the Hazard Identification Checklist Tool 2 resulted in the suggestion of multiple strategies. In combination with the correct subsystem for trial design development for self-extinguishing capacities, a reduction of the consequences was achieved. The likelihood could have also been increased taking measures for a higher level of moisture content due to their direct relationship. Vegetative systems are designed to operate at healthy conditions which is why the likelihood increases as the moisture content level does resulting in a reduction on the consequences.

Uncertainties around vegetative systems comprise the vegetation and the modeling of it, moisture content, environmental conditions, and fuel intensity. Compensating for these expected uncertainties should be included in the calculations.

Based on the previous research, the Fire Safety Strategies Tool 4 was developed considering the three main objectives which relates to the NFPA general branches for managing fires. The strategies mentioned on the Tool 4 are linked to the hazards from the Hazard Identification Checklist Tool 2. The tool exposes the strategies in a condensed manner but further explanations can be obtained following the building safety requirement columns and the information from the previous chapter.

Active and passive features are included for green roofs and walls. Key fire safety strategies involve the inclusion of an irrigation system which can be considered as a passive and active measure at the same time. Passive since it is working constantly keeping the plants hydrated and active when it operates on a “fire mode” delivering additional water. Fully active features such as sprinklers might be the only solution at the moment for many systems that require to be self-extinguished. Passive measures, like fire breaks or segmentation might help to limit the fire to certain area for a period of time.

Documentation is required for both, prescriptive and performance-based approaches. Design brief, performance-based design report, specifications and drawings, and operations and maintenance manual are required documents depending on the approach used. The manual is of great importance since, as explained in the building lifecycle, operation is an ongoing stage where the risk level is prone to increase due the evolving nature and non-traditional characteristics of vegetative systems. Specifying the safety requirements to maintain a high moisture content is relevant. The limitations of the design should also be indicated. An Inspection Checklist Tool 5 is included as a guide to perform on-site revisions.

The last section analyses the strengths and weaknesses of the guideline. The general steps, even though extensive are considered complete. The tools, summarize a great amount of information and are structured in a useful way for the section they belong to. Certain tools are referenced between them and in general can be used together. The examples demonstrate the process followed and how the tools provide with useful considerations. The flexibility that is provided by the tools allow them to be modified and applied to multiple conditions. This openness also results in certain sections not being able to be developed in the examples due to the lack of details. The next step would be to apply this guideline and tools to a real project to evaluate and improve it.

The process of performing a fire safety design on vegetative systems contrast between what a prescriptive and a performance approach require. The first one, when allowed, provide a straight forward but rigid process. The second one, allows more than one solution that are custom-made but require multiple steps. Both approaches address vegetation as a construction element in a building requiring the provision of fire safety strategies to maintain the element at a safety level.

Chapter VII

Conclusion and Outlook

This final chapter concludes the work previously done throughout the entire research and presents future research possibilities. Diagram 8 expose the two sections that compose this chapter and their main subsections.

Conclusion and Outlook Overview
7.1 Conclusion Main Findings
7.2 Outlook Future Research

Diagram 8. Conclusion and Outlook - Chapter VII Overview

7.1 Conclusion

Vegetative systems were analyzed from a fire safety perspective in this research by performing a literature review of multiple documents from a global scale. The problem statement, in addition with an early definition of the aim, the development of a Best Practice Guideline, and the four objectives guided the entire research and provided with a clear structure.

The first objective, regarding a review of the state-of-the-art of vegetative systems, exposed the variety of systems that have been developed which include multiple components. In general, in order to have an optimal operation, the systems require of technical knowledge from the designers and consultants in several fields of expertise. When it comes to fire safety, many of the existing standards and rating schemes do not address this issue or is not developed in an extended manner. This situation is even more notorious for green walls due to its recent popularity. In many cases, the advices coming from these documents may be rigid and only applicable for projects with a low level of complexity. This basic understanding provided with initial signs of fire hazards that were developed in the next chapters. Vegetation is already identified as an element that changes through time affected by multiple factors which makes it a non-traditional material when applied in buildings. A deeper analysis of the fire behavior of these systems became evident for this research.

The second objective, concerning a fire review of green roofs and walls, provided with a better understanding of the fire behavior of these systems. Given the scarce research specifically on this matter, inputs from wildland fires became relevant. The moisture content level, plant type, and environmental conditions are again mentioned as key aspects. Standards specific on this matter are scarce and even more for green walls. The lack of specific testing standards forces these systems to use the testing and classification of regular systems or construction materials. Vegetation, having an evolving nature and being a non-traditional material suggests the need to be analyzed in a different manner. The experiments on the vegetation highlighted the relationship between the moisture content of the plant and the ignitibility and fire spread propensity. The growing medium, in general, is considered to be hard to ignite but the other supportive components should be revised further since the materials can be flammable. In general, further tests at small and large scales should be performed at different moisture content levels, specific conditions, and including safety features. Modelling of vegetation on CFD programs require as an initial input a fire curve for which testing is the best source of data. This powerful tool needs to be exploded more sharing the results with the research community. Identifying the fire hazards becomes relevant as the next step after understanding the fire behavior.

The third objective, identifying fire hazards imposed by vegetative systems, reunited in five categories hazards recognized by several documents. A total of 16 hazards were identified that may affect the means of escape, interior linings, structure, exterior envelope, and fire services. A revision of the available case studies provided insights on the process of performing a risk assessment following an engineering approach. The importance of considering the likelihood related to the risk is also highlighted. The experiments performed on the report about the three species clearly expose how the decrease of moisture content in the vegetation directly increases the risk levels and how this evolution differs between species. Cases of fire incidents on existing green elements is also limited at this time which prevents to gain a knowledge from previous experiences and lessons learned. The hazards can be created by the vegetative systems but also by a combination with the building general design. Strategies to address the identified hazards became apparent.

The fourth objective, regarding the analysis of fire safety strategies, considered inputs coming from multiple documents that addressed the hazards identified previously in the same five categories. Above forty strategies comprising active and passive elements were revised that may address multiple hazards. Similarities among green roofs measures were found with differences on small details. Green walls considered measures from wood and double-skin façades due to the lack of specific information. Measures preventing the evolution of the systems are important for the vegetation. Strategies following an engineering approach stressed the importance of irrigation as a preventive measure but also as an active feature that can operate on a “fire mode”. A review of the suitability of each approach is exposed, the level of complexity of the systems have a big impact since, given the novelty of these systems, a prescriptive approach might not satisfy the requirements of the projects suggesting a custom-made solution that is provided following an engineering approach. Multiple strategies where gathered from these two approaches which will prevent fires, limit their spread, or extinguish them. The analyzed strategies are considered and exposed in the guideline.

Based on the research performed on the four objectives, the *Best Practice Guideline* was developed corresponding to the aim of the research. This document provides guidance on the design of fire safety measures for vegetative systems installed in buildings. Starting with the reception of the initial considerations taken by the designers, a prescriptive or an engineering approach is selected. The first one, mostly for low complexity projects, provide a straight forward but rigid process tied to the local regulations. The second one, the focus of the guideline, allows more than one solution that are custom-made but require multiple steps. Three main objectives, prevention of a negative changes, limiting the extended of fire, and ability to self-extinguishing, cover the main requirements of a fire safety design. These objectives are developed further and provide a clear structure on categorizing information at each step. Each step provided with specific remarks on vegetative systems. The tools developed to support the steps summarize the wide literature review performed in the previous chapters, exposing the information in a useful way by following the existing categories of the step where they belong to. The tools can be modified to be applied to multiple conditions which provides flexibility but lacks of details required at certain stages. Examples of the process and the way to use the different tools are also provided resulting in an easy way to identify hazards, measure their risk, and provide with strategies. The guideline also stresses on the importance of the operation stage on the building lifecycle since vegetative systems have an evolving nature.

Vegetative systems are a recent effort to bring greenery into the cities which provides multiple benefits for the people and the environment. These technological systems do not equal to safety and require to be solved from a fire safety perspective. Vegetation is a non-traditional material when included as part of a building. These “living technologies” have an evolving nature that needs to be addressed in order to maintain the system healthy with low risk levels throughout its entire lifespan. Traditional and innovative strategies may be used to confront the fire hazards proper from the system. The inclusion of these innovative systems properly designed will result in safe and more sustainable buildings.

7.2 Outlook

This thesis analyzed vegetative systems from a fire safety perspective by performing a literature review. Recommendations for further work can be divided into experimental testing and a detailed application of the guideline.

The scarce published experiments available and their relevant findings indicate the need of performing further testing on vegetative systems. This should be done for horizontal green roofs systems but is specially required for vertical green walls systems where there is a current lack of information. The experiments should be done at small and large scale and comprising the three main components, vegetation, growing medium, and other components in an individual and combined manner. Real systems from what is available on the market should be considered.

Vegetation requires special attention; commonly used species should be tested at different moisture contents after a natural drying process and exposed to different levels of heat flux. Systems that are composed by multiple species should also be reviewed. Different mixtures of the growing medium should be evaluated. Other components for support of the systems should also be examined.

The effectiveness of fire safety strategies could also be tested. This includes active features such as sprinklers and an irrigation system on “fire mode” but also passive measures such as fire breaks for horizontal systems and segmentation for vertical elements.

The results from the experiments will provide useful data on plant species for their selection on new designs. The outcome will also provide with the inputs for numerical simulations on CFD which is a key tool while doing a performance-based design. Validating the simulations with these tools would be a following step.

Further evaluation of the guideline can also be done by developing design fire scenarios with detailed information on the fire, building, and occupant characteristics. These three elements should be quantified and a fire curve should be developed. Trial designs should be evaluated by performing numerical simulations on CFD and revising the results against the specific performance criteria. A comparison with the prescriptive solutions can also be performed to contrast the safety levels.

A detailed evaluation of the guideline under real scenarios will provide with useful feedback to measure the benefits of the document and update the tools and steps including possible improvements.

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Annex A

Leadership in Energy and Environmental Design (LEED), is a popular green building rating scheme that is analyzed in terms of the contribution that vegetative systems pose towards achieving credits. Based on the information found on the official U.S. Green Building Council, the following information corresponds to the latest version available LEED v4.1 [54].

For this research, *LEED for Building Design+Construction* (LEED BD+C) is the rating scheme analyzed since it is the one most likely to use vegetative systems. This classification is meant for:

- New construction & major renovation
- Core & shell development
- Schools
- Retail
- Data centers
- Warehouses & distribution centers
- Hospitality
- Healthcare
- Homes & multifamily low-rise
- Multifamily midrise

Projects pursue one of the four LEED rating levels: Certified (40-49), Silver (50-59), Gold (60-79), and Platinum (80+). Based on the amount of credits achieved, one of these certifications is awarded. Projects earn points across the nine following areas:

1. Integrative process
2. Location and transportation
3. Sustainable sites
4. Water efficiency
5. Energy and atmosphere
6. Materials and resources
7. Indoor environmental quality
8. Innovation
9. Regional priority

Vegetative systems can provide with credits to the overall score. Each project and each vegetative system are unique, by following certain specific indications, the next credits may be achieved.

- **Sustainable Sites**
    - SS Credit: Protect or Restore Habitat (1-2 points)
      Vegetative systems aid in the goal to conserve existing natural areas and to promote biodiversity by providing habitat. The selected plants must be suitable for the design aim, site conditions, and local climate.
    - SS Credit: Open Space (1 point)
      Green roofs that are physically accessible promote social interaction, physical and recreational activities, and encourages environmental interaction.
    - SS Credit: Rainwater Management (1-3 points)
      Vegetative systems, in special green roofs, help to reduce the runoff volume of rain water. The systems can retain on site the water by infiltration, evapotranspiration, and together with systems that reuse the water for irrigation purposes.
    - SS Credit: Heat Island Reduction (1-2 points)
      Vegetative systems reduce the heat island effect generated towards the urban and natural environment by providing shade and reducing the exterior finishes temperature.

- **Water Efficiency**
    - WE Prerequisite: Outdoor Water Use Reduction (Required)
    - WE Credit: Outdoor Water Use Reduction (1-3 points)
      Vegetative systems with a correct plant species selection in combination with an efficient irrigation system reduce the outdoor water consumption. Extensive green roofs as well as climbing walls may even work without an irrigation system.
- **Energy and Atmosphere**
    - EA Prerequisite: Minimum Energy Performance (Required)
    - EA Credit: Optimize Energy Performance (1-20 points)
      Vegetative systems aid in increasing the levels of energy performance of a building by avoiding excessive energy consumption related to air conditioning. This is created by the insulation that green roofs provide and the shade that green walls produce to the exterior of the building.
- **Materials and Resources**
    - MR Credit: Building Life-Cycle Impact Reduction (1-5 points)
      By performing a Life-Cycle Assessment, vegetative systems can contribute to attaining credits by having a lower environmental impact when compared to standard solutions.
    - MR Credit: Building Product Disclosure and Optimization – Sourcing of Raw Materials (1-2 points)
      Vegetative systems help in achieving credits under this category since its composition is of mostly plants and bio-based materials. Also, the use of native plants, which source is within 160 km, increase the contribution to attaining the credit.
    - MR Credit: Building Product Disclosure and Optimization – Material Ingredients (1-2 points)
      Vegetative systems, by being mostly composed of natural materials, have a better environmental life-cycle impact which contributes to attaining credits under this category.
- **Indoor Environmental Quality**
    - EQ Credit: Enhanced Indoor Air Quality Strategies (1-2 points)
      Interior green walls may be used for filtering the interior air as active systems.
    - EQ Credit: Indoor Air Quality Assessment (1-2 points)
      Interior green walls may be used for filtering the interior air as active systems.
    - EQ Credit: Acoustic Performance (1-2 points)
      Interior green walls contribute to achieve an effective acoustic space by reducing noise levels inside the building.
- **Innovation**
    - IN Credit: Innovation (1-5 points)
      Vegetative systems can help in providing credits under the options of innovation, pilot credit, and exemplary performance.

Since each project and each vegetative system are unique, defining an amount of credits that these systems can contribute is not measurable in a general way. Over forty possible credits spread across six areas indicate a high contribution towards certification. The credit contributions are suggestions based on a website research from articles and companies that manufacture these systems.

The credits revised from the USGBC LEED v4.1, *LEED for Building Design+Construction,* document do not address fire safety concerns in any section. The focus of LEED is to transform the way buildings are designed in an environmental, social and healthy manner.

Annex B

Fire Risks & Prescriptive Strategies			
B1	Means of Warning and Escape		
	1	Potential slide of green roof components towards people on the lower levels.	
			Perimeter Parapet Walls
	2	Potential interrupt of the evacuation of tenants due to building's exit and/or egress route obstruction.	
			Exit Protection
			Material Selection
			Fire Resistance
B2	Internal Fire Spread (Linings)		
	1	Potential fire spread from a vegetative system into the building and the other way around.	
			Internal Linings Compliance
	2	Potential change in the system classification evolving into a combustible lining.	
			Species Selection
			Growing Medium Composition
			Testing
			Irrigation
			Maintenance
B3	Internal Fire Spread (Structure)		
	1	Potential horizontal fire spread over a compartment wall through a green roof between adjacent compartments.	
			Fire Stop
			Fire Break
			Wall Extension
			Protective Layer
			"Fire Break" on Insulation Layer
	2	Potential vertical or horizontal fire spread across a compartment floor or wall through a green wall between adjacent compartments.	
			Fire Stopping
			"Fire Break" on Insulation Layer
B4	External Fire Spread		
	1	Potential ignition and fire spread from adjacent buildings.	
			Separation Distance and Material Classification
			System Classification
			Extinguishing Systems
	2	Potential change in the system classification evolving into a combustible lining.	
			Species Selection
			Growing Medium Composition
			Testing
			Irrigation
			Maintenance
	3	Potential fire spread to a green roof by openings or protruding elements and vice versa.	
			Fire Breaks
			Growing Medium Requirements
	4	Potential fire spread of a green roof in a horizontal manner.	
			Fire Breaks
	5	Potential vertical fire spread of an exterior green wall and ignition from the interior of the building by a window fire plume.	
			Horizontal Measures
	6	Potential fire spread in a double-skin green wall system.	
			Segmentation
			Extinguishing System
			Material Selection
B5	Access and Facilities for Fire Service		
	1	Potential impact on fire service operations and roof access.	
			Dry Rising Main Outlets
			Fire Hydrants
			Border Zone
			Fire Break
	2	Potential interrupt of the access of fire-fighters into the building due to an obstruction of the entrance.	
			Exit Protection
	3	Potential impact on fire service operations due to the height of the building.	
			Height and Material Classification
			Extinguishing System
	4	Potential visual and intervention impact for the fire brigade with a double-skin wall system.	
			Segmentation
			Extinguishing System
			Material Selection

Summary of Fire Risks and Prescriptive Strategies
Chapter 4 and Chapter 5

Annex C

The five tools developed as part of the *Best Practice Guideline* in Chapter 6, can be examined in the original Excel format. The file includes the following tabs:

- Tool 1. General Considerations
- Tool 2. Hazard Checklist
- Tool 3. Event Tree
- Tool 4. Fire Safety Strategies
- Tool 5. Inspection Checklist