A MULTI-CRITERIA APPROACH TO DESIGN OF BUILDING FAÇADES

Saviz Moghtadernejad

Department of Civil Engineering and Applied Mechanics

McGill University

Montreal, Canada

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ABSTRACT

The current design and construction trends towards sustainable development have led to increased attention to designing high-performance building structures, emphasizing the reductions in energy consumption and CO_2 emissions. Façades have the potential to drastically affect the building energy performance and the comfort level of the occupants, therefore more attention and vigour needs to be given to their design than at present. However, the involvement of various interdisciplinary professionals and the need for satisfying different design criteria makes the design process considerably complicated. This complexity is related to the required integration and provision of a balance between all necessary functions of a façade system, which can be conflicting with each other. Consequently, most designers still tend to use the conventional design methods that lack consideration of all required criteria or use solutions that are optimized with respect to one objective only. In this research, proper sequencing and life cycle considerations are proposed along with the application of appropriate multi-criteria decision-making methods to enhance the façade performance throughout its life cycle.

The search of the available state of the art clearly shows that application of Choquet integrals would enable designers to consider and integrate all performance requirements in façade design, according to the project needs and priorities. Contrary to all other MCDM methods, Choquet integrals have the benefit of accounting for positive and negative interactions of the design criteria. However, application of this method in building engineering is unprecedented. This is because of the difficulties of determining interaction indices, due to lack of data and complexities of using professionals' opinion. Hence, as a part of this research,

appropriate approaches were undertaken to extract the related fuzzy measures for the design of façades. These approaches include a supervised approach using the experts' opinion and an unsupervised approach using principal component analysis.

In the final step of the research, the Choquet integral with the two most favoured decision-making methods namely, AHP and TOPSIS have been used in a case study to rank 16 façade alternatives with regards to 15 decision criteria, and the results are compared.

RÉSUMÉ

Les tendances actuelles vers le développement durable ont attiré l'attention des concepteurs sur la conception de structures de bâtiments à haute performance, en mettant l'accent sur la réduction de la consommation d'énergie et des émissions de CO_2. Les façades ont le potentiel d'affecter considérablement la performance énergétique du bâtiment et le niveau de confort des occupants; par conséquent plus d'attention et de vigueur devrait être accordée à leur conception que pour le moment.

Cependant, la participation de divers professionnels interdisciplinaires et la nécessité de satisfaire à différents critères de conception compliquent considérablement le processus de conception. Cette complexité est liée à l'intégration requise pour assurer un équilibre entre toutes les fonctions nécessaires d'une façade, qui peuvent être contradictoires entre elles. Par conséquent, la plupart des concepteurs préfèrent toujours utiliser les méthodes de conception classiques qui ne tiennent pas compte de tous les critères requis.

Dans cette recherche, les considérations de cycle de vie nécessaires sont identifiées avec la proposition d'utiliser une méthode de prise de décision multi-critères pour améliorer la performance de la façade tout au long de son cycle de vie.

La recherche montre que l'application des intégrales Choquet permettrait aux concepteurs de prendre en compte toutes les exigences de performance dans la conception des façades, en fonction des besoins et des priorités du projet. Contrairement à toutes les autres méthodes MCDM, Choquet a l'avantage de prendre en compte les interactions positives et négatives des critères de conception. Cependant, l'application de cette méthode dans

l'ingénierie du bâtiment est sans précédent. Ceci est dû aux difficultés de détermination des «mesures floues» de Choquet, en raison du manque de données et de la complexité de l'utilisation de l'opinion des professionnels.

Par conséquent, dans cette recherche, des approches appropriées ont été utilisées pour extraire les mesures floues pour la conception des façades. Ces approches comprennent une approche supervisée utilisant l'opinion des experts et une approche non-supervisée utilisant l'analyse en composantes principales.

Dans la dernière étape de cette recherche, Choquet avec les deux méthodes MCDM les plus favorisées, AHP et TOPSIS, sont utilisées dans une étude de cas pour classer 16 alternatives de façades en fonction de 15 critères de décision, et les résultats sont comparés.

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NOMENCLATURE

AAMA	American Architectural Manufacturer's Association
AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BIM	Building Information Model
CBA	Choose by Advantage
CR	Condensation Resistance
CRF	Condensation Resistance Factor
DIF	Dynamic Increase Factor
EER	Energy Efficiency Ratio
EIFS	Exterior Insulation Finish Systems
ELECTRE	Elimination and Choice Translating Reality
ESLC	Estimated Service Life of the Component
FRP	Fibre-Reinforced Polymer
GMM	Geometric Mean Method
HAM	Heat, Air, Moisture
HVAC	Heating, Ventilation, and Air Conditioning
ISO	International Standards Organization
LCA	Life Cycle Assessment
MADM	Multi-Attribute Decision Making
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-Criteria Decision Making
MFP	Multi-Criteria Façade Performance Indices
MODM	Multi-Objective Decision Making
NBC	National Building Code of Canada
NECB	National Energy Code of Canada for Buildings
NFC	National Fire Code of Canada

NFRC	National Fenestration Rating Council
NSE	Non- Structural Elements
O&M	Operation and Maintenance
PCA	Principal Component Analysis
PROMETHEE	Preference Ranking Organization Method
PV	Photovoltaic
PVT	Photovoltaic-Thermal
RH	Relative Humidity
RSLC	Reference Service Life of a Component
SCES	Standing Committee on Environmental Separation
SE	Structural Elements
SHGC	Solar Heat Gain Coefficient
SIF	Static Increase Factor
SIP	Structural Insulating Panels
STC	Sound Transmission Class
SUAVE	Smart Virtual Unmanned Aerial Vehicle Examination
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
UV	Ultra-Violet
VIKOR	Vlsekriterijumska Optimizacija I Kompromisno Resenje
VT	Visible Transmittance
WAM	Weighted Arithmetic Mean
WASPAS	Weighted Aggregated Sum Product Assessment
WPM	Weighted Product Method
WSM	Weighted Sum Method
WWR	Window to Wall Ratio

Chapter 1 Introduction

1.1 Introduction

The word “Façade” originates from the French language, meaning "frontage" or "face" [1] that comprises the exterior part of a building with special architectural features. Hence, it can be interpreted as the soul of the building since it sets the tone for the rest of the building.

Façade is a part of the building enclosure whose primary and basic function is to provide a skin on the exterior of the building to separate the interior and exterior environments.

With advances in technology and the growing expectations for achieving high-performance levels, the building enclosure is presently required to satisfy numerous performance parameters that were not considered as design criteria in the past. In the beginning, façades were required to be durable and provide a degree of environmental separation; however, presently, they must simultaneously address multiple issues, such as energy efficiency and environmental impacts.

This is mainly because presently sustainable development urgently requires reducing the current energy consumption and the environmental footprint of the buildings. The building sector is the largest consumer of energy, and accounts for one-third of the energy consumption around the world and is an important source of CO_2 emissions [2].

The building enclosure, including the façade, plays the most important role in determining the amount of consumed energy. Improving the building envelope can decrease the heating and cooling energy demands under a low-carbon scenario up to 40% [2]. Lower heating and cooling demands will also allow downsizing of the equipment needed to reach a desired indoor temperature.

It is important to implement design strategies to mitigate climate changes since it has the potential to cause serious problems in the various disciplines, including the construction industry (e.g. distress due to increased flooding, precipitation, storms, etc.)

The increasing occurrence of natural disasters serves as a reminder that sustainable design and insurance of durability and serviceability can only be attained through a shift in the current design attitudes which should advance beyond sustainable design, energy efficiency (net zero or regenerative design strategies)[3]. Failure to adopt appropriate measures and make immediate investments will lead to costly consequences in the future.

Due to changes in expectations, application of the latest building science principles and strategies is a more appropriate approach for façade design, than relying on past experiences [4]. However, it is noted that the current design practices are mostly based on the designers' experience and intuition.

1.2 Problem statement

Recently, several research initiatives in architecture and engineering have focused on improving the performance of façades by developing high-performance systems; however, a thorough and reliable definition of what constitutes a high-performance façade is not yet available.

In current building façades, "high-performance" is mostly related to energy efficiency; especially, during the operational phase of a building. While the prevailing worldwide energy crisis and the associated greenhouse gas emissions have reached a critical stage and must be considered as central criteria for the design of high-performance façade systems; however, a comprehensive assessment of façade performance requires more detailed considerations. Presently, some new building façades are mistakenly considered to be high-performance and may not truly comply with the needed measures of sustainability and durability [5].

In general, the design of a façade system involves the participation of architects and civil, mechanical and electrical engineers. In such multidisciplinary systems, design activities within one domain can affect what is performed in the other domains. For example, in a recent study [6], it has been shown that a building designed for energy efficiency can increase the susceptibility to fire and decrease the fire resistance of the building. This inherent interaction of domains requires some integration and collaboration among the various specialists. However, although an interactive and integrated design approach is desirable for such systems, most façade designers still prefer to use the traditional design methods, due to lack of a formal and systematic approach for façade design. These traditional methods include a custom-tailored approach, in which, each of design factors is considered as a distinct challenge, and usually lack consideration of all major criteria in an optimal façade design [7].

As a result, in current façade designs, while the current provisions of national codes in terms of minimum performance requirements and in some new cases energy efficiency are satisfied, they do not adequately address the issues of durability, environmental impacts, related maintenance, or inspection needs, etc. [8-10].

1.3 Research objectives

The proposed research program is aimed at providing façade designers with a systematic approach to design optimal façade, with the help of a multi-criteria decision support system. The overall objective of the proposed research can be described briefly as follows:

(1) Deliver a precise definition of a high-performance façade system and the required design criteria.

(2) Provide designers with an integrated, interactive and comprehensive guide for building façade design which outlines the necessary considerations in each stage of the façade life cycle.

(3) Establishment of multi-criteria façade performance (MFP) matrix, used in evaluating conceptual and preliminary stages of façade design.

(4) Allowing for integrating new technologies (e.g. photovoltaic-integrated or hybrid façades) in the decision-making process to evaluate the alternatives.

1.4 Methodology

Designing high-performance façades is a relatively new field and comprehensive evaluation of building enclosures is non-existent in the literature. The various national codes and standards have made provisions for minimum performance requirements of building enclosures; however, a thorough and systematic design approach is not available to designers. This research program is aimed at developing the design paradigm through eight main steps as follows:

(1) Identification of main performance attributes that must be considered to achieve a high-performance façade system.

(2) Identification and implementation of suitable passive design strategies in the building design stage.

(3) Determination of design criteria (based on identified design attributes) and their interdependencies (separate, redundancy or complementary).

(4) Determination of the necessary considerations in each stage of the façade life cycle to mitigate risks and excessive costs.

(5) Comparison of most common decision-making methods and selection of most suitable ones for preliminary façade design.

(6) Assessment and quantification of the various criteria.

(7) Extraction of interaction indices among the design criteria.

(8) Application of the developed design paradigm to a case study.

1.5 Original contributions

The original contributions of the author in this research include:

(1) Development of a systematic approach for façade design considering all life cycle stages of the system, including design, construction, operation and maintenance, and decommissioning.

(2) Introducing the MFP index used in façade design performance assessment.

(3) Application of Choquet integral as an aggregation tool in façade design, to help the designers select the most suitable alternative among a pool of feasible alternatives.

(4) Extraction of façade design fuzzy measures for Choquet integral with a supervised and unsupervised approach, using the experts' judgment and principal component analysis method respectively.

1.6 Research publications

(1) Moghtadernejad, S., Chouinard, L.E., and Mirza, S. (2018) Multi-criteria decision-making methods for preliminary design of sustainable façades. Journal of Building Engineering.19:181-190.

(2) Moghtadernejad, S., Mirza, S., and Chouinard, L.E. (2018) Façade design stages; issues and considerations. ASCE Journal of Architectural Engineering. DOI: 10.1061/(ASCE)AE.1943-5568.0000335.

(3) Moghtadernejad, S., Chouinard, L.E. and Mirza, S. A design paradigm for optimal building façades. Submitted to the Journal of Building and Environment in August 2018. Ref.: BAE-D-18-02050.

(4) Moghtadernejad, S., Mirza, S., and Chouinard, L.E. Determination of the Choquet integral fuzzy measures related to optimal façade design. Submitted to the Journal of Building Engineering in September 2018. Ref.: JOBE_2018_1121.

(5) Moghtadernejad, S., Chouinard, L.E. and Mirza, S. A data-driven approach towards sustainable façade design: learning from successful designs. To be submitted to the Journal of Computer-Aided Civil and Infrastructure Engineering

1.7 Manuscript layout

This thesis consists of eight chapters. Chapter 1 briefly introduces the important role of façades in the building performance level, current expectations, and design trends along with the inefficacy of the current design process. Subsequently, research objectives, methodology and the layout of the manuscript is presented.

Chapter 2 reviews the historical façade development and the characteristics of main façade types (based on their materials). The performance attributes of building envelopes are discussed in detail and the current design procedures are reviewed with the design requirements related to the National Building Code of Canada (NBC) for environmental separators.

Chapter 3 provides a guideline for designers aimed at explaining the deliberations and strategies that must be considered in each stage of a building façade's life cycle.

Chapter 4 reviews the most commonly-used multi-criteria decision-making (MCDM) methods in civil engineering and compares their strengths and limitations for the façade design problem and identifies the three most suitable methods.

In Chapter 5, the design criteria identified in Chapter 3 (based on the performance attributes introduced in Chapter 2), are quantified for 16 feasible façade alternatives, using various quantitative procedures and simulations.

Chapter 6 provides a strategy to extract the Choquet integral fuzzy measures and the interaction indices among the design criteria, using a principal component analysis (PCA) method and the data from the profile sets (façade alternatives) quantified in Chapter 5.

In Chapter 7, the 16 façade alternatives are compared and ranked using the three selected MCDM methods in Chapter 4, after constructing the MFP matrix, and the results are discussed.

Finally, Chapter 8 presents the summary and conclusions of this study, along with some recommendations for future research.

Chapter 2 Literature Review

2.1 Introduction to the history of building enclosures

Building enclosures are directly related to the architecture of buildings and as a result, have changed throughout history through the evolution of architectural styles. Construction of buildings began with simple forms of shelter from all types of precipitations, wind, and sun. As the desire for better shelter grew, appropriate materials for each climatic condition were identified, and construction skills were developed. Using different materials and construction methods to suit a variety of functions and climates, led to the emergence of different architectural renderings and highly varied forms of façades.

The earliest building enclosures were mostly constructed with clay, brick, stone, and wood, depending on the locally available materials and the climatic conditions surrounding the building. These enclosures provided proper thermal protection through their mass that allowed for natural heat storage [11].

Concrete was first used in Roman architecture during the 1st century [12]. The invention of Roman concrete caused a revolution in the construction industry, that led to the appearance of different architectural styles. The Industrial Revolution led to the rapid development of new materials and techniques. New forms of energy generation and equipment facilitated space conditioning even in less hospitable climates.

Between the 19th century and the present time, mass-production was slowly introduced into the building industry. The superstructure and the building enclosure were considered as separate specialized components.

In 1884, the first modern skyscraper was constructed with no load-bearing walls, and the entire building weight was carried by the steel frame. The thin masonry façade panels were hung from the frame like a curtain, supported by the shelf angles fastened to the spandrel beams.

The development of self-supporting building with steel or reinforced concrete frames led to the application of thin building skins, consisting of lightweight façade panels and larger window areas, with limited regard for the site, climate, and locality, despite the considerable increase in the expectations for comfort and durability.

Table 2.1 presents the common façade types according to the construction material used and their characteristics.

Table 2.1 Façade types and characteristics [7, 13]

Façade types	Characteristics
Masonry and brick façades	Used in low-rise residential and commercial buildings; ordinary or decorative with colour and shape variety; easily moulded; inexpensive; minimal repair costs.
Wooden façades	Used in low-rise residential buildings; unique colours; susceptible to ageing and aggressive environments; should be treated to prevent decay.
Stone façades	Used in prestigious buildings; unique textures and colours; durable; high compressive strength; lack of construction flexibility.
Concrete façades	Various shapes, colours, textures and finishes; usually prefabricated; appropriate fire resistance, energy efficiency, acoustics, and vibration control; construction flexibility; have higher weight and durability problems.
Metal façades	Various forms, design and construction flexibility; usually made from composite metals or stainless steel with high strength and corrosion resistance; remain shiny and stain-free for a long time; higher initial costs but lower maintenance costs.
Glass façades	Used in modern, high-rise buildings; desirable for architects; allow natural light and heat to enter; availability of folded glass façades and high-performance glazing products with minimum energy consumption
Double-skin façades	Consists of two skins with a void in the middle, through which air flows; single or double glazing; natural, fan-supported or mechanical ventilation; enhance building energy performance; higher costs and lower usable space
Vinyl siding	Introduced as a replacement for aluminum siding and is the most commonly installed exterior cladding for residential buildings in North America. Comes in various colours; the colour will fade over time due to exposure to sunlight; tendency to crack in very cold weather when struck by a hard object can release toxic fumes when burning.
Stucco façades	Durable, attractive, and weather-resistant; various finishing textures and colours; it is brittle hence a metal lath is added to provide support and increase the tensile strength to control cracking.
Fibre composite façades	Have higher stiffness, strength, lower density and weight; corrosion resistance and manufacturing flexibility. They are durable and cost-effective. Drawbacks: susceptibility to high temperatures, ultra-violet (UV) radiation and exposure to light; moisture effects; poor fire resistance (can be improved by using phenol-based composites but are costly).
Sandwich panel façades	Made of two thin layers (FRPs, stainless steel, metal composites, concrete, etc.) and a low-density core (usually made of different foams); cost-efficient and prefabricated; high stiffness with minimum weight; can be used in industrial and commercial buildings, sports facilities and warehouses.
Photovoltaic-integrated façades	Can be used as a supplementary source of electric power; improved building energy performance by use of a hybrid design (generating both heat and electrical energy)

2.2 Building envelope design attributes

According to Hutcheon [14], the building envelope must protect the occupants from :

- Cold
- Heat
- Rain
- Solar radiation

- Outside noise
- Pollution
- Smoke
- Fire-spread

And it must also be:

- Structurally sound
- Durable
- Aesthetically pleasing
- Economical

A schematic illustration of the principal building envelope roles is presented in Figure 2.1. These performance attributes are categorized into five general categories; namely, safety, human comfort, sustainability, durability and cost efficiency, which will be reviewed in the following sections. Each of these attributes consists of some criteria that define them and would need to be satisfied (Table 2.2).

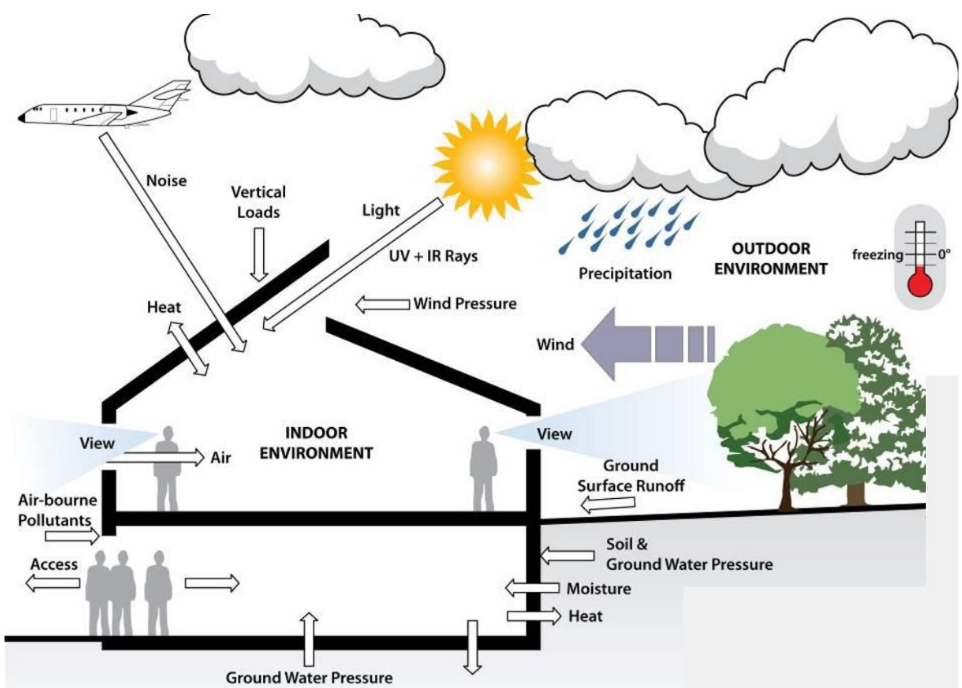


Figure 2.1 The roles of building envelopes [11]

Table 2.2 Major performance attributes of building enclosures [7, 13]

Safety	Human comfort	Sustainability	Durability and maintainability	Cost efficiency
Resisting mechanical and environment loads and natural and man-made hazards Security (keeping burglars out and kids in)	Visual comfort (physically and mentally related) Aesthetics Heating and cooling needs Controlling air leakage Control of moisture flow Natural ventilation and indoor air quality Daylight control Glare control Acoustics Ease of construction	Energy efficiency Use of renewable resources Environmental footprint	Provisions to avoid premature failure of the system before the end of service life Provisions to resist deteriorations caused by aggressive environments. The expected service life of each system in a specific environment. Ease of access for inspection and rehabilitation work	Costs of design and construction (initial costs) Operating costs Costs of rehabilitation and maintenance work Costs of disassembly

2.2.1 Safety

In terms of safety, as self-load bearing structural elements, building envelopes must resist the relevant mechanical and environmental loads (wind, rain, earthquake and blast loading), have an acceptable fire resistance, allow for differential movements (caused by moisture, temperature variations and structural movements), and also keep the burglars out and the kids in [5].

2.2.2 Human comfort

Along with meeting aesthetical considerations and heating and cooling needs of the occupants, façades significantly influence human comfort level through creating visual and physical connections between inside and outside, glare control and providing optimum acoustic characteristics [15, 16].

Controlling air and moisture flow will also result in both occupant satisfaction and the durability and sustainability of the façade system.

2.2.3 Sustainability

The state of sustainability requires no negative environmental, economic and social impact on future generations. The World Commission on Environment and Development has defined sustainable development as "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [17]. Sustainable development in civil engineering focuses on the carefully planned use of natural and man-made resources throughout the design, construction and operation phases of a project. The effectiveness of development relies on the positive impact of the structure on its environment, and vice-versa [18].

With the current energy crisis and climate change concerns, building envelope becomes a key consideration in design, construction, and operation of ultra-low energy buildings; since approximately 40% of the energy consumption and carbon emissions are related to buildings [16, 19].

Building façades have the potential to reduce the energy consumption and peak electricity demands through optimum use of daylight by redirecting and filtering it, providing natural air circulation and controlling heat transfer.

In addition to implementing the needed preservation methods, sustainability can be achieved by using renewable resources, reducing waste, and using recycled materials [20], or using materials with a lower environmental footprint. This can be achieved through consideration of the life cycle performance of façade assemblies.

Life cycle assessment of building enclosures is one of the critical criteria in sustainable decision-making. Thus, during the process of selecting a construction material for a project, the following should be considered:

- Elements used in the manufacturing process of the materials
- Site transportation procedure (local/non-local materials, transportation vehicle, etc.)
- Related wastes and resources used in the materials during the life cycle of the building
- End of life cycle plan (reusable/recyclable, disposal plan, etc.)

It is obvious that without quantified data, it is only possible to guess the best estimates of the outcome of the decisions involved in the design process.

It is crucial to realize that including the life cycle analysis in the design process, enables consideration of the trade-offs and the results in informed decision-making (with respect to environmental impacts) rather than simply distinguishing good products from bad ones.

2.2.4 Durability

Façades contribute to the durability of a structure by resisting condensation on interior surfaces, preventing moisture ingress and facilitating the migration of excess humidity from inside the building to the outside [8, 21].

Similar to the structural elements of a building, it is important to design façades for durability. The importance of durability in construction disciplines has been known since the establishment of very first buildings. Over the ages, designers have acquired considerable knowledge of best construction practices by careful surveillance of the building performance over time [22]. With considerably increased housing demands in the 1960s, the major construction concern was to build a maximum floor space at a minimum cost. While these buildings had a service life expectancy of approximately 100 years, most of them needed complete renovation within 40 years of their construction, especially their exteriors as their façades and roofs were severely deteriorated.

It is necessary to ensure that the façade system fulfills its major functional, environmental and economic roles, and that it satisfies all the needs for the ultimate and serviceability limit states during the design service life. The designer must consider all probable system deterioration modes and failure mechanisms during the design stage to ensure façade durability. Durability considerations should be integrated into façade design by visualizing the performance of components over time under specific aggressive environmental conditions to predict the façade performance over its service life.

2.2.5 Cost efficiency

The importance of focusing on the life cycle costs of an asset, rather than considering the investment costs (design and construction) as the only economic parameter, was an important lesson learnt from the 1960s. Therefore, the designer must consider the costs of design, construction, operation, maintenance, major rehabilitation, if needed, and demolition of a façade system in the related life-cycle cost calculations. These calculations show that it is more economical to make large initial investments to offset the excessive costs during the operation or maintenance phases [22].

The cost efficiency can be maximized once the various systems related to a specific performance attribute are integrated with each other [16]. For instance, in a high-performance façade, since the peak cooling loads are reduced due to optimum heat transfer and natural ventilation, a smaller heating, ventilation, and air conditioning (HVAC) system or a low-energy alternative can be used (to reduce energy consumption). Integration of the façade and HVAC system (in mild climates) can eliminate the need for cooling altogether. Whenever possible, it is recommended to adopt simple robust design solutions that have a generally predictable impact on energy consumption, such as appropriate building massing and alignment, optimum window to wall area ratio (WWR), use of high-performance glazing and application of exterior shadings.

2.3 Current design procedure

The façade design procedure can vary from one country to another and from one project to another. Hence there is no unique method available for designers. However, there are similarities among the currently available practices around the world (whether the architect, a special façade engineering group or a façade contractor is the façade designer).

Building design teams often consider façade system attachments as secondary components of the project. In fact, design, fabrication, and erection of façade systems are often delegated to a specialty contractor, who is part of the construction team. The specialty contractor's team typically includes façade system manufacturers, erectors, designers, detailers, and other consultants.

In most cases, façade design is implemented in two phases. The first phase comprises architectural design, followed by an execution phase handled by the constructor.

2.3.1 Architectural design

Despite the differences, in most countries, there is a basic sequence in which façade architectural design is implemented. Firstly, there is a definition of functions and the overall system performance, that leads to a preliminary design. As the design is further refined, the design must be negotiated with the authorities for approval. Subsequently, all technical details of the construction are specified and related documents are developed [23]. The design team's documents typically provide guidance on submission and review procedures, as well as a general design-responsibility description.

After formalizing the contract, the technical details are developed and approved. It is best to hire the designer to perform the supervision on the construction site. All aspects of each phase must be accepted by all stakeholders. Hence, the façade designer must take predefined steps and provide the results as feedback on the previous phases, due to the iterative nature of the process. In the current practice, the designer tends to make decisions as late as possible to incorporate possible design adjustments. Hence, considerable experience is needed to conduct a façade design effectively.

The end of life scenarios are normally not a part of the designer's services and at best, his involvement ends at the operations and maintenance phase. Although, even in some European countries (such as Netherlands and Germany), despite the strict regulations in energy saving, monitoring of the energy performance is not a dedicated item in the service descriptions of a façade designer [20].

2.3.2 Execution design

Façade specialists (or façade constructors) conduct several design phases. Although each company has its own strategy, the process usually consists of the following steps:

Generally, façade engineers/constructors conduct two or three executional design phases. First, the design is developed based on the architectural design documents and possible missing elements in the documents are discovered [23].

In the second phase, the design is elaborated and completed. This can be a very complex and time-consuming procedure that requires a lot of knowledge and experience. Usually, the results of each design phase are sent to the architect/consultant for approval; which requires consideration of extra time that is needed.

Finally, the production and assembly design phase starts. Although the design is often based on existing façade systems (with specified related benefits and disadvantages), the façade designer draws every profile in detail including all metal panels and foldouts.

It is necessary to order the complex systems products with all the necessary components, which often require support from the system supplier. The façade designer needs to know the material properties, sizes, and weights. Structural calculations must be performed at this stage (either by the façade designer or a structural designer). The sequencing of the work, such as the coating processes, must be considered. The time schedule defines all the decisions that should be made at a certain time to keep the process from coming to a halt.

Due to the delegated design arrangement, coordination is vital between the design professionals for the overall building project and the design professional that performs the delegated design of the façade systems. Without sufficient clarity and information in the design documents, as well as appropriate coordination, the design responsibility is often blurred, and project deliverables, schedule, and overall quality can suffer; in the worst case scenario, this can lead to disastrous results [24].

2.4 Requirements related to Canadian codes and standards

The Standing Committee on Environmental Separation (SCES) in Canada, prepares recommendations for environmental separation needs in the National Building Code Documents that are related to the following items [8]:

- Structural and environmental loads impacting environmental separators and assemblies exposed to the outdoor
- Heat transfer (different from fire resistance)
- Air transfer
- Water vapour diffusion
- Precipitation, surface water, and moisture ingress
- Sound transmission

These provisions are mostly included in Part 5 of Division B of the National Building Code of Canada (NBC) [25]. The overview provisions in the NBC that must be considered while designing environmental separators are categorized as follows:

2.4.1 Resistance to loads

Structural loads or actions are characterized as forces, deformations, or accelerations applied to a structure or its elements [26]. It is known that loads can result in stresses, deformations, and displacements in structures [27]. One can assess the effects of loads by using the different available methods of structural analysis. Designers also must deal with the possibility of excessive or extraordinary loads causing structural failure, unless such a possibility is seriously controlled by design.

According to NBC, materials, components, or assemblies that separate different environments and are exposed to the exterior, are needed to be designed to resist structural loads. These loads are to be determined in accordance with Part 5 of NBC [25] as:

- "All environmental loads and effect of those loads
- Structural loads and effect of those loads that may reasonably be expected"

These loads mainly include the following:

- Dead loads (self-weight) of the assemblies
- Wind loads (including the up-lift imposed on roofing), snow, rain, hydrostatic and earth pressure loads,
- Air pressure loads on the air barrier
- Loads due to thermal or moisture-related expansion and contraction, deflection, deformation, creep, shrinkage, settlement, and differential movement" [25].

It is expected from the environmental separator that is subject to these loads, to transfer these loads to the building structure without any adverse effects on other components and without causing excessive deflections that might adversely affect the performance of other assemblies or components. Part 4 of NBC [25] provides a detailed explanation of the calculation of these loads.

2.4.1.1 Seismic requirements

The various structural elements (SE) of a building must safely transfer earthquake-induced inertia forces to the foundations. There are components in the building (such as façades) that are supported by the SEs and their seismic inertia forces are also are carried to foundations by the SEs; these components are known as non-structural elements (NSEs).

The physical characteristics of NSEs are described as follows [28, 29]:

- "Accelerations imposed on NSEs are higher than those on buildings, primarily due to the amplification of the ground motion along the height of the building.
- NSEs do not possess significant ductility to dissipate the energy received during a strong shaking.

- Ductility of NSEs depends largely on their internal design and on the design of their connections with SEs.
- Damping associated with NSEs is normally low.
- NSEs can undergo resonance when their natural frequencies are close to the fundamental and other dominant frequencies of the building.
- Generally, NSEs are connected at multiple points to the SEs.
- Responses of NSEs under earthquake shaking are different from those of SEs."

It is evident that the building envelope components need a more conservative design approach to avoid falling of the façade panels onto sidewalks and pedestrians during an earthquake [30]. It has been learnt from past experience that using higher load factors will not eliminate the danger of such hazards and proper detailing of the components and their connections are critical in designing NSEs for earthquakes.

NBC suggests the design force V_p for NSEs [25, 30]:

$$V_p = 0.3\, F_a S_a(0.2)\, I_E S_p W_p \tag{2. 1}$$

where F_a is the acceleration-based site coefficient, $S_a(0.2)$ is the spectral response acceleration value for a period of 0.2 s, I_E is the earthquake importance factor, S_p is the force factor for the NSE calculated from Eq. 2.2, and W_p is the weight of the component.

$$S_p = C_p A_r A_x / R_p \tag{2. 2}$$

where C_p is the element or component factor, A_r is the dynamic amplification factor of the component, and A_x is the height factor and R_p is the element or component response modification factor which represents the energy-absorption capacity of the component and its attachments.

A lower limit for S_p is set to be 0.7 and a conservative maximum value is 4.0 as set in the provisions (refer to Article 4.1.8.18 of NBC for more information).

2.4.2 Fire code requirements

To assess how a given material or assembly will perform in a fire, building codes and standards have categorized construction materials into four categories:

- Combustible
- Non-combustible
- Fire-resistant
- Ignition-resistant

Combustible is referred to materials that readily ignite and burn such as wood. Flame spread index and heat release rate are two properties that are used in characterizing the relative combustibility of the different materials which are measured by various tests.

The heat release rate can be assessed by measuring the amount of mass loss of a burning material or by measuring the total energy release or the rate of its release when it is burning.

Non-combustible is referred to a material that is not capable of undergoing combustion under specified conditions specified in ASTM E 176 [31]. Non-combustibility can be assessed by ASTM E-136 [32], a standard test method for the behaviour of materials in a vertical tube furnace at 750 °C.

Fire-resistant and ignition resistant can refer to a material or an assembly and is related to the potential of the material to withstand fire or ignition.

The National Fire Code of Canada (NFC) and the NBC (3.1.4.8) require that at least 90% of the exterior cladding on each exterior wall of the building be non-combustible or meet the following conditions (stated in Article 3.1.5.5):

- The building should have more than three storeys or
- Be sprinklered throughout and have an acceptable performance when tested in accordance with CAN/ULC-S134, fire test of exterior wall assemblies, in terms of:

   i. Flaming spread on the wall is less than 5 m above the opening and
   ii. The heat flux during the flame exposure on the wall assembly is less than 35 kW/m^2 measured at 3.5 m above the opening.

"A wall assembly permitted by Article 3.1.5.5 that includes combustible cladding of fire retardant treated wood shall be tested for fire exposure after cladding has been subjected to an accelerated weathering test as specified in ASTM D 2898, accelerated weathering of fire-retardant-treated wood for fire testing" [25].

Moreover, the environmental separators are required to have a minimum fire resistance rating in accordance with their relevant building group (see the NFC code).

With the recent trends to build taller structures, consideration of fire safety issues related to façades become more urgent due to new design complexities (use of curved surfaces and rotated floors) and the hidden details of the fire barrier assemblies [33]. Also, it is important to understand the effect of various façade components and façade orientation on its fire performance.

The current codes and standards suggest that the risk associated with fire spread along the exterior of a façade can be mitigated with a properly designed and operational sprinkler system. However, according to O'Connor [33], this is a critical assumption and while our understanding of fire spread mechanism is intact, the risk of fire spread related to tall building façades, is not well examined and further research and investigation is needed in this field to avoid tragedies such as Grenfell Tower [34] incident.

2.4.3 Resistance to deterioration

As reported in NBC [25], materials that are used in building components and assemblies separating naturally unlike environments, as well as assemblies that are exposed to the outdoor, should fulfil the following two conditions:

- "Being compatible with adjoining materials,
- Being resistant to any mechanisms of deterioration that can possibly occur, provided the particular nature and function of the materials, and their geographic location and climatic exposure conditions" [25].

A partial list of environmental loads that need to be considered consists of sound, light and other types of radiation, temperature, moisture, air pressure, acids, and alkalis. The sound-related requirements can be found in Part 3 of NBC.

The mechanisms of deterioration consist of:

- "Structural (such as impact and air pressure),
- Hydrothermal (for instance, freeze-thaw cycles, differential movement due to thermal expansion and contraction, and ice lensing),
- Electrochemical (e.g., oxidation, electrolytic action and galvanic action),
- Biochemical (such as biological attack and intrusion by insects and rodents)" [25].

One can find information on the effects of deformations in building elements, in the structural commentaries in the NBC.

It is possible to determine the resistance to deformation based on field performance, accelerated testing, or compliance with guidelines, as provided by the evaluation agencies approved by the authority having jurisdiction [8].

Building components are to be designed with adequate knowledge of the length of the time interval during which they are expected to perform their intended function effectively. The actual service life depends on the materials used in the design, as well as the surrounding environment.

The designers are expected to consider the following factors: each component function together with the notions of premature failure, accessibility for maintenance, repair, and replacement purposes, and the cost of repair or replacement.

In cases where maintenance, repair or replacement is expected with a high probability, for certain elements prior to the building being subjected to a major retrofit, special attention should be focused on providing necessary access to those elements.

Where the use of a building, space, or service, is subject to a significant change, the impact of the changes on the environmental separators should be assessed to prevent premature failures that could possibly create hazardous conditions.

2.4.4 Heat transfers

Section 5.3 of NBC seeks levels of thermal resistance that are required to optimize the amount of condensation on or within the environmental separators, and to guarantee proper thermal conditions for the building use. According to energy regulations, if these conditions exist, the levels of thermal resistance required for energy efficiency should be specified [25].

According to NBC [25], in cases where a building component or assembly is subject to an intended temperature differential, the element or assembly should consist of materials to suppress heat transfer, or a means to dissipate heat that has been transferred. Materials to resist heat transfer are not required to be illustrated in cases where uncontrolled heat transfer will not have an adverse impact on any of the following:

- “Health or safety of the building users,
- Projected use of the building,
- The process of building services” [25].

Therefore, wherever there is an intended temperature difference across the building assembly, the heat flow must be controlled. The use of the term “intended” implies that whenever the interior space is separated from exterior space, temperature differentials would occur. However, it should be noted that in many cases, such as adjacent interior spaces, there is an intended, although not substantial temperature difference. In these cases, the provisions to control the heat flow might be little, or that provided by any standard interior separator.

2.4.4.1 Properties to resist heat transfer, or dissipate heat

Taking into consideration the conditions on either side of the environmental separator, materials and elements installed to serve the required resistance against heat transfer, or the means employed to dissipate the transferred heat, shall provide adequate resistance or dissipation, as follows:

- “Minimize the surface condensation on the warm side of the component or assembly.
- Minimize condensation within the component or assembly and in union with other materials and elements in the assembly.

- Fulfill the interior design thermal conditions for the intended occupancy, in conjunction with the systems installed for air conditioning of the space, and
- Minimize ice blocking on sloped roofs" [25].

2.4.4.2 Use of thermal insulation, or mechanical systems for environmental control

The level of thermal resistance needed to considerably avoid condensation on the warm side of an assembly or within it (at the vapour barrier), and to allow the maintenance of appropriate indoor conditions, depends on several items:

- "The habitation,
- Air temperature of the exterior,
- Air temperature of the interior and relative humidity,
- The capacity of the heating system, and
- The means of delivering heat" [25].

For controlling the condensation on the interior surface of an exterior wall, the interior surface must stay above or at the dew point of the interior air. As an example, if temperature and relative humidity (RH) of the interior air are 24°C and 30% respectively, the dew point will be 5°C. If the interior air temperature is 21°C with relative humidity 50%, the dew point will be 10°C (see the Psychrometric chart in Figure 2.2).

In locations with cold temperature on the exterior, assuming the required interior RH during the heating season is estimated around 35%, and the exterior and interior temperatures are -20°C and 23°C respectively, the materials in the environmental separator would be required to provide a mere RSI (R-value using the SI units, R-value is used to measure a material's thermal conductivity and resistance) 0.182 for condensation on the interior surface to be avoided.

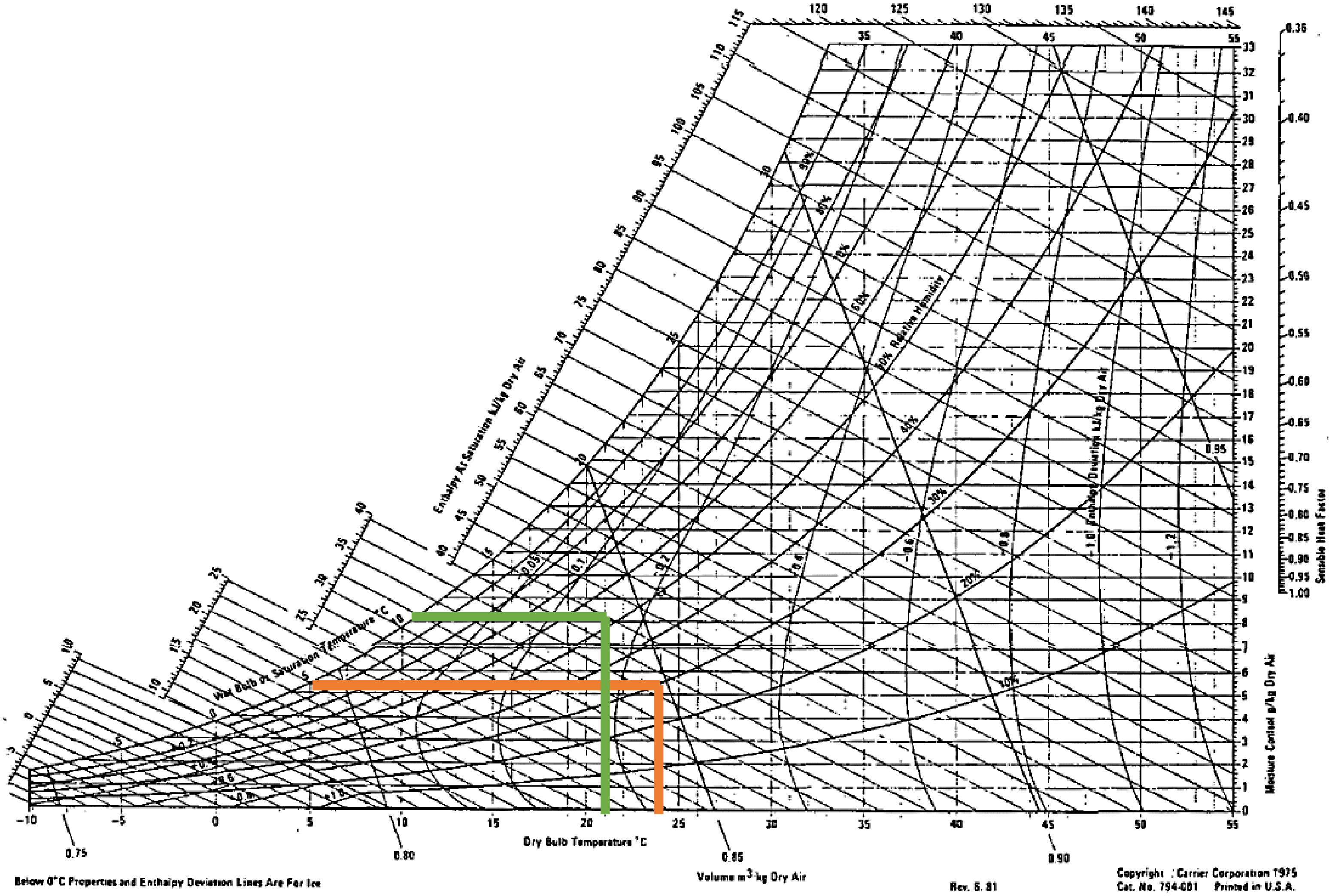


Figure 2.2 Psychrometric chart

Exterior temperatures may be significantly lower for some of the regions of Canada. Also, people might prefer to maintain the interior RH between 40-45%. In these cases, insulation or increased heat delivery to the environmental separator are required to maintain interior temperatures of the vapour barrier above or at the dew point.

It would generally be impractical and inefficient to directly deliver heat over the entire surface of the environmental separator. It should be noted that increased heat delivery would normally entail excessive energy costs and adverse environmental impacts. Besides controlling condensation, interior surface temperatures must be sufficiently warm not to cause occupant discomfort because of excessive heat lost through heat transfer mechanisms. Thus, installation of insulation may be necessary, even where condensation control is not required, depending on the occupancy of the spaces.

National Energy Code of Canada for Buildings (NECB) [35], prescribes the minimum thermal resistance of walls, roofs and windows based on climatic zones and building destination.

2.4.5 Air leakage

A separating component or assembly may separate interior conditioned space from the exterior, interior space from the ground, or environmentally different interior spaces. Where a separator performs, the position and properties of the materials, components or assemblies are such that air leakage is controlled or venting to the exterior is permitted to:

- “Provide fairly acceptable conditions for occupants of the building,
- Maintain proper conditions necessary for the intended use of the building,
- Minimize the accumulation of condensation and the diffusion of precipitation into the building component or assembly,
- Not compromise the procedure of building services” [25].

To provide the principal resistance against air leakage, an air barrier system shall be installed. This system is not required, where uncontrolled air leakage will not have any adverse effect on the health or safety of the building users, and on the projected use of the building.

An air barrier system in above-grade building components and assemblies that separates conditioned interior space from the exterior, will decrease the chance of condensation caused by air leakage, the penetration of dust and other pollutants, and intrusion in the performance of building services, such as HVAC and plumbing. It should be noted that serious health or safety threats can be implied by these difficulties, as defined in the following:

The most noticeable and important troubles are currently due to degradation of the moisture-related material, such as rot and corrosion, which can result in the failure of the component connections. Furthermore, a wide range of health problems can be the consequence of the infiltration of dust and other pollutants. The pollutants may include fungus spores where the separator is subject to high moisture levels. Finally, interference with the performance of building services can result in unhealthy and hazardous conditions in many regions during the heating season.

In a few buildings projected for human occupancy, the interior space is conditioned although an air barrier system is not required to be installed. This would rely, on the following parameters: the levels of interior conditioning provided, the ventilation levels, the protection provided for the workers, and the tolerance of the building to the accumulation of condensation and potential precipitation ingress.

For some industrial buildings, only limited conditioning is provided. For instance, radiant heating and ventilation levels can be adequate to decrease relative humidity to the desired level, i.e., a level at which condensation will not accumulate to a degree that is challenging. Conversely, some industrial buildings, due to the operational processes, operate at very high temperatures and ventilation levels. In such cases, the building envelope is maintained at temperatures at which condensation is avoided. In both examples, the occupants are protected from unacceptable levels of pollutants, by either the ventilation rates or protective gear in the work environment.

2.4.6 Vapour diffusion

Where a building component or assembly is exposed to a temperature differential and a water vapour pressure differential, the element or assembly should include a vapour barrier [25]. The principal resistance against water vapour diffusion is provided by installing a vapour barrier, which is not required if it can be shown that uncontrolled vapour diffusion does not affect any of:

- “Health or safety of the building users,
- Projected use of the building,
- The process of building services” [25].

The vapour barrier shall have adequately low transport properties, and be positioned in the building component, or assembly to:

- “Minimize moisture transfer by diffusion, to sufficiently cold surfaces within the assembly that would cause condensation at the design temperature and relative humidity, or
- Decrease moisture transfer by diffusion, to sufficiently cold surfaces within the assembly that would cause condensation at the design temperature and relative humidity, to a degree that will not allow adequate accumulation of moisture causing degradation” [25].

2.4.7 Precipitation

In case a building component or assembly is exposed to precipitation, the element or assembly shall,

- "Minimize precipitation ingress into the element or assembly, and
- Prevent precipitation ingress into interior space" [25].

Protection from precipitation ingress is not necessary if it can be shown that such ingress has no adverse effect on the building and its services.

Materials, elements, assemblies, joints in materials, connections between elements or assemblies exposed to precipitation should be sealed to avoid precipitation ingress or drained to direct precipitation to the outside; except if one can show that omitting sealing or drainage does not have a harmful impact on the building and its services [25].

In cases where the accumulation of water, snow or ice can occur on a building, provision must be made to reduce the chance of hazardous conditions arising from such an event.

All connections between vertical assemblies and sloped or horizontal assemblies must be designed and constructed in such a way that the water flow from the sloped or horizontal assembly onto the vertical assembly, is minimized.

The building should be located where the building site is graded, or catch basins are installed, to prevent the accumulation of surface water alongside the building [25]. The foundation walls should be constructed so that the surface water does not enter the building or damage the materials that are vulnerable to moisture.

2.4.8 Moisture protection

Materials and elements installed to provide the needed moisture protection should have adequately low water transport characteristics to form an impervious and continuous barrier for water infiltration or accumulation of water against the building [25]. These barriers should accommodate the construction imperfections, joints, and junctions between various building assemblies. The waterproofing materials are not necessary in cases where the building can accommodate water infiltration and accumulation; or where the moisture ingress and accumulation will not adversely influence the occupants' health, and the safety and serviceability of the building.

According to the NBC, the control of moisture ingress into the interior space from the ground is independent of the type of the building, the use of the space, or the space being conditioned or not [25]. This indicates that high humidity levels, with or without standing water, possibly undesirably affect both health of the building occupants and the durability of the building structure.

The assembly separating the subject interior space from the outside environment, cannot normally be depended for delivering adequate moisture protection for the occupants of the building. Depending on the construction of the separator, it may also be in danger of moisture-related degradations.

The exclusions to this necessity include only those cases for which the subject interior space is unoccupied and the separator itself delivers the needed protection and is resistant against a highly humid environment, or the moisture loads are limited enough as to not have undesirable effects on the building or its occupants.

2.4.9 Sound transmission

According to ASTM E413, "Classification for rating sound insulation", sound transmission class (STC) ratings should be determined, using the outcomes from measurements in accordance with:

- ASTM E90, “Laboratory measurement of airborne sound transmission loss of building partitions and elements”, or
- ASTM E336, “Measurement of airborne sound attenuation between rooms in buildings” [25].

2.5 Current design deficiencies and needs

While the main criteria in façade design is considered to be safety, sustainability, human comfort, durability and cost efficiency; which should be incorporated in façade design, currently, except for minimum required safety provisions in codes (in terms of resistance to mechanical and environmental loads), and performance requirements such as appropriate heat, air, moisture (HAM) transport and acoustics, other criteria are mostly neglected.

As mentioned earlier, it must be emphasized that with the current worldwide environmental crisis, the sustainability of façades should be considered as a central criterion of high-performance systems.

However, the provisions of enhancing the energy efficiency of façades, are not used in the majority of current design practices (especially in low rise buildings). Even in best present practices, the issue of sustainability (in terms of the environmental footprint), durability or related maintenance costs and inspection needs are not considered.

In designing multi-domain systems such as building façades where the design criteria within one domain can affect or be contradicting to what is performed in the other domains; it is essential to have a balance between façade design criteria to have an optimal façade performance. This task can be quite challenging due to excessive costs, the related complexity of the design procedure, ignorance or lack of an available systematic design approach to all façade designers to integrate all these design criteria and to decrease the design complexity and time consumption. To solve this issue, the author suggests a new approach to facilitate façade design which will be discussed in Chapter 3.

2.6 Summary

This chapter reviewed the history of building envelope development through history along with the growing expectations from façade performance level. Presently, with new developments, building envelopes can significantly improve the occupant's comfort level and positively affect the environmental footprints. These expected performances are mainly characterized into five categories namely, structural integrity and safety, human comfort, sustainability, durability and cost efficiency.

The NBC has provided some provisions related to the design of environmental separation which were discussed in detail. However, despite the present knowledge on the potentials and availability of the code requirements, the current design procedure impedes the true performance potential of the envelopes. This is because building envelope design is a complex procedure that requires consideration of multiple criteria that may be sometimes conflicting with each other. Moreover, the codes and standards do not impose rigorous requirements on designing the building envelopes, hence the designers are reluctant to change their design procedure as it would be cognitively challenging to consider all design criteria. As a result, there is a need for a systematic approach that would facilitate this process. The author proposes a new and integrated approach that is discussed in Chapter 3.

Chapter 3 Proposed Building Façade Design Procedure

3.1 Introduction

Although many researchers have emphasized the importance of an integrated design in constructing a high performance and sustainable building [36-38], designers are still continuing to use the traditional design methods in practice.

To replace the traditional façade selection methods that were mainly based on the designers' intuition, with a systematic decision-making process that will assist the designers in exploring their priorities and choosing an alternative that satisfies their needs, it is necessary to define the nature of the design problem, project goals, limitations, and constraints.

As mentioned in Chapter 2, the design criteria (performance attributes) are mainly distributed in five principal categories of structural integrity and safety, human comfort, sustainability, durability and cost efficiency.

These attributes cannot be attained in a single step and in-time actions are required to achieve the optimal performance (at minimum costs) as illustrated in Figure 3.1.

This chapter reviews the required actions and considerations in each phase in detail to provide a simplified guideline for façade designers in achieving optimal façade design.

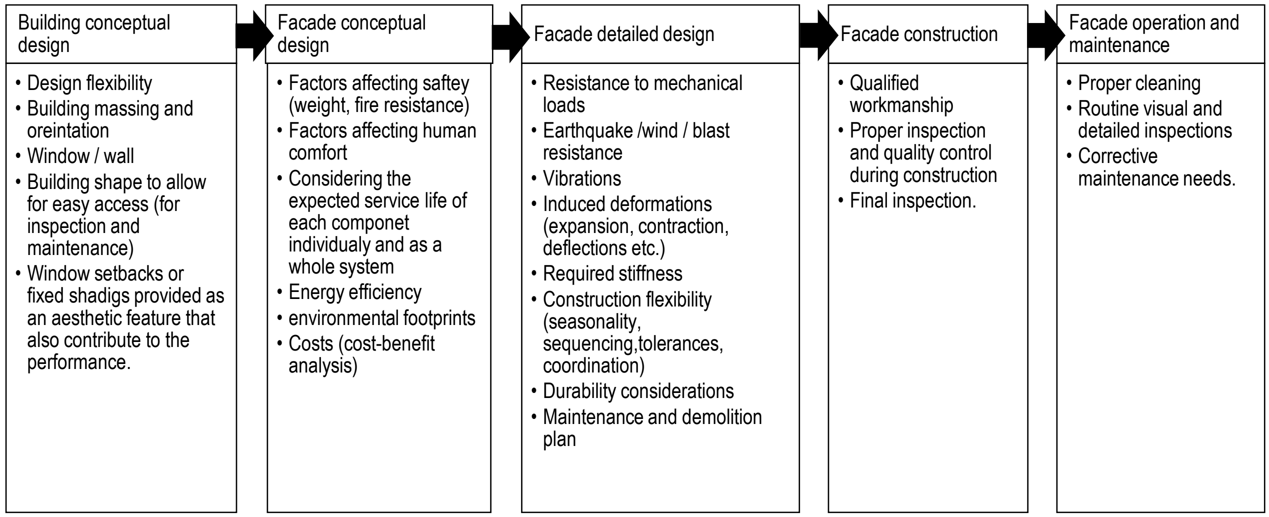


Figure 3.1 Summary of the necessary façade considerations during various life cycle stages

3.2 Building conceptual design

Although the most important factor affecting the performance of the façade system is the selection of a proper façade system for each project, there are some passive design strategies that can significantly enhance the performance of the building which are independent of material and components that are selected for the building envelope. Such considerations include proper building massing and orientation, optimal window to wall ratio and building shape which must be made during the conceptual design phase of the building, regardless of whether the architect is the façade designer or not. These strategies are introduced here as follows:

3.2.1 Identification of project constraints

Each project has its own limitations and constraints. Some limitations including the site properties (such as shape, size, and slope) or the available budget might indirectly affect the building envelope but other limitations, such as municipal regulations to allow for using only specific type of building materials for façades, can directly affect the decision-making process. For this reason, it is best to identify the constraints at the earliest stage of façade design and adopt appropriate strategies to obtain the best possible solutions despite the constraints.

3.2.2 Building massing and orientation

Building massing and orientation directly influence the fenestration layout and have an important impact on the building performance and costs [16] and when incorporated at the earliest stages of building design, will eliminate the need for some later strategies, such as automated shading and operable windows which are more complex and costly.

It is recommended to minimize the façade exposure on the east and west elevations and orient the building so that its long elevations face north and south. This will facilitate the control of solar heat gain through the implementation of exterior shading.

It is also necessary to consider an optimum floor plate depth along with the layout of core spaces and services. This will enhance the effective distribution of daylight in building spaces. For example, a floor depth greater than approximately 12 meters will lead to the formation of an internal zone with very limited access to the façade. This will result in needing a mechanical ventilation system. In mild climates minimizing the floor plate depth in combination with a properly shaded façade system (and sometimes application of operable windows) can result in the elimination of the need for air conditioning systems which is a more energy efficient solution [16].

However, in some cases due to site constraints, it may not be possible to achieve optimal building orientation. Hence the design team should seek other strategies, if possible. For example, the design team may choose to have a central courtyard to minimize the floor plate depth and bring in additional light when forced to have a square-shaped plan.

It should be noted that selecting a simple building shape will facilitate the construction, inspection and maintenance procedure and reduce the associated costs.

3.2.3 Window to wall ratio

Window systems have a major role in providing ample daylight and visual comfort to the occupants. For this reason, there has been a design trend in recent years towards highly glazed façades that provides the occupants with a sense of connection to the outside.

Despite the aesthetics, there are some disadvantages associated with fully transparent façades, including the relatively higher heat transfer of the façade and the complexities associated with daylight control. Moreover, these design solutions are not very environmentally friendly or cost efficient [16].

It is recommended to use more solid, yet aesthetically pleasing solutions rather than investing in expensive façade solutions as a means for mitigating heat gains and losses in highly-glazed façades. Moderate WWR combined with high-performance window systems can allow for meeting occupant comfort requirements, as well as an optimal building energy use. To achieve an optimal energy performance, the NEBC [35] suggest the maximum allowable WWR be determined from Eq. 3.1:

$$WWR = 0.4 \quad for\ HDD_{18} < 4000$$

$$WWR = \frac{2000 - 0.2HDD_{18}}{3000} \quad for\ 4000 < HDD_{18} < 7000 \qquad (2.3)$$

$$WWR = 0.2 \quad for\ HDD_{18} > 7000$$

where HDD_{18} is the heating degree days of the location of the building determined in accordance with the Sentence 1.1.4.1(1) of the Code [35].

3.2.4 Solar control

It is possible to offset the daylight load by the correct use of solar control solutions. Generally, solar control is achieved through the application of appropriate glazing units, shadings, and louvres. These provisions are normally implemented during the façade conceptual design phase. However, even in building design conceptual phase, appropriate application of window setbacks can deliver good shading potential as well as some attractive architectural features to the building.

3.2.5 Design flexibility

The term "flexibility" in architectural design is usually referred to the potential of the building to adapt, transform and convert. These are normally used when the function of the designed area changes; however, the flexibility intended here, is referred to the potential of the building to adapt to various façade alternatives and detailing. This provides façade designers with the possibility of having more options and changing a selected alternative with another one, if needed, at minimum costs.

3.3 Façade conceptual design

Façade conceptual design phase is the most important stage since the decisions made in this stage will directly influence the outcome and success of the later stages. This stage consists of several phases as explained in the following:

3.3.1 Identification of criteria to be considered in the conceptual design phase

In this stage, the expectations (performance attributes) from the project should be clearly defined. The comprehensive list of the façade performance attributes is presented in Table 2.2. Subsequently, the design criteria must be identified based on the intended performance attributes. It is necessary for the criteria to be exhaustive, meaning that consideration of these criteria will satisfy all intended performance attributes (assuming that the requirements for other life cycle stages are met). Table 3.1 illustrates the recommended design criteria to be considered in a conceptual façade design stage.

Table 3.1 Criteria to be considered in conceptual façade design stage

Design criteria	Reason for consideration and assessment method
Thickness	Thinner walls are desired to maximizing living space.
Weight	Ease of construction, maintenance and decommissioning.
Resistance to fire	Higher resistance is required. Fire rating of the wall assemblies should be considered.
Resistance to vapour diffusion	Higher resistance is required to control indoor air quality and avoid moisture damage. The permeance of materials in wall assembly should be considered.
Thermal resistance	Higher resistance is required to prevent heat transfer mechanisms. The overall thermal resistance of the wall assembly should be considered
Acoustics	Block outside noise. Sound transmission class of the wall assembly should be considered.
Visual comfort	After adjusting the WWR in the building conceptual design phase, the next step is controlling the amount of visible radiation passing through the fenestration system.
Controlling solar radiation	Controlling the solar heat gain, and daylight control through window/shading components
Ease of construction	To reduce construction time and costs.
Energy efficiency	To avoid energy waste and if possible produce energy by using photovoltaic (PV) or photovoltaic-thermal (PVT) hybrid systems.
System effect on the environment	The goal is to have a minimum adverse effect on the surrounding environment. Life cycle Assessment of the system should be considered.
Durability	The expected service life of a material in certain weather conditions considering no undue damages will occur.
Cost efficiency	Life cycle costs should be considered. It will give the designer an idea of the investment return time
Aesthetics	Depends on the stakeholders' or designer's preferences and subjective opinion.

3.3.2 Selection of feasible design alternatives

In this stage, feasible design alternatives are selected after consulting the related codes and standards (Section 2.4) and the following:

3.3.2.1 Strategies to control solar radiation

Strategies to control solar radiations are aimed at controlling heat transfer, or visible light as demonstrated in Table 3.2. Some of these strategies such as orientation and WWR should be considered in the building conceptual design phase.

Table 3.2 Strategies to control solar radiation [4]

Controlling heat	Controlling visible light
Orientation	Orientation
WWR	WWR
Various forms of shading	Various forms of shading
Thermal resistance of the glazing	Glazing optical properties
Glazing reflection and emissivity	

According to the project needs, constraints (such as initial budget, maintenance needs), climatic conditions, and the expected performance level, the designer must decide on the type of windows (fixed or operable to provide natural ventilation) and shadings (fixed or automated). The glazing properties are considered in this stage.

For each climatic condition, the designer must decide on the number of glazing panes, the framing system, in-filled gas(es) between glazing panes, and the coatings (type, colour and glazing surfaces with the coating is applied to them), based on the required thermal resistance, visual transmission and heat gain properties.

3.3.2.2 Strategies to control heat transfer

To control the heat transfer in a building envelope, which occurs through conduction, radiation, and convection, it is necessary to use a radiation barrier (solar control as explained in Section 3.3.2.1), thermal insulation, and air barrier systems.

Application of thermal insulation is the most effective solution to control the heat transfer through the wall assembly since they:

- Increase energy efficiency by reducing the building's heat loss or gain
- Control surface temperatures for occupant comfort
- Help in controlling temperatures within an assembly, to reduce the potential for condensation

Moreover, thermal insulations can sometimes add structural strength to a wall, such as in structural insulating panels (SIP), provide support for a surface finish (e.g. exterior insulation finish systems (EIFS)), impede water vapour transmission and air infiltration, reduce noise and vibration, and reduce damage to structures from exposure to fire and freezing conditions.

It must be noted that poorly designed or improperly installed thermal insulation may promote moisture condensation and subsequent damage within a building envelope.

Thermal insulation materials are divided into the following categories based on their physical structure and form:

- Loose-fill insulation
- Semi-rigid or flexible insulation
- Rigid board insulation
- Formed-in-place insulation

The designer must select the most suitable insulation form, considering the envelope materials, construction requirements and their thermal resistance.

3.3.2.3 Strategies to control air leakage

Air leakage through the building envelope can cause several problems such as thermal discomfort, higher energy consumption, condensation, the formation of ice dams on the roofs, durability issues, development of mould, noise transmission, odour and poor indoor air quality.

Air leakage occurs due to three driving forces namely, wind, stack effect, and combustion and ventilation and through the following paths:

- Cracks and joints between elements
- Poor connection between wall and roof, wall and windows, etc.
- Porous materials (e.g., concrete blocks, fibre boards)
- Discontinuities in the air barrier
- Openings for building services (pipes, electrical outlets, etc.)

To control air leakage, the designer must use a well-detailed, buildable and workmanship-tolerant air barrier system. It is important for the air barrier to be continuous, structurally supported and durable. It is preferable to place the air barrier system on the warm side of an insulated assembly, but it can be changed when it is suitable for a given construction practice, or due to the type of materials that are used.

3.3.2.4 Strategies to control moisture migration

Moisture migration through the building envelope occurs due to the following mechanisms:

- Rain penetration (bulk water)
- Air leakage
- Vapour diffusion

Rainwater penetration is the most important source of moisture problems in envelopes. The rainwater can penetrate the building when there is an opening in the envelope and a driving force to move the water through the opening. These driving forces include kinetic energy, surface tension, pressure assisted capillarity, gravity, and air pressure differentials. Strategies to control rainwater penetration include [4]:

- Deflection using overhangs, balconies, or placing the wall to the orientation with least wind-driven rain exposure (although the complete elimination of water on the envelope is not practical, the water sources can be greatly reduced).
- Elimination of openings by sealing all of the cracks or joints is known as face-sealed walls also known as perfect barrier walls.
- Focus on controlling the forces that cause rain penetration: rain screens, compartmentalization of the cavity, capillary break, etc.
- Proper drainage and application of storage wall systems.

To control the moisture migration due to air leakage, an air barrier system must be used as explained in Section 3.3.2.3. In addition, another strategy to control the moisture migration through air leakage is the application of thermal insulation, because when the air leaks through the layers of the building envelope, condensation only occurs when the temperature of the layer is below the dew point. For this reason, proper application of thermal insulation can eliminate this problem. However, the control of air leakage is necessary for other reasons, as mentioned earlier.

Vapour diffusion in the envelope is the process by which water vapour migrates through the material and is caused by the partial vapour pressure differential across the envelope. The moisture flux depends on partial vapour pressure differential and resistance of the material to moisture movement. To eliminate or more accurately, to retard the passage of moisture as it diffuses through the assembly of materials in a wall, a proper vapour barrier must be installed. It must be placed on or near the warm side of the insulation, which is normally the high vapour pressure side. The placement of vapour retarder should not prevent drying and the designer should avoid any “double-barrier” situation.

3.3.3 Selection of the proper façade system

After considering the various design strategies to enhance the occupant comfort level and to mitigate the risks involved, the designer must select the most appropriate alternative from a pool of feasible design choices. For this purpose, it is necessary to compare these alternatives using a proper decision-making method. This process contains several stages as demonstrated in Figure 3. 2. These steps are explained in detail in Chapters 4, 5, 6 and 7.

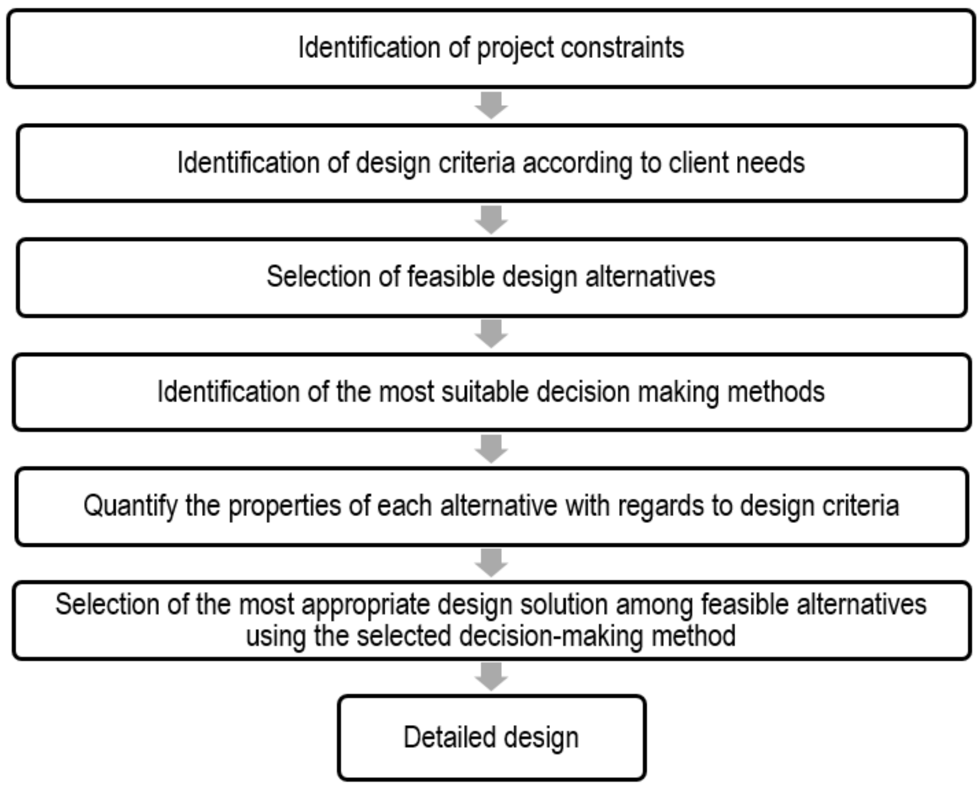


Figure 3.2 Façade conceptual design stage: the required steps for the selection of the most appropriate system.

3.4 Façade detailed design

In the detailed design stage, the designer or the structural engineer must design the building envelopes for the loads discussed in Section 2.4.1.

In designing the system for dead loads, earth pressure loads, hydrostatic loads, thermal and moisture expansion and contraction and air pressure inflicted on air barrier, the design is for static loads, and the components should remain elastic and should comply with the lower-bound material properties for design [39]. The façade connections are designed for their tributary load.

To design for resisting wind loads, the equivalent static peak wind force (see the NBC for the calculation procedure) is considered and the components are designed to remain elastic when subjected to loads. The design should also meet the strength and serviceability requirements of the code. In some zones, it might be necessary to design for additional impacts related to hurricanes and tornados [39].

The current codes and standards estimate these loads with consideration of the local history. However, these estimates do not protect the building envelope against wind loads for every situation and have some shortcomings [40]. For example, evaluation of wind loads for square plans and simple façades are available in the codes; however, many building shapes are not covered by the standard shapes. The other shortcoming of the codes relates to their lack of including the effect of neighbouring buildings on wind loads and the lack of full consideration of effects of pressure equalization, which may reduce but mostly increase the wind loads. However, presently it is possible to determine the performance of façade elements by appropriate wind tunnel tests.

Similar to wind loads, although the seismic loads are dynamic in nature, the equivalent static loads are normally considered in design (see Section 2.4.1.1) and the components should remain elastic for these loads, along with consideration of the lower bound material properties.

However, the seismic design also carries additional detailing requirements and factors to ensure that connections have additional resistance to endure the excessive loads due to an earthquake and are designed for seismic deformations.

In some buildings, along with designing the building envelope for conventional loads, it is necessary to consider the blast impact as well. While designing for blast loading the designer must consider two factors: the static increase factor (SIF) used for factoring the lower bound strength in determining the required material strengths and the dynamic increase factor (DIF) to include loading rate effects on the various material characteristics [39]. In designing for blast loads, the components can undergo inelastic deformations since the intention of such provisions is to prevent any loss of life during the impact. Hence, the connections must be designed for the out of plane ultimate flexural capacity of the attached components.

In the traditional design approach, the designer considers each load case independently. In such approaches, the design can undergo some necessary iterations (since the synergy or conflicts among various design cases are not considered).

In an efficient design, it is necessary to consider all detailed design criteria and their interactions during each step, i.e., dividing the detailed design phase by various tasks rather than by discipline.

McKay et al. [39] provide two sets of flowcharts that demonstrate the traditional (ineffective) and the recommended (effective) design procedure as demonstrated in Figure 3.3 and Figure 3.4.

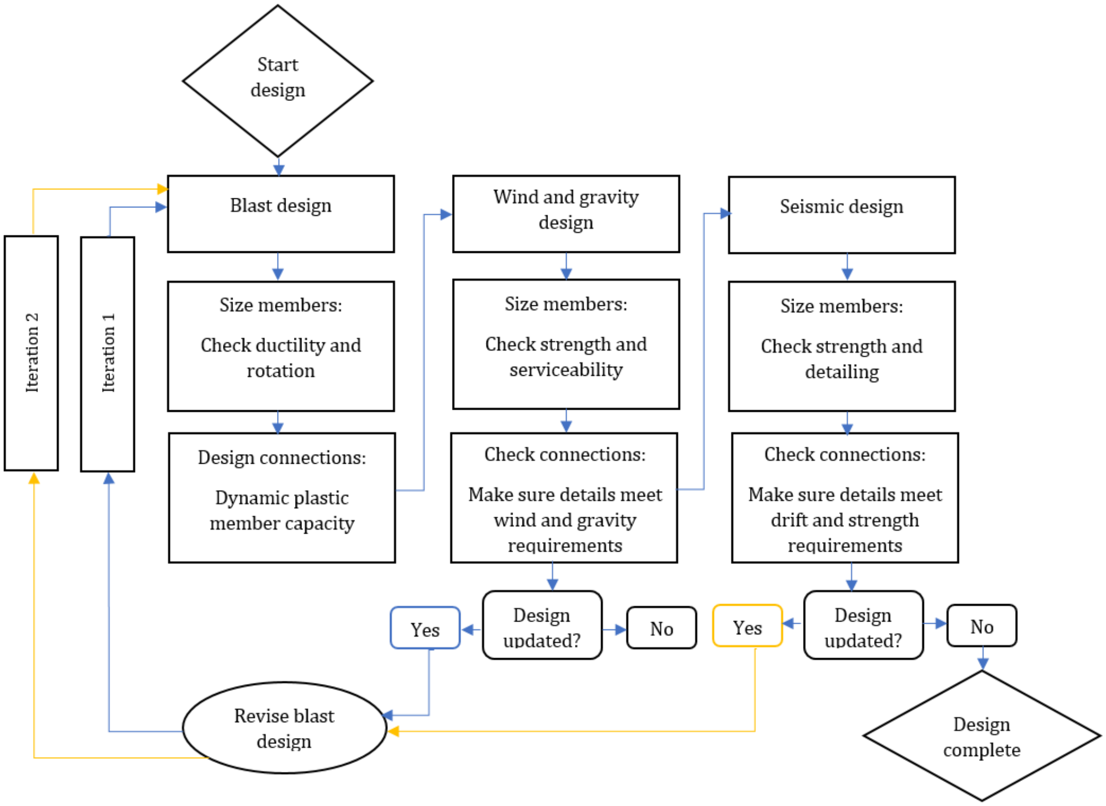


Figure 3.3 Traditional design process [39]

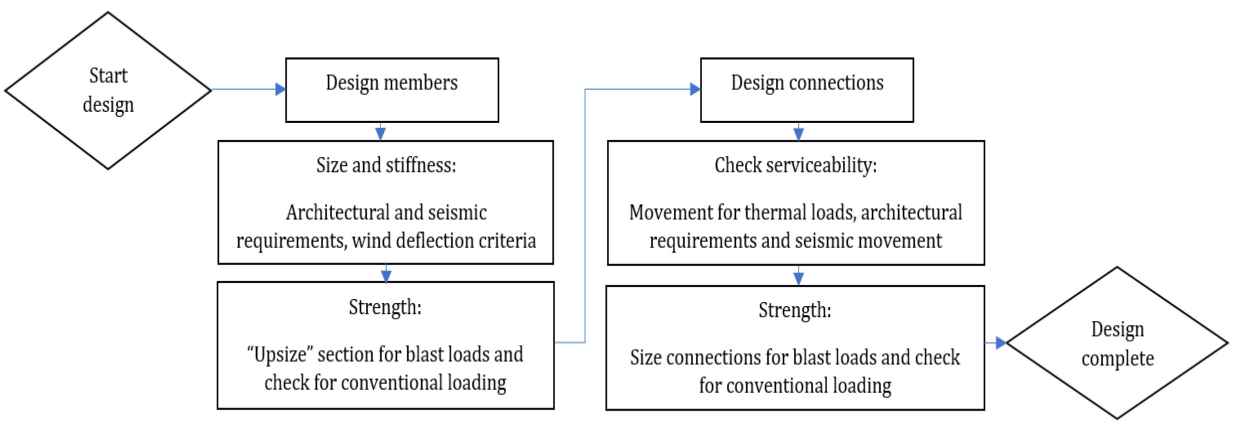


Figure 3.4 Recommended design process [39]

It is necessary to allow for construction alterations, such as when alignment during erection changes from the original design. Moreover, the connections should be able to accommodate the tolerances associated with the erection process.

Other considerations in this phase include some durability considerations in detailing of the façade and its connections, such as details related to caulking, expansion joints, the appropriate number of joints (to eliminate water infiltration).

It is the responsibility of the designer to ensure the constructability (ease and efficiency of the construction phase) and inspectability of the design during the pre-construction phase. This includes identification of the obstacles, to eliminate or reduce errors and delays or unexpected costs.

It is also recommended to provide a maintenance, inspection and end-of-life plan for the building envelope at this stage.

3.4.1 Application of a building information model (BIM)

Application of a building information model (BIM) can significantly facilitate the integration of the tasks from the design stage, with construction and maintenance phases.

BIM provides a reliable basis for building life cycle decision making from the conception phase to the final demolition, in the form of a shared information resource thereby facilitating the cost evaluation, construction and project management processes [41]. BIM dimensions are related to the way in which specific data are linked to a model [42]. Increasing the dimensions of the model would normally provide a better understanding of the project (i.e., how it will be delivered, the costs and required maintenance).

These intelligent 3D shared information models are transferred from the design team to the construction contractor, then on to the owner and the maintenance team. It is the responsibility of each professional to add or update any specialty-specific information on the shared model.

The 4D BIM (construction sequencing) adds an extra dimension of information in terms of scheduling data [42]. The data provides accurate information and visualization on the sequential development of the project. The 5D BIM provides accurate life cycle cost information. This model enables the automatic counting of components/systems involved in a project and gives notifications when changes are made. The 6D BIM program, also recognized as integrated BIM, includes the data related to the operation and maintenance (O&M) phases such as installation date, essential maintenance, proper configuration and operation of a component for optimal performance, along with the decommissioning information.

Using these models help data losses that usually occur when a new team is assigned to a project and delivers more detailed and comprehensive information on complex projects.

3.5 Façade construction

As mentioned in Section 3.4, it is important to ensure the constructability of a façade system (i.e. construction flexibility, consideration of details with acceptable clearances, alignments and proper sequencing, availability of materials and elements, attainable workmanship, seasonality, etc.), as it is a key factor in attaining the required performance attributes. To ensure façade integrity and good performance, it is important to correctly mount façade panels [10, 13, 43]. To minimize on-site deficiencies, designers favour prefabricated unitized or panelized façade systems whose performance can be tested before installation on site. It is essential for the manufacturer to verify the as-built dimensions and the building frame elevation prior to the commencement of the prefabrication procedure [44]. While excellent quality control and rapid assembly are the benefits of prefabricated construction, the negative aspects include the small error margin, complexity of connections, necessity of bracing throughout the on-site assembly, and occasionally lack of design flexibility.

Construction quality can be promoted through close collaboration between the design and construction teams and a clear definition of the responsibilities of the various parties involved. With good workmanship and quality control on site, it is possible to guarantee the safety, strength, serviceability, and durability provisions that were specified in an original design. However, good workmanship and quality control are only conceivable through accurate detailing and clear specifications of the system (e.g. waterproofing components, proper flashing, sealants, joint types, spacing, and appropriate drainage). Hence, the use of simple and executable member and connection details is highly recommended in the design phase. Availability of efficient and competent personnel to perform on-site work is a key factor in ensuring construction quality. The existence of an appropriate sampling plan and testing facilities are essential to satisfy code requirements that require testing and approval of façade materials before being used on-site.

Other important considerations to improve construction quality include using mock-ups and inspection and monitoring of the completed work [45]. It is recommended to involve the façade designers in the inspection of façade panels and their connections, both during and after the completion of construction work.

3.6 Façade operation and maintenance

Once façade installation is completed, some degradation mechanisms commence within a short duration and have a negative influence on the façade performance. A general expectation is that properly designed façades maintain their aesthetical and functional performance, with minimal costs for maintenance, repairs, and rehabilitation. To ensure the proper functional performance of façades throughout their life cycle, planned cleaning and inspections must be carried out regularly [13, 46]. The costs of these activities depend on the accessibility and simplicity of the selected system. The accessibility of the façade is a function of the complexity of façade shape and influences the decommissioning (removal work) and the time required to perform repairs and replacements.

3.6.1 Preventive maintenance: Role of regular inspection

Over the years, there have been multiple incidents of disastrous, complete or partial detachment of façade components from the building structure that have caused injuries or deaths. Barns [47] and Moghtadernejad and Mirza [9] have reported that a façade failure takes place in North America once every three weeks. In response to these failures, several cities in the USA (e.g. New York, Chicago) and in Canada (Montreal) have by-laws requiring regular inspections. Diebolt [48] has provided a list of these cities and the related by-laws in detail.

It is recommended to perform regular inspections, based on the maintenance needs of each façade assembly that are determined in the maintenance plan provided at the end of the design stage. In such plans, the designer usually considers the most severe combinations of factors that degrade the façade [49] and determines the inspection intervals. Maintenance work is then prioritized based on the results of the inspections.

The required façade assessments are typically performed in three stages. In the first stage, the related façade documents are reviewed (through data from BIM or other available documents), and as-built drawings are prepared in case such documents are not available.

In the second stage, initially, a visual inspection is performed under appropriate lighting conditions, since sometimes sunlight or shading may obscure areas of a building at certain viewing angles [50]. In a visual inspection, it is possible to detect element movements and evident visual defects, such as cracks and spalls. Due to the inability of the inspectors to detect hidden signs of distress and deterioration that are developing, a second survey normally consists of a close-up and detailed inspection of façade elements using scaffolding or other appropriate means and probing of selected elements for hidden deterioration. Some of these assessments can be performed with thermal imaging, laser assessment or smart virtual unmanned aerial vehicle examination (SUAVE) systems [51], that have the potential to examine sections of façades with limited accessibility and hidden elements.

In the final stage, the inspector is responsible for evaluating the façade condition and communicating the results to the building owner and the local building authority. The inspection records should be maintained throughout the service life of the building for any future assessment.

3.6.2 Preventive maintenance: Façade cleaning

Safety, serviceability and cleaning requirements vary considerably for different types of façades. However, the latter depends on the desired level of aesthetic appearance, building location and function, in addition to the atmospheric conditions [52]. Aesthetics is the main reason to clean building façades; this also provides the possibility of façade condition evaluation and repair. In addition, to prevent any acceleration of façade deterioration, it is important to clean façades from pollutants, such as sulphur, nitrogen oxides, and acid rain impurities. It is known that moisture is the principal cause of panel decay. In the presence of waterproof coatings, moisture can be captured inside the façade panel. However, façade cleaning removes the waterproof coating, leaving the panel pores unsealed which facilitates moisture perspiration.

Generally, it is more practical to perform façade cleaning before any repair work. To do so, appropriate preparations must be made, including the knowledge of the prevailing climate, protection of building materials that should remain without cleaning against damage during façade cleaning and performing test-cleaning on a small façade region. Façade cleaning methods include chemical, non-chemical (water cleaning), abrasive and a hybrid approach that utilizes a combination of these techniques. Each façade type requires an appropriate strategy that must be defined by the cleaning agency in consultation with the design professionals.

3.6.3 Corrective maintenance

Corrective maintenance work is carried out because of inspections that are performed on a specific façade. Corrective maintenance can be performed in the form of repair, rehabilitation, or strengthening. For rehabilitation, major repairs are carried out to restore the safety and serviceability of the façade to its approximate original condition [8]. Strengthening is implemented to enhance the load-bearing capacity of the façade and restoration its stiffness and strength to its original conditions.

The service life of façades is generally lower than the projected building service life of approximately 60 years. Hence, it is important to note that deferring proper façade maintenance can increase repair costs due to accelerated rates of deterioration [53], and can also cause serious distresses and failures, involving large economic losses, injuries and even death.

3.7 Summary

This chapter reviews the needed considerations and strategies in the different stages of the façade service life, which are aimed at enhancing the level of performance, mitigating risks and avoiding excessive costs. The service life of a façade system has been categorized into five stages; namely, building conceptual design, façade conceptual design, façade detailed design, construction, maintenance, and disassembly.

The necessity of integrating the service life stages of a façade system has been identified earlier. However, there has been no practical approach available to the designers, especially in the conceptual façade design phase. In-time considerations of important criteria were identified to offset the associated risks and cost overruns.

Chapter 4 Comparison of Available Decision Support Methods for Conceptual Façade Design

4.1 Introduction

In earlier days, complex multi-objective problems were adjudicated by a single or a group of knowledgeable individuals. More recently, developments in computer science and numerical procedures have promoted the development of multiple decision analysis tools such as linear or dynamic programming, inventory control, hypothesis testing, and operational control. Multi-criteria decision making (MCDM), which is a branch of operational research, is the most relevant in assisting a decision-maker in identifying the best solution among a set of alternatives [7, 54].

MCDM methods are very well known for assistance in selecting appropriate solutions in a design problem, and they are receiving increasing attention in sustainable design and daylight or energy optimization problems. However, their application in façade design, in particular, is very limited in research and almost non-existent in practice. The only direct application of MCDM methods in the selection of a proper façade system is by Zavadskas et al. [55]. In this research, the weighted sum, the weighted product, and the weighted aggregated sum product assessment (WASPAS) methods were used for ranking of four alternatives in terms of 12 criteria, for public or commercial building façades. According to the results, sandwich panels were the most suitable for public or commercial buildings. In a recent study, Guzelcoban [56] proposed a theoretical fuzzy model for evaluating the predesigned details in the façade design process.

In civil engineering, on the other hand, application of MCDM methods has received increasing attention. There are several relevant research studies on building energy optimization or design for sustainability. For instance, Arroyo [57] compared the adequacy of multi-objective optimization, value-based, outranking and choosing by advantages methods (CBA), for sustainable design of commercial buildings and recommends the application of CBA methods, since these methods avoided double counting of factors by considering only advantages, and not advantages and disadvantages. Pons et al. [58] used the Spanish integrated value model for sustainability assessment (MIVES) as a sustainability assessment MCDM method for architecture and civil engineering applications. This method is capable of holistic sustainability assessment to obtain the global sustainability indices and allows minimizing of subjectivity in the assessment. Si et al. [59] presented a state-of-the-art for green technology selection and applied the analytical hierarchy process (AHP) in a case study for formulating green technology selection decisions in existing buildings. In a study by Hopfe et al. [60] building performance was assessed under uncertainty using MCDM methods. In this study, the AHP method including uncertainty information was used to make a rational decision.

Recently, some papers have reviewed the applications of the MCDM methods. Jato-Espino et al. [61] briefly discussed the application of the most significant methods in the construction industry and identify the most frequently used methods in the literature. In a two-part state-of-the-art survey [62] and [63], Zavadskas et al. reviewed the history of MCDM methods from their origins to the present. The authors used the Web of Science database to overview the publications that contained the keyword “MCDM” and were included in the civil engineering category. The publications were categorized according to the year of publication, country, journals and the MCDM methods that were used in the paper. In another study Kumar et al. [64] reviewed and compared the various decision-making methods that could be used in renewable energy development and stated that no MCDM method could be ranked as the best or the worst, and depending on the objectives of planning, each method had its own strength and limitations.

In this chapter, the necessary conditions for the application of MCDM methods to building façades are identified and the most popular MCDM methods are introduced along with their advantages and limitations.

4.2 Expectations from a proper MCDM method in façade design

The first step in identifying the most suitable MCDM method is to determine the expectations with respect to the application of the selected method. The first and most important requirement is the "ease of application". It is necessary to provide the designers with a method that is fast, straightforward and not demanding to use so that they will not be reluctant to make the transition from traditional methods to the new approach [7]. The method (or combination of methods) should also be able to combine both qualitative and quantitative data analysis since some façade design attributes, such as aesthetics are qualitative and dependant on the designers' (or stakeholders') preferences.

Another important factor that has generally been ignored in the decision-making process is the interaction among various criteria. In using the current MCDM methods, the decision criteria should be independent. However, this is not easy (and sometimes not feasible) to attain; especially when dealing with energy efficiency and sustainability criteria which are generally interrelated. This problem will lead to double-counting in the analysis, if not addressed properly.

It is also important to note that although the preference of the decision maker is the most important factor in the selection process, the preferences are subjective, and the proper aggregation method should not over-prioritize (or deprioritize) the alternatives.

4.3 Classification of MCDM methods

The MCDM methods are usually categorized with regards to their problem-solving technique (value-based, outranking or CBA methods), or their mathematical nature namely multi-objective decision making (MODM), multi-attribute decision making (MADM) or a combination of both) as illustrated in Figure 4.1.

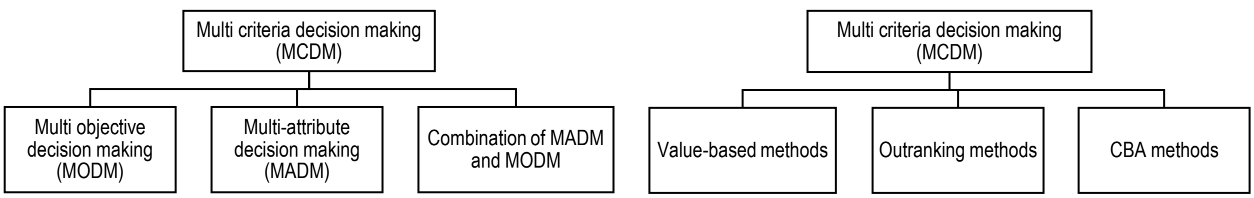


Figure 4.1Most common classifications of MCDM methods; on the left, methods are categorized based on their mathematical nature, and on the right, based on their method of problem-solving [7, 64, 65].

Value-based methods are based on partial or total compensation of the various factors involved [57]. For instance, a good performance on energy efficiency can compensate for a poor performance on the initial costs factor. In these methods, numerical scores for each criterion or factor are constructed, and then the decision makers choose their preferences using an aggregation model in accordance with the weights of the different criteria. The outranking methods first compare the alternatives in terms of each criterion, and after aggregating the preferences, favour selection of one alternative over the other. In choosing by advantages (CBA) methods, decisions are based on the advantages of the various alternatives, and not their advantages and disadvantages. This is helpful in avoiding double counting of factors. After identifying the advantages of each alternative, these methods assess the importance of the advantages by performing comparisons among them. The CBA methods are less commonly used and not appropriate for façade design problems where the number of alternatives and decision criteria are large. Most applications of CBA methods are time-consuming and very subjective. Another shortcoming which rules out their utilization is that in CBA cost cannot be a factor, while in façade design, the life cycle cost of the alternatives is an important decision criterion and is not regarded as merely a design constraint.

The MODM methods assume continuous solution spaces and are based on continuous mathematical spaces [65]. The goal of these methods is to determine the optimal trade-offs and solve the problem as a mathematical programming model. These powerful methods have the shortcoming of having limited value for the designers since mathematical programming does not solve the majority of MCDM-problems in practice. The MADM methods are based on discrete mathematics and solve problems in discrete decision spaces, where the decision alternatives are predetermined.

Another popular classification is based on the data type used, which would provide deterministic, stochastic, and fuzzy MCDM methods or a combination of thereof. In this chapter, most commonly-used methods are introduced based on their chronological development and evaluated based on their ability to address the façade design problem.

4.4 Review of the commonly-used MCDM methods in civil engineering

There has been a proliferation of MCDM methods over the last few years, which utilize single or hybrid approaches. However, researchers in construction and building technology favour few of these which are discussed briefly in the following sections.

4.4.1 Weighted sum method (WSM)

The WSM is a value-based method and is the earliest and most commonly used MCDM approach. In this method, non-negative weights are set by the decision maker for each criterion and the various alternatives are ranked based on the evaluated value of the weighted sum of the criteria [66]. Triantaphyllou and Mann [67] proposed that WSM should be used as a standard for evaluating MCDM methods [68] because each multicriteria method should perform appropriately in single dimensional problems, and as it can be seen in Eq.4.1, the WSM generates the most suitable results in single-criteria problems.

A difficulty in the application of this method would be in multi-dimensional problems where the criteria units are different, and their numerical values are occasionally several orders of magnitude apart. Of course, one possible solution is to resort to normalization.

$$A_{WSM-Score} = \sum_{j=1}^{n} a_{ij} w_j \qquad (4.1)$$

where $A_{WSM-Score}$ is the WSM score of each alternative, with n decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.

4.4.2 Weighted product method (WPM)

This method which is very similar to WSM was proposed by Bridgeman [69] and creates a ranking of the various alternatives based on a multiplicative measure [65, 68, 70]. The WPM was proposed as an alternative to overcome the single-dimensionality problem of the WSM. As indicated in Eq.4.2, two alternatives A_k and A_l, are compared as follows:

$$S(A_k/\,A_l) = \prod_{j=1}^{n} (a_{kj}/a_{lj})^{w_j} \tag{4. 2}$$

where n is the number of criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion. If the term $S(A_k/\,A_l)$ is greater than one, then it indicates that alternative A_k is more desirable than alternative A_l. Hence, the best alternative is the one that is better than all others. The benefit of this method is that it is dimensionless, and can be used in single or multi-dimensional decision-making problems; also, as Triantaphyllou [65] has demonstrated, one can use relative values instead of measured ones in this method.

Alternatively, Eq.4.2 can be rewritten for the performance value P of an alternative A_k.

$$P(A_k) = \prod_{j=1}^{n} (a_{kj})^{w_j} \tag{4. 3}$$

A disadvantage of this method is that it prioritizes or deprioritizes the alternative which is far from average [64, 71].

4.4.3 Elimination and choice translating reality (ELECTRE)

The ELECTRE is an outranking method that was first presented by Benayoun, et al. [72]. In this method, an alternative is dominated, if another alternative outranks it in one or more criteria and is equal for the remaining criteria [65]. This method can deal with discrete quantitative and qualitative criteria [73]. However, this method is formulated so that it selects the alternatives that are favoured over most of the criteria and do not have an unacceptable performance in any of the other criteria. The concordance and discordance threshold values are determined and graphs for strong and weak relationships are developed with respect to these thresholds. The ranking of the alternatives is obtained using an iterative procedure by using the developed graphs.

This method involves several steps including, normalizing the decision matrix and associating appropriate weights to the matrix, determination of the concordance and discordance sets and construction of the related matrices, determination of the concordance and discordance dominance matrices and the aggregate dominance matrix and finally elimination of the less favourable alternatives (see [65] for a detailed example). It should be noted that the index of global concordance C_{lk} between alternatives A_l and A_k, ranges between [0, 1] and as it is presented in Eq. 4.4, this index demonstrates the creditability of concordance among all decision criteria, assuming that alternative A_l is preferred to A_k [73]:

$$C_{lk} = \sum_{j=1}^{n} w_j c_j(A_l A_k) / \sum_{j=1}^{n} w_j \tag{4. 4}$$

where w_j is the weight associated with j^{th} criterion. Although there have been four revisions of the ELECTRE method, it is still not perfect, and sometimes it cannot identify an optimal alternative. This is mainly because this method only provides a better view of the available alternatives by discarding the less favourable ones. Another shortcoming of this method is that it is very time consuming [71].

4.4.4 Analytic hierarchy process (AHP)

This method was introduced by Saaty [74] and breaks a complex MCDM problem into a system of hierarchies [65]. The AHP is the most preferred method in academic papers dealing with multi-criteria decision makings in sustainable energy planning; however, very few discuss the reason why they have chosen AHP [57].

The AHP uses a matrix A of dimension $m \times n$, where m is the number of alternatives with n criteria. This matrix is generated by rating the relative importance of the alternatives for each criterion. Then the best solution can be obtained as:

$$A_{AHP-Score} = max \sum_{j=1}^{n} a_{ij} w_j \tag{4. 5}$$

where a_{ij} are elements of the matrix A, and w_j is the weight assigned to the j^{th} criterion, using pairwise comparisons and calculating the priority vector (normalized principal eigenvector). The AHP and the weighted sum method are quite similar; however, AHP can be used for both single or multi-dimensional decision-making problems since it uses relative values instead of actual ones [65].

Belton and Gear [75] demonstrate that the AHP model can produce inconsistent rankings. These inconsistent rankings occur when a new alternative is added to a decision problem and the relative ranking of the initial alternatives is modified. To prove the inadequacy of the AHP model, Belton and Gear [75] add an identical alternative to the previous ones and the results demonstrate the logical inconsistency of the AHP model proposed by Saaty. To solve this issue, the authors propose to divide the relative values of the alternatives by the maximum value of the relative values (see [65] for a detailed example), since they believed that the inconsistency occurred because the relative values for each criterion had to sum up to 1 in the original version. This new model was severely criticized by Saaty [76], stating that the proposition had the problem of using identical alternatives which should not be considered in the decision process.

The AHP is very popular and has certain advantages such as being adaptable, intuitive and verifiable for inconsistencies, computationally non-demanding and having a simple definition of the importance factors of criteria. However, it has several shortcomings when there are multiple decision makers involved, that question the appropriateness of this method in façade design. These limitations include the complexity of assigning weights and the difficulty of accounting for uncertainties associated with judgment [7, 57, 64, 77].

A further shortcoming is that AHP assumes that there is no dependency among the criteria, which is not true in real life decision-making [7, 78]. This shortcoming is shared with all decision-making aggregation methods except for the Choquet integrals.

4.4.5 Technique for order preference by similarity to ideal solutions (TOPSIS)

TOPSIS was introduced by Huang and Yoon [79] as an alternative to the ELECTRE method and is based on the distance of an alternative from the ideal solution [68]. Basically, a design that has the shortest distance from the ideal point and farthest distance from the negative-ideal will be selected. In this method, the Euclidean distance approach is used to evaluate the distances of the alternatives from the ideal solution and the ranking of the alternatives is derived from comparisons of these relative distances.

There are several steps involved in this method. After construction of the normalized decision matrix and weighted normalized decision matrix (weights are adjusted with regards to decision maker's preferences), the ideal and the negative-ideal solutions will be identified. The separation measure and the relative closeness to the ideal solution will be calculated as indicated in Eq.4. 6 and 4.7. In this method, it is a necessity for the criteria values to be permuted [65].

$$S_i^* = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - \nu_j^*)^2} \ , \qquad and \quad S_i^- = \sqrt{\sum_{j=1}^{n} (\nu_{ij} - \nu_j^-)^2} \tag{4. 6}$$

$$C_i^* = \frac{S_i^-}{S_i^- + \ S_i^*} \tag{4. 7}$$

where S_i^* and S_i^-, are ideal and negative-ideal solutions, respectively, and ν_{ij} is the weighted normalized value of the i^{th} alternative. ν_j^* and ν_j^- are respectively the best and the worst scores of j^{th} criterion among alternatives. C_i^* corresponds to the relative closeness to the ideal solution that is the basis for ranking the alternatives.

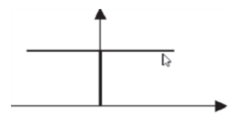
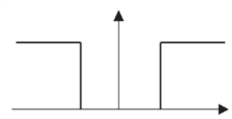
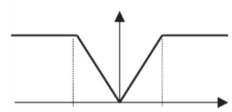
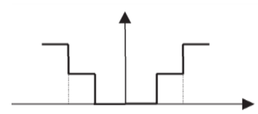
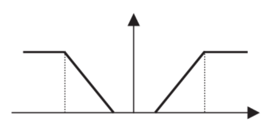
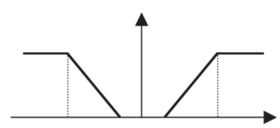
Clearly, this method works with fundamental rankings and makes full use of allocated information that does not need to be necessarily independent. However, since it uses Euclidian distances, it does not differentiate between negative and positive values [64].

4.4.6 Preference ranking organization method (PROMETHEE)

PROMETHEE is also an outranking method based on pairwise comparisons of the alternatives that was first introduced by Brans [80]. In this method, after defining the criteria, it is necessary to define the preference function $P(a, b)$ for the alternatives a and b. In the comparison, alternative a is preferred to alternative b, with regards to criterion f, if $f(a) > f(b)$. The preference can take a value from zero to one [81]. Brans and Vincke [82] presented six types of criteria and preference functions, to perform the comparison task

[73]. Each of these criteria groups has a specific preference function as indicated in Table 4.1.

Table 4.1 PROMETHEE preference functions and shapes [83]

Preference function	Shape
Usual	
U-Shape	
V-Shape	
Level	
Linear	
Gaussian	

These preference functions are multiplied by the weights that are assigned to each criterion by the decision maker. Aggregated preference indices are then obtained by summing the values in the previous step. (Eq.4. 8 and 4.9):

$$IP(a,b) = \sum_{j=1}^{n} w_j P_j(a,b) \tag{4. 8}$$

where $IP(a, b)$ indicates the index of preferences of alternative a in relation to alternative b, and w_j is the weight assigned to the j^{th} criterion.

$$T(a) = \frac{\sum_{x \in A} IP(a, x)}{i - 1} \tag{4. 9}$$

where $T(a)$ is the flow index that represents the significance of each alternative. PROMETHEE I gives a partial ranking by using the calculated positive and negative outranking flows and PROMETHEE II ranks the alternatives by summing the outranking flows to get the net outranking flow [68, 73]. This method has limitations such as not structuring the criteria properly, the difficulty of assigning weights and the complexity of the process and its dependence on the presence of experts.

4.4.7 Choquet integral

The Choquet integral was proposed by the French mathematician Gustave Choquet [84]; however, it was first exploited in decision making in the late 1980s [85]. This method is unique among all multi-attribute utility theory (MAUT) models and aggregation operators, due to its ability to represent interactions between the criteria, ranging from redundancy (negative interaction) to synergy (positive interaction). There is no other well-established method to deal with criteria interdependence, and usually, this problem is avoided by constructing independent criteria, which can cause inaccuracies for decision making in design problems [86]. This innovative feature of Choquet integrals is the reason for its distinction among the other MCDM methods. The general form of Choquet aggregation function assigns a score to alternative D with n criteria as [87]:

$$D_\mu^K(x_1, \dots, x_n) = \sum_{i=1}^{n} \left(x_{(i)} - x_{(i-1)}\right) \mu(A_i) \tag{4. 10}$$

where μ denotes the fuzzy measures, (i) is the permuted rank of a criterion such that $0 \leq x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(n)}$, $x_{(0)} = 0$ and $A_{(i)} = \{x_{(i)}, \dots, x_{(n)}\}$.

Another benefit of this method is that it can dynamically update value changes [64]. However, the main difficulty with this method is the complexity of determining the fuzzy measures that depends on the input from a panel of experts.

4.4.8 VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)

The VIKOR method was designed by Opricovic and Tzeng [88], and similar to TOPSIS, it ranks the alternatives based on their distance from the ideal solution. In this method, the decision maker is responsible for determining the weights of the criteria; and the units of various criteria will be eliminated by normalizing the related values (see [89] for a detailed example). This method can potentially generate multiple solutions, instead of one; which occurs when none of the alternatives stands out, and there are several alternatives as close to the ideal solution as the one that is the closest [68].

The steps in the VIKOR method include normalizing the decision matrix, determination of the best f_j^* and worst f_j^- values of all criteria, calculating the utility (S_i) and the regret measure (R_i) as illustrated in Eq. 4.11 [90]:

$$S_i = \sum_{j=1}^{n} \left[\frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)}\right], \qquad R_i = max_j \left[\frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)}\right] \tag{4. 11}$$

where w_j is the weight of the j^{th} criteria, and i is the number of alternatives. The final step is the determination of the ranking order of alternatives by finding Q_i values.

$$Q_i = \frac{\upsilon(S_i - S^*)}{(S^- - S^*)} + \frac{(1-\upsilon)(R_i - R^*)}{(R^- - R^*)}$$

$$S^* = \min S_i \;, \; S^- = \max S_i \,, \qquad R^* = \min R_i \;, \; R^- = \max R_i \tag{4.12}$$

where υ is the weight of the maximum group utility which is in the range of [0, 1] and is usually considered as 0.5.

VIKOR can be interpreted as an updated version of TOPSIS. Lately, VIKOR has become more interactive and allows the decision maker to adjust the weights via the information generated by a trade-off analysis [91]. According to Kumar et al. [64], VIKOR needs some modifications as it is sometimes "difficult to model a real-time model" and that this method has difficulty dealing with conflicting situations.

4.4.9 Spanish integrated value model for sustainability assessment (MIVES)

MIVES is a value-based MCDM method that was developed in 2007 [58, 92, 93], used for obtaining global indices by defining specialized and holistic sustainability assessment models. This method uses value functions to assess the satisfaction of the different decision makers/stakeholders that are involved in a project, to minimize the subjectivity in the decision-making process. The global index is obtained from Eq. 4.13:

$$GI = V(P_x) = \sum_{i=1}^{i=N} \alpha_i \,.\, \beta_i \,.\, \gamma_i \,.\, V_i(P_{i,x}) \tag{4.13}$$

where $V(P_x)$ measures the index of the alternative x evaluated with respect to the various criteria. α_i are the weights of each requirement, β_i are the weights of each criteria and γ_i are the weights of the different indicators. Generally, these weights are derived by consulting a panel of experts and applying the AHP method.

4.5 Discussions

After reviewing the most well-known and commonly-used MCDM methods (Table 4.2) and evaluating their strengths and limitations (Table 4.3) for façade design applications, it can be concluded that although none of the methods fulfill all of the criteria, some provide suitable methodologies. As mentioned earlier, façade design requires multiple qualitative and quantitative criteria (in contrast to other decision-making problems) that need to be assessed with regards to the project requirements. It is necessary to provide the fastest, most accurate and yet, computationally non-demanding methods.

A comparison of aggregation functions shows that the basic approaches of WSM, WPM, AHP and Choquet integrals are similar. The AHP improves over WSM and WPM by using dimensionless scores (relative values instead of the actual ones) and does not prioritize or deprioritize alternatives which are far from the average alternative. In addition, the AHP method provides the most consistent solutions for assigning weights to design criteria. AHP can be used as a single approach or in combination with other methods (hybrid approach) to help designers in evaluating qualitative information or structure design preferences.

The most important shortcoming of the AHP model in façade design problems is that it assumes that there are no dependencies among the criteria, which is not true in real life decision-making [78]. This limitation can result in double counting in the comparisons. Of course, this is a shared limitation among all MCDM aggregation methods except for the Choquet integrals.

It is worth mentioning that the analytic network process (ANP) which is a generalization of the AHP method can account for relative interdependences among criteria [61]. However, this method is very subjective, extremely time-consuming, cumbersome and infeasible to use when the number of criteria is large.

The Choquet aggregation function, shares the same core as WSM and AHP, except that the fuzzy measures account for the importance of each subset of criteria. This feature makes it is a very desirable method, although its application in civil engineering is unprecedented. The main difficulty associated with this method is the complexity of determining the fuzzy measures. In addition, as there are 2^n fuzzy measures involved in the decision-making process (n being the number of criteria), the task of assigning fuzzy measures would be too time consuming and almost impossible as the number of criteria increases.

TOPSIS is another popular method that was introduced as an alternative to improve the shortcomings of the ELECTRE method, which is time-consuming and cannot always identify an optimal alternative. Although VIKOR was introduced as an updated version of TOPSIS (more interactive and allows the decision maker to adjust the weights via the information generated by a trade-off analysis), it is not as favoured and needs some modifications. The difficulty of dealing with conflicting situations and modelling a real-time model are the main drawbacks of this method.

PROMETHEE and MIVES are also not the appropriate methods to be used in façade conceptual design phase and are ruled out. The main reason is that both methods are very time-consuming and complicated to apply which will discourage the designers from adopting the new design approach.

Table 4.2 Most commonly-used MCDM methods in construction and building technology and their field of application [7]

Methods	Steps	Area of application	References
Weighted Sum Method (WSM)	$$A_{WSM} = \sum_{j=1}^{n} a_{ij} w_j$$ where A_{WSM} is the WSM score of each alternative, with n decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion.	Structural optimization and energy planning	[57, 66-68, 94-97]
Weighted Product Method (WPM)	$$P(A_i) = \prod_{j=1}^{n} (a_{ij})^{w_j}$$ where $P(A_i)$ is the WPM score of each alternative, with n decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion	Optimization	[64, 65, 67-71]
Elimination and Choice Translating Reality (ELECTRE)	Associating appropriate weights to the matrix, determination of the concordance and discordance sets and construction of the related matrices, determination of the concordance and discordance dominance matrices and the aggregate dominance matrix and finally elimination of the less favourable alternatives. If alternative A_l is preferred to A_k : $$C_{lk} = \sum_{j=1}^{n} w_j c_j (A_l A_k) / \sum_{j=1}^{n} w_j$$ where w_j is the weight associated with j^{th}criterion.	Energy management, building structures and seismic retrofitting	[64, 71-73, 98-105]
Analytic Hierarchy Process (AHP)	$$A_{AHP-Score} = \sum_{j=1}^{n} a_{ij} w_j$$ where a_{ij} are elements of the matrix A, and w_j is the weight assigned to the j^{th} criterion, using pairwise comparisons and calculating the priority vector (normalized principal Eigenvector).	Energy planning, sustainable building, building structures, intelligent building, construction technologies, and demolition	[57-59, 64, 65, 74, 77, 106-119]
Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)	$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}\ , \quad and \quad S_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \quad C_i^* = \frac{S_i^-}{S_i^- + S_i^*}$$ where S_i^* and S_i^-, are ideal and negative-ideal solutions respectively, and v_{ij} is the weighted normalized value of i^{th} alternative. v_j^* and v_j^- are respectively the best and the worst scores of j^{th}criterion among alternatives. C_i^* corresponds to the relative closeness to the ideal solution which is the basis for ranking the alternatives.	Building structures, energy management, construction technologies, demolition, and seismic retrofitting	[64, 68, 79, 104, 105, 110, 115-117, 120-125]
Preference Ranking Organization Method (PROMETHEE)	$$IP(a,b) = \sum_{j=1}^{n} w_j P_j(a,b)$$ where $IP(a,b)$ indicates the index of preferences of alternative a in relation to alternative b, and w_j is the weight assigned to the j^{th}criterion. $$T(a) = \frac{\sum_{x \in A} IP(a,x)}{i-1}$$ where $T(a)$ is the flow index that represents the significance of each alternative.	Risk analysis, building structures and seismic retrofitting	[64, 73, 80-82, 103, 105]
Choquet Integral	$$C_\mu^K(x_1, \ldots, x_n) = \sum_{i=1}^{n} \left(x_{(i)} - x_{(i-1)}\right) \mu(A_i)$$ where μ denotes the fuzzy measures, (i) is the permuted rank of a criteria such that $0 \leq x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(n)}$, $x_{(0)} = 0$ and $A_{(i)} = \{x_{(i)}, \ldots, x_{(n)}\}$.	Unprecedented in civil engineering	[84, 85]
VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	$$S_i = \sum_{j=1}^{n} \left[\frac{w_j (f_j^* - f_{ij})}{(f_j^* - f_j^-)}\right], \qquad R_i = max_j \left[\frac{w_j (f_j^* - f_{ij})}{(f_j^* - f_j^-)}\right]$$ where w_j is the weight of the j^{th} criteria, and i is the number of alternatives. Q_i values determine of the ranking order of alternatives $$Q_i = \frac{\upsilon(S_i - S^*)}{(S^- - S^*)} + \frac{(1-\upsilon)(R_i - R^*)}{(R^- - R^*)} \ ;$$ $$S *= \min S_i\ , \ S-= maxS_i, \quad R *= minR_i\ , R-= maxR_i$$ where υ is the weight of the maximum group utility which is in the range of [0, 1] and is usually considered as 0.5.	Energy policy and seismic retrofitting	[68, 88, 89, 104, 105]
Spanish Integrated Value Model for Sustainability Assessment (MIVES)	$$SI = V(P_x) = \sum_{i=1}^{i=N} \alpha_i \,.\, \beta_i \,.\, \gamma_i \,.\, V_i(P_{i,x})$$ $V(P_x)$ measures the degree of sustainability of the alternative x evaluated with respect to various criteria. α_i are the weights of each requirement, β_i are the weights of each criteria and γ_i are the weights of the different indicators.	Sustainable building and construction technologies	[58, 114]

Table 4.3. Summary of advantages and disadvantages of commonly-used MCDM methods [7]

Methods	Description	Advantages	Disadvantages
Weighted Sum Method (WSM)	Earliest and most commonly used MCDM approach. Triantaphyllou and Mann [67] proposed that WSM should be used as a standard for evaluating MCDM methods.	WSM generates the most suitable results in single-criteria problems. Simple computation	Only a basic estimate of designer's preferences. Difficulty in multi-dimensional problems where the criteria units are different and their numerical values are occasionally several orders of magnitude apart.
Weighted Product Method (WPM)	Very similar to WSM and creates a ranking of alternatives based on a multiplicative measure. It was proposed as an alternative to overcome the single-dimensionality problem of the WSM.	It's dimensionless and can be used in single or multi-dimensional decision-making problems.	It priorities or deprioritizes the alternative which is far from average.
Elimination and Choice Translating Reality (ELECTRE)	An outranking method that uses pairwise comparisons to evaluate the degree of preferences between available alternatives. It selects the alternatives that are favoured over most of the criteria and do not have an unacceptable performance in any of the other criteria.	Deals with both quantitative and qualitative criteria. Final results are validated with reasons. Deals with heterogeneous scales.	Despite having 4 revisions it is still not perfect and sometimes cannot identify an optimal alternative. It only provides a better view of the available alternatives by discarding the less favourable ones. Time-consuming.
Analytic Hierarchy Process (AHP)	Breaks a complex MCDM problem into a system of hierarchies.	Can be used for both single or multi-dimensional decision-making problems. It's adaptable, intuitive and verifiable for inconsistencies. Computationally non-demanding. The most suitable and consistent method for defining criteria weights. Deals with both quantitative and qualitative criteria.	Rank reversals. Interdependency between objectives and alternatives leads to hazardous results. The complexity of assigning weighs when there are multiple decision makers involved. The difficulty of accounting for uncertainties associated with judgment.
Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)	An alternative to the ELECTRE method and is based on the distance of an alternative from the ideal solution.	Works with fundamental rankings and makes full use of allocated information.	Since it uses Euclidian distances it does not differentiate between negative and positive values. Lack of consideration of interactions among criteria.
Preference Ranking Organization Method (PROMETHEE)	An outranking method based on pairwise comparisons of the alternatives. After defining the criteria, it is necessary to define the preference function $P(a, b)$ for the alternatives a and b.	The possibility of group level decision making. Deals with qualitative and quantitative information. It can incorporate uncertain and fuzzy information.	It does not structure the criteria properly. The difficulty of assigning weights and the complexity of the process. It's time-consuming and dependant on the presence of experts. Lack of consideration of interactions among criteria.
Choquet Integral	This method is unique among all Multi-Attribute Utility Theory (MAUT) models due to its ability to represent interactions between the criteria.	Can be used for both single or multi-dimensional decision-making problems Mathematically not demanding. Deals with uncertainty. Considers the interaction among criteria. Can deals with qualitative and quantitative criteria. Can dynamically update value changes.	The difficulty of assigning weights which depends on the input from a panel of experts. It can be time-consuming when the number of criteria increases.
VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	It ranks the alternatives based on their distance from the ideal solution. It can generate multiple solutions instead of one; which occurs when none of the alternatives stands out, and there are several alternatives as close to the ideal solution as the one that is the closest.	An updated version of TOPSIS. It has become more interactive and allows the decision maker to adjust the weights via the information generated by a trade-off analysis [91]. It is effective in situations where the decision maker does not have any preferences at the beginning of the design.	It needs some modifications as it is sometimes difficult to model a real-time model. The difficulty of dealing with conflicting situations. Lack of consideration of interactions among criteria.
Spanish Integrated Value Model for Sustainability Assessment (MIVES)	This method is capable of specialized and holistic sustainability assessment to obtain global sustainability indices.	Allows minimizing the subjectivity in the assessment.	The difficulty of assigning weights and the complexity of the process which depends on the input from a panel of experts. Time-consuming Lack of consideration of interactions among criteria.

4.6 Summary

Presently, due to the complexity of integrating various disciplines in façade design and absence of a formal and systematic approach, most façade designers still prefer to use the traditional design methods that lack consideration of all design criteria. Application of MCDM methods, in façade preliminary design can be are very useful in assisting the designers with their decision making. However, there are numerous MCDM methods available with their related advantages and limitations and choosing the best available method can be quite challenging.

In this chapter, a detailed literature survey of the available MCDM methods was conducted to determine the limitations and strengths of each method for the design of façades. Although the researchers lean towards the application of AHP and after that the TOPSIS method, the author believes that these methods do not reflect the most precise evaluation of the performance of the alternatives in real life design cases, since they do not consider the interactions among various design criteria and consider them as independent. This can be an important factor, especially in cases, where the concept scores are close and there is no evident best alternative available. Among all decision analysis functions and aggregation operators, Choquet is the only decision-making method capable of considering such interactions that are totally neglected in civil engineering applications. In addition, Choquet can be integrated with AHP to assign consistent preferences and deal with qualitative and quantitative information. Hence, it can produce reliable results in comparison. Consequently, the author believes that Choquet and after that TOPSIS and AHP are the most suitable approaches for decision support in the conceptual façade design phase.

Chapter 5 Quantification of Decision Criteria for Profile Sets

5.1 Introduction

As mentioned earlier, despite their diversities, the MCDM methods have some common characteristics [126], such as a set of alternatives, multiple attributes, conflicting criteria, incommensurable units, weighting functions, and matrix formulations.

While the importance of each design attribute is evident to designers, depending on the specifications and requirements of each project, to enable comparison of the various decision criteria, it is necessary to assign numerical values to each attribute. This can be a challenging task, since many of these design attributes, such as sustainability, are inherently qualitative.

Although some decision-making methods such as the Analytical Hierarchy Process (AHP) have the distinct ability to compare qualitative attributes through pairwise comparisons, this may not always result in the most reliable outcome. This method works well in comparing alternatives with regards to subjective criteria, such as aesthetics. However, for comparing some qualitative criteria such as sustainability, one cannot rely solely on the designers' perception of the degree of sustainability in a pairwise comparison of alternatives.

Consequently, it is necessary for designers to adopt appropriate quantitative measures to perform such comparisons. The task is implemented by detecting the measurable indicators that define or affect each criterion and by performing simulations or by using measuring techniques to assign a numerical value to the assessed criterion.

This chapter applies the recommended procedures and techniques to quantify the attributes that need to be considered during the conceptual design phase for the 16 feasible façade alternatives of a two-storey commercial building in Montreal. Identification of the steps follows:

5.2 Selection of design alternatives

The design procedure proposed in Chapter 3 requires the designer to select the most suitable option among a pool of "feasible" façade alternatives. It is evident that feasible alternatives vary depending on the functionality and location of each project.

Table 5.1 demonstrates the specifications of 16 feasible façade alternatives for a two-storey commercial building to be constructed in Downtown Montreal. The area of the building per floor is 930 m^2 and the overall window to wall ratio (WWR) for all design concepts is selected as 40%.

The window systems, thickness, and position of the insulations, vapour barriers and air barriers are selected in accordance with the needs for the Montreal weather conditions which fall under zone 6 (cool climate) according to American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) climate zones [127](Figures 5.1 to 5.3).

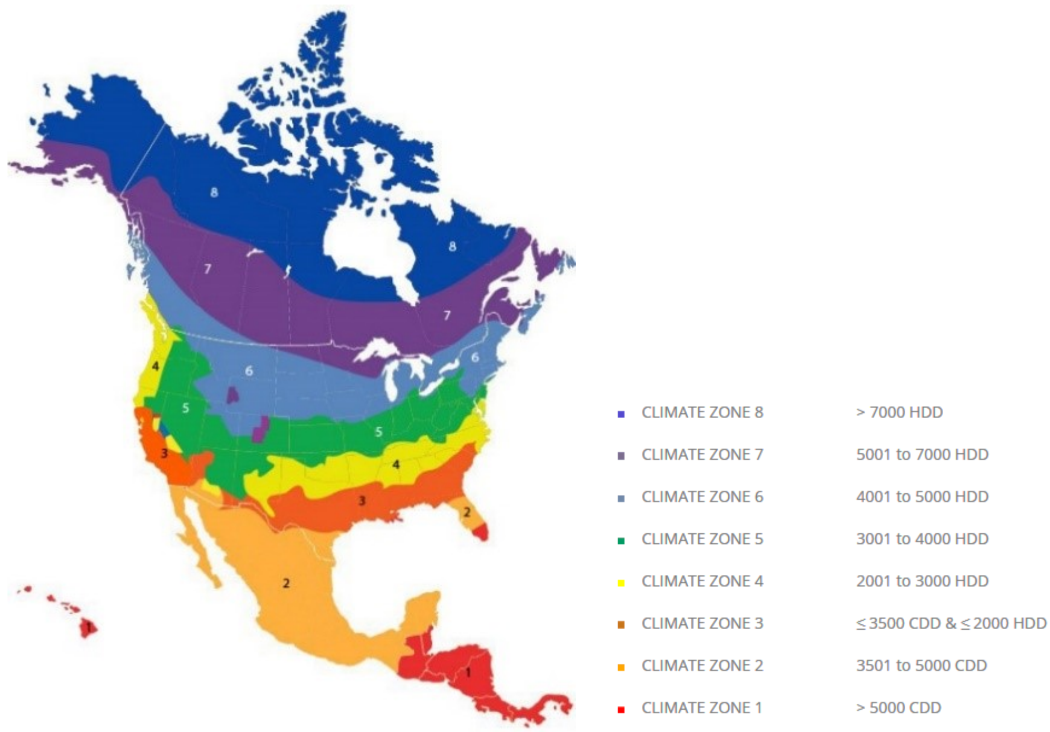


Figure 5.1 Classification of climatic zones in North America with respect to HDD_{18} [128]

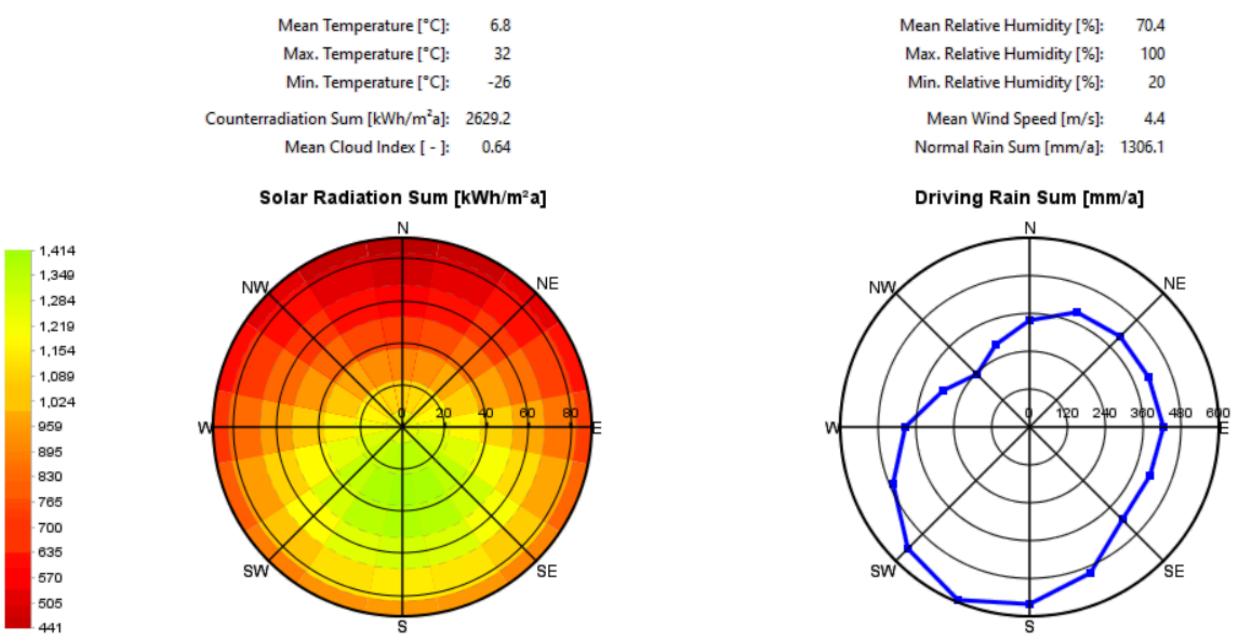


Figure 5.2 Montreal weather data retrieved from WUFI software [129]

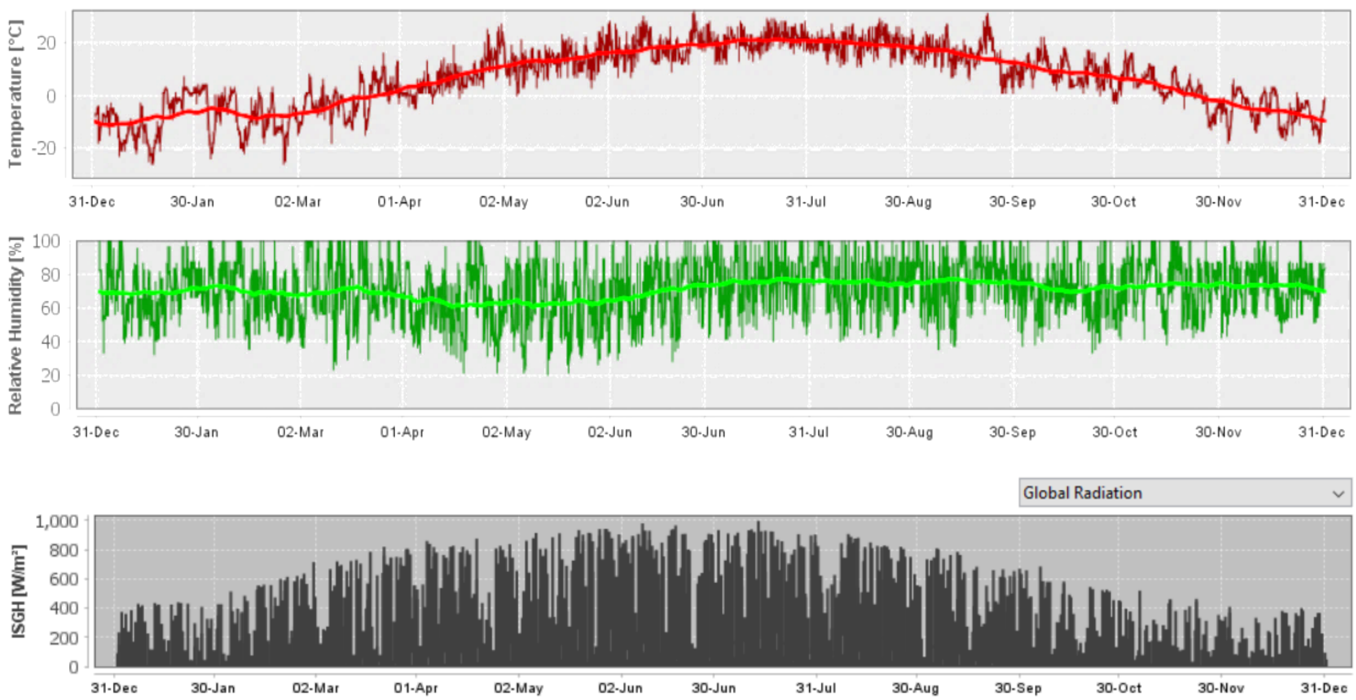


Figure 5.3 Montreal weather data throughout the year retrieved from WUFI software

The wall systems were assessed using WUFI® Pro software [129], version 6, to check their compatibility with the Montreal weather conditions for a two-year period starting 1/10/2017 to 1/10/2019.

The WUFI simulates the hygrothermal progress in building materials. This program considers the relative humidity as the primary potential for moisture transport and considers the moisture content as a secondary quantity to be checked. The benefit of this method over the traditional methods and hand calculations (such as Glazer method) is that WUFI accounts for the rain penetration, solar and long-wave radiation, summer condensation and capillary suction; while those methods are limited to considering the winter condensation effects.

The results of the simulations indicated no potential moisture or condensation problems. The relative humidity never reached 100%, and in each layer, the dew point is always below the temperature in each layer which is as desired since condensation happens when the temperature is below the dew point. The overall water contents of the wall assemblies were mostly decreasing (as desired since it shows less potential for condensation) except for alternatives with Stucco cladding. Even in case of the assemblies with increasing water content, the increased amounts were 0.07 and 0.08 lb/ft^2 (0.34 and 0.39 kg/m^2) and the water content in each layer never reached 20% (around 11.5 % at most). The simulation results related to the critical layers of the wall assemblies are summarized in Appendix A. Table 5.1 summarizes the specifications of 16 feasible façade alternatives.

Table 5.1 Specifications of 16 façade alternative for a low-rise commercial building

Alternative 1		**Alternative 2**	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • 4 inch exterior brick • 40 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • 4 inch exterior brick • 40 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 3		**Alternative 4**	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • 4 inch Granite stone (dark) • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • 4 inch Granite stone (dark) • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 5		**Alternative 6**	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • 4 inch Limestone (light) • 25mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • 4 inch Limestone (light) • 25mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.

Table 5.1 Specifications of 16 façade alternative for a low-rise commercial building-Cont'd

Alternative 7		Alternative 8	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • Cedar shiplap siding • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • Cedar shiplap siding • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 9		**Alternative 10**	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • Stucco with metal lath • One layer of Tyvek weather-barrier membrane • ½ inch Gypsum • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • Stucco with metal lath • One layer of Tyvek weather-barrier membrane • ½ inch Gypsum • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 11		**Alternative 12**	
Wall	Window	Wall	Window
Metal framing 25ga. 6" NLB, 24 OC • Fibre cement • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	Metal framing 25ga. 6" NLB, 24 OC • Fibre cement • 25 mm air space • One layer of Tyvek weather-barrier membrane • ½ inch plywood, exterior grade • 6 inch glass fibre insulation • 3 ml PE membrane, VB • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 13		**Alternative 14**	
Wall	Window	Wall	Window
• 4 inch exterior brick • 40 mm air space • 3.5 inch rigid insulation • 3 ml PE membrane, VB •8 inch concrete block • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	• 4 inch exterior brick • 40 mm air space • 3.5 inch rigid insulation • 3 ml PE membrane, VB •8 inch concrete block • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.
Alternative 15		**Alternative 16**	
Wall	Window	Wall	Window
• Stucco • One layer of Tyvek weather-barrier membrane • 4 inch XPS • 3 ml PE membrane, VB • ½ inch Gypsum •8-inch concrete block • ½ inch gypsum board	2 layers of 4mm Low-E glass (surface 2 and 5), clear 4mm glass in between, 12mm argon space. Timber and aluminum frame.	• Stucco • One layer of Tyvek weather-barrier membrane • 4 inch XPS • 3 ml PE membrane, VB • ½ inch Gypsum • 8-inch concrete block • ½ inch gypsum board	2 layers of 4mm Low-E glass on surface 3, 16mm argon space. Timber and aluminum frame.

5.3 Identification of performance attributes

As mentioned earlier, for each stage of façade design, some or a part of the design attributes must be considered. Façade system selection is undertaken in the conceptual design phase of the building enclosure and the performance attributes that need to be satisfied in this step are summarized in Table 3.1. The next step involves defining measurable factors for each of these attributes. It must be noted that while it is impossible to realistically define the design criteria so that they be independent of each other, it is necessary for the criteria to be collectively exhaustive (meaning that the defined criteria must include all necessary attributes of an ideal façade system). These measurable factors are summarized in Table 5.2.

Since most of the conventional construction materials used in the façade systems and the software used in this research were mainly using imperial units, the quantified measures presented in the Appendixes are in imperial units and the converted SI measurements are presented in the tables of this chapter.

Table 5.2 Design attributes expressed in terms of measurable criteria

Design Criteria	SI Units
A_1: Thickness	m
A_2: Weight per unit area*	kN/m^2
A_3: Fire rating	minutes
B_1: Vapour resistance	$ng/Pa \cdot s \cdot m^2$
B_2: Thermal resistance	RSI (m^2K/W)
B_3: Sound transmission	STC
B_4: Window performance	Points
Visible transmission	-
Solar heat gain coefficient	-
Condensation resistance	-
B_7: Ease of construction	labour hours/m^2
C_1: Energy consumption (cooling/heating/ lighting)	kWh/m^2
C_2: System effect on environment	points
Global warming potential	kg CO_2 eq /m^2
Acidification potential (land and water)	kg SO_2 eq/m^2
Human health (HH) criteria	kg PM2.5 eq/m^2
Eutrophication potential	kg N eq/m^2
Ozone depletion potential	kg CFC-11 eq/m^2
Ground level ozone (smog) creation	kg O_3 eq/m^2
Total primary energy	MJ/m^2
Non-renewable energy	MJ/m^2
Fossil fuel consumption	MJ/m^2
D: Expected service life	years
E_1: Initial cost (design and construction)	\$/ m^2
E_2: Operation and maintenance cost	\$/ m^2
E_3: Decommissioning cost	\$/ m^2
F: Aesthetics	points

* Each assembly has specified thickness

In the following sections, the performance of the alternatives will be assessed in accordance with the above criteria.

5.3.1 The thickness of wall assemblies

The general idea of considering the thickness of wall assemblies is to maximize the living space. However, the wall thickness may indirectly affect the initial costs, environmental effects, such as the amount of raw material used, CO_2 emissions, etc. To calculate the total thickness of the wall, thicknesses of different materials are added together, considering the required air gaps. It must be noted that the thickness of the window system is ignored since the frames are not from the floor to the ceiling and hence the overall thickness is governed by the thickness of the wall. In case of the floor to ceiling windows, the weighted average (in accordance with the window to wall ratio) of the wall and window thicknesses may be considered. The calculated thicknesses of the alternatives are summarized in Figure 5.4.

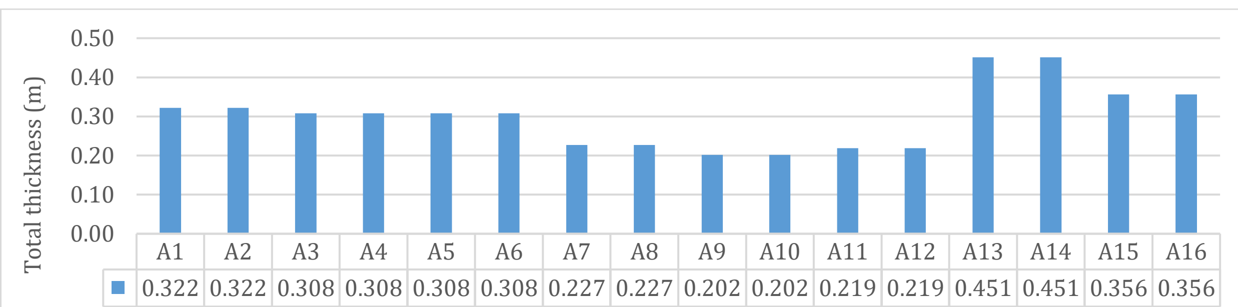


Figure 5.4 Measured thicknesses of the 16 façade alternatives

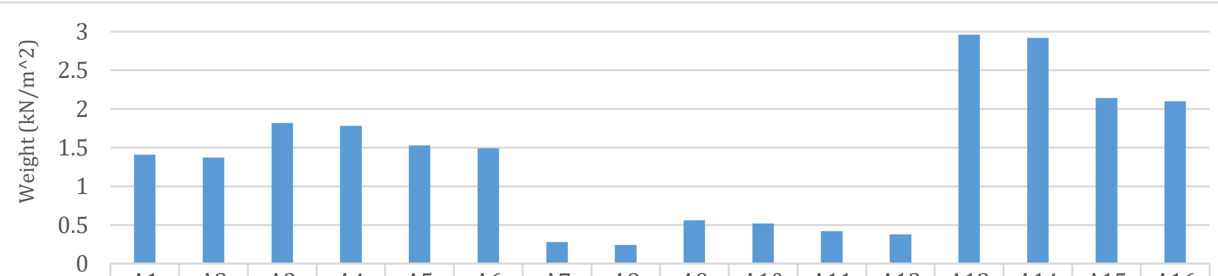
5.3.2 Weight

Similar to the wall thickness, it is preferable to keep the enclosure to be as light as possible, to facilitate construction and rehabilitation operations. Moreover, from the structural point of view, lighter façades induce lower stresses on the building frame. Attention to the proper detailing of the connections for the transmission of the overall weight of the façade is critical.

As each assembly has specified thickness, the weight of the window and the wall assemblies are calculated as sum of the weight of materials used per unit area. The overall weight of each alternative is the weighted sum of the wall and window system per square meter (in this research $W_{enclosure} = 0.6\, W_{wall\ system} + 0.4\, W_{window\ system}$). The weight of required construction materials for the wall assemblies can be found in ASHREA Handbook of Fundamentals [127] and online sources [130-132], and are listed in Table 5.4 The weight of the window system was also calculated from $[\frac{(W_{frame}+W_{glazing})}{Area\ of\ the\ window\ (m^2)}]$ and the specifications are found in the manufacturer's manual [133]. The final results are summarized in Figure 5.5.

Table 5.3 Weights of the construction materials

Material	kN/m²
Metal framing 25ga. 6" NLB, 24 OC	0.0135
Tyvek	0.0105
½ inch plywood exterior grade	0.0720
6 inch fibreglass insulation	0.0240
½ inch gypsum board	0.0780
4 inch brick Siding	1.9500
4 inch granite	2.6400
4 inch limestone	2.1550
¾ inch cedar siding	0.0661
Stucco	0.4788
¾ inch fibre cement	0.2562
3½ inch rigid insulation	0.0278
8 inch concrete block	2.6813
4 inch XPS	0.0321



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
■	1.41	1.37	1.82	1.78	1.53	1.49	0.28	0.24	0.56	0.52	0.42	0.38	2.96	2.92	2.14	2.1

Figure 5.5 Measured weights of the 16 façade alternatives per unit area

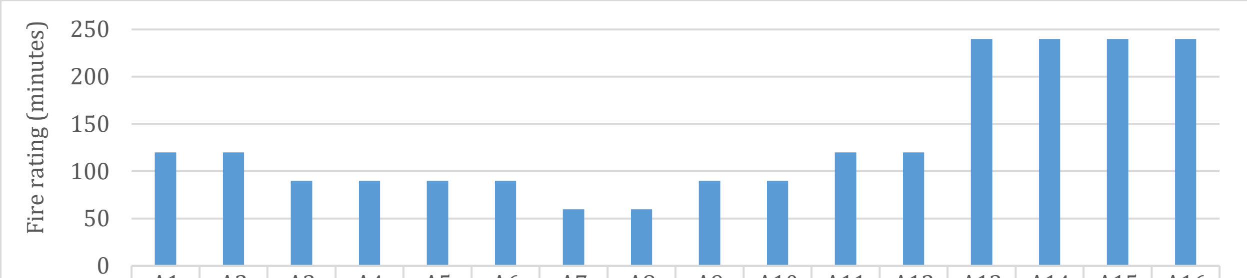
5.3.3 Fire rating

While conventional building materials are not completely fireproof, well-constructed buildings can help prevent tragedies caused by fire through the use of materials that are relatively fire-resistant. The National Building Code of Canada (NBC) and the National Fire Code of Canada (NFC) provide detailed guidance to ensure the safety of the occupants during the occurrence of fire in a building structure; these provisions are updated at regular intervals.

In addition to the general requirements related to building design and provision of fire safety assemblies (permitted materials, use of sprinklers, etc.), the codes require minimum fire resistance rating of building assemblies in each building group (the buildings are classified with regard to the occupant load, area, height and whether they have functional sprinklers). In case of low-rise office buildings, NBC requires a minimum fire-resistance-rating of 45 minutes for the exterior walls [134].

The NBC describes "fire-resistance rating" as: "the time in minutes or hours that a material or assembly of materials will withstand the passage of flame and the transmission of heat when exposed to fire under specified conditions of the test." The NBC uses tests and acceptance criteria that are defined in the "Standard method of fire endurance tests of building construction and materials", CAN/ULC-S101-14, which is published by the ULC Standards [135].

To estimate the fire-resistance-rating of the various alternatives, the data from NBC presented in Table 9.10.3.1-A which provides the fire resistance and sound transmission class of basic wall assemblies were used along with the data in Table 7.20.1.(1) of Chapter 7 of the International Building Code [136] related to fire-resistance-rated construction, the Fire ratings of archaic materials and assemblies [137], and Fire-resistance classifications of building materials [138]. The results are presented in Figure 5.6 which suggest that concrete blocks (used in alternatives 13,14,15 and 16) significantly increase the fire rating of wall assemblies.



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
■	120	120	90	90	90	90	60	60	90	90	120	120	240	240	240	240

Figure 5.6 Fire resistances of the 16 façade alternatives

5.3.4 Vapour resistance

Diffusion is the process that permits water vapour to migrate through the material; this can lead to material deterioration and finally its failure. The driving force for vapour diffusion across the building envelope is partial vapour pressure differential. The moisture flux is dependent on this partial vapour pressure differential and the resistance of the material to moisture movement.

The vapour resistance of a material is a measure of the ability of a material to inhibit the water vapour from passing through it. The vapour permeability of a material is a property that allows the transfer of water vapour through it. Therefore, the vapour resistance of a material is the inverse of its vapour permeability.

$$Z = \frac{t}{\mu} \tag{5.1}$$

where Z is the vapour resistance ($\frac{ng}{Pa.s.m^2}$), t is the material thickness and μ is the water vapour transmission coefficient of the material. The vapour permeability of a material is measured by using dry-cup or wet-cup methods in which the test assemblies are initially weighed and during the course of the test, the weight change of the complete test assembly is measured until the results become linear (Figure 5.7). ASHREA Handbook of Fundamentals [127], Chapter 26 provides typical water vapour permeance (water vapour transmission coefficient) for common building materials.

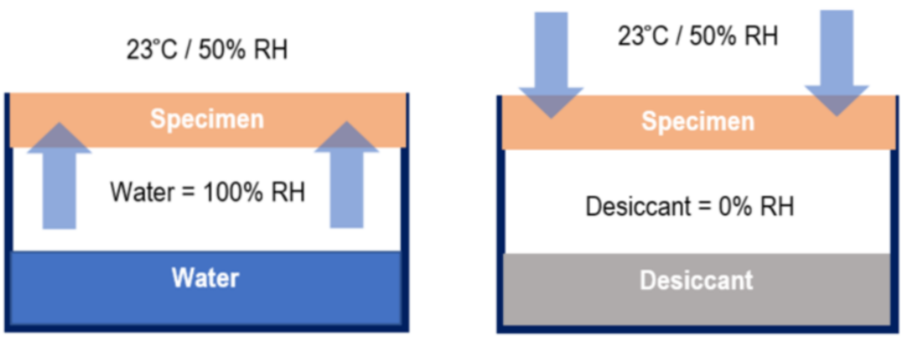
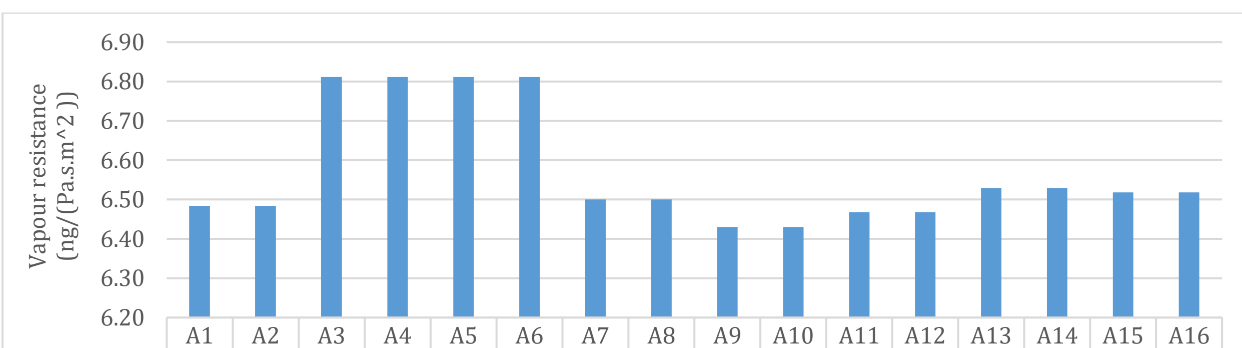


Figure 5.7 (a) Wet cup method and (b) dry cup method

In this research, the overall vapour resistance of a wall assembly is determined by the summation of vapour resistance of each material. The results are summarized in Figure 5.8 and suggest that limestone and granite façades have better vapour resistance (the vapour barriers are the same for all systems).



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
■	6.48	6.48	6.81	6.81	6.81	6.81	6.50	6.50	6.43	6.43	6.47	6.47	6.53	6.53	6.52	6.52

Figure 5.8 Vapour resistances of the 16 façade alternatives

5.3.5 Thermal resistance

It is known that the heat energy moves from a location of higher temperature to a location to lower temperature. This process occurs through three mechanisms (Figure 5.9):

(1) Conduction

$$Q_{Conduction,wall} = kA\,\frac{T_1 - T_2}{L} \qquad (5.2)$$

where Q is the heat flow, k is the thermal conductivity $(\frac{W}{m.K})$, L is the material thickness, A is the area, and T_1 and T_2 are the temperatures on either side of the material.

(2) Convection

$$Q_{Convection,wall} = hA_s\,\frac{T_s - T_a}{L} \qquad (5.3)$$

where Q is the heat flow, h is the convective heat transfer coefficient $(\frac{W}{m.K})$, L is the material thickness, A_s is the surface area, and T_s is the surface temperature and T_a is the ambient air temperature.

(3) Radiation

The radiation is between the wall inside surface temperature T_s and the mean radiant surface temperature of all inside surfaces T_{mrt} . For simplification, T_{mrt} is considered equal the ambient air temperature to T_a (Eq. 5.4)

$$Q_{Radiation} = \varepsilon\sigma A_s(T_s^4 - T_a^4) \qquad (5.4)$$

where Q is the heat flow, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant which is equal to $5.67 \times 10^{-8}\,\frac{Wm^2}{K^4}$, and A_s is the surface area.

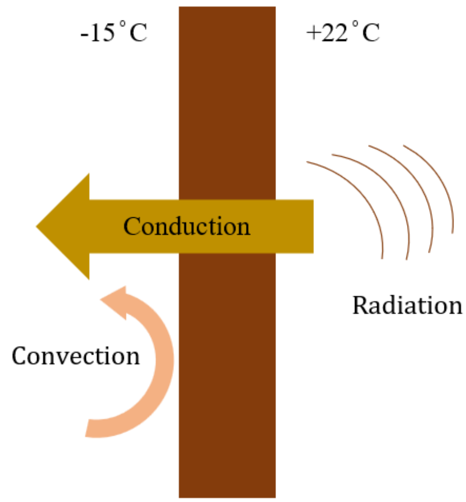


Figure 5.9 Heat transportation mechanisms

Low heat transportation property of a wall assembly can lead to significant savings in annual building energy consumption. Hence, in selecting a façade system, one must pay attention to the thermal resistance of the assembly to prevent energy dissipation. The general idea is that in the steady-state heat transfer, the heat flows into the wall is equal to the heat flows through the wall and equal to the heat flows from the wall (i.e. $\frac{T_1 - T_{\infty_1}}{R_{eq1}} = \frac{T_2 - T_2}{R_{eq2}} = \frac{T_2 - T_{\infty_2}}{R_{eq3}}$; Figure 5.10).

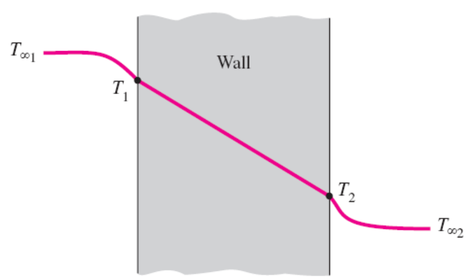


Figure 5.10 The thermal resistance network for heat transfer through a plane wall subjected to convection on both sides

$$Q = \frac{T_{\infty_1} - T_{\infty_2}}{R_{total}} \tag{5.5}$$

where Q is the heat flow, R is the overall heat transfer resistance ($\frac{m^2K}{W}$), and T_{∞_1} and T_{∞_2} are the ambient temperature of the inside and outside of the wall. As the overall wall resistance increases, the heat flow would decrease. The overall thermal resistance of a wall assembly can be calculated using different methods depending on the framing material. The thermal resistance of wood frame walls can be derived from equivalent electrical circuits, by (1) parallel path and (2) isothermal planes method. For assemblies containing metal, zone method, modified zone method (ASHRAE Handbook of Fundamentals Ch. 27.5) and 2D heat transfer simulation programs such as THERM can be used. For more complicated geometries, 3D heat transfer modeling can be used.

In this research, THERM 7.6 [139]which is a finite-element-based simulation tool to perform the thermal analysis of building assemblies and components, has been used to calculate the overall heat transfer resistance of the wall assemblies. The overall thermal resistance of the window systems have been extracted from Window-THERM simulations (0.6 and 1.05 $\frac{m^2K}{W}$ for double and triple pane windows respectively). The simulation results of wall assemblies are included in Appendix B, and the final results that are the weighted average of the window and wall resistances are presented in Figure 5.11 (converted to SI units). The results suggest that window systems (even the tripled pane windows) significantly decrease the thermal resistance of the enclosure.

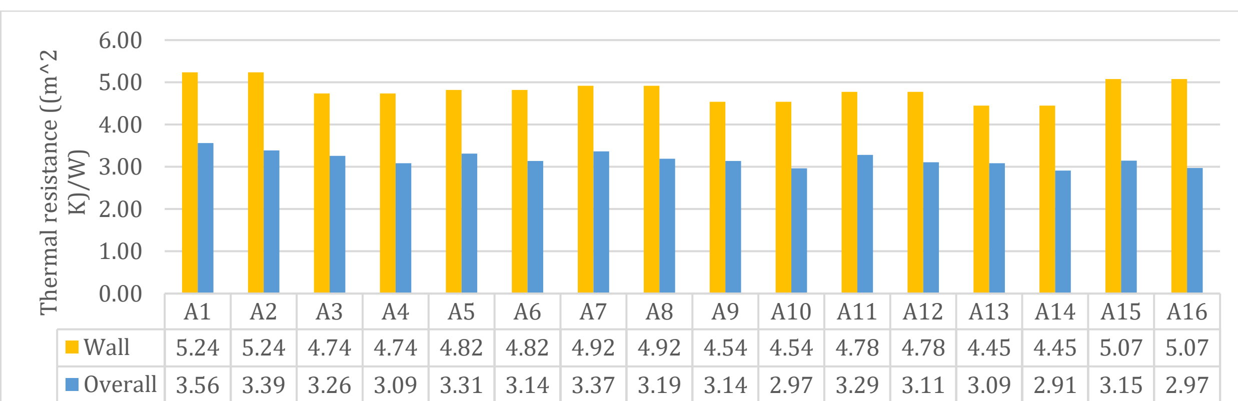


Figure 5.11 Thermal resistances of the 16 façade alternatives

5.3.6 Sound transmission

One of the attributes of an efficient façade system is to protect the occupants from outside noise and provide some extent of soundproofing. One of the measures to identify the effectiveness of an assembly or material in attenuating airborne sound is using the sound transmission class (STC) which is widely used in North America to rate the interior partitions, exterior walls, ceilings and window systems. To obtain the STC of an assembly, the sound attenuation values are verified at sixteen standard frequencies (from 125 Hz to 4000 Hz) and then plotted on a sound pressure level graph. The resulting curve is compared to a standard reference contour and fitted to the appropriate transmission loss curve to determine an STC rating. These tests are performed under rigid procedures required by the American Society for Testing and Materials (ASTM Procedure E90-90).

The sound transmission class of façade assemblies in this research were estimated in consultation with ASTM E413 – 16 [140] and NBC [134]. The STC of the window systems were determined from the manufacturer's manual (32 and 40 for double and triple pane windows, respectively [133]). Figure 5.9 shows the final STC values (weighted average of the window systems and walls) for the 16 alternatives. The results suggest that alternatives with triple pane window systems have better sound transmission class.

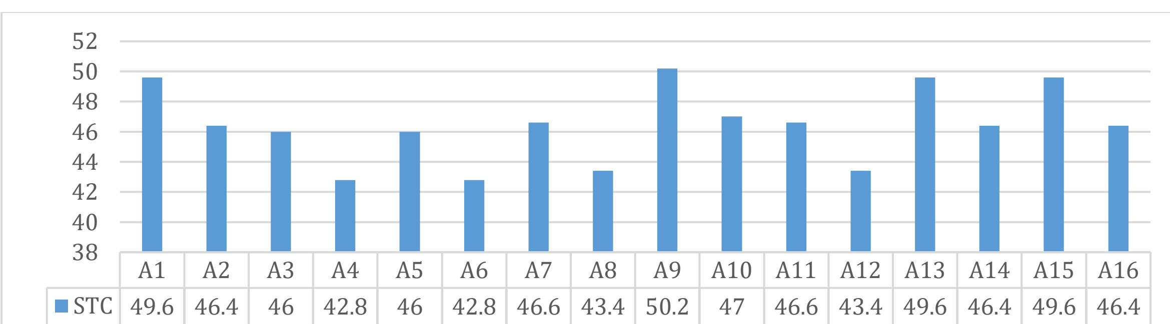


Figure 5.12 Estimated sound transmission classes of the 16 façade alternatives

5.3.7 Visible transmission

Visible transmittance (VT) is the solar radiation transmitted through fenestration weighted with respect to the photonic response of the human eye, i.e. "amount of light in the visible portion of the spectrum" [141]. VT represents the perceived clearness of the fenestration.

$$VT_w = VT_g \times \frac{A_g}{A_w} \quad (5.6)$$

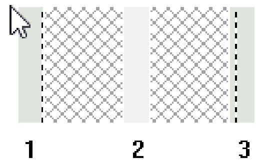
where, VT_w is the visible light transmission of the total window, VT_g is the measured visible light transmission of the glazing, A_g is the total glass area, and A_w total window area.

A higher VT provides the opportunity for more daylight in a space, which, if designed appropriately, can lead to offsetting the electric lighting and the associated cooling loads. The glazing type, coatings and the number of panes, are some factors that influence the visible transmittance. To measure the VT of window systems in this research, THERM-Window simulations have been performed. Initially, the specifications of the window glazing units (Figures 5.13, 5.14, 5,16 and 5.17) were modelled in Window 7.6 simulator.

To simulate the window frame in THERM, the window frame layout was drawn in AutoCAD and then imported in THERM 7.6. Then the glazing specifications from Window 7.6 were inserted and the boundary conditions of the frame were assigned. Figures 5.15 and 5.18 illustrate the analysis performed on triple and double pane window systems, respectively.

Finally, the THERM model was inserted in Window 7.6 to get the data related to the VT, solar heat gain coefficient (SHGC) and condensation resistance (CR) that will be discussed in the following sections. The measured VTs of the window systems are summarized in Table 5.4.

The results suggest that the double pane window system used in this study would allow more visible daylight to enter.



	ID	Name	Mode	Thick	Flip	Tsol	Rsol1	Rsol2	Tvis	Rvis1	Rvis2	Tir	E1	E2	Cond	Comment
Glass 1	2027	LoE270-4.CIG	#	4.0	☐	0.370	0.341	0.470	0.765	0.074	0.055	0.000	0.840	0.037	1.000	
Gap 1	2	Argon		12.0												
Glass 2	13501	CLEAR 4T.KCC		4.0	☐	0.808	0.076	0.076	0.891	0.084	0.084	0.000	0.837	0.837	1.000	
Gap 2	2	Argon		12.0												
Glass 3	2027	LoE270-4.CIG	#	4.0	☒	0.370	0.470	0.341	0.765	0.055	0.074	0.000	0.037	0.840	1.000	

Figure 5.13. Olsen Thermo 80 Alu triple pane window specifications modelled in Window 7.6

		Layer 1		Layer 2		Layer 3		
	Outside Air	Outer Surface	Inner Surface	Outer Surface	Inner Surface	Outer Surface	Inner Surface	Inside Air
Ufactor	-18.0	-17.1	-17.0	0.1	0.2	16.8	16.9	21.0
SHGC	32.0	43.8	44.3	47.1	47.0	34.3	34.1	24.0

Ufactor	SC	SHGC	Rel. Ht. Gain	Tvis	Keff	Layer 1 Keff	Gap 1 Keff	Layer 2 Keff	Gap 2 Keff	Layer 3 Keff
W/m2-K			W/m2		W/m-K	W/m-K	W/m-K	W/m-K	W/m-K	W/m-K
0.697	0.348	0.303	225	0.528	0.0288	1.0000	0.0191	1.0000	0.0197	1.0000

Figure 5.14. Olsen Thermo 80 Alu triple pane window center of glass results and temperature data, modelled in Window 7.6

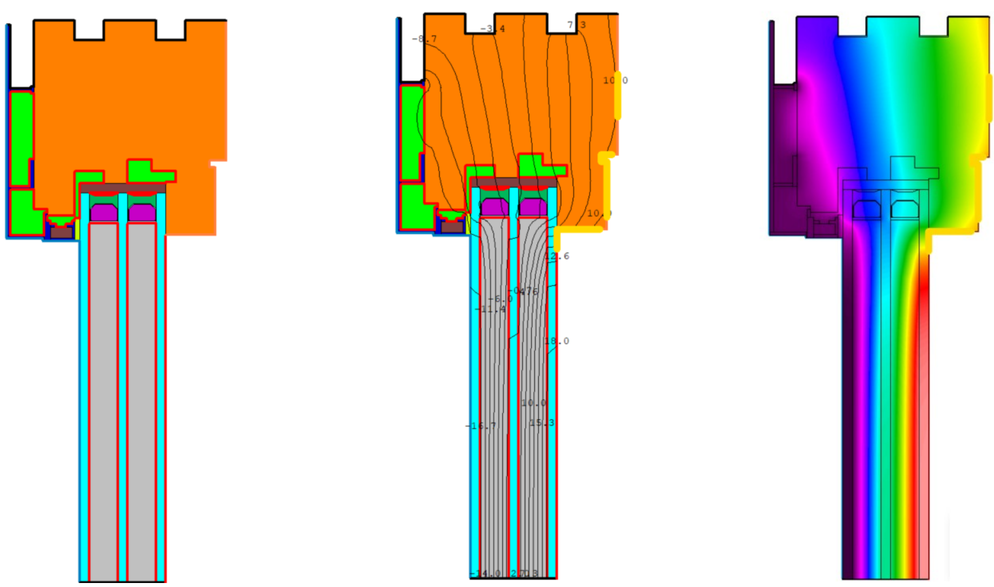
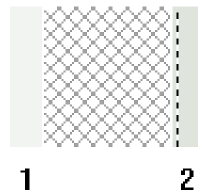


Figure 5.15. Olsen Thermo 80 Alu triple pane window and frame specifications and analysis modelled in THERM 7.6



	ID	Name	Mode	Thick	Flip	Tsol	Rsol1	Rsol2	Tvis	Rvis1	Rvis2	Tir	E1	E2	Cond	Comment
Glass 1	8203	01_Clear_4.syp	#	4.0	☐	0.847	0.078	0.078	0.902	0.081	0.081	0.000	0.840	0.840	1.000	
Gap 1	2	Argon		16.0												
Glass 2	2027	LoE270-4.CIG	#	4.0	☒	0.370	0.470	0.341	0.765	0.055	0.074	0.000	0.037	0.840	1.000	

Figure 5.16. Olsen Thermo 80 Alu double pane window specifications modelled in Window 7.6

Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties | Radiance Results

		Layer 1		Layer 2		
	Outside Air	Outer Surface	Inner Surface	Outer Surface	Inner Surface	Inside Air
Ufactor	-18.0	-16.1	-15.9	12.8	13.1	21.0
SHGC	32.0	36.5	36.7	37.8	37.6	24.0

Ufactor	SC	SHGC	Rel. Ht. Gain	Tvis	Keff	Layer 1 Keff	Gap 1 Keff	Layer 2 Keff
W/m2-K			W/m2		W/m-K	W/m-K	W/m-K	W/m-K
1.412	0.525	0.457	339	0.693	0.0453	1.0000	0.0307	1.0000

Figure 5.17. Olsen Thermo 80 Alu triple pane window center of glass results and temperature data, modelled in Window 7.6

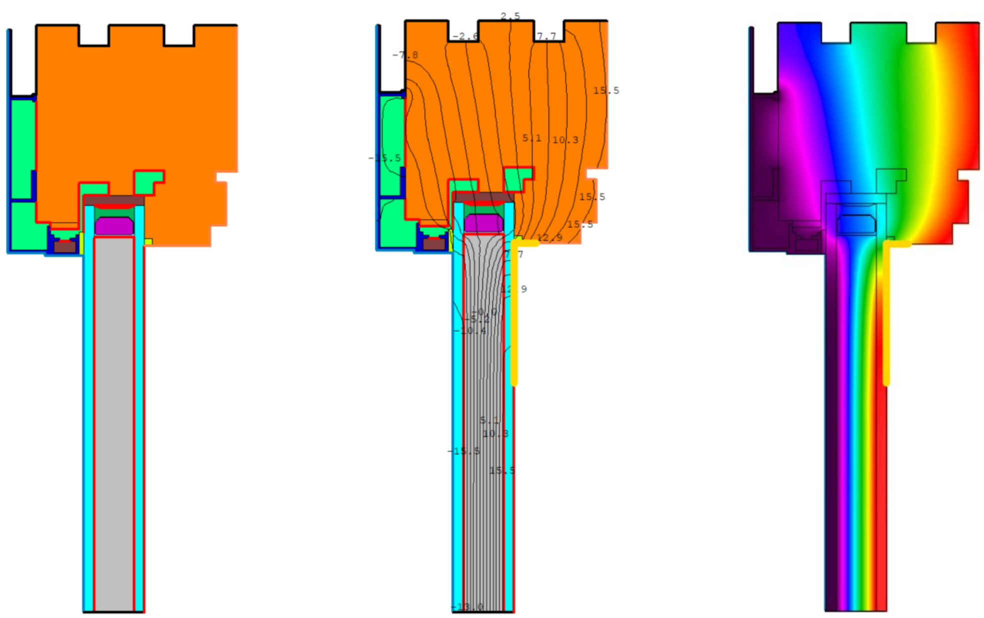


Figure 5.18. Olsen Thermo 80 Alu double pane window and frame specifications and analysis modelled in THERM 7.6

Table 5.4 Visible transmissions of the 2 window system alternatives

Alternatives	Triple pane Low-E window system	Double pane Low-E window system
VT	0.432	0.569

5.3.8 Solar heat gain coefficient

Solar heat gain coefficient (SHGC) is the ratio of solar heat gain through a window component to the solar radiation incident on it, for a given angle of incidence and for given environmental conditions (indoor temperature, outdoor temperature, wind speed, and solar radiation), it includes directly transmitted portion and the absorbed and re-emitted portion of light (Figure 5.19). The absorbed solar energy can be redirected to the indoor space by radiation and convection.

This property is dependent on the performance of the entire glazing unit, including the type of glass and the number of panes, tinting, coatings, as well as the available shadings. The SHGC is a dimensionless number that ranges between zero and one. This measure is very important in hot sunny climates (cooling dominant areas), where glazing with lower SHGC (below 0.4) should be used. Buildings in cold climates should generally have higher SHGC to enable passive solar heating and to reduce heating loads.

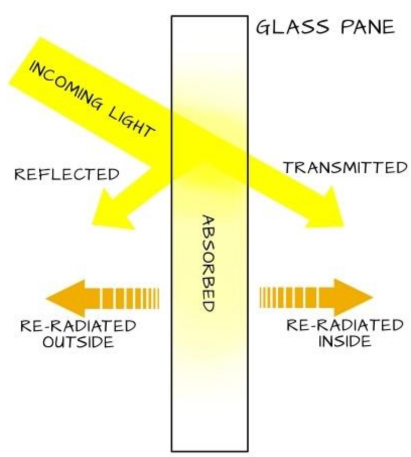


Figure 5.19. Heat transmission and radiation from a window [142].

The SHGC can be measured by determining the fenestration thermal performance using simulated solar irradiance (Eq. 5.7) or by THERM-Window simulations.

$$SHGC_w = \frac{SHGC_{edge}A_{edge} + SHGC_{frame}A_{frame} + SHGC_{center\ of\ glass}A_{cg}}{A_{frame} + A_{edge} + A_{cg}} \qquad (5.7)$$

and

$$SHGC_i = \alpha_i^s (\frac{U_i}{h_i})(\frac{A_i}{A_{surf,i}}) \qquad (5.8)$$

where α_i^s is the solar absorptivity of the outdoor surface (frame, edge or center of glass), h_i is the heat transfer coefficent between the outdoor environment and frame, edge or center of the glass, and $(\frac{A_i}{A_{surf,i}})$ is the projected to surface area ratio. ASHRAE Handbook of Fundamentals provides some estimation for SHGC and VT of window systems in Chapter 15, Table 10.

For the purpose of this study, the SHGC of the window systems were determined using the THERM-Window analysis of the window systems, as explained earlier, and the results are summarized in Table 5.5. It can be observed that the double pane windows have better SHGC (for Montreal climate conditions), although the related thermal resistance is lower for double pane windows. This is another example of the need for providing a balance among the design criteria.

Table 5.5 Solar heat gain coefficients of the 2 window system alternatives

Alternatives	Triple pane Low-E window system	Double pane Low-E window system
SHGC	0.25	0.378

5.3.9 Condensation resistance

In cold winters, when the indoor relative humidity is high, condensation can occur on cold interior surfaces, that is caused by thermal bridging to the exterior. Condensation mostly occurs on windows because windows are the least insulated part of a wall system.

Condensation resistance (CR) rating, introduced by the National Fenestration Rating Council (NFRC); and the condensation resistance factor (CRF), introduced by the American Architectural Manufacturer's Association (AAMA) are the most well-known standards that measure how well a window resists the formation of condensation on the interior surfaces. These standards consider the thermal conductivity, thermal variation, geometry, and airflow resistance.

The CR and CRF share the same goal but use different methods to achieve it. The primary method of determining the CR rating is through simulations (such as THERM-Window), while the CRF is based on measured data and is usually provided in the manufacturer's manual.

Since the data related to the CRF, for the proposed window systems were not provided in the manuals, THERM-Window 7.6 simulations were used to determine the condensation resistance (CR) of the proposed window systems as explained in earlier sections. This measure is based on a 1-100 scale where a higher value represents higher resistance to condensation. This rating is based on a series of simulations that assess the performance of specific parts of the window assembly (center-of-glass, edge-of-glass, and frame) at 30%, 50%, and 70% indoor relative humidity for a given outside air temperature and inside temperature, under 15 mph wind conditions. The measured CRs of the proposed window systems are presented in Table 5.6 where the selected double pane window, has a better CR value in comparison to the triple pane window.

Table 5.6 Condensation resistances of the 2 window system alternatives

Alternatives	Triple pane Low-E window system	Double pane Low-E window system
CR	59	63

5.3.10 Ease of construction

Constructability was one of the attributes of an optimum building enclosure, which was explained in Chapter 3 in detail. The goal is to determine the efficiency and ease of construction of a project and to make it even more efficient and easier.

The implementation of constructability is not a single-stage procedure and starts from the initial building design until the end of the construction phase. The provisions that must be considered during the conceptual design phase are mostly related to the determination of the ease of construction. This attribute can significantly affect the initial cost of the project. The measurable criteria defining the ease of construction were set as labour hours and the level of skill required.

The RSMeans 2017 Building Construction Cost Data [143] was the data source used to extract the following information :

- Square foot costs of the façade components
- Crew sizes, labour hours and labour rates
- City cost indices and location factors for Montreal to get accurate costs.

The information related to the crew and labour hours of the wall assemblies and window systems are presented in Table 5.7, which were used to quantify the ease of construction of the 16 façade alternatives (converted to SI units). The results suggest that the building envelope with the wood siding (alternatives 7 and 8) are the easiest to construct.

Table 5.7 Construction workmanship and labour hours the alternatives

Wall Alternatives	A_1, A_2	A_3, A_4	A_5, A_6	A_7, A_8	A_9, A_{10}	A_{11}, A_{12}	A_{13}, A_{14}	A_{15}, A_{16}
Labour hours (ft^2)	0.267	0.246	0.116	0.036	0.286	0.120	0.367	0.220
Crew	D08	D10	D10	1 Carp	D08	D08	D08	D08

Window systems	Triple pane Low-E window system	Double pane Low-E window system
Labour hours (ft^2)	0.057	0.05
Crew	1 Carp	1 Carp

Crew definitions and labour hours		
Crew D08	**Crew D10**	**1 Carp**
3 Bricklayers 3 Brick helpers	1 Bricklayer foreman (outside) 1 Bricklayer 1 Brick helper 1 Equipment operator (crane) 1 S.P Crane, 4x4, 12 Ton	1 Carpenter
48 Labour hours	32 Labour hours	8 Labour hours

Alternatives	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
Labour hours (m^2)	1.97	1.94	1.83	1.80	1.83	1.80	0.96	0.93

Alternatives	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
Labour hours (m^2)	2.10	2.06	1.02	0.99	2.61	2.58	1.67	1.64

5.3.11 Energy consumption (cooling/heating/ lighting)

Energy efficiency of a building is one of the most important factors contributing to both life cycle costs and environmental impact. The annual energy consumption of a typical building is dependent on numerous factors (such as outside temperature, wind conditions, height, location and orientation of the building and components). Hence, the best way to compare the variations in the annual energy consumption of a building, with changing façade system alternatives is to perform energy consumption simulations.

The energy simulation analysis of the proposed building was performed using the eQUEST 3.65 [144] software, which is a graphical frontend for the DOE software, that combines user-friendly wizard modes with a powerful engine to simulate heat transfer from building components and the ambient environment. For this purpose, certain parameters were assigned to the building model. The details of the 16 envelope alternatives have already been specified in Table 5.1; these parameters were input into the program using material details specified by layer. A custom interior wall and roof assembly were used from the built-in material database found within eQUEST. The simulation requires certain basic inputs to determine the buildings usage, schedule, and internal loads. These values were used based on the requirements of the NECB [35], specifically Chapter 8 which deals with energy modelling. NECB 2015 stipulates that a two-storey commercial building will have an HVAC system type 3. This is defined as a rooftop packaged unit with DX air-cooled coils for cooling and electric resistance heating. No natural gas will be used in the proposed building, which entails that the domestic hot water heater is operated on electricity as well. Table 5.8 summarizes eQUEST parameters derived in accordance with the NECB recommendations.

Simulation results for the 16 alternatives are available in Appendix C and the results are converted to SI units and summarized in Figure 5.20. According to the e-QUEST simulation results, using the triple pane window would enhance the energy consumption significantly.

Table 5.8 eQUEST input parameters in accordance with NECB provisions

Sample input parameters	Unit
Total floor area	20000 ft^2
Area/floor	10000 ft^2
Floor height	12'
Ceiling height	9'
Perimeter zones	15' from the window
Infiltration	0.05 cfm/ft^2
Minimum airflow	0.4 cfm/ft^2
Window to wall ratio	40%
DX Air-cooled Packaged Unit	
Energy efficiency ratio (EER)	11.2
Electric Baseboard Heat	
Power output	88.1 kw

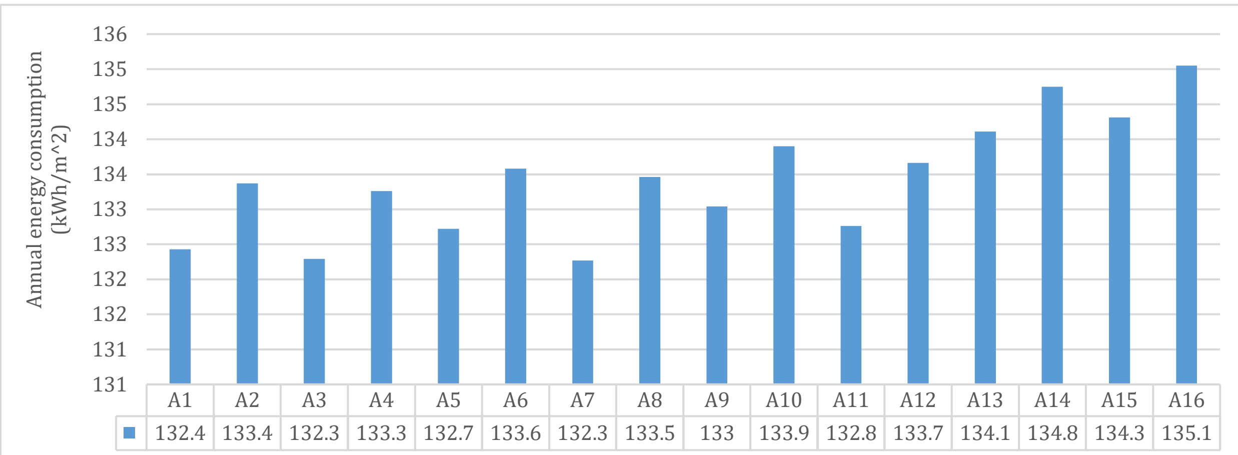


Figure 5.20 Annual energy consumption of the simulated building using the 16 façade alternatives

5.3.12 System effect on the environment

As mentioned in Chapter 3, life cycle assessment (LCA) of building envelopes is one of the key factors in sustainable decision making which enables informed consideration of life cycle impacts of using construction materials in a project.

It is necessary to measure actual performance rather than relying on prescriptive guesses, whereby materials are considered to have environmental benefits based on their attributes. For instance, recycled content, renewability, and local procurement are assumed environmentally beneficial characteristics without any quantified supporting data. For this matter, LCA is a widely accepted and appropriate method for scientific quantification of the environmental footprint of the various materials.

In LCA, data is collected at every phase of a material's life, and assessed with regards to environmental impact measures, including the potential for global warming, use of natural resources, primary energy consumption, and air and water pollution. In this research program, the Athena impact estimator for buildings [145], version 5, has been used to determine the environmental impacts of the 16 façade alternatives through the following stages:

- Resource extraction and recycled content
- Material manufacturing,
- Related transportation
- Construction
- Building occupancy, and maintenance and replacement
- Building demolition/ materials end-of-life disposition (disposal or transfer for recycling or reuse)

The results from the individual alternatives are demonstrated in tables by assembly group and life cycle stage in Appendix D. The simulation results are presented in terms of:

- Global warming potential
- Acidification and acid deposition (land and water)
- Toxic releases to air, water and land (human health criteria)
- Neutrification/eutrophication of water bodies
- Stratospheric ozone depletion
- Ground level ozone (smog) creation
- Total Primary Energy
    - Fossil fuel depletion
    - Non-renewable resource use

To assign an environmental impact score to each alternative, a weighted sum average (with equal weights) of the normalized results, was performed on each alternative and an environmental impact point was delegated to each alternative (from 0-1), where the higher value represented a better alternative in terms of environmental impact. The final results are summarized in Figure 5.21, which suggest that alternative 8 (building envelope with wood siding and double pane windows) gets the highest score.

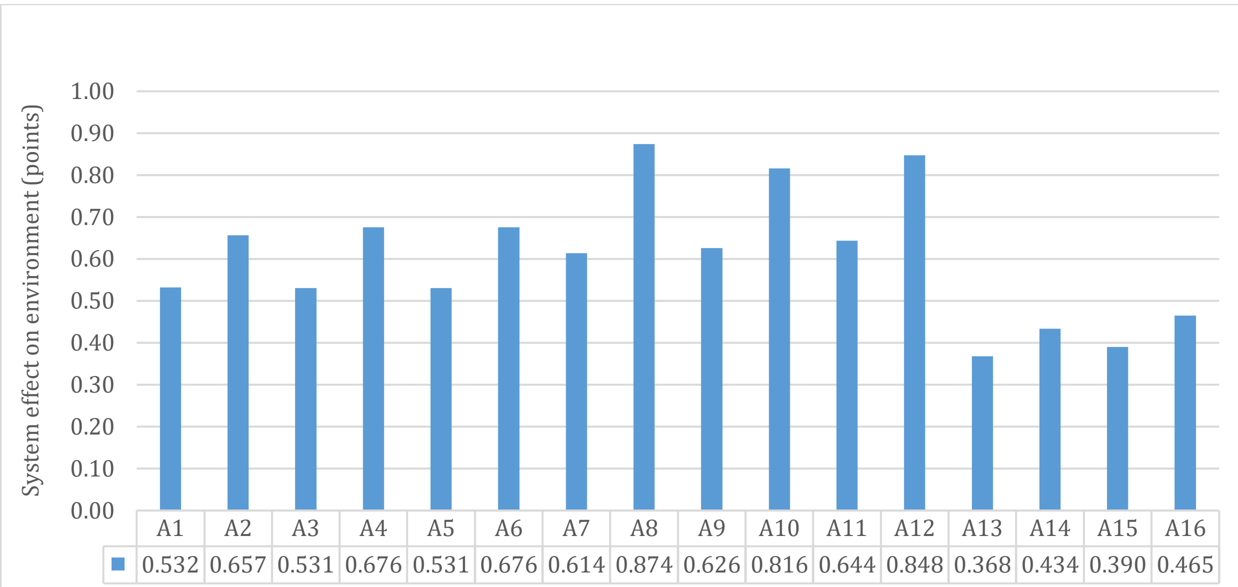


Figure 5.21 Environmental impacts of the 16 façade alternatives

5.3.13 Expected service life

Similar to constructability, the durability of an envelope system is an attribute that can be achieved through in-time provisions and planning. Most of these provisions must be considered during the detailed design of the system and should be achieved through meticulous design, high-quality workmanship, inspection and regular maintenance. However, while choosing an optimal alternative, it is important to predict the performance of the system throughout its life cycle. This is important in minimizing the maintenance needs and service life costs of the envelope.

As the demand for estimation of construction material service life grew from the 1980s, a substantial amount of research has been undertaken in the field. The Architectural Institute of Japan (AIJ) published an English version of their 1989 guideline "Principal guide for service life planning of buildings" in 1993 [146]. This was followed by the British Standards Institution (BSI) [147] and the Canadian Standards Association (CSA) [148] who provided some methods for prediction of the service lives of building components and assemblies along with provisions for appropriate construction practices.

The International Standards Organization (ISO) has dealt with service life planning of construction materials in 11 parts. The ISO 15686-2:2012 -Part 2: Service life prediction procedures [149], ISO 15686-7:2017-Part 7: Performance evaluation for feedback of service life data from practice [150], and ISO 15686-8:2008-Part 8: Reference service life and service-life estimation [151], are the standards which can be used for service life prediction procedures.

There are three main approaches to predict the service life of building components or assemblies. In the first approach, the principles of structural engineering are applied in estimating the structural integrity of materials in accordance with loading conditions and ongoing degradation over time, including the effects of chemical deterioration mechanisms.

Another approach in service life prediction is the factor method that uses a series of factors to modify the reference service life of a component (RSLC) to estimate its actual service life. The ISO 15686-1: 2011 [152] defines the estimated service life of the component (ESLC) as :

$$ESLC = RSLC \times Factor\ A \times Factor\ B \times Factor\ C \times Factor\ D \times Factor\ E \times Factor\ F \times Factor\ G \quad (5.9)$$

where factor A represents the quality of the components, factor B defines the design level, the factor C is related to the work execution level, the factors D and E are for the indoor environment and outdoor environment respectively, factor F represents the in-use conditions and the factor G is used for the maintenance level. Although this is a very commonly used method, its accuracy is questionable due to the subjectivity in assigning the factors.

Using empirical data is the third approach to predict the service life. There are some data sources available as service life reference. Mainly, there are three categories of service life data [153]:

- The service life of products, based on experience or condition surveys
- Maintenance intervals, based on experience
- Information gained from testing materials and components, in accelerated or long-term tests, including the data based on the manufacturer's warranties.

It is important to note that in using reference data, one must consider the environmental conditions of the site where the assembly is installed.

In this research, to avoid any bias in measuring the expected service life of assemblies, the reference data from the Canadian sources were used without applying the factor method. The expected service life of the 16 façade alternatives were estimated in consultation with CSA S478-1995 guideline on durability in buildings [148], and a report published by Canada Mortgage and Home Corporation that provides reference service life data based on a Delphi study by building managers throughout Canada [154]. Figure 5.22 presents the results, which suggest that stone veneers (limestone and granite) have the longest life expectancy.

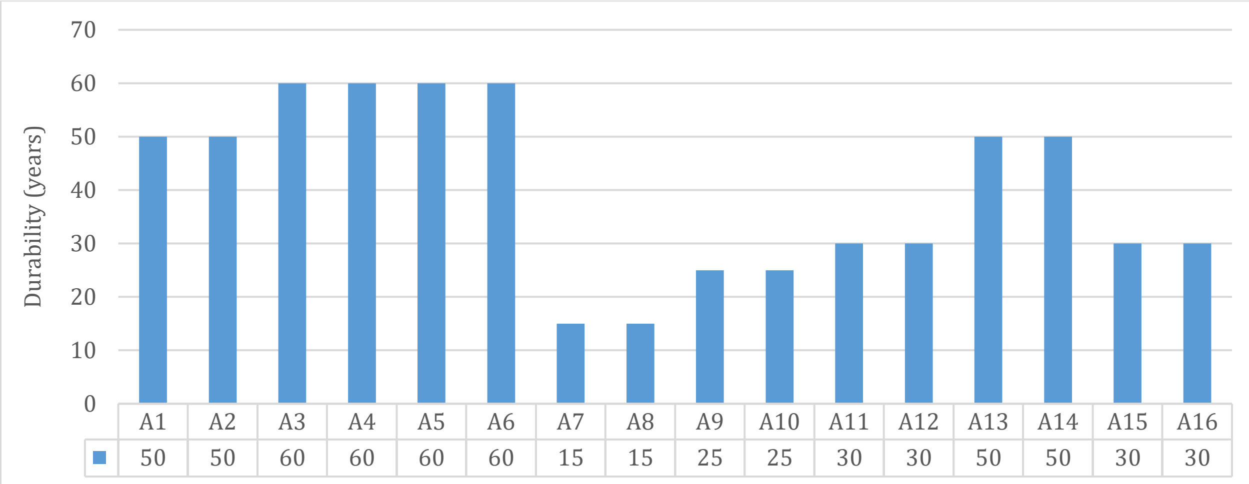
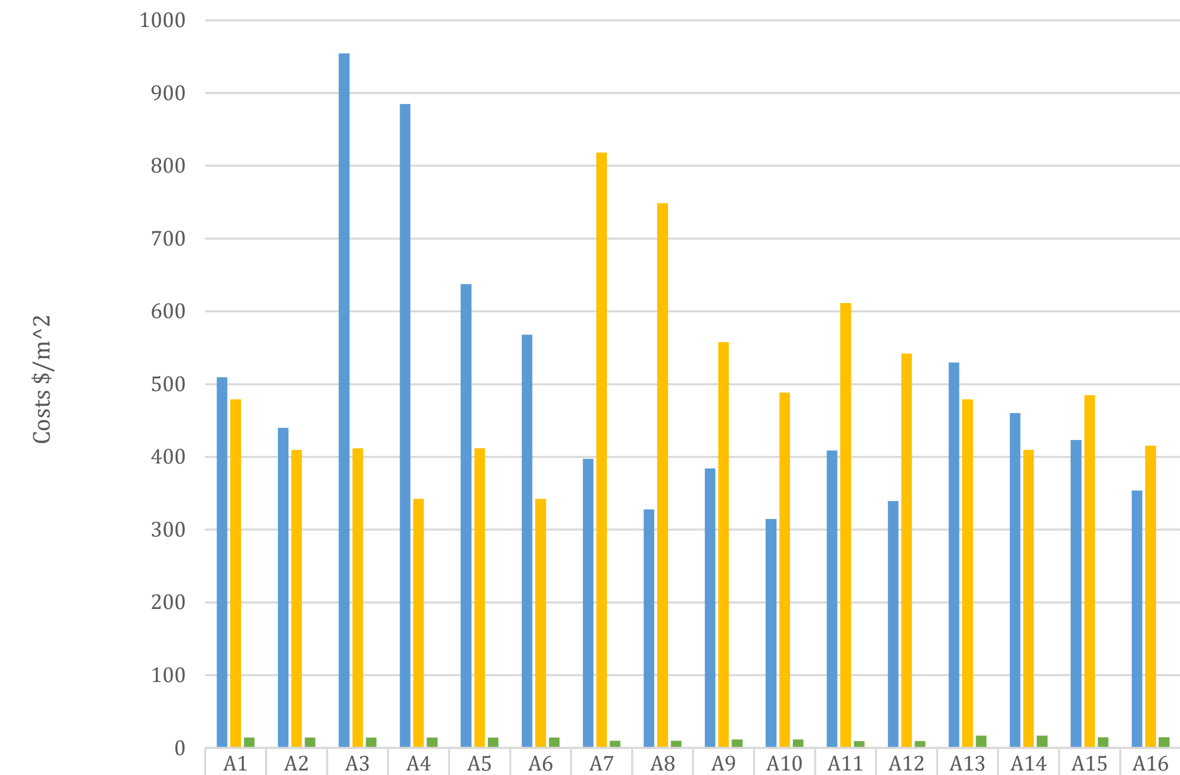


Figure 5.22 Expected service life of the 16 façade alternatives (considering a service life of 60 years for the building)

5.3.14 Life cycle costs

As previously emphasized, it is important to consider the life cycle costs of the building envelope systems in decision makings rather than only focusing on the initial costs. The calculations show that it is more economical to make large initial investments to offset costs during the operation or maintenance phases [155].

Initial (design and construction) and demolition costs of the 16 façade alternatives were determined through consulting RSMeans 2017 Building construction cost data [143] and RSMeans 2017 Assemblies costs book [156]. The maintenance costs were estimated using the information from the expected service life of the components and their maintenance needs [148, 154] and using the related repair/replacement costs in consultation with data provided in RSMeans 2017 Building construction cost data [143]. The energy consumption costs of the alternatives were not considered in the calculations to minimize the interactions among criteria (since energy efficiency is already defined as a separate criterion). Figure 5.23 presents the related life cycle costs. It can be observed from the results that although stone façades have the highest initial costs, their operation and maintenance costs are the least.



	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
Initial	509.7	440.1	954.7	885.1	637.6	568.0	397.3	327.8	384.1	314.6	408.6	339.1	529.7	460.2	423.1	353.6
O&M	479.3	409.7	411.8	342.3	411.8	342.3	818.3	748.8	557.7	488.2	611.4	541.8	479.3	409.7	484.8	415.2
Decommissioning	14.2	14.1	14.2	14.1	14.2	14.1	9.9	9.8	11.8	11.6	9.3	9.2	16.9	16.9	14.7	14.6

Figure 5.23 Life cycle costs of the 16 façade alternatives (considering a service life of 60 years for the building)

5.3.15 Aesthetics

Attributes such as aesthetics are completely subjective and dependant on the preferences of the decision maker. Hence, they cannot be measured in the same way as the other commensurable attributes.

To assign a relevant score to such attributes, the most appropriate and consistent approach is constructing the priority vector by using the pairwise comparison of the alternatives. In this procedure, a value from 1 as "equally aesthetic" up to 9 for "extremely more aesthetic," is assigned to the relative aesthetical preference of two alternatives i and j in a pairwise comparison of the alternatives.

While comparing the relative preference of alternative i to j, it is evident that if the i^{th} alternative dominates the j^{th} alternative (with regards to a criterion), then the j^{th} alternative cannot dominate the i^{th}, hence if the relative preference of alternative i to j is 5, then the the relative preference of alternative j to i would be $\frac{1}{5}$.

After the construction of the pairwise comparison Matrix A, the eigenvalue of the matrix is calculated and then the associated eigenvector is normalized to adjust the aesthetic score of each alternative as demonstrated bellow.

Matrix A: Pairwise comparisons of the façade alternatives for "Aesthetics" criterion

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
A_1	1.00	1.00	0.14	0.14	0.20	0.20	3.00	3.00	0.33	0.33	0.33	0.33	1.00	1.00	0.33	0.33
A_2	1.00	1.00	0.14	0.14	0.20	0.20	3.00	3.00	0.33	0.33	0.33	0.33	1.00	1.00	0.33	0.33
A_3	7.00	7.00	1.00	1.00	3.00	3.00	9.00	9.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
A_4	7.00	7.00	1.00	1.00	3.00	3.00	9.00	9.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
A_5	5.00	5.00	0.33	0.33	1.00	1.00	7.00	7.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
A_6	5.00	5.00	0.33	0.33	1.00	1.00	7.00	7.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
A_7	0.33	0.33	0.11	0.11	0.14	0.14	1.00	1.00	0.20	0.20	0.20	0.20	0.33	0.33	0.20	0.20
A_8	0.33	0.33	0.11	0.11	0.14	0.14	1.00	1.00	0.20	0.20	0.20	0.20	0.33	0.33	0.20	0.20
A_9	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00
A_{10}	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00
A_{11}	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00
A_{12}	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00
A_{13}	1.00	1.00	0.14	0.14	0.20	0.20	3.00	3.00	0.33	0.33	0.33	0.33	1.00	1.00	0.33	0.33
A_{14}	1.00	1.00	0.14	0.14	0.20	0.20	3.00	3.00	0.33	0.33	0.33	0.33	1.00	1.00	0.33	0.33
A_{15}	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00
A_{16}	3.00	3.00	0.14	0.14	0.20	0.20	5.00	5.00	1.00	1.00	1.00	1.00	3.00	3.00	1.00	1.00

Hence the preference score of the alternatives would be as summarized in Figure 5.24, meaning that aesthetically, alternatives 3 and 4 are the most favoured and alternatives 7 and 8 are the least preferred ones.

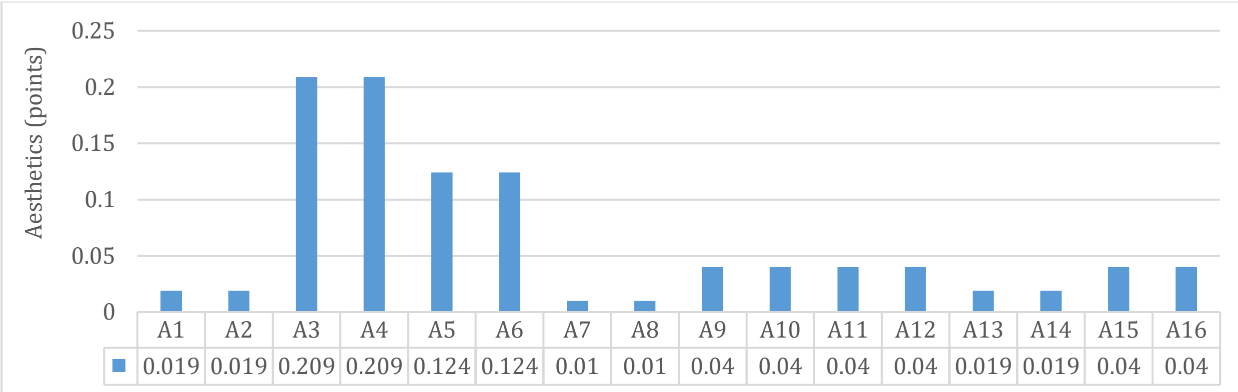


Figure 5.24 Preference scores of the 16 façade alternatives with regards to "Aesthetics" criterion

Although the pairwise comparison of alternatives is a very good method in assessing subjective criteria (which is the major strength of the AHP method), it can be inconvenient as the number of alternatives increases, since there would be $\frac{n(n-1)}{2}$ comparisons required, where n is the number of alternatives. An alternate solution would be asking the decision makers to assign a number from 1 to 9 to the degree of preference for each alternative (with regards to a specific criterion), 1 being a low preference, and 9 being an extreme preference, and then normalize the weights, where the total equals to 1. However, the pairwise comparison seems to be more reliable and accurate for measuring such criteria, since the consistency in decision making can be checked.

To ensure that the decision maker is consistent with the pairwise comparison, the consistency ratio CR should be less than 0.1. To obtain the consistency ratio, the consistency index CI is calculated, as indicated in Eq. 5.10:

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{17.016 - 16}{15} = 0.067 \tag{5. 10}$$

$$CR = \frac{CI}{RI} = \frac{0.067}{1.595} = 0.042 < 10\% \implies consistent$$

where λ_{max} is the largest eigenvalue, and RI is the random consistency index, which is equal to 1.595 , for $n = 16$ [157].

5.4 Summary

In multi-criteria decision making, it is necessary for designers to adapt quantification measures to perform the comparisons between alternatives with regards to the required design criteria. This is undertaken by identifying the measurable indicators that define or affect each criterion and performing simulations or measuring techniques to assign a numerical value to each criterion.

This chapter recommends procedures and techniques to quantify the attributes that must be considered during the conceptual façade design phase and applies these procedures to assess 16 façade alternatives for a two-storey commercial building in Montreal.

Chapter 6 Extraction of Choquet Fuzzy Measures from Profile Sets

6.1 Introduction

In practical decision-making applications, the variables involved normally have some interactions amongst them. For example, in a multi-criteria façade system design, the criteria "annual energy consumption" and "environmental impacts" convey some common information since CO_2 emissions are represented in both criteria. However, each criterion also conveys independent information such as operations cost efficiency, and recyclability of materials, respectively. Establishing the decision criteria to be as independent as possible can often improve this situation, but some interaction will generally remain.

As mentioned in Chapter 4, the Choquet integral is a proper aggregation operator in building façade design, where decision criteria are intertwined. This method has several advantages, including the potential to be used for either single or multi-dimensional decision-making problems, being mathematically non-demanding, dealing with uncertainty, and most importantly considering the interactions among criteria. This method can be integrated with AHP to assign reliable preferences and deal with qualitative and quantitative information, and because of these advantages, it can produce reliable results in the decision-making process.

Choquet method uses fuzzy measures that model the importance of each subset or combination of criteria, rather than considering only the importance of individual criteria. However, estimating the fuzzy measures in practice can be problematic and a challenging task for decision makers, which usually requires access to extensive data information.

This Chapter will introduce two methods to estimate the fuzzy measures in absence of judgment on the ranking of design alternatives. A supervised and an unsupervised approach are used in different case studies to determine the fuzzy measures related to decision criteria when there are (1) few and (2) many decision criteria involved respectively.

6.2 Choquet fuzzy measures

To identify the best way to estimate the fuzzy measures, it is necessary to be familiar with their nature and definition. The concept score of a design alternative D, with respect to n criteria using Choquet integral, is written as Eq.6.1 [87, 158]:

$$D_\mu^K(x_1, \dots, x_n) = \sum_{i=1}^{n} \left(x_{(i)} - x_{(i-1)}\right) \mu(A_i) \tag{6. 1}$$

where μ denotes the fuzzy measures, (i) is the permuted rank of a criterion such that $0 \leq x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(n)}$, $x_{(0)} = 0$ and $A_{(i)} = \left\{x_{(i)}, \dots, x_{(n)}\right\}$.

In general, these measures (μ)s are counted as the weighting factor of a subset of criteria on the universe C satisfying the following equations [159]:

$$\mu(\phi) = 0, \qquad \mu(N) = 1 \tag{6. 2}$$

$$A \subseteq B \subseteq N \ \rightarrow \mu(A) \leq \mu(B) \tag{6. 3}$$

where A and B represent the fuzzy sets. Hence, it is evident that a Choquet decision making with n criteria will have 2^n fuzzy measures (Figure 6.1).

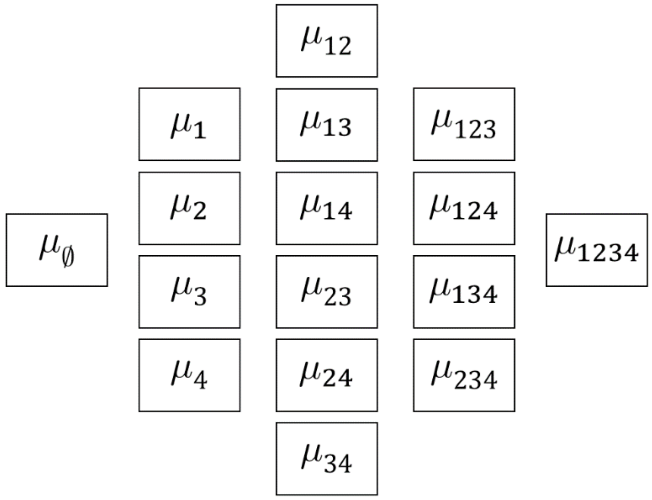


Figure 6.1 Lattice of the Choquet fuzzy measure with n=4 criteria.

The Möbius transform of μ is a set function on X defined by [160]:

$$m(A) = \sum_{B \subset A} (-1)^{|A/B|} \mu(B), \qquad \forall A \subset X \tag{6. 4}$$

The transformation is invertible such that:

$$\mu(A) = \sum_{B \subset A} m(B), \qquad \forall A \subset X \tag{6. 5}$$

A fuzzy measure μ is k-order additive if its Möbius transform $(A) = 0$, for any A such that $|A| > k$ and there is at least one subset A, of X of exactly k elements, and $m(A) \neq 0$. Accordingly, μ is 2-additive if its Möbius transform m satisfies the Eq.6.6 and Eq.6.7 [161]:

$$\forall T \in 2^N, m(T) = 0 \text{ if } |T| > 2 \tag{6. 6}$$

$$\forall T \in 2^N, \text{such that } |B| = 2 \text{ and } m(T) \neq 0. \tag{6. 7}$$

If the coefficients $\mu(\{i\})$ and $\mu(\{i\,,j\})$ are given for all $i\,, j\ \in C$, then the necessary and sufficient conditions that μ is a 2-additive measure are [161]:

$$\sum_{\{i,j\} \subseteq N} \mu(\{i,j\}) - (n-2) \sum_{i \in N} \mu(\{i\}) = 1 \qquad \text{(Normality)} \tag{6. 8}$$

$$\mu(\{i\}) \geq 0, \forall i \in N \qquad \text{(Non-negativity)} \tag{6. 9}$$

$$\forall A \subseteq N, |A| \geq 2, \forall k \in A,$$
$$\sum_{i \in A \setminus \{k\}} (\mu(\{i,k\}) - \mu(\{i\})) \geq (|A| - 2)\mu(\{k\}) \qquad \text{(Monotonicity)} \qquad (6.10)$$

The Shapley importance index S^{μ} of criterion c_i is defined by [162, 163]:

$$S^{\mu}(c_i) = \sum_{A \subseteq C \setminus \{c_i\}} \frac{(|C| - |A| - 1)!\,|A|!}{|C|!} [\mu(A \cup \{c_i\}) - \mu(A)] \qquad (6.11)$$

where $A \subseteq C \setminus \{c_i\}$ is the subset A of C, where A is any set of criteria which does not contain c_i, $|C|$ is the cardinal of C, and $|A|$ is the cardinal of A. The Shapley value ranges between [0, 1] so that $\sum_{i=1}^{n} S^{\mu}(c_i) = 1$. These values can be interpreted as a "weighted average value of the marginal contribution of criterion c_i alone in all coalitions" [163].

The difference between $\mu(c_i, c_j)$ and $\mu(c_i) + \mu(c_j)$ reflects a degree of interaction between criteria i and j. If $\mu(c_i, c_j) = \mu(c_i) + \mu(c_j)$, there is no interaction between criteria, if $\mu(c_i, c_j) < \mu(c_i) + \mu(c_j)$, there is redundancy and when $\mu(c_i, c_j) > \mu(c_i) + \mu(c_j)$, there is synergy. Murofushi and Soneda [164] have introduced a coefficient of interaction which utilizes similar concepts used in calculating the Shapley index. This Interaction index is presented in Eq. 6.12 [162, 164].

$$I(\mu, ij) = \sum_{A \subseteq C \setminus \{c_i, c_j\}} \frac{(|C| - |A| - 2)!\,|A|!}{(|C| - 1)!} \left[\mu(A \cup \{c_i, c_j\}) - \mu(A \cup \{c_i\}) - \mu(A \cup \{c_j\}) + \mu(A)\right] \qquad (6.12)$$

where $A \subseteq C \setminus \{c_i, c_j\}$ is the subset A of C, where A is any set of criteria which does not contain c_i and c_j. The interaction index ranges in [-1, 1]. For two criteria c_i and c_j, when the interaction index $I(\mu, ij) = 0$, the criteria are independent. It is obvious from Eq.6.13, that when the criteria are independent, the assessment of the alternative is obtained by a simple weighed sum. $I(\mu, ij) > 0$ when there is a complementary interaction among c_i and c_j , meaning that both criteria must be met to get a satisfactory alternative. If $I(\mu, ij) < 0$, then there is a substitutability or redundancy among c_i and c_j. This implies that the satisfaction of one of the two criteria is sufficient to have a satisfactory alternative.

If the conditions of the 2-additivity are met (or for simplicity where the interactions among three or more criteria are close to zero), Choquet function can be expressed as in Eq. 6.13.

$$D_\mu^K(x_1, \dots, x_n) = \sum_{i=1}^{n} (S_i x_i) - \frac{1}{2} \sum_{\{i,j\} \subseteq N} I_{ij} |x_i - x_j| \qquad (6.13)$$

where $S^\mu(c_i)$ is the importance weight of criteria i and $I(\mu, ij)$ is the interaction index between criteria i and j.

6.3 Identification of fuzzy measures

Similar to the weighted sum or other MCDM methods, an aggregation operator first requires the definition of the weight vector w; the application of the Choquet integral first requires the definition of the fuzzy measures μ. These weights or fuzzy measures can be determined based on the initial preferences of the decision maker (i.e. ideas regarding the importance of the attributes, relationships among them, etc. [163, 165]). Such an approach that accounts for a decision maker's point of view is referred to as a supervised approach.

As mentioned earlier, application of Choquet integral with n criteria will require identification of 2^n fuzzy measures (possible subsets of C, including C and $\emptyset$). Two of these measures are already known (refer to Eq.6.2 where $\mu(\emptyset) = 0$ and $\mu(C) = 1$). In principle, these measures need to be identified by the decision-maker, but as the number of criteria increases the identification of these $2^n - 2$ measures becomes increasingly challenging and time consuming to the point that for $n > 6$ this undertaking will probably exceed human cognitive abilities. In such cases, an unsupervised approach must be used for determination of the measures.

Although there are few proposed unsupervised procedures to identify these measures, some of them cannot be used in design problems with no learning data or knowledge regarding the relationship among criteria. In most of the methods, the DM needs to have knowledge on the ranking of the alternatives or relationship among criteria [87, 166].

In the following sections, two approaches will be used in the identification of fuzzy measures related to façade design criteria. The first is a supervised approach which uses the collective intuition of experts in design problems, followed by an unsupervised approach where only data related to the performance of alternatives with respect to each criterion is required and the decision maker has no preferences or previous knowledge of the ranking of the alternatives. These two methods are summarily explained in the following sections.

6.3.1 Supervised approach: Using collective experts' opinion

This supervised method can be used to identify the fuzzy measures when the number of criteria is not large or when the 2-additive Choquet is used (whether the conditions are met, or according to designers' intuition, the interactions among three or more criteria are close to zero and negligible).

For this purpose, generally, a questionnaire is designed and distributed among experts in the field to ask their opinion on the degree of influence of criterion i on criterion j. Moghtadernejad et al [13] have applied this method to find the fuzzy measures $S^{\mu}(c_i)$ and $I(\mu, ij)$ of a 2-additive Choquet model. In this study the $S^{\mu}(c_i)$ measures that are representation of the importance weight of criteria, were assigned using the pairwise comparison of the 8 façade design criteria namely, aesthetics (c_1), weight (c_2), fire resistance (c_3), acoustics (c_4), environmental impacts (c_5), ease of construction (c_6), durability (c_7), and initial costs (c_8). The pairwise comparison was conducted, as explained in Section 5.3.15, and the $S^{\mu}(c_i)$ measures were determined as illustrated in Eq.6.14.

$$C = \begin{array}{c} \\ c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \end{array} \begin{array}{c} \begin{array}{cccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 \end{array} \\ \begin{bmatrix} 1 & 3 & 1 & \frac{1}{3} & \frac{1}{3} & 3 & \frac{1}{7} & \frac{1}{5} \\ \frac{1}{3} & 1 & \frac{1}{3} & \frac{1}{5} & \frac{1}{5} & 1 & \frac{1}{5} & \frac{1}{9} \\ 1 & 3 & 1 & \frac{1}{3} & \frac{1}{5} & 3 & \frac{1}{5} & \frac{1}{5} \\ 3 & 5 & 3 & 1 & 1 & 3 & \frac{1}{3} & \frac{1}{3} \\ 3 & 5 & 5 & 1 & 1 & 5 & \frac{1}{3} & 5 \\ \frac{1}{3} & 1 & \frac{1}{3} & \frac{1}{3} & \frac{1}{5} & 1 & \frac{1}{9} & \frac{1}{5} \\ 7 & 5 & 5 & 3 & 3 & 9 & 1 & 7 \\ 5 & 9 & 5 & 3 & \frac{1}{5} & 5 & \frac{1}{7} & 1 \end{bmatrix} \end{array} \quad \begin{array}{c} S^{\mu}(c_i) \\ 0.049646 \\ 0.024799 \\ 0.047042 \\ 0.104249 \\ 0.174126 \\ 0.026359 \\ 0.421846 \\ 0.151932 \end{array} \tag{6. 14}$$

The consistency ratio of the preference matrix was determined to be 6.9% which is less than 10% and acceptable (Eq. 5.10).

To find the $I(\mu, ij)$ measures, that are interaction indices between criteria i and j, a questionnaire was distributed among 47 façade designers and building science experts, around the world, to identify the interactions among the design criteria. Figures 6.2 and 6.3 represent the fields and level of expertise of the participants.

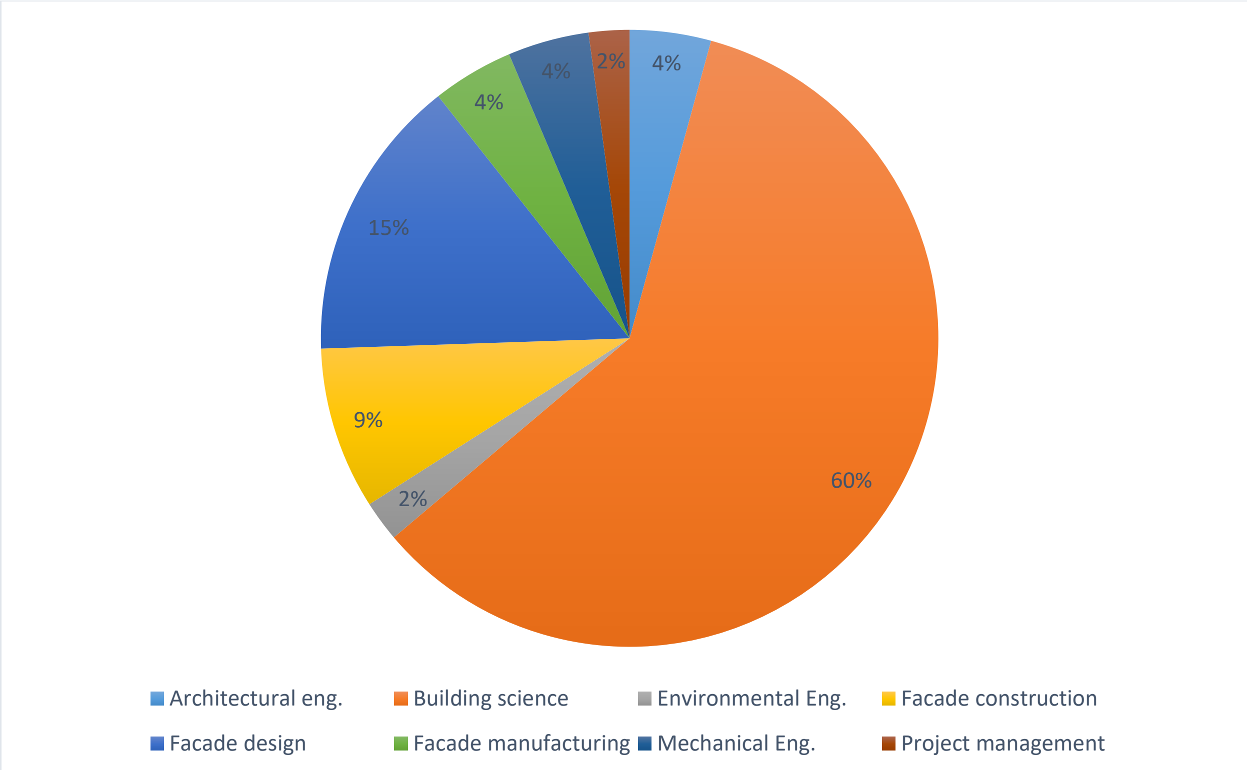


Figure 6.2 Field of expertise of the questionnaire participants

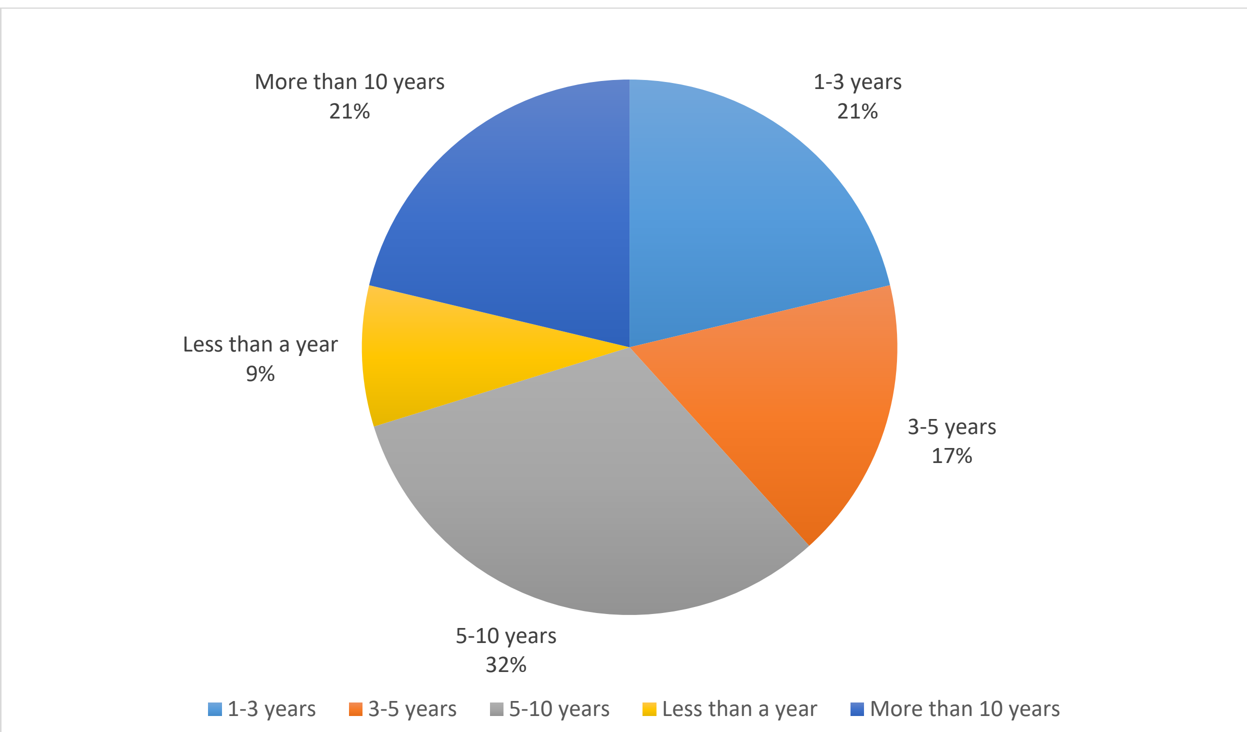


Figure 6.3 Level of expertise of the participants

In this process, the separate criteria, the redundancy or complementarity among criteria were identified based on the intuition of the authors. It was hypothesized that the interacting criteria were 11 sets as defined in Table 6.1 and the rest of the interactions were zero or negligible. Table 6.1 illustrates the questionnaire results, which is the average of the responses from experts where the outliers have been omitted from calculations. The raw results of the questionnaire are presented in Appendix E.

Table 6.1 Identified interacting (dependent) criteria

c_2, c_5	c_2, c_6	c_2, c_8	c_3, c_5	c_3, c_7	c_3, c_8	c_4, c_8	c_5, c_7	c_5, c_8	c_6, c_8	c_7, c_8
0.51	0.68	0.45	0.21	0.39	0.36	0.33	0.39	0.32	0.46	0.54

One potential problem with this method is that in some situations, there is little consensus among the experts and the opinion of one expert may vary significantly from that of another. To resolve this problem, one solution may be assigning weighs to the opinion of each expert as a function of their experience level in the field.

6.3.2 Unsupervised approach: Using data from profile sets

Using an unsupervised approach to extract the fuzzy measures is needed when the number of decision criteria is very large. Presently, most unsupervised approaches require some knowledge on the ranking of alternatives or access to extensive data sets. For instance, Kojadinovic [165, 167] has proposed an unsupervised approach in the absence of initial preferences and estimated the fuzzy measures $\mu(A_i) = \frac{h(A_i)}{\mathrm{h(C)}}$, where A_i are a subset of criteria set C, and $h(A_i)$ is the entropy of any of the $(n-i+1)!$ vectors made of the probability distributions of the observations $p \in A_i$. However, this method requires a large number of profile sets (as it grows exponentially with the increase in the number of criteria) to accurately estimate these measures.

The method that seems most appropriate for the purpose of this research was introduced by Rowley et al. [163] which extracts the fuzzy measures using the principal component analysis (PCA) method.

The method is based on identifying a measure of independence χ^* among the design criteria. It is evident that in case of a completely uncorrelated criteria, $\chi^* = n$, (n is the number of criteria) and the correlation matrix will be an $(n \times n)$ matrix I. Hence, as proposed by Rowley et al. [163], for A_i as a subset of criteria set C, fuzzy measures would be identified as in Eq. 6.15 [163]

$$\mu(A_i) = \frac{\chi^* (A_i)}{\chi^* (\mathrm{C})} \tag{6. 15}$$

To calculate the χ^* the principal component analysis will be used.

The PCs of a set of assessments on any A_i as a subset of criteria set C (including C itself) are calculated by developing an orthonormal basis so that "each successive PC captures maximal remaining variance present in the evaluations, while being independent of the previously-determined PCs" [163, 168]. The vector z of PCs can be identified using the Eq.6.16, where z_i is the PC related to the i^{th} element of the basis.

$$z = \Phi^T A \tag{6. 16}$$

where Φ is the square orthogonal matrix with its i^{th} column being the eigenvector related to the i^{th} largest eigenvalue λ_i of the constructed correlation matrix, and A is a subset of criteria set C (including C itself). It is possible to determine the proportion of variance that is captured separately by each PC (Eq.6.17).

$$v_i = \frac{\lambda_i}{\sum_i \lambda_i} \tag{6.17}$$

Rowley et al. [163] suggested selecting the measures of independence, χ^*, based on Eq. 6.18.

$$\chi^* \, (A_i) \; = \sum_{i;\lambda_i<1} \lambda_i + |\{ \; \lambda_i | \; \lambda_i \geq 1\}| \tag{6.18}$$

where | | denotes the number of elements in a combination.

It is proven [163] that the estimated measures meet the three rules of Choquet fuzzy measures by showing that :

$$\mu(\emptyset) = \frac{\chi^*(\emptyset)}{\chi^*(\mathrm{C})} = 0$$

$$\mu(N) = \frac{\chi^*(\mathrm{C})}{\chi^*(\mathrm{C})} = 1$$

if $A_i \subseteq \; A_j \; \Rightarrow \; \mu(A_i) < \; \mu(A_j)$

6.4 Extraction of façade design fuzzy measures from assessed profile sets

As previously mentioned, the supervised approach can be used only in design problems with few criteria. Hence, it cannot be a suitable approach for the purpose of this research. As a result, the unsupervised approach was adopted utilizing the previously assessed profile sets (MFPs of the 16 façade alternatives in Chapter 5) to extract the Choquet fuzzy measures, using the PCA method. The MFP Matrix of the alternatives is demonstrated in Table 6.4.

To avoid the excessive influence of criteria with larger scales and unit order of magnitudes, Rowley et al. [163] propose normalizing the criteria using Eq. 6.19.

$$C_i^* \; = \frac{\alpha_i C_i - min\{\alpha_i C_i\}}{max\{\alpha_i C_i\} - min\{\alpha_i C_i\}} \tag{6.19}$$

where C_i^* are the elements of the normalized matrix, C_i are the partial scores of alternatives with respect to criterion i, and α_i are factors (+1 or -1) depending on whether a higher value of the criterion is preferred, or a lower one.

However, in this research, a different method of normalization was adopted since the results generated by Eq.6.18 would map the assessed value of design criteria between 0 and 1, meaning that with respect to a certain criterion, the best alternative will receive 1 and the worst 0.

Using this method of normalizing will excessively prioritize or deprioritize an alternative, hence an alternate method was utilized depending on whether higher values of the criteria are desirable, or lower ones. The normalizing factors are presented in Eq.6.20 and Eq. 6.21.

For a criterion that requires a higher value, the normalized value would be equal to:

$$C_i^* = \frac{C_i}{max(C_i)} \qquad (6.20)$$

and for a criterion that a smaller value is more desirable (e.g. costs), the normalized value should be derived from:

$$C_i^* = \frac{min\,(C_i)}{C_i} \qquad (6.21)$$

The resulting normalized MFP matrix is shown in Table 6.5.

Table 6.2 Performance scores for the 16 façade alternatives

#	Design criteria	Unit	Pref	Assessed performance of the alternatives															
				A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
1	Total thickness	m	L	0.322	0.322	0.308	0.308	0.308	0.308	0.227	0.227	0.202	0.202	0.219	0.219	0.451	0.451	0.356	0.356
2	Weight	kN/m²	L	1.410	1.370	1.820	1.780	1.530	1.490	0.280	0.240	0.560	0.520	0.420	0.380	2.960	2.920	2.140	2.100
3	Fire rating	minutes	H	120	120	90	90	90	90	60	60	90	90	120	120	240	240	240	240
4	Vapour resistance	ng/Pa·s·m²	H	6.484	6.484	6.811	6.811	6.811	6.811	6.500	6.500	6.430	6.430	6.468	6.468	6.529	6.529	6.518	6.518
5	Thermal resistance	RSI (m²K/W)	H	3.560	3.385	3.262	3.087	3.313	3.138	3.369	3.194	3.142	2.967	3.285	3.110	3.089	2.914	3.146	2.971
6	Sound transmission class	STC	H	49.60	46.40	46.00	42.80	46.00	42.80	46.60	43.40	50.20	47.00	46.60	43.40	49.60	46.40	49.60	46.40
7	Window solar performance	Points	H																
	VT	-	H	0.432	0.569	0.432	0.569	0.432	0.569	0.432	0.569	0.432	0.569	0.432	0.569	0.432	0.569	0.432	0.569
	SHGC	-	H	0.250	0.378	0.250	0.378	0.250	0.378	0.250	0.378	0.250	0.378	0.250	0.378	0.250	0.378	0.250	0.378
	CR	-	H	59.00	63.00	59.00	63.00	59.00	63.00	59.00	63.00	59.00	63.00	59.00	63.00	59.00	63.00	59.00	63.00
8	Ease of construction	labour hours/m²	L	1.970	1.940	1.834	1.804	1.834	1.804	0.956	0.926	2.093	2.062	1.020	0.990	2.616	2.586	1.666	1.636
9	Annual energy consumption	kWh/m²	L	132.43	133.37	132.29	133.26	132.72	133.58	132.27	133.46	133.04	133.90	132.76	133.66	134.11	134.75	134.31	135.05
10	System effect on environment	points	L																
	GWP	kg CO_2 eq /m²	L	3.250	2.463	2.613	1.829	2.613	1.829	-0.070	-0.854	2.142	1.358	1.765	0.981	6.423	5.639	5.260	4.476
	Acidification potential (land and water)	kg SO_2 eq/m²	L	0.039	0.031	0.026	0.018	0.026	0.018	0.028	0.019	0.024	0.016	0.025	0.017	0.054	0.046	0.042	0.033
	HH criteria	kg PM2.5 eq/m²	L	0.004	0.003	0.007	0.007	0.007	0.007	0.003	0.003	0.004	0.004	0.005	0.004	0.007	0.006	0.007	0.007
	Eutrophication potential	kg N eq/m²	L	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003	0.002
	Ozone depletion potential	kg CFC-11 eq/m²	L	1.86E-07	1.29E-07	1.85E-07	1.27E-07	1.85E-07	1.27E-07	1.83E-07	1.26E-07	1.86E-07	1.28E-07	1.88E-07	1.31E-07	2.00E-07	1.43E-07	2.00E-07	1.43E-07
	Smog potential	kg O_3 eq/m²	L	0.497	0.425	0.480	0.408	0.480	0.408	0.514	0.441	0.387	0.315	0.362	0.290	0.741	0.669	0.688	0.615
	Total primary energy	MJ/m²	L	75.900	62.146	77.998	64.228	77.998	64.228	66.506	52.736	62.012	48.242	58.341	44.571	108.04	94.273	99.376	85.606
	Non-renewable energy	MJ/m²	L	53.800	44.427	48.470	39.057	48.470	39.057	42.722	33.309	42.358	32.945	37.972	28.559	85.922	76.510	78.444	69.032
	Fossil fuel consumption	MJ/m²	L	50.100	40.695	44.542	35.176	44.542	35.176	39.153	29.786	38.215	28.849	34.238	24.872	82.311	72.945	74.464	65.097
11	Durability	years	H	50	50	60	60	60	60	15	15	25	25	30	30	50	50	30	30
12	Initial costs	$/ m²	L	509.67	440.14	954.65	885.12	637.55	568.01	397.30	327.76	384.12	314.59	408.60	339.06	529.69	460.16	423.13	353.59
13	O&M costs	$/ m²	L	479.27	409.74	411.78	342.25	411.78	342.25	818.34	748.80	557.74	488.21	611.35	541.81	479.27	409.74	484.76	415.23
14	Decommissioning costs	$/ m²	L	14.21	14.08	14.21	14.08	14.21	14.08	9.88	9.75	11.75	11.62	9.25	9.20	16.91	16.85	14.66	14.61
15	Aesthetics	points	H	0.019	0.019	0.209	0.209	0.124	0.124	0.01	0.01	0.04	0.04	0.04	0.04	0.019	0.019	0.04	0.04

"H" denotes a higher value is preferred while "L" means a lower value is desirable

Table 6.3. The normalized elements of MFP Matrix

#	Design criteria	Pref.	Assessed performance of the alternatives															
			A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
1	Total thickness	L	0.627	0.627	0.656	0.656	0.656	0.656	0.890	0.890	1.000	1.000	0.922	0.922	0.448	0.448	0.567	0.567
2	Weight	L	0.170	0.175	0.132	0.135	0.157	0.161	0.857	1.000	0.429	0.462	0.571	0.632	0.081	0.082	0.112	0.114
3	Fire rating	H	0.500	0.500	0.375	0.375	0.375	0.375	0.250	0.250	0.375	0.375	0.500	0.500	1.000	1.000	1.000	1.000
4	Vapour resistance	H	0.952	0.952	1.000	1.000	1.000	1.000	0.954	0.954	0.944	0.944	0.950	0.950	0.958	0.958	0.957	0.957
5	Thermal resistance	H	1.000	0.951	0.916	0.867	0.931	0.881	0.946	0.897	0.882	0.833	0.923	0.874	0.868	0.818	0.884	0.834
6	Sound transmission class	H	0.988	0.924	0.916	0.853	0.916	0.853	0.928	0.865	1.000	0.936	0.928	0.865	0.988	0.924	0.988	0.924
7	Window solar performance	H	0.786	1.000	0.786	1.000	0.786	1.000	0.786	1.000	0.786	1.000	0.786	1.000	0.786	1.000	0.786	1.000
	VT	H	0.759	1.000	0.759	1.000	0.759	1.000	0.759	1.000	0.759	1.000	0.759	1.000	0.759	1.000	0.759	1.000
	SHGC	H	0.661	1.000	0.661	1.000	0.661	1.000	0.661	1.000	0.661	1.000	0.661	1.000	0.661	1.000	0.661	1.000
	CR	H	0.937	1.000	0.937	1.000	0.937	1.000	0.937	1.000	0.937	1.000	0.937	1.000	0.937	1.000	0.937	1.000
8	Ease of construction	L	0.470	0.477	0.505	0.513	0.505	0.513	0.968	1.000	0.442	0.449	0.907	0.935	0.354	0.358	0.556	0.566
9	Annual energy consumption	L	0.999	0.992	1.000	0.993	0.997	0.990	1.000	0.991	0.994	0.988	0.996	0.990	0.986	0.982	0.985	0.979
10	System effect on environment	L	0.532	0.657	0.531	0.676	0.531	0.676	0.614	0.874	0.626	0.816	0.644	0.848	0.368	0.434	0.390	0.465
	GWP	L	0.034	0.042	0.040	0.052	0.040	0.052	0.157	1.000	0.046	0.062	0.053	0.074	0.020	0.022	0.023	0.027
	Acidification potential (land and water)	L	0.403	0.516	0.599	0.887	0.599	0.887	0.568	0.822	0.648	1.000	0.627	0.951	0.290	0.344	0.376	0.473
	HH criteria	L	0.734	0.840	0.377	0.404	0.377	0.404	0.852	1.000	0.648	0.730	0.587	0.654	0.398	0.427	0.361	0.385
	Eutrophication potential	L	0.741	0.881	0.757	0.905	0.757	0.905	0.721	0.854	0.822	1.000	0.812	0.985	0.539	0.610	0.550	0.625
	Ozone depletion potential	L	0.679	0.978	0.683	0.991	0.683	0.991	0.688	1.000	0.680	0.983	0.671	0.965	0.630	0.881	0.632	0.885
	Smog potential	L	0.583	0.681	0.603	0.709	0.603	0.709	0.564	0.656	0.748	0.919	0.800	1.000	0.391	0.433	0.421	0.471
	Total primary energy	L	0.587	0.717	0.571	0.694	0.571	0.694	0.670	0.845	0.719	0.924	0.764	1.000	0.413	0.473	0.449	0.521
	Non-renewable energy	L	0.531	0.643	0.589	0.731	0.589	0.731	0.668	0.857	0.674	0.867	0.752	1.000	0.332	0.373	0.364	0.414
	Fossil fuel consumption	L	0.496	0.611	0.558	0.707	0.558	0.707	0.635	0.835	0.651	0.862	0.726	1.000	0.302	0.341	0.334	0.382
11	Durability	H	0.833	0.833	1.000	1.000	1.000	1.000	0.200	0.200	0.417	0.417	0.500	0.500	0.833	0.833	0.500	0.500
12	Initial costs	L	0.617	0.715	0.330	0.355	0.493	0.554	0.792	0.960	0.819	1.000	0.770	0.928	0.594	0.684	0.743	0.890
13	O&M costs	L	0.714	0.835	0.831	1.000	0.831	1.000	0.418	0.457	0.614	0.701	0.560	0.632	0.714	0.835	0.706	0.824
14	Decommissioning costs	L	0.647	0.653	0.647	0.653	0.647	0.653	0.931	0.943	0.782	0.791	0.994	1.000	0.544	0.546	0.627	0.629
15	Aesthetics	H	0.091	0.091	1.000	1.000	0.593	0.593	0.048	0.048	0.191	0.191	0.191	0.191	0.091	0.091	0.191	0.191

In addition, this method can be used when there is information available on the ranking or the preference of the alternatives. In such cases, a weighted correlation matrix will be constructed using Eq.6.22. Otherwise, an unweighted Pearson correlation matrix is constructed, as was done in this case study.

$$r_{ij} = \frac{\sum_{k=1}^{m} \frac{m y_k}{\sum_l y_l} \left(p_i^k - \bar{p_\iota}\right)\left(p_j^k - \bar{p_J}\right)}{\sqrt{\sum_{k=1}^{m} \frac{m y_k}{\sum_l y_l} \left(p_i^k - \bar{p_\iota}\right)^2 \sum_{k=1}^{m} \frac{m y_k}{\sum_l y_l} \left(p_j^k - \bar{p_J}\right)^2}} \tag{6. 22}$$

$$\bar{p_\iota} = \sum_{k=1}^{m} \frac{y_k}{\sum_l y_l} \left(p_i^k\right) \tag{6. 23}$$

where y_k is the importance (degree of preference) of each alternative and $\sum_l y_l$ is the total importance.

After constructing the normalized MFP matrix, the 2^n measures were extracted by using the procedure explained in Section 6.3.2. Due to the infeasibility of printing these 2^{15} measures, the related MATLAB codes for extracting these measures are included in Appendix F. The Shapley interaction indices are presented in Table 6.6.

6.5 Discussion

It can be deduced from Table 6.6 that most of the interactions are not high which suggests that the decision criteria have been selected to be almost independent (-1 and 1 being the perfect dependency). It is noted that most significant interactions are negative, which denotes positive correlation and redundancy among criteria. The highest interaction (0.065) is between the thermal resistance (c_5) and annual energy consumption (c_9), which is reasonable as the thermal resistance of a façade assembly can influence the energy performance of the building. The thermal resistance is also interactive with the window performance (c_7).

The second strongest interaction is between the sound transmission class (c_6) and the window performance that is around 0.058. Though SHGC, VT and CR, do not directly influence the sound transmission rate, it is noted that windows with enhanced performance (SHGC, VT and CR) will have a better performance with respect to sound transmission, therefore, the sound transmission of the entire assembly will be affected as well. The same goes for the sound transmission class and vapour resistance (c_4) interactions, which suggest that a wall assembly with better resistance to vapour diffusion will have a better performance in attenuating the airborne sound. Moreover, the window performance is interactive with the system effect on the environment (c_{10}), meaning, enhanced window performance will decrease the environmental footprint.

Other significant interactions are between the fire rating of the assembly (c_3), and the annual energy consumption and the system effect on the environment which are rational.

Improving the vapour resistance of the assembly will improve its durability while affecting the initial costs (c_{12}). The demolition costs (c_{14}) is dependant on the ease of construction (c_8), which conforms with the author's expectations.

The interaction of the durability with the initial costs (c_{12}) and operations and maintenance costs (c_{13}), also sounds logical.

Table 6.7 shows the variance explained (VE) and the cumulative variance explained (CVE) gained from the PCA model which provides further insight into the structure of the data. It can be observed that only 4 PCs are required to obtain 90% of the variance in the dataset.

Table 6.4 Shapley interaction indices of 16 façade alternatives

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
c_1		-0.0190	-0.0300	-0.0066	0.0033	0.0030	0.0016	-0.0035	-0.0118	-0.0308	-0.0172	-0.0136	-0.0099	-0.0285	0.0005
c_2			-0.0144	-0.0070	-0.0010	-0.0056	0.0004	-0.0311	-0.0053	-0.0173	-0.0266	-0.0138	-0.0290	-0.0277	-0.0002
c_3				-0.0121	-0.0196	-0.0122	0.0043	-0.0002	-0.0456	-0.0370	-0.0006	0.0005	-0.0008	-0.0117	-0.0009
c_4					0.0038	-0.0365	0.0044	0.0011	-0.0092	0.0017	-0.0286	-0.0455	-0.0244	-0.0069	-0.0056
c_5						-0.0084	-0.0333	-0.0057	-0.0643	0.0041	-0.0028	-0.0081	-0.0042	-0.0017	0.0006
c_6							-0.0582	-0.0179	0.0061	-0.0276	-0.0036	-0.0005	-0.0098	-0.0076	-0.0016
c_7								0.0026	-0.0374	-0.0345	0.0015	-0.0106	-0.0185	0.0017	0.0004
c_8									-0.0040	-0.0057	-0.0194	-0.0062	-0.0219	-0.0349	0.0001
c_9										-0.0028	-0.0017	-0.0187	-0.0029	-0.0076	-0.0006
c_{10}											-0.0042	-0.0085	-0.0003	-0.0203	0.0002
c_{11}												-0.0356	-0.0347	-0.0181	-0.0017
c_{12}													-0.0174	-0.0120	-0.0036
c_{13}														-0.0195	-0.0018
c_{14}															0.0002
c_{15}															

Table 6.5 PCA model for the dataset

PC#	Eigenvalue	VE	CVE
1	6.49286910	0.4634453319	0.4634453319
2	3.14167617	0.2242452655	0.6876905973
3	2.70088497	0.1927826529	0.8804732503
4	0.76479709	0.0545893710	0.9350626213
5	0.51274609	0.0365985787	0.9716612000
6	0.19226308	0.0137232745	0.9853844745
7	0.11447854	0.0081712018	0.9935556763
8	0.05500199	0.0039259094	0.9974815858
9	0.02710553	0.0019347276	0.9994163134
10	0.00702432	0.0005013789	0.9999176923
11	0.00088749	0.0000633469	0.9999810392
12	0.00018187	0.0000129818	0.9999940210
13	0.00005740	0.0000040971	0.9999981181
14	0.00002633	0.0000018797	0.9999999977
15	0.00000003	0.0000000023	1.0000000000

6.6 Summary

Choquet integrals is a decision-making method that uses fuzzy measures to model the importance of each subset or combination of criteria, rather than only considering the importance of the individual criterion. However, estimating the fuzzy measures in practice can be problematic and cognitively challenging for decision makers and the recently developed approaches require prohibitively large data information.

This Chapter introduced two feasible methods to estimate the fuzzy measures when there are no initial preferences or knowledge on the rankings of the alternatives. A supervised approach with 8 decision criteria was used to extract the fuzzy measures related to a 2-additive Choquet function. In this method, the decision maker constructed the pairwise preference matrix to identify the importance weights of decision criteria $S^{\mu}(c_i)$, and a questionnaire was distributed among a panel of experts to define the interaction indices

$I(\mu, ij)$. The problem with this method is that it can only be used when the number of fuzzy measures to be identified are small (i.e. the number of criteria must be small).

The second method was an unsupervised approach using the principal component analysis. This method was applied to the MFP of 16 façade alternatives, to estimate the fuzzy measures related to 15 decision criteria. The results related to the interaction indices show that the extracted measures are logical and can be used in either 2-additive or k-additive Choquet functions. However, it must be noted that in presence of an expert's judgement on the ranking of the alternatives, the weighted correlation matrix could be used in the procedure and the fuzzy measures could have been extracted with more precision.

Chapter 7 Application of AHP, TOPSIS and Choquet Integral in Comparison of Façade Alternatives

7.1 Introduction

In this chapter, the three most suitable MCDM methods, namely, Choquet integrals, AHP and TOPSIS that were introduced in Chapter 4, will be applied to rank the 16 façade alternatives based on the performance assessments that were conducted in Chapter 5 and the results are compared. The evaluation is performed with regards to 15 criteria as summarized in Table 6.4 and the Multi-criteria Façade Performance (MFP) matrix is constructed using appropriate normalizing factors for each method.

7.2 Constructing the multi-criteria façade performance (MFP) matrix

To cancel the excessive influence of criteria with larger units, it is necessary to normalize the raw criteria scores for each alternative. For this reason, all criteria must be normalized depending on whether a higher or a lower value of the criteria is desired (Eq. 6.20 and Eq. 6.21). The elements of the MFP matrix are shown in Table 6.5. For AHP and TOPSIS, it is necessary to divide the elements of the constructed MFP matrix by appropriate normalizing factors that are expressed in Eq.7.1 and Eq.7.2. The normalized matrices for AHP and TOPSIS are shown in Table 7.1 and Table 7.2 respectively.

$$r_{ij\,(AHP)} = \frac{x_{ij}}{\sum_{k=1}^{m} x_{kj}} \tag{7.1}$$

$$r_{ij\,(TOPSIS)} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{m} x_{kj}^{2}}} \tag{7.2}$$

Table 7.1 Normalized performance scores for AHP

#	Design criteria	Pref.	Assessed performance of the alternatives															
			A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
1	Total thickness	L	0.054	0.054	0.057	0.057	0.057	0.057	0.077	0.077	0.087	0.087	0.080	0.080	0.039	0.039	0.049	0.049
2	Weight	L	0.032	0.033	0.025	0.026	0.030	0.031	0.163	0.190	0.081	0.088	0.108	0.120	0.015	0.016	0.021	0.022
3	Fire rating	H	0.057	0.057	0.043	0.043	0.043	0.043	0.029	0.029	0.043	0.043	0.057	0.057	0.114	0.114	0.114	0.114
4	Vapour resistance	H	0.062	0.062	0.065	0.065	0.065	0.065	0.062	0.062	0.061	0.061	0.062	0.062	0.062	0.062	0.062	0.062
5	Thermal resistance	H	0.070	0.066	0.064	0.061	0.065	0.062	0.066	0.063	0.062	0.058	0.065	0.061	0.061	0.057	0.062	0.058
6	Sound transmission class	H	0.067	0.062	0.062	0.058	0.062	0.058	0.063	0.058	0.068	0.063	0.063	0.058	0.067	0.062	0.067	0.062
7	Window solar performance	H	0.055	0.070	0.055	0.070	0.055	0.070	0.055	0.070	0.055	0.070	0.055	0.070	0.055	0.070	0.055	0.070
8	Ease of construction	L	0.049	0.050	0.053	0.054	0.053	0.054	0.102	0.105	0.046	0.047	0.095	0.098	0.037	0.038	0.058	0.059
9	Annual energy consumption	L	0.063	0.063	0.063	0.063	0.063	0.062	0.063	0.062	0.063	0.062	0.063	0.062	0.062	0.062	0.062	0.062
10	System effect on environment	L	0.055	0.068	0.055	0.070	0.055	0.070	0.063	0.090	0.065	0.084	0.066	0.088	0.038	0.045	0.040	0.048
11	Durability	H	0.079	0.079	0.095	0.095	0.095	0.095	0.019	0.019	0.039	0.039	0.047	0.047	0.079	0.079	0.047	0.047
12	Initial costs	L	0.055	0.064	0.029	0.032	0.044	0.049	0.070	0.085	0.073	0.089	0.068	0.083	0.053	0.061	0.066	0.079
13	O&M costs	L	0.061	0.072	0.071	0.086	0.071	0.086	0.036	0.039	0.053	0.060	0.048	0.054	0.061	0.072	0.060	0.071
14	Decommissioning costs	L	0.055	0.056	0.055	0.056	0.055	0.056	0.080	0.081	0.067	0.068	0.085	0.086	0.047	0.047	0.054	0.054
15	Aesthetics	H	0.019	0.019	0.209	0.209	0.124	0.124	0.010	0.010	0.040	0.040	0.040	0.040	0.019	0.019	0.040	0.040

Table 7.2 Normalized performance scores for TOPSIS

#	Design criteria	Pref.	Assessed performance of the alternatives															
			A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
1	Total thickness	L	0.211	0.211	0.221	0.221	0.221	0.221	0.299	0.299	0.336	0.336	0.310	0.310	0.151	0.151	0.191	0.191
2	Weight	L	0.098	0.100	0.076	0.077	0.090	0.092	0.491	0.573	0.246	0.265	0.328	0.362	0.046	0.047	0.064	0.066
3	Fire rating	H	0.205	0.205	0.153	0.153	0.153	0.153	0.102	0.102	0.153	0.153	0.205	0.205	0.409	0.409	0.409	0.409
4	Vapour resistance	H	0.247	0.247	0.259	0.259	0.259	0.259	0.247	0.247	0.245	0.245	0.246	0.246	0.248	0.248	0.248	0.248
5	Thermal resistance	H	0.279	0.265	0.256	0.242	0.260	0.246	0.264	0.250	0.246	0.233	0.258	0.244	0.242	0.229	0.247	0.233
6	Sound transmission class	H	0.267	0.250	0.247	0.230	0.247	0.230	0.251	0.233	0.270	0.253	0.251	0.233	0.267	0.250	0.267	0.250
7	Window solar performance	H	0.218	0.278	0.218	0.278	0.218	0.278	0.218	0.278	0.218	0.278	0.218	0.278	0.218	0.278	0.218	0.278
8	Ease of construction	L	0.186	0.189	0.200	0.203	0.200	0.203	0.383	0.395	0.175	0.177	0.359	0.370	0.140	0.142	0.220	0.224
9	Annual energy consumption	L	0.252	0.250	0.252	0.250	0.251	0.250	0.252	0.250	0.251	0.249	0.251	0.250	0.249	0.248	0.248	0.247
10	System effect on environment	L	0.213	0.263	0.213	0.271	0.213	0.271	0.246	0.351	0.251	0.327	0.258	0.340	0.148	0.174	0.156	0.186
11	Durability	H	0.291	0.291	0.349	0.349	0.349	0.349	0.070	0.070	0.145	0.145	0.175	0.175	0.291	0.291	0.175	0.175
12	Initial costs	L	0.212	0.245	0.113	0.122	0.169	0.190	0.271	0.329	0.281	0.343	0.264	0.318	0.204	0.234	0.255	0.305
13	O&M costs	L	0.239	0.279	0.278	0.334	0.278	0.334	0.140	0.153	0.205	0.234	0.187	0.211	0.239	0.279	0.236	0.276
14	Decommissioning costs	L	0.217	0.219	0.217	0.219	0.217	0.219	0.312	0.316	0.262	0.265	0.333	0.335	0.182	0.183	0.210	0.211
15	Aesthetics	H	0.053	0.053	0.581	0.581	0.345	0.345	0.028	0.028	0.111	0.111	0.111	0.111	0.053	0.053	0.111	0.111

7.3 Constructing the weighted (MFP) matrix

Importance weights, w_j, are determined by using the pairwise comparison of the various decision criteria. A value from 1 (equally important) up to 9 (extremely more important) is assigned to c_{ij} while comparing the relative importance of criteria i to j. Matrix B, illustrates the pairwise comparisons of the 15 decision criteria. The weight of each criterion is identified by normalizing the elements of the principal eigenvector as shown in Table 7.5 The principal eigenvector is the eigenvector that contains the largest eigenvalue of the matrix.

Matrix B: Pairwise comparison decision criteria

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
c_1	1.000	0.333	3.000	0.200	0.200	0.333	0.200	0.333	0.111	0.111	0.143	0.200	0.200	0.200	0.111
c_2	3.000	1.000	3.000	0.200	0.200	0.333	0.333	0.333	0.111	0.143	0.200	0.200	0.200	0.200	0.143
c_3	0.333	0.333	1.000	0.200	0.200	0.333	0.333	0.200	0.111	0.111	0.143	0.200	0.200	0.200	0.200
c_4	5.000	5.000	5.000	1.000	1.000	5.000	5.000	5.000	0.143	0.200	0.333	1.000	1.000	1.000	1.000
c_5	5.000	5.000	5.000	1.000	1.000	5.000	7.000	5.000	0.111	0.143	0.200	1.000	1.000	1.000	3.000
c_6	3.000	3.000	3.000	0.200	0.200	1.000	1.000	0.200	0.111	0.111	0.111	0.200	0.200	0.200	0.200
c_7	5.000	3.000	3.000	0.200	0.143	1.000	1.000	1.000	0.143	0.111	0.143	0.333	0.333	0.333	0.200
c_8	3.000	3.000	5.000	0.200	0.200	5.000	1.000	1.000	0.143	0.111	0.143	0.333	0.333	0.333	0.200
c_9	9.000	9.000	9.000	7.000	9.000	9.000	7.000	7.000	1.000	3.000	3.000	5.000	3.000	5.000	1.000
c_{10}	9.000	7.000	9.000	5.000	7.000	9.000	9.000	9.000	0.333	1.000	5.000	3.000	3.000	3.000	0.333
c_{11}	7.000	5.000	7.000	3.000	5.000	9.000	7.000	7.000	0.333	0.200	1.000	3.000	3.000	3.000	1.000
c_{12}	5.000	5.000	5.000	1.000	1.000	5.000	3.000	3.000	0.200	0.333	0.333	1.000	1.000	1.000	0.200
c_{13}	5.000	5.000	5.000	1.000	1.000	5.000	3.000	3.000	0.333	0.333	0.333	1.000	1.000	1.000	0.333
c_{14}	5.000	5.000	5.000	1.000	1.000	5.000	3.000	3.000	0.200	0.333	0.333	1.000	1.000	1.000	0.200
c_{15}	9.000	7.000	5.000	1.000	0.333	5.000	5.000	5.000	1.000	3.000	1.000	5.000	3.000	5.000	1.000

Table 7.3 Preference weights of design criteria

c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}
0.012	0.015	0.011	0.056	0.074	0.018	0.021	0.026	0.208	0.128	0.127	0.052	0.055	0.052	0.145

The constructed priory vector, w_j, illustrates that energy efficiency (c_9), life cycle costs (summation of c_{12} , c_{13} , c_{14}), aesthetics (c_{15}), environmental impacts(c_{10}) and durability (c_{11}), have the highest weights according to the decision maker. To ensure that the decision maker has been consistent with assigning preferences, the consistency ratio CR should be less than 0.1. The consistency ratio, is calculated, as indicated in Eq.7.3.

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{1.52}{14} = 0.108$$
$$CR = \frac{CI}{RI} = \frac{0.108}{1.583} = 0.068 < 10\% \implies consistent \tag{7.3}$$

where CI is the consistancy index, λ_{max} is the largest eigenvalue, and RI is the random consistency index, which is equal to 1.583 , for $n = 15$ [157].

As mentioned earlier, the pairwise comparison of criteria is a good measure to assess preferences. However, it can become inconvenient as the number of criteria increases. In an alternate method, the decision maker(s) could assign a value from 1 to 9 to the degree of preference of the criteria and then normalize the values.

7.3.1 Assigning weights with more than one decision maker

The above method to assign criteria weights can be used when only one decision maker is involved. However, in real life design situations, this is hardly the case and there is usually a multitude of decision makers involved, with very different expectations and preferences.

To initiate the group decision-making process, it must be first clarified whether the decision makers are considered as equals or not.

Generally, the importance weights of members of a group are equal in arriving at a group consensus. However, there are situations when the members are not considered to be equal. In such cases, it might not be possible to assign weights to each decision maker (DM) through consensus among the group members; hence the weights would be based on the level of expertise, number of shares, etc. After assigning weights to each DM, it is proposed to obtain the weights of decision criteria through one of the following methods.

(1) Geometric mean method (GMM)

This method is used when the weights of the DMs are equal [169]. In this process, each DM constructs the pairwise comparison matrix and the elements of the decision matrix would be generated from the geometric mean of the values provided by the DMs (Eq.7.4). Then the priority vector would be constructed the same as the procedure in Section 7.3.

$$a_{ij}^{*} = \left(a_{ij}^{1} * a_{ij}^{2} * \dots * a_{ij}^{N} \right)^{\frac{1}{N}} \tag{7.4}$$

where a_{ij}^{*} are the elements of the decision matrix and N is the number of DMs.

(2) Weighted arithmetic mean method (WAMM)

Another option would be using the weighted arithmetic mean method where the importance weights of the DMs are not equal. In this procedure, the importance of criteria based on the judgment of each DM (using pairwise comparisons or by using a scale from 1 to 9 as discussed in Section 7.3) is identified. Then these identified importance weights are multiplied by the importance weight of each DM to obtain the final weights for decision criteria (Eq. 7.5) [169].

$$P(c_j) = \sum_{i=1}^{n} w_i P_i(c_j) \qquad (7.5)$$

where $P(c_j)$ is the group importance weight of criteria j, $P_i(c_j)$ is the importance weight of criteria j given by the i^{th} DM, w_i is the importance weight of the i^{th} DM, and n is the number of DMs.

7.4 Concept scores and results

After constructing the normalized matrix for each method and identifying the appropriate weights with respect to the preferences of the DM(s), the alternative scores are calculated based on the aggregation procedure for each method.

The general form of an aggregation function is illustrated in Eq. 7.5 where $F(.)$ represents an aggregation function, and $g(.)$ indicates whether a design constraint is fulfilled ($g(c_i) = 1$ if the constraint is fulfilled, otherwise $g(c_i) = 0$). For the purpose of this research, no initial constraints were assumed.

$$FCS = F(c_1, c_2, \dots, c_n). \prod_{i=1}^{n} g(c_i) \qquad (7.6)$$

AHP uses the aggregation function indicated in Eq.4.5, where the associated normalized matrix is multiplied by the weights assigned to each criterion to generate the alternative scores.

For TOPSIS, after constructing the weighted normalized matrix, the ideal S^*, and the negative-ideal S^-, solutions are identified as indicated in Eq.4.6. For this purpose, two hypothetical alternatives, A^* and A^- , are defined that represent respectively the best and the worst scores of i^{th} criterion among alternatives. The ideal and negative-ideal alternatives for TOPSIS are indicated in Table 7.4.

Table 7.4 Ideal and negative ideal alternatives for each criterion

	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
A^*	0.0040	0.0086	0.0045	0.0145	0.0207	0.0049	0.0058	0.0103
A^-	0.0018	0.0007	0.0011	0.0138	0.0169	0.0041	0.0046	0.0036
	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}	c_{15}	
A^*	0.0525	0.0449	0.0443	0.0178	0.0184	0.0174	0.0843	
A^-	0.0514	0.0189	0.0089	0.0059	0.0077	0.0095	0.0040	

To obtain the alternative scores using the Choquet aggregation method, the function illustrated in Eq. 6.13 is used with the interaction indices generated in Table 6.6. The final results and the ranking of alternatives based on their scores, using these three MCDM methods are demonstrated in Table 7.5.

Table 7.5 Concept scores of the 16 façade alternatives using AHP, TOPSIS, and Choquet

Alt.	AHP Score	Rank	TOPSIS Score	Rank	Choquet Score	Rank	Rank change in AHP &TOPSIS	Rank change in AHP &Choquet	Rank change in TOPSIS &Choquet
A_1	0.0560	11	0.1288	8	0.8516	10	3	1	-2
A_2	0.0587	8	0.1556	6	0.8671	8	2	0	-2
A_3	0.0843	2	0.9291	2	1.0200	2	0	0	0
A_4	0.0870	1	0.9560	1	1.0516	1	0	0	0
A_5	0.0728	4	0.6735	4	0.9597	4	0	0	0
A_6	0.0758	3	0.7187	3	0.9900	3	0	0	0
A_7	0.0518	16	0.0439	16	0.8513	12	0	4	4
A_8	0.0566	9	0.1099	12	0.8979	5	-3	4	7
A_9	0.0566	10	0.0874	13	0.8515	11	-3	-1	2
A_{10}	0.0604	6	0.1521	7	0.8882	7	-1	-1	0
A_{11}	0.0602	7	0.1171	10	0.8588	9	-3	-2	1
A_{12}	0.0641	5	0.1857	5	0.8929	6	0	-1	-1
A_{13}	0.0523	15	0.1121	11	0.8308	14	4	1	-3
A_{14}	0.0541	13	0.1219	9	0.8439	13	4	0	-4
A_{15}	0.0535	14	0.0672	15	0.8072	16	-1	-2	-1
A_{16}	0.0557	12	0.0838	14	0.8305	15	-2	-3	-1

According to the results, all three methods show that A_4, A_3, A_6, A_5 are respectively the most suitable concepts. While AHP and TOPIS are unanimous on the 5th rank, the ranking changes for Choquet integral and drops to 6th and A_8 is ranked the 5th. Figures 7.1-7.3 illustrate the comparison of the concept scores for AHP-TOPSIS, AHP-Choquet and TOPSIS-Choquet respectively, while Figure 7.4 demonstrates the changes in the ranking of alternatives for all three MCDM methods.

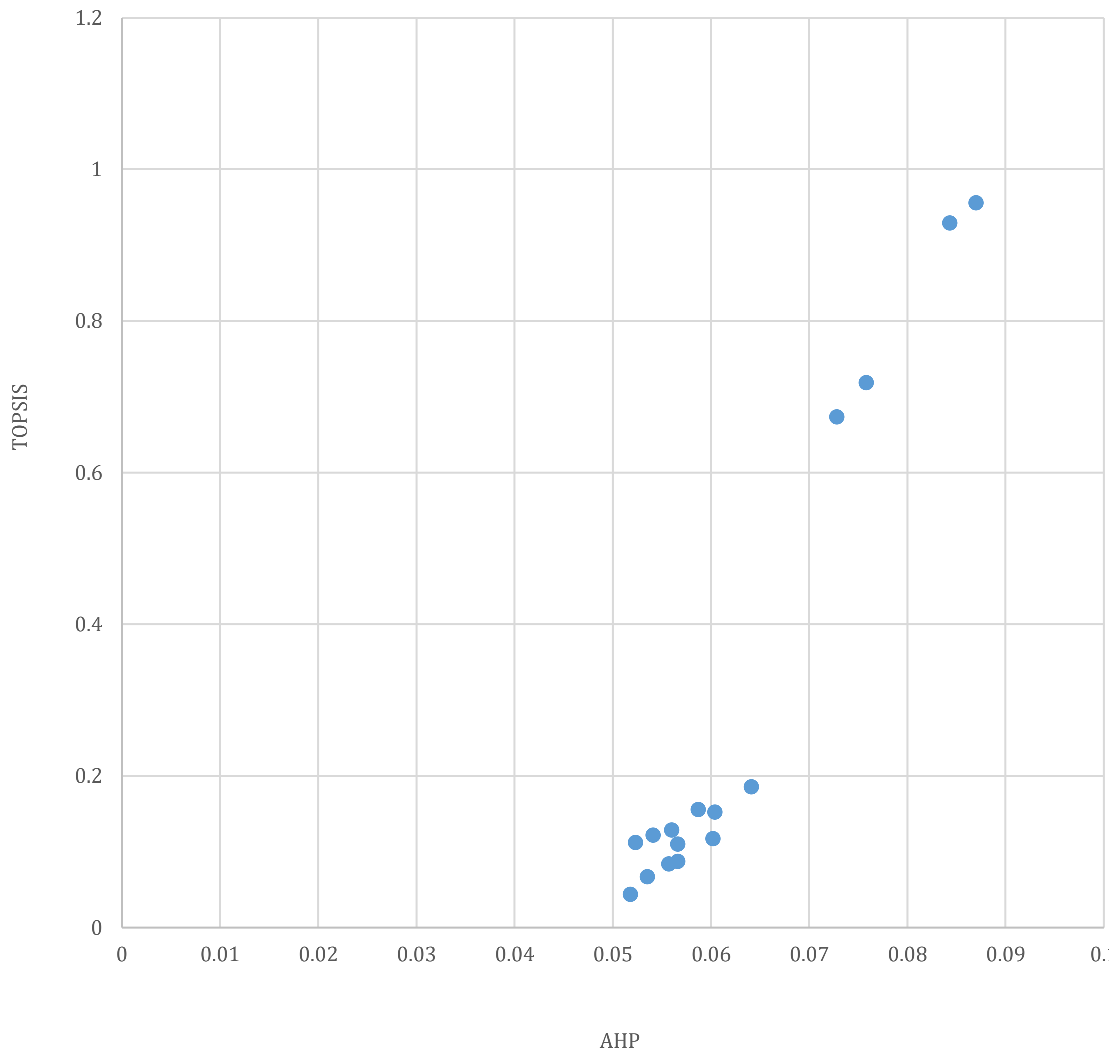


Figure 7.1 AHP vs. TOPSIS concept scores

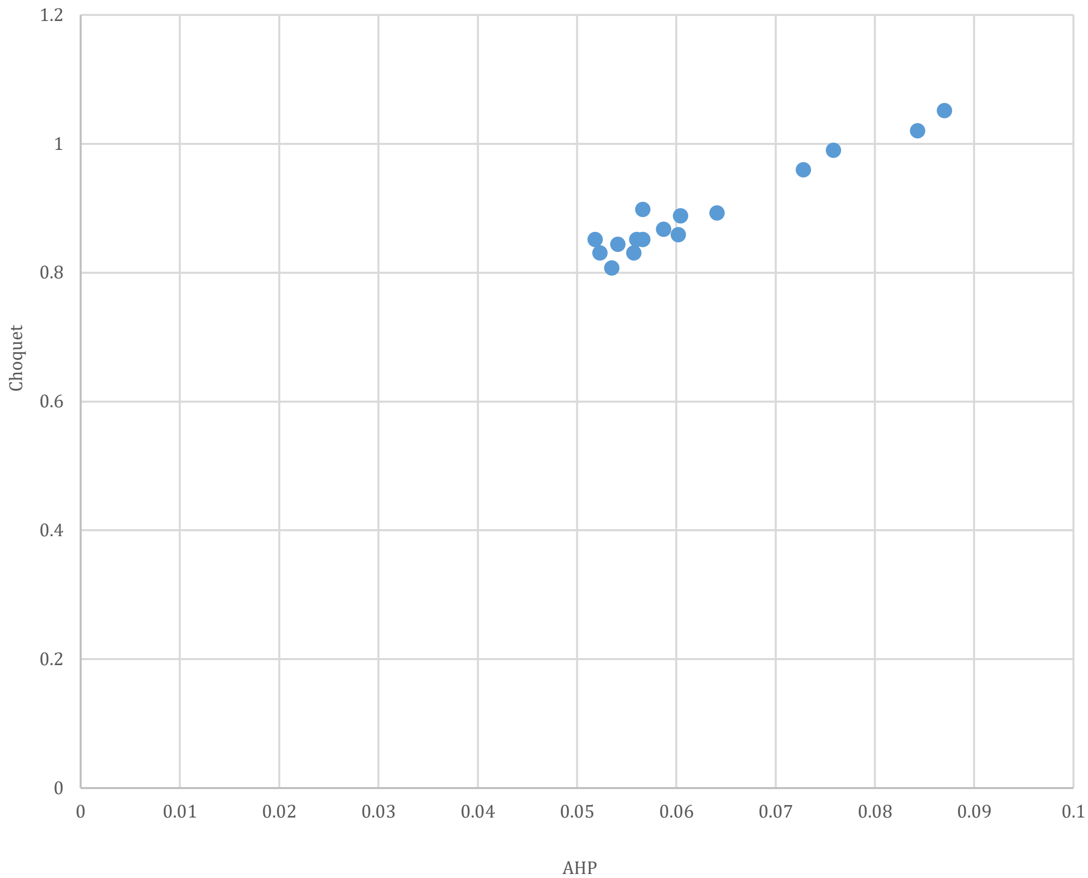


Figure 7.2 AHP vs. Choquet concept scores

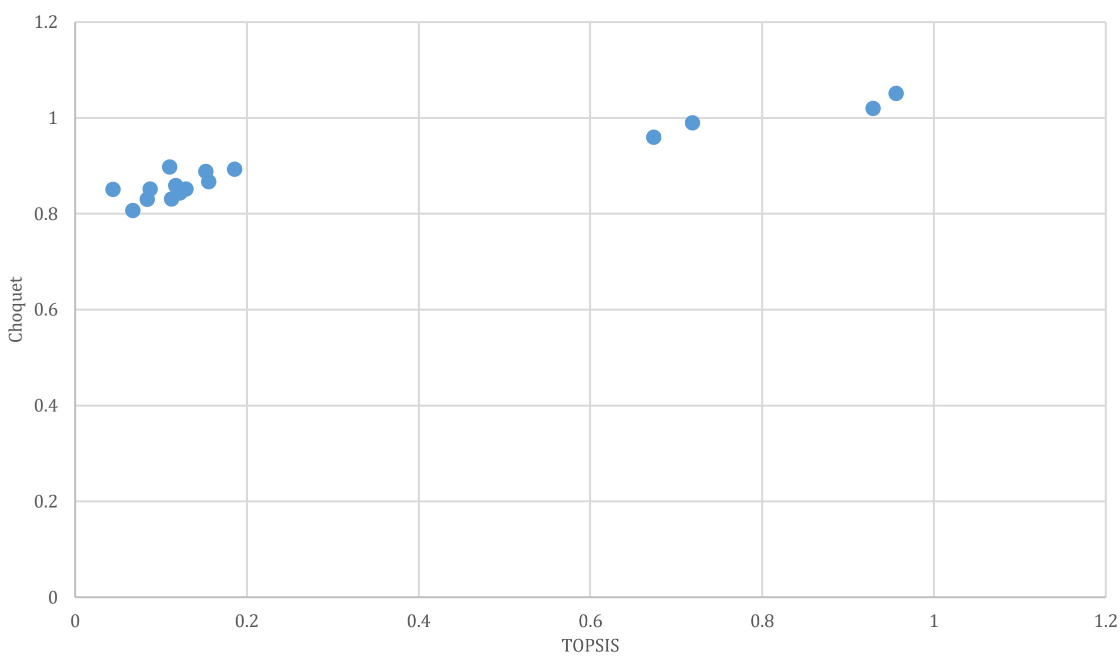
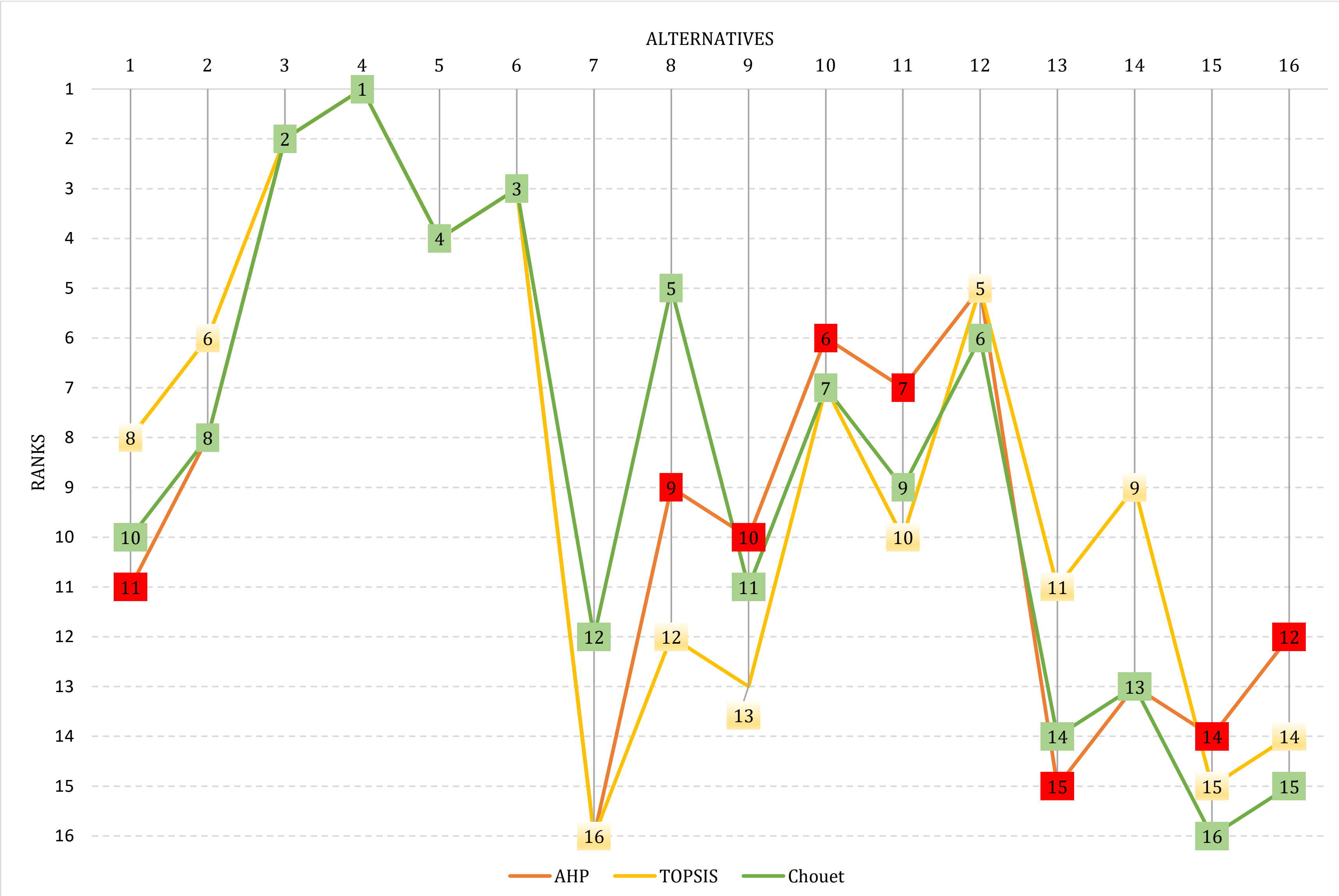


Figure 7.3 TOPSIS vs. Choquet concept scores

Figure 7.4 Changes in the ranking of the 16 façade alternatives



7.5 Discussion

As Table 7.5 illustrates, the 4 best alternatives, are the same using the AHP, TOPSIS and Choquet methods. This is logical since these 4 alternatives have very good partial scores for C_4, C_5 , C_9 , C_{11}, $C_{13}$and C_{15} which all have high importance weights. While AHP and TOPSIS rank A_{12} as the 5th best alternative, with Choquet integral A_8 is ranked 5th. This shows a significant rank change for A_8 which is ranked 9th and 12th with AHP and TOPSIS respectively. The reason for this difference lies within the nature of these methods.

As discussed earlier, Choquet integral not only considers the importance of each criterion (as in AHP and TOPSIS) but also considers the importance of each subset of criteria [170]. In practice, façade design criteria are not independent, and when two criteria are interacting, such as thermal resistance and annual energy consumption, when only the weighted partial scores of the criteria are combined, their scores will be double counted.

In other instances, in the decision-making process presence of some criteria may not contribute individually to the total score by themselves, but in conjunction with other criteria, the total score may rise sharply. For example, in façade design, a very high score in vapour resistance of system may not be important by itself if the assessed value for the O&M costs of the system is not influenced by it, but in combination, it may significantly contribute to the total score of an alternative.

In this case study, it is noted that the main superiority of A_{12} over A_8 is due to the higher scores in C_{11}, C_{13}, C_{15} which have high importance weights, hence when considering only the individual weights, this alternative gets a better overall score. A_8 has a better performance in C_2, C_8 , C_{10} and C_{12} where only C_{10} has a high importance weight individually; and the difference of the partial scores for A_{12} and A_8 with regards to C_{10}, is not very high. However, it can be noted that the when C_2 and C_8 get high scores simultaneously, the overall score will be improved (see Eq. 6.13 and Table 6.6).

7.6 Summary

This chapter, applied the three most suitable MCDM methods (AHP, TOPSIS and Choquet integrals) that were identified in Chapter 4, in a case study where the 16 façade alternatives that were assessed in Chapter 5, were compared to each other in term of 15 design criteria and the results were presented and discussed. Comparison of the results shows that Choquet integral is a suitable method where there is interdependence among criteria as it considers the importance of each subset of criteria instead of the importance of each individual criterion, and this can result in rank alterations.

Chapter 8 Summary and Conclusions

8.1 Summary of the thesis

Over the past decade, a new trend has emerged towards the development of sustainable building design and construction, which has caused an increased focus on designing high-performance building structures. Amongst all these building structures and components, façades have the potential to drastically affect the comfort level of occupants, energy performance and the environmental footprint of buildings; therefore, more attention and effort needs to be dedicated to their design, development, and integration.

Like most modern technological developments, various disciplines and knowledge bases are involved in the process of designing façade systems. The multidisciplinary nature of façade design, in addition to the urge for satisfying distinctive design and performance criteria, cause the design process to become considerably complex. This complexity is more tangible during the integration, where a balance should be maintained between all necessary functions of a façade system, which can be conflicting with each other. Consequently, most designers still prefer to use conventional design methods which tackle each objective sequentially and lack consideration of all required criteria.

In this thesis, a relatively new and useful, systematic approach is proposed to support the design of the optimal façade system using multicriteria decision support tools. To this end, and to pursue the first research objective, major metrics, and criteria which constitute a high-performance façade system, were defined.

To address the second research objective, the designers were provided with an interactive and comprehensive guideline for façade design which outlines the necessary considerations for each stage of the façade life cycle.

To identify the best decision-making tools to be used in the preliminary design phase, most common MCDM methods were reviewed and the three most suitable ones were selected. The selected methods are Choquet integral, AHP and TOPSIS. The similarity between all these methods is the necessity of assessing the alternatives with regards to the design criteria and related importance weight functions.

Consequently, an assessment approach for each performance criterion was proposed and various simulation tools were utilized to assess the performance of sixteen façade system alternatives and the multi-criteria façade performance (MFP) matrix was established.

AHP and TOPSIS require importance weights, based on the preference of the decision maker. However, in the case of Choquet integral, there is a need to determine the importance weight of each subset of decision criteria. This implies defining 2^n measures. It is evident that with an increased number of criteria, it would be cognitively impossible for the human brain to determine these measures. Hence, an unsupervised approach should be used to determine the fuzzy measures. However, most unsupervised methods require some knowledge on the ranking of alternatives or access to large data (a large number of assessed alternatives). Therefore, to resolve this issue an approach using the PCA was adopted and the fuzzy measures and the interaction indices for façade design criteria were identified.

To evaluate the efficiency of the method, in a case study, the three selected MCDM methods namely, Choquet, AHP, and TOPSIS were used in ranking the sixteen façade alternatives that were previously assessed. In this step, the importance weights of decision criteria were assigned using a pairwise comparison method and proper factors were used to normalize the MFP matrix for each method. Finally, the ranking order of the alternatives was determined using the aggregation function for each method.

It was deduced that considering the importance of each subset of design criteria (coalitions) will result in more reliable rankings; since in some cases, the importance of one criterion might noticeably increase in presence of other criteria. Also considering the interactions among criteria will avoid the double counting problems.

A promising benefit of using decision support tools in preliminary design, in addition to facilitating the integration of various disciplines and life cycle considerations, is the possibility of incorporating new technologies in the design and decision-making process for evaluating various design alternatives.

Nevertheless, there are some limitations to this approach as well. The most important limitation would be the necessity of determining the fuzzy measures in case different design criteria are used. This would make the decision-making process time-consuming. However, this issue can be resolved with the presence of the industrialized calculators which would only require the MFP matrix to generate the fuzzy measures.

8.2 Future work

It is evident that a more accurate assessment would result in the extraction of more reliable fuzzy measures. This can be achieved through, assessing more design alternatives (using large data) and identifying new criteria assessment methods.

Other possible future research work includes:

- Extending the design criteria beyond the scope of this research. Since, as the technology advances, the performance expectations will grow.
- Extending the proposed design approach to design other building components and infrastructure systems.
- Identification of new approaches to identify fuzzy measures such as machine learning, other optimization tools, and techniques.

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APPENDIX A WUFI Simulations

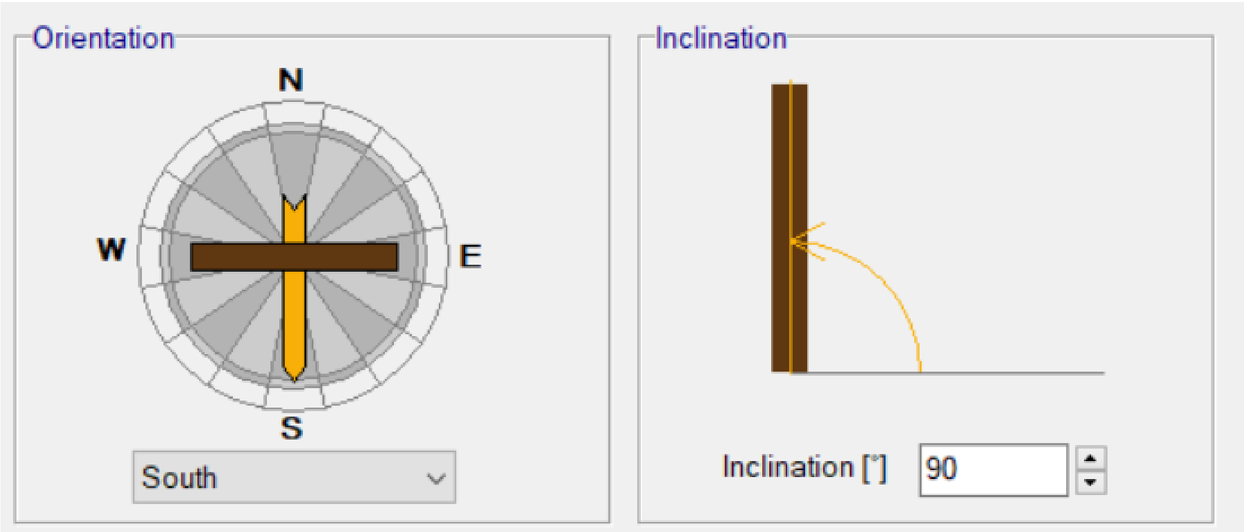


Figure A.1 Initial conditions for all assemblies:
The orientation of the simulated commercial building for all cases

WALL ASSEMBLY 1: ALTERNATIVE 1 AND 2

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content $[lb/ft^3]$
1	Brick 800	3.93701	6.2428
2	Air Layer 40 mm	1.5748	0.117
3	Spun Bonded Polyolefin Membrane (SBP)	0.03937	0.0
4	Plywood, Exterior-Grade	0.47638	4.4386
5	Glass-Fiber Board	6.0	0.0837
6	PE-Membrane 0,2 mm (sd = 87 m)	0.11811	0.0
7	Gypsum Board	0.5	0.3933

Figure A.2 Initial water content in different layers of Alternatives 1 and 2

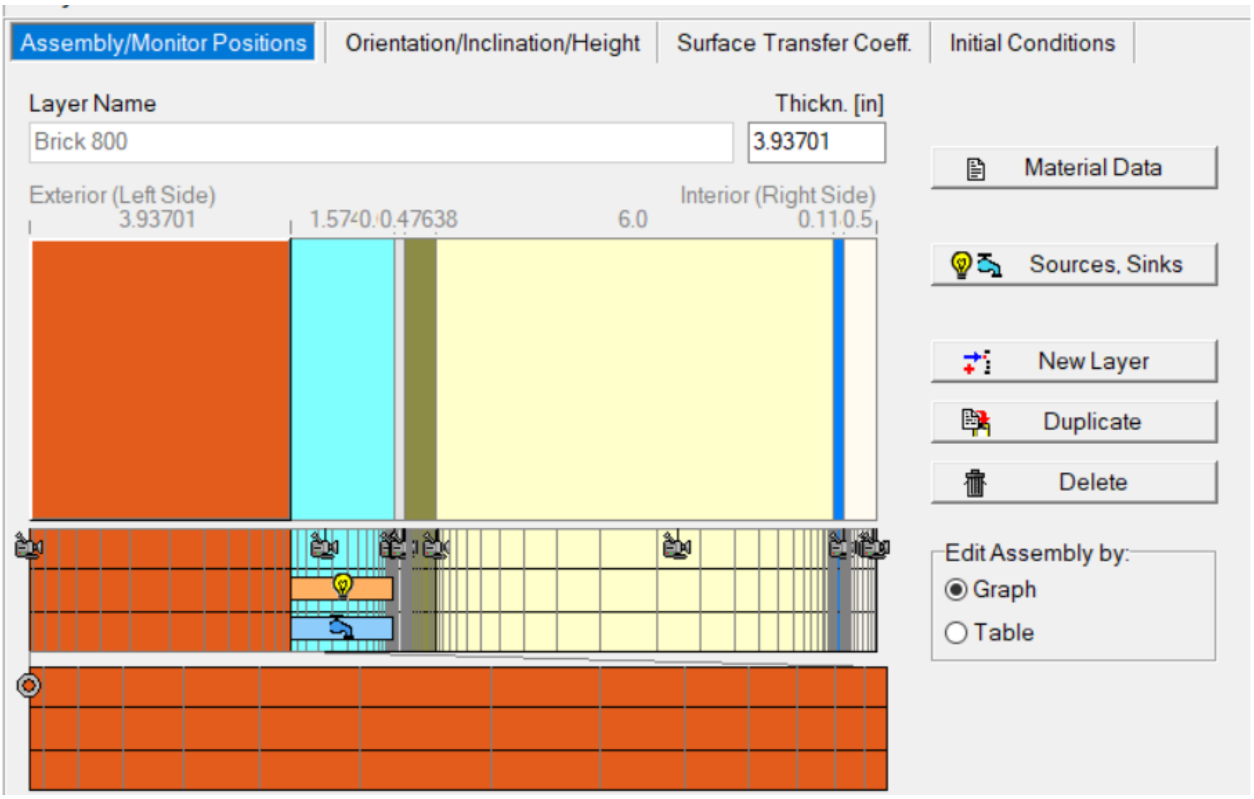


Figure A.3 Assembly layers of Alternatives 1 and 2

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	2.3	0.54	0.33	3.13

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Brick 800	6.24	1.05	0.45	8.78
Air Layer 40 mm	0.12	0.05	0.01	0.55
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Plywood, Exterior-Grade	4.44	3.78	2.88	4.67
Glass-Fiber Board	0.08	0.05	0.03	0.08
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board	0.39	0.33	0.14	0.39

Figure A.4 Water content in different layers of Alternatives 1 and 2

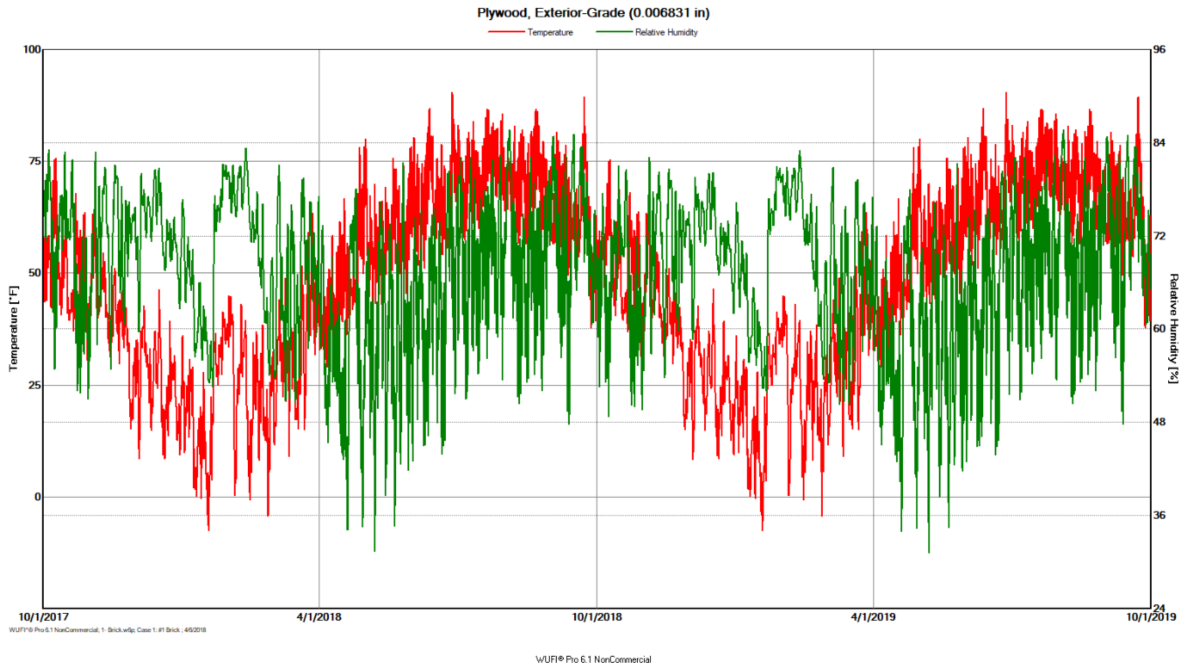


Figure A.5 Relative humidity of the critical layer (plywood) for Alternatives 1 and 2

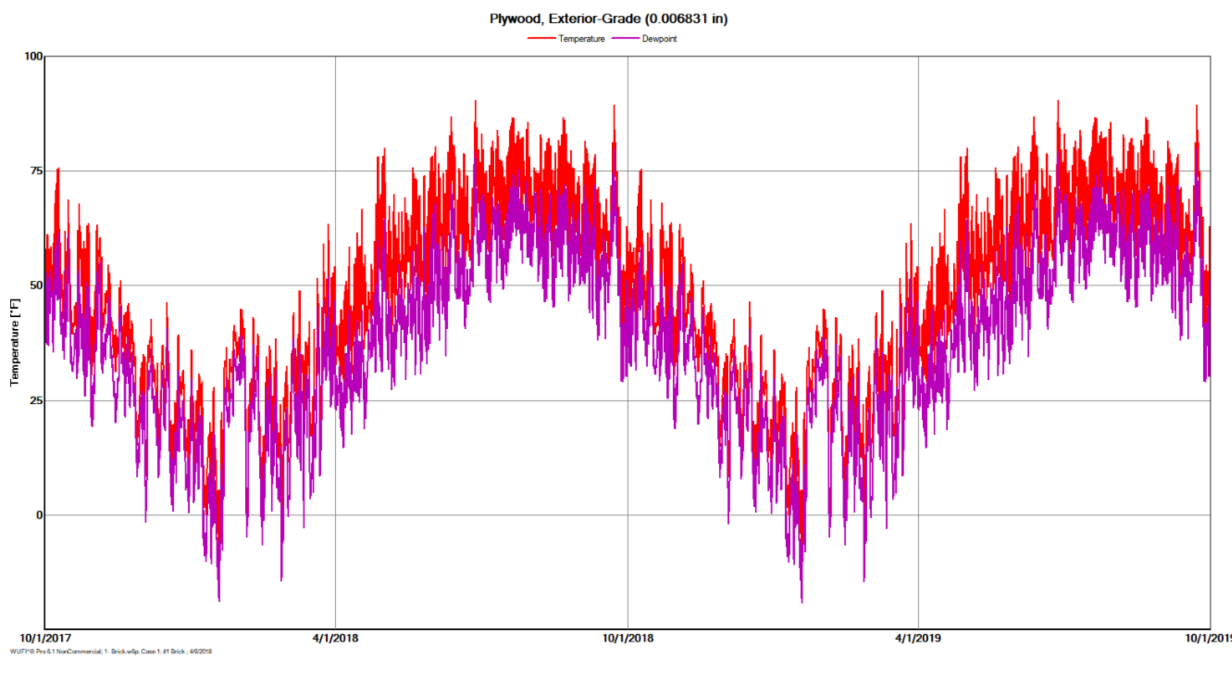


Figure A.6 Dew point of the critical layer (plywood) for Alternatives 1 and 2

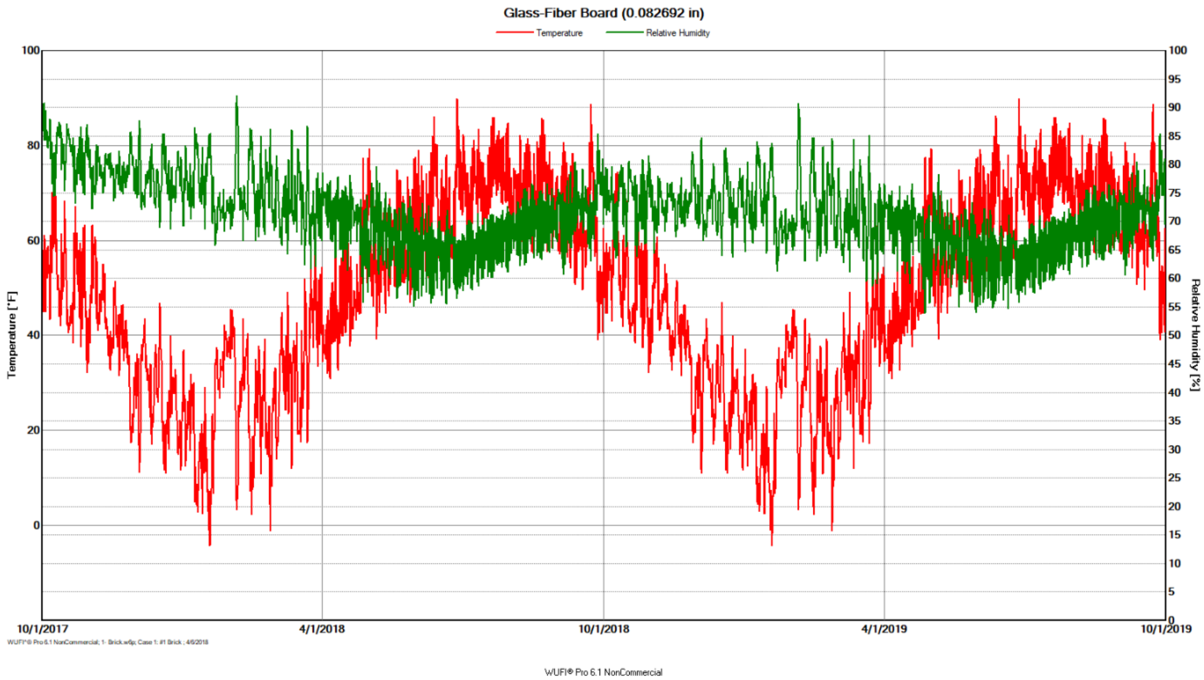


Figure A.7 Relative humidity of the critical layer (Glass-fibre) for Alternatives 1 and 2

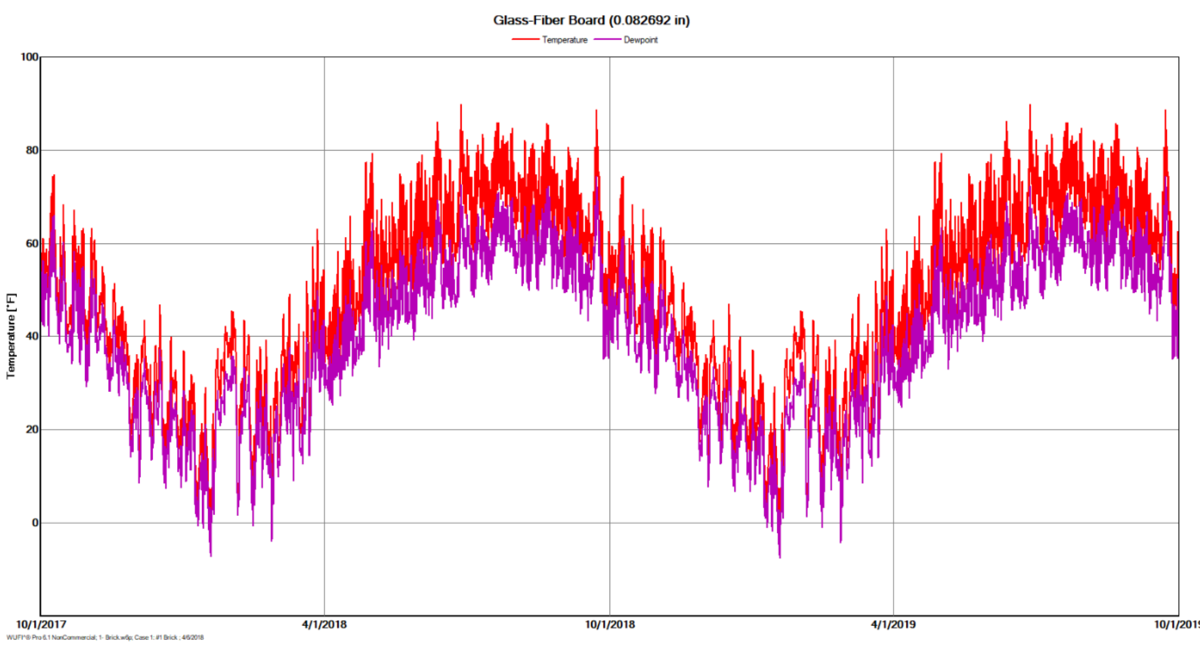


Figure A.8 Dew point of the critical layer (Glass-fibre) for Alternatives 1 and 2

WALL ASSEMBLY 2: ALTERNATIVE 3 AND 4

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Granite	4.0	0.457
2	Air Layer 25 mm	0.98425	0.117
3	Spun Bonded Polyolefin Membrane (SBP)	0.03937	0.0
4	Plywood, Exterior-Grade	0.5	4.4386
5	Glass-Fiber Board	6.0	0.0836
6	PE-Membrane 0,2 mm (sd = 87 m)	0.11811	0.0
7	Gypsum Board (USA)	0.5	2.185

Figure A.9 Initial water content in different layers of Alternatives 3 and 4

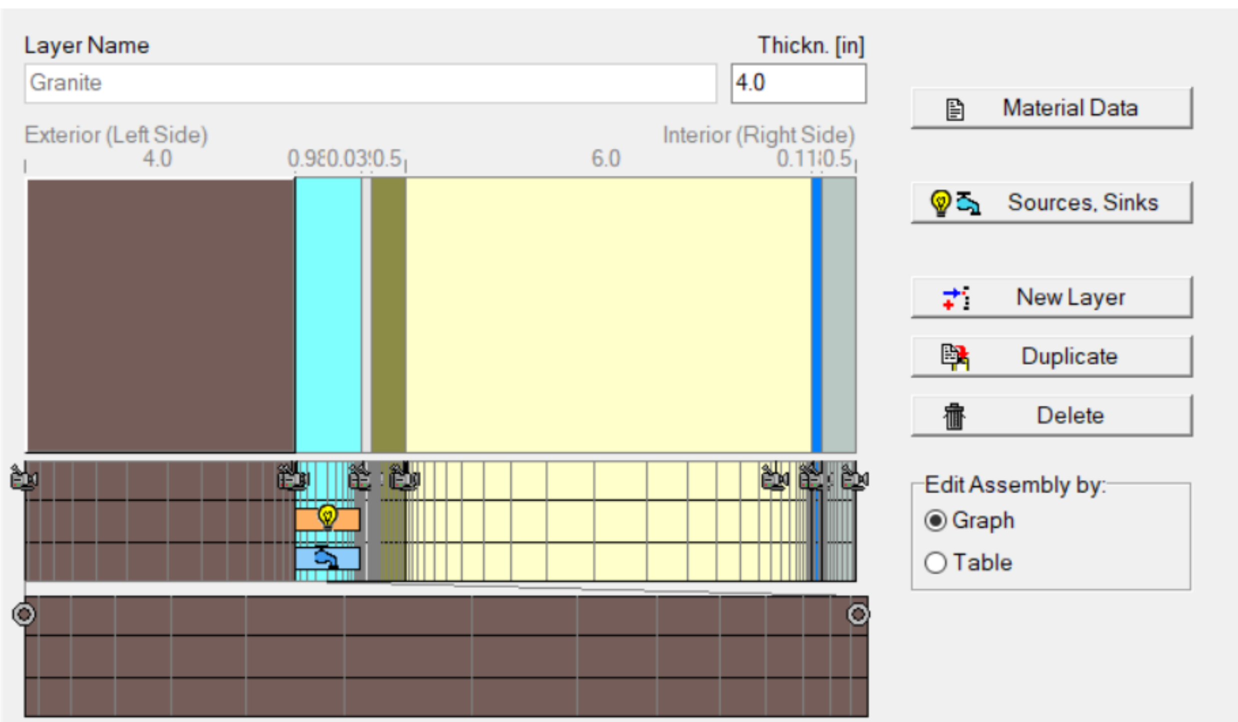


Figure A.10 Assembly layers of Alternatives 3 and 4

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.48	0.43	0.3	0.95

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Granite	0.46	0.77	0.41	2.10
Air Layer 25 mm	0.12	0.03	0.00	0.31
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Plywood, Exterior-Grade	4.44	3.07	2.45	4.44
Glass-Fiber Board	0.08	0.05	0.03	0.08
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.28	0.11	2.18

Figure A.11 Water content in different layers of Alternatives 3 and 4

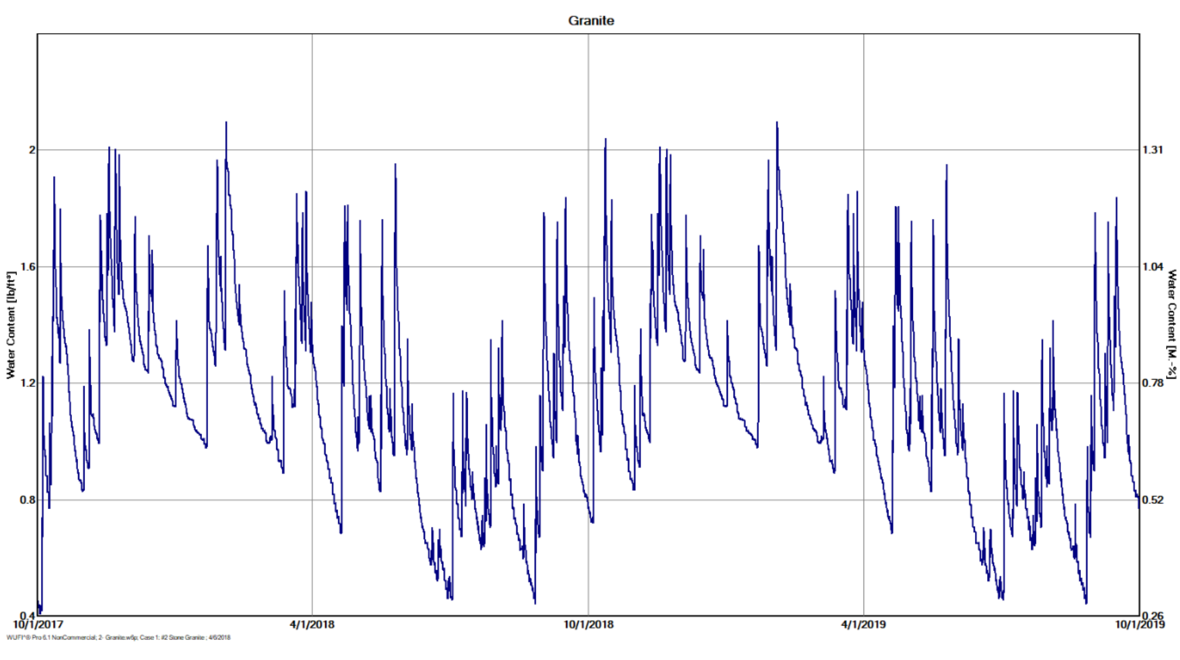


Figure A.12 Water content in Granite for Alternatives 3 and 4 increases from 0.25 % to 0.52% which is much below 20%.

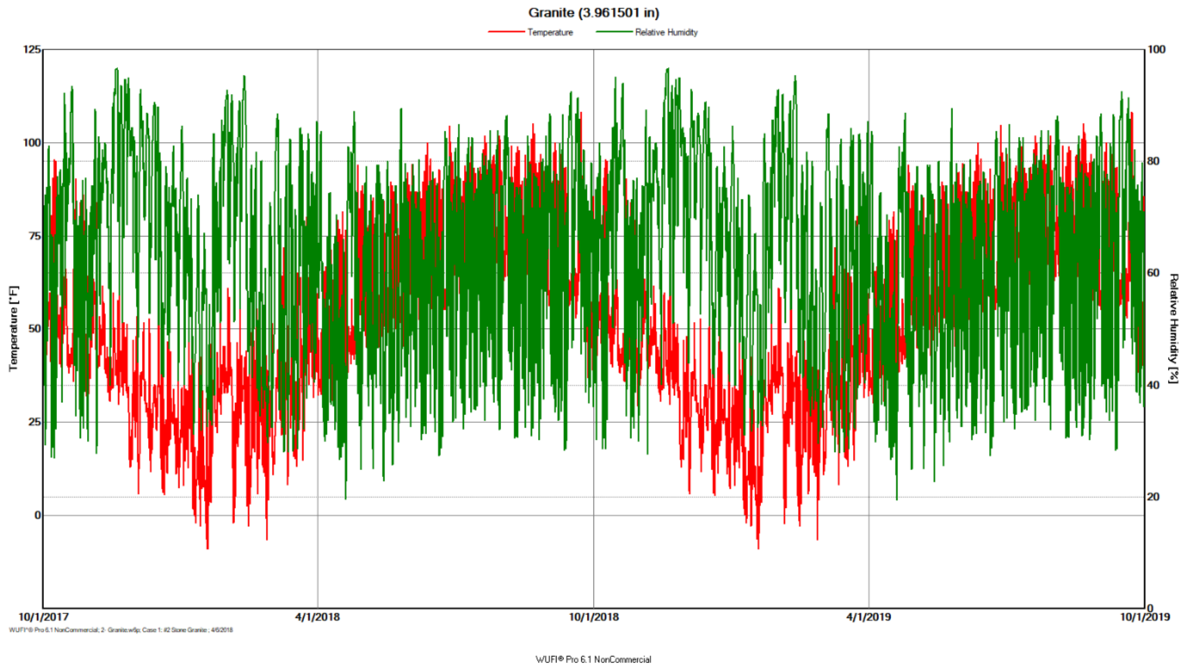


Figure A.13 Relative humidity of the critical layer (Granite) for Alternatives 3 and 4

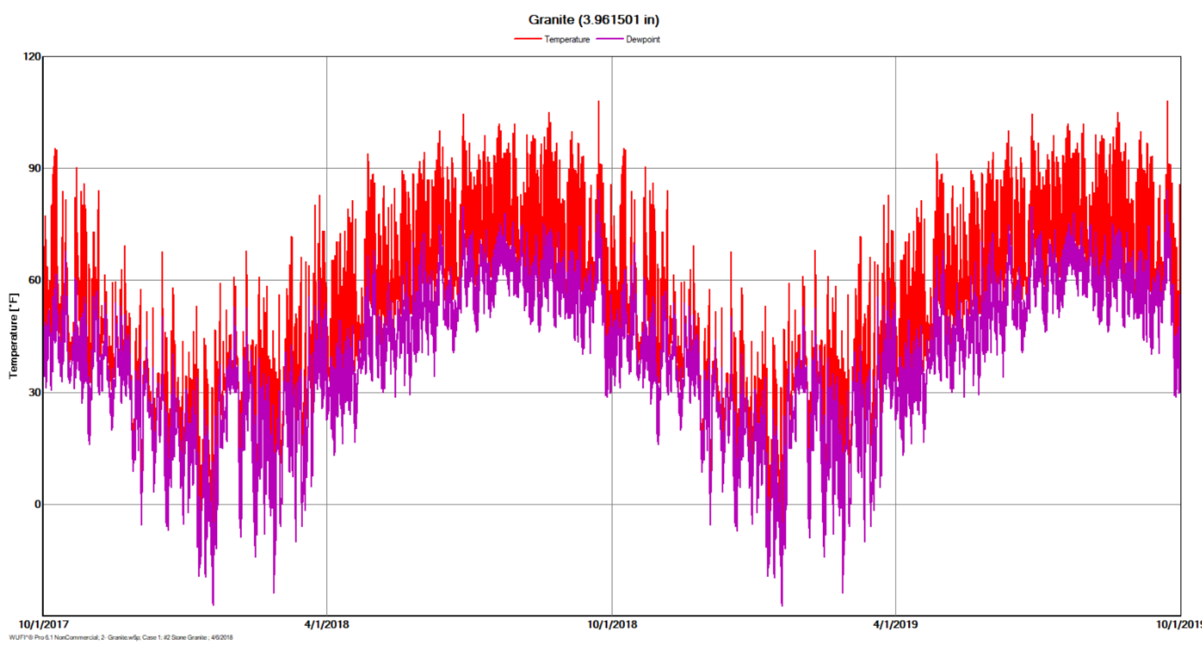


Figure A.14 Dew point of the critical layer (Granite) for Alternatives 3 and 4

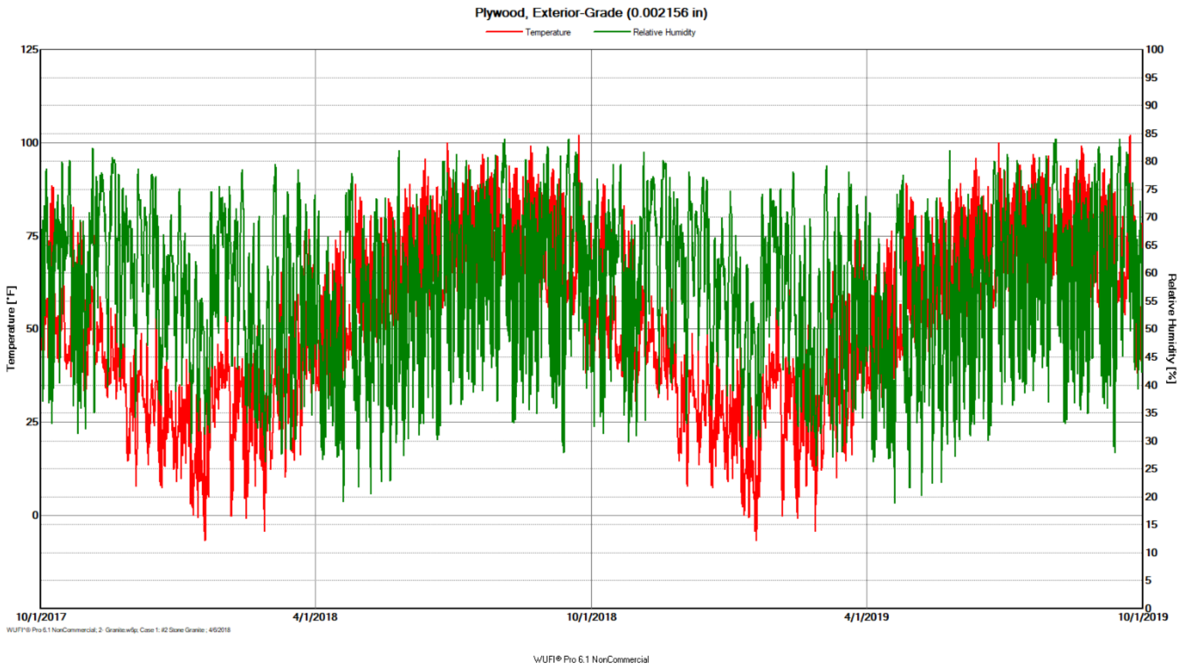


Figure A.15 Relative humidity of the critical layer (Plywood) for Alternatives 3 and 4

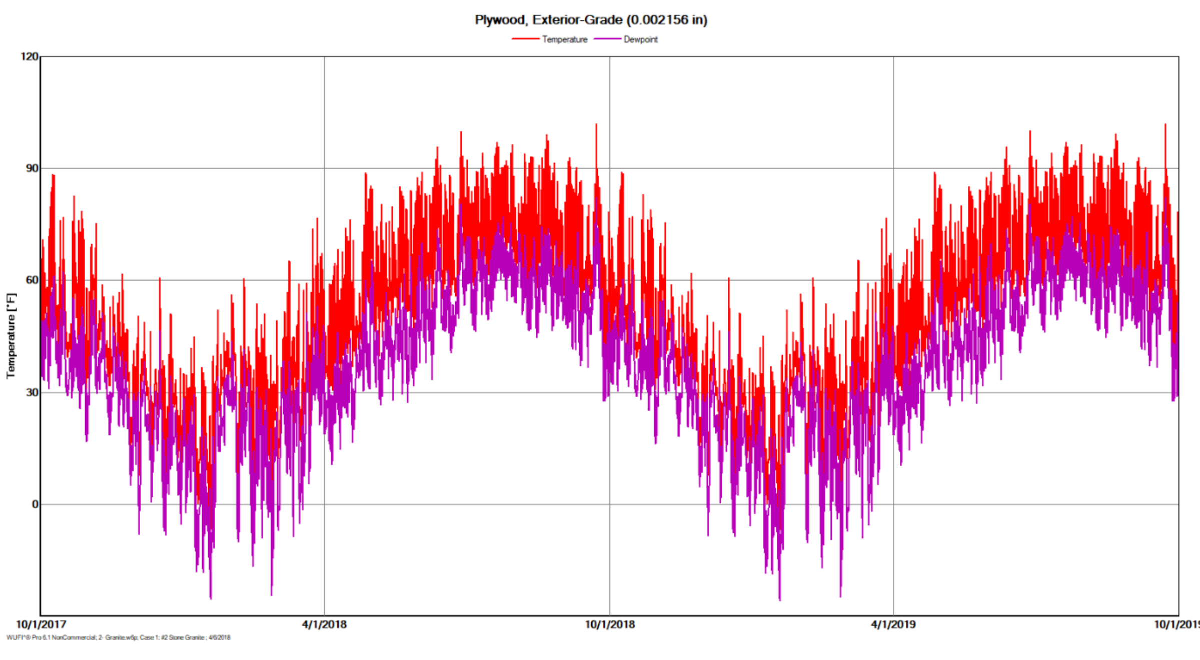


Figure A.16 Dew point of the critical layer (Plywood) for Alternatives 3 and 4

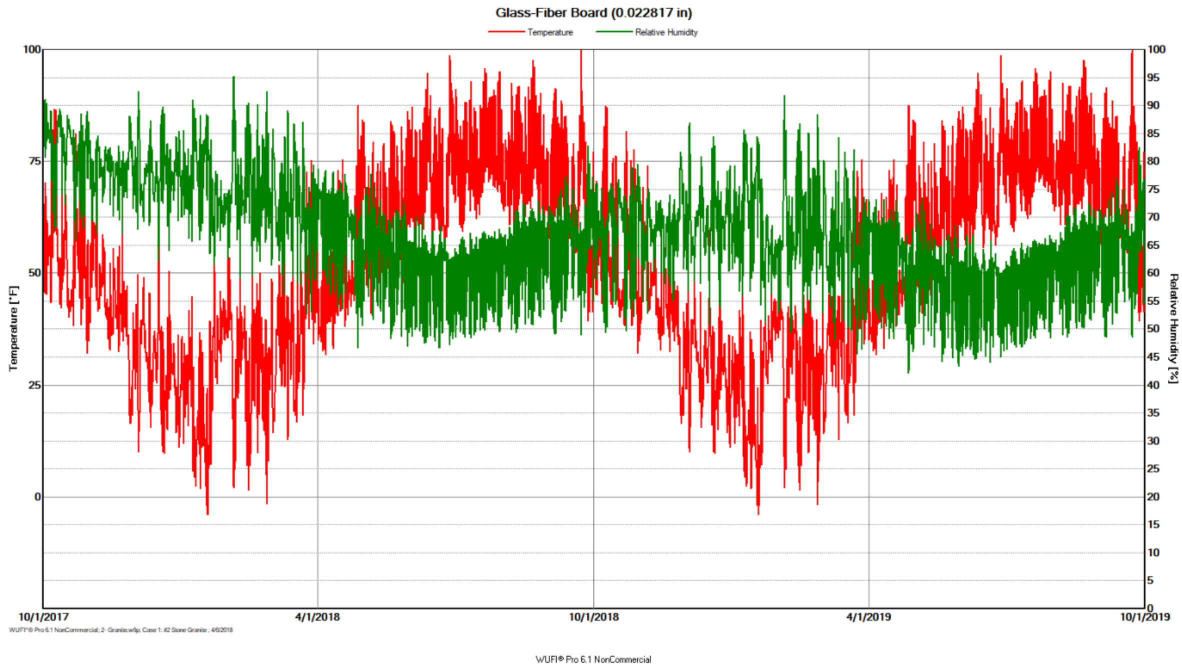


Figure A.17 Relative humidity of the critical layer (Glass fibre) for Alternatives 3 and 4

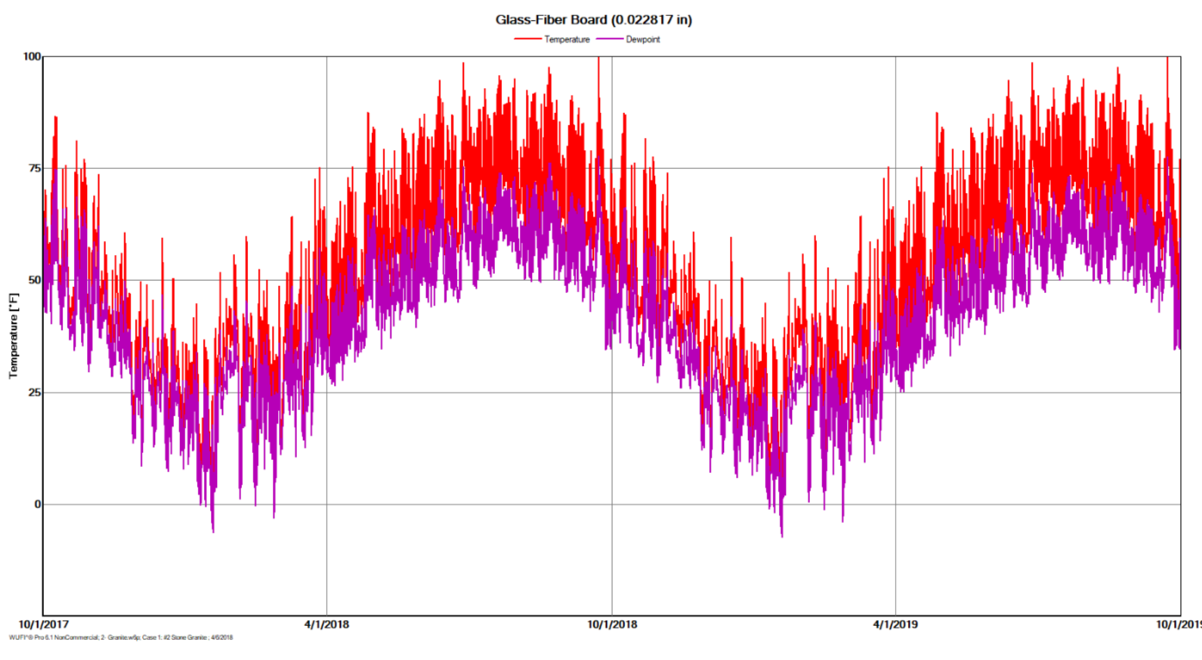


Figure A.18 Dew point of the critical layer (Glass fibre) for Alternatives 3 and 4

WALL ASSEMBLY 3: ALTERNATIVE 5 AND 6

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Limestone (Georgian Bay Limestone)	4.0	0.0874
2	Air Layer 25 mm	0.98425	0.117
3	Spun Bonded Polyolefin Membrane (SBP)	0.03937	0.0
4	Plywood, Exterior-Grade	0.5	4.4386
5	Glass-Fiber Board	6.0	0.0837
6	PE-Membrane 0,2 mm (sd = 87 m)	0.11811	0.0
7	Gypsum Board (USA)	0.5	2.185

Figure A.19 Initial water content in different layers of Alternatives 5 and 6

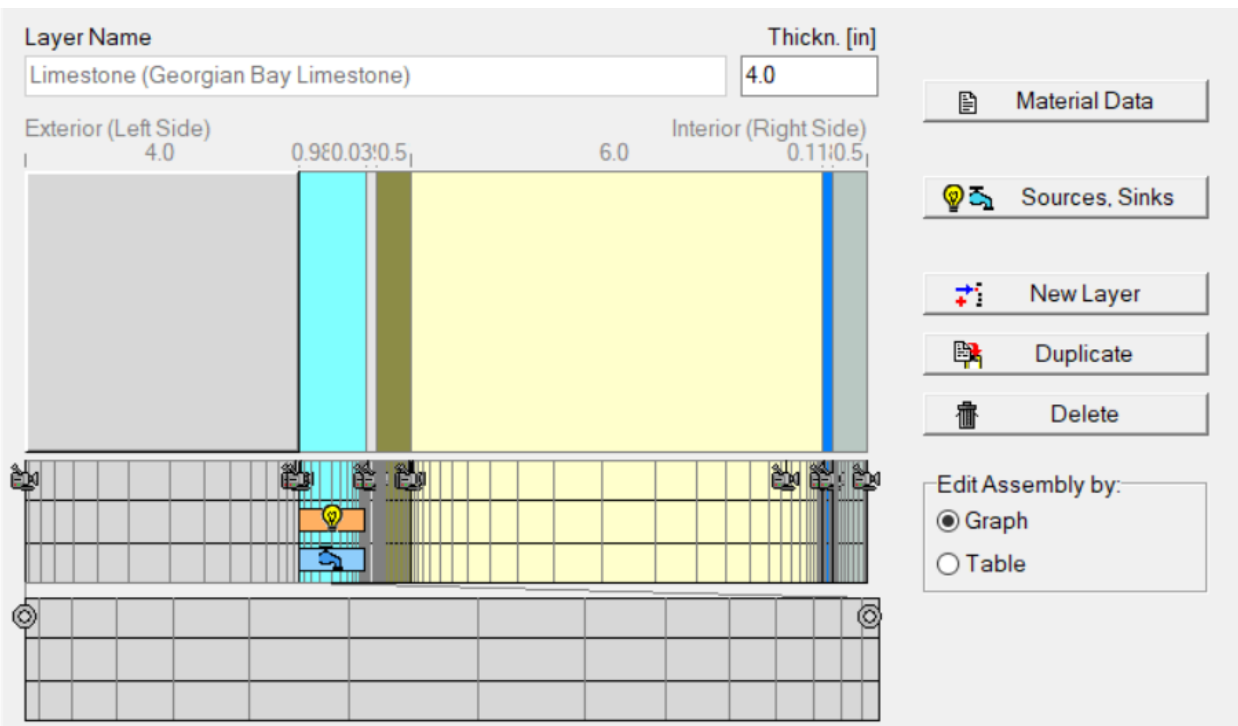


Figure A.20 Assembly layers of Alternatives 5 and 6

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.36	0.23	0.19	0.37

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Limestone (Georgian Bay Limestone)	0.09	0.12	0.08	0.20
Air Layer 25 mm	0.12	0.04	0.01	0.37
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Plywood, Exterior-Grade	4.44	3.54	2.74	4.50
Glass-Fiber Board	0.08	0.05	0.03	0.08
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.28	0.11	2.18

Figure A.21 Water content in different layers of Alternatives 5 and 6

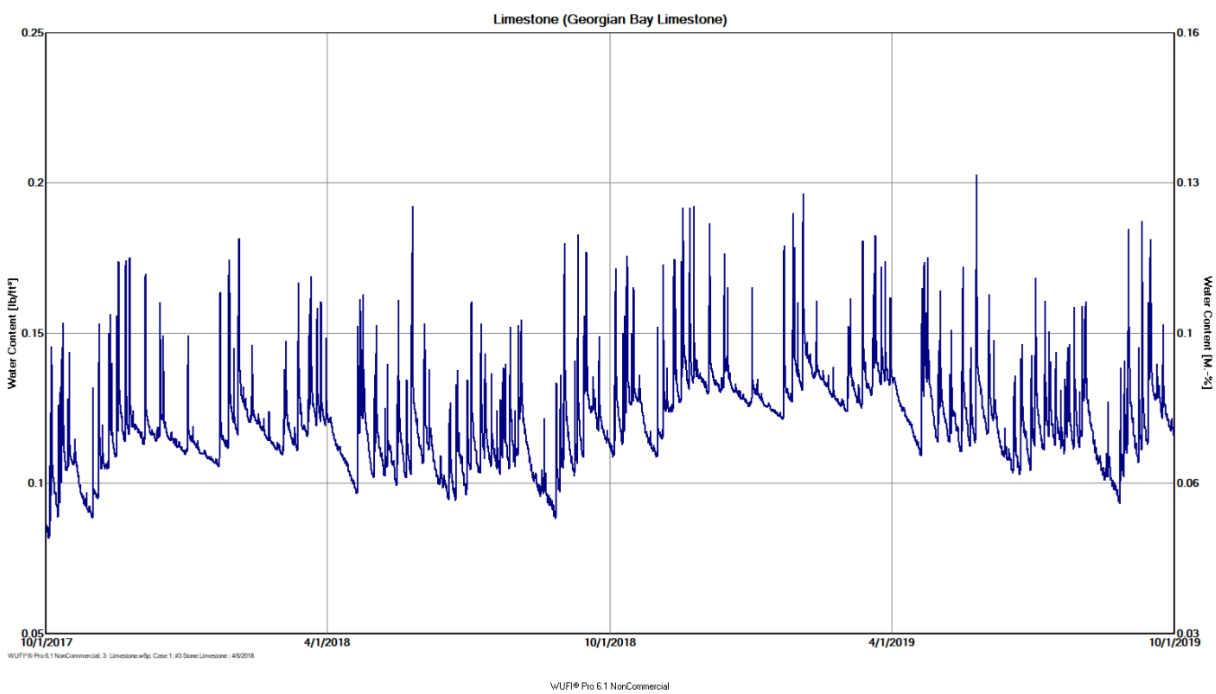


Figure A.22 Water content in Limestone for Alternatives 5 and 6 increases from 0.04% to 0.075% which is much below 20%.

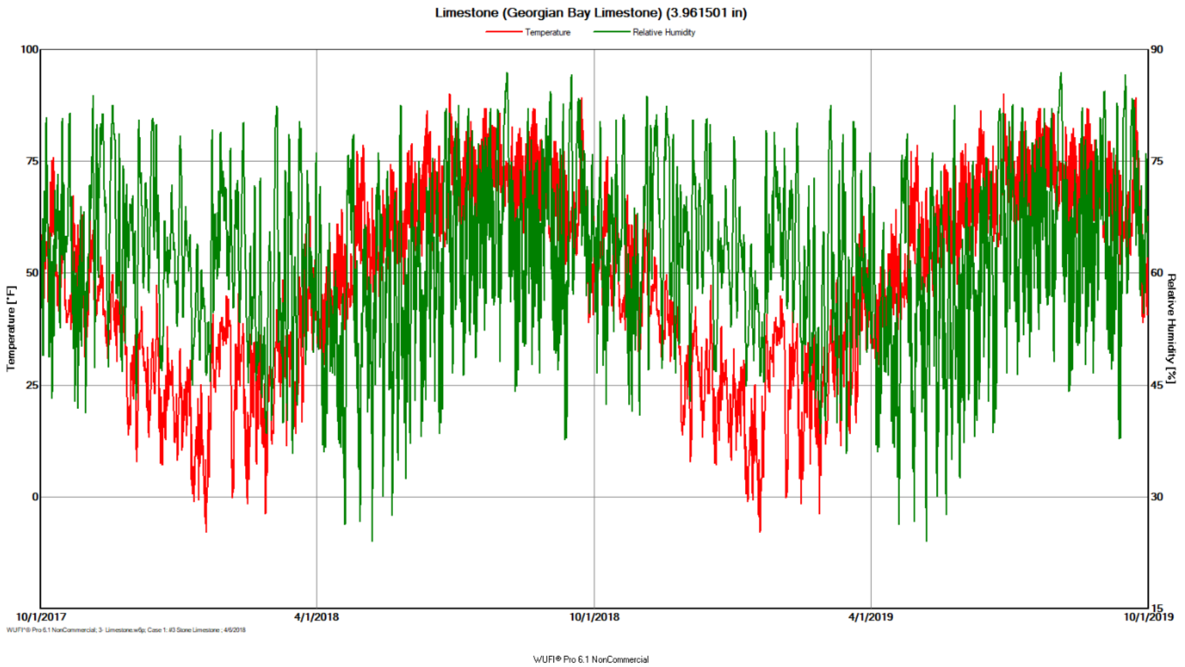


Figure A.23 Relative humidity of the critical layer (Limestone) for Alternatives 5 and 6

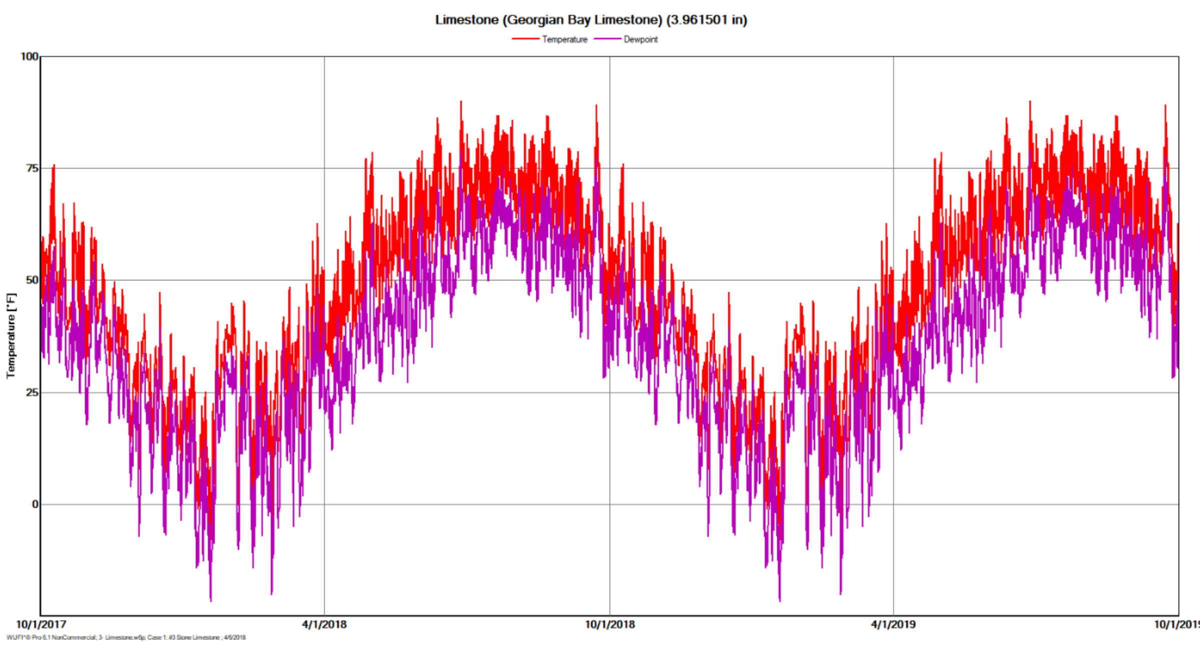


Figure A.24 Dew point of the critical layer (Limestone) for Alternatives 5 and 6

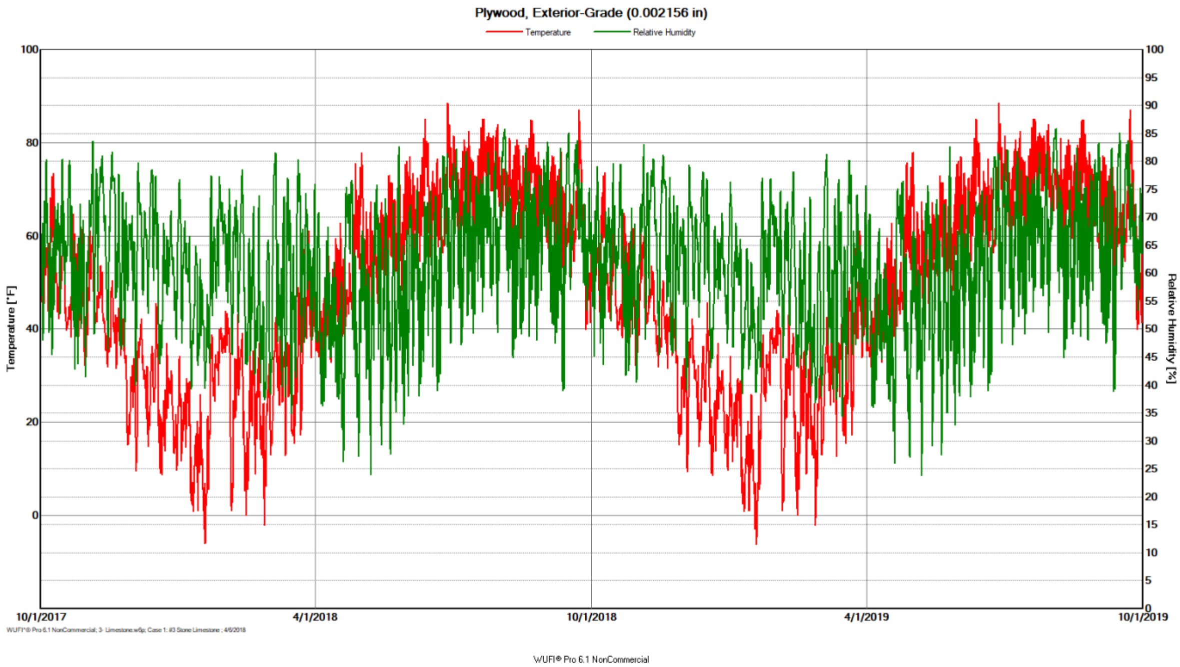


Figure A.25 Relative humidity of the critical layer (Plywood) for Alternatives 5 and 6

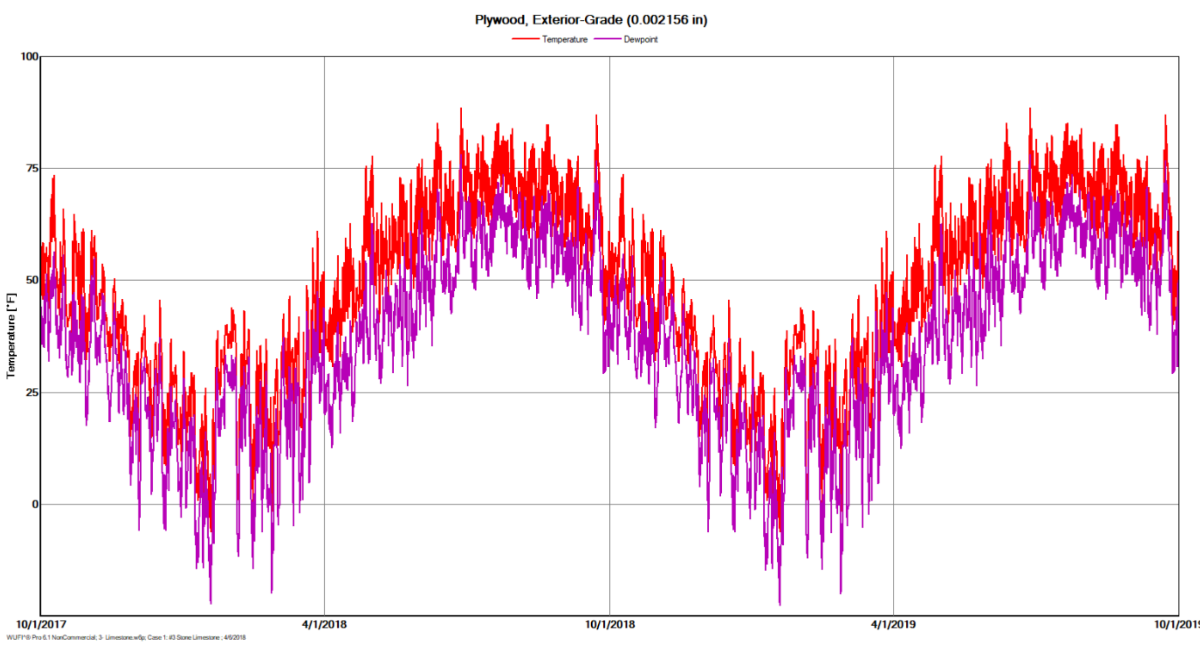


Figure A.26 Dew point of the critical layer (Plywood) for Alternatives 5 and 6

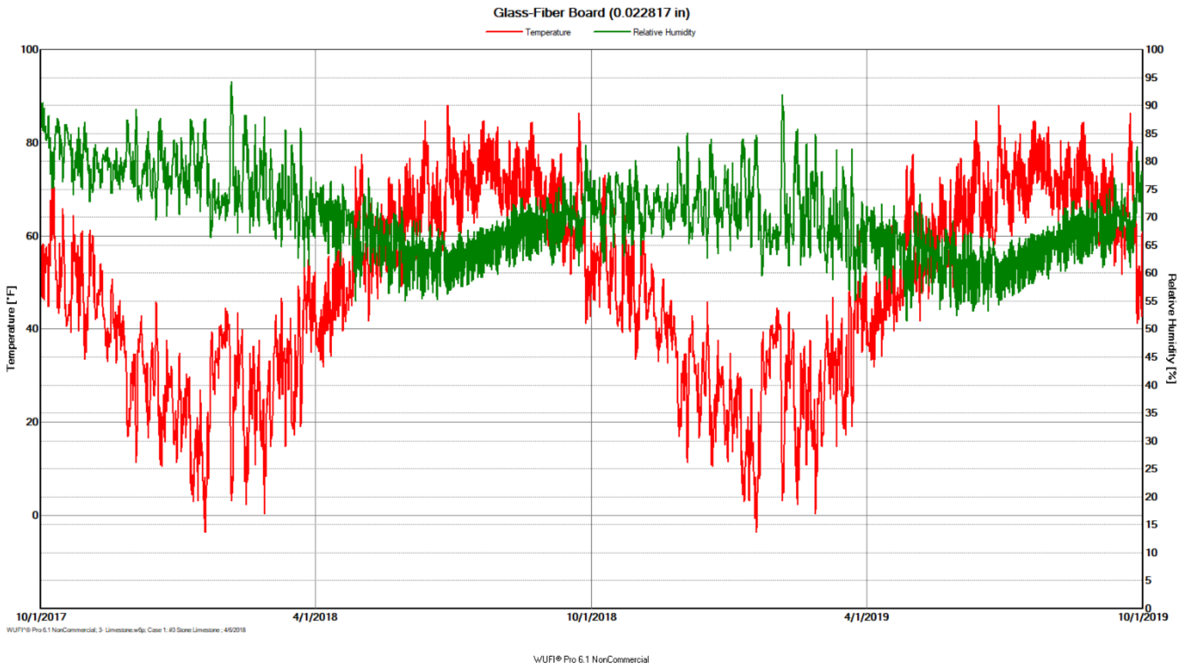


Figure A.27 Relative humidity of the critical layer (Glass fibre) for Alternatives 5 and 6

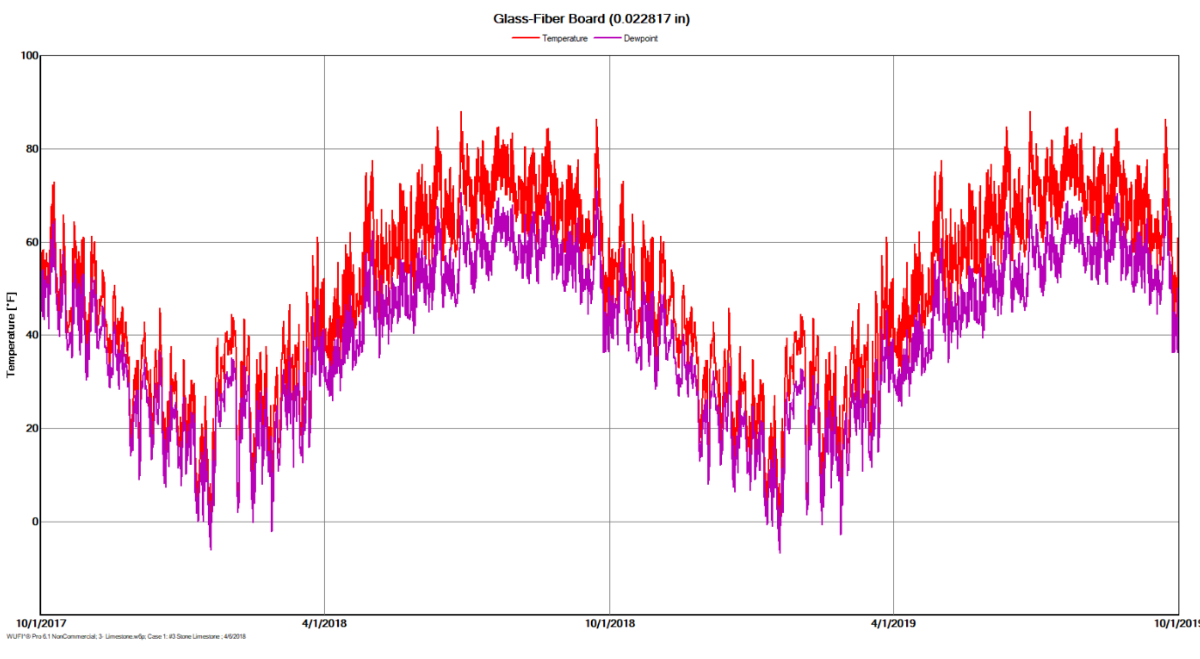


Figure A.28 Dew point of the critical layer (Glass fibre) for Alternatives 5 and 6

WALL ASSEMBLY 4: ALTERNATIVE 7 AND 8

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Western Red Cedar	0.7874	2.185
2	Air Layer 25 mm	0.98425	0.0006
3	Spun Bonded Polyolefin Membrane (SBP)	0.03937	0.0
4	Plywood, Exterior-Grade	0.5	4.4386
5	Glass-Fiber Board	6.0	0.0837
6	PE-Membrane 0,2 mm (sd = 87 m)	0.11811	0.0
7	Gypsum Board (USA)	0.5	2.185

Figure A.29 Initial water content in different layers of Alternatives 7 and 8

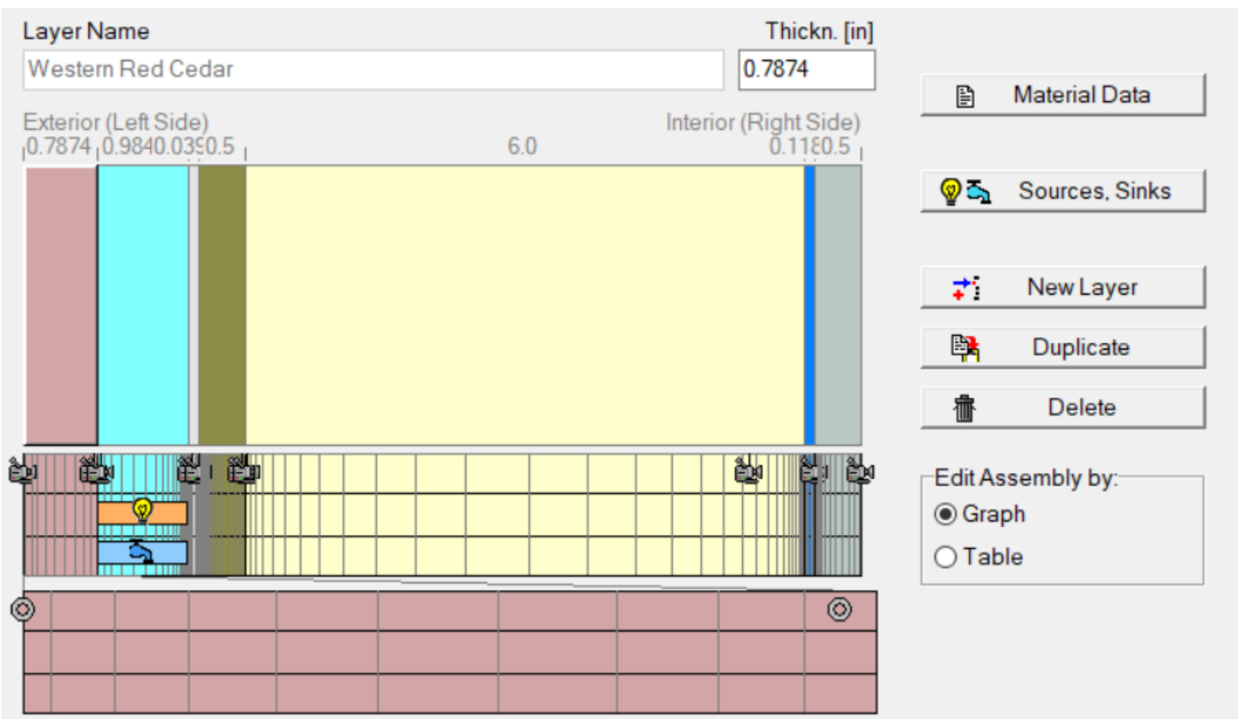


Figure A.30 Assembly layers of Alternatives 7 and 8

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.46	0.25	0.18	0.5

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Western Red Cedar	2.18	1.16	0.69	2.81
Air Layer 25 mm	0.00	0.06	0.00	0.25
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Plywood, Exterior-Grade	4.44	3.17	2.46	4.47
Glass-Fiber Board	0.08	0.05	0.03	0.08
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.28	0.11	2.18

Figure A.31 Water content in different layers of Alternatives 7 and 8

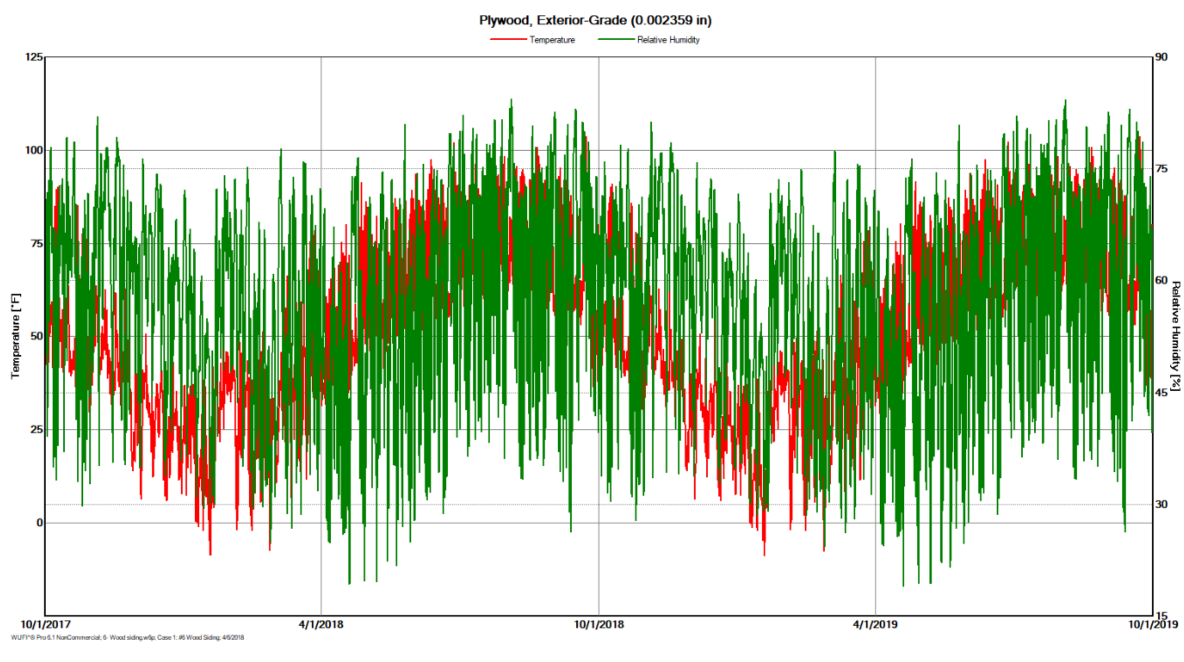


Figure A.32 Relative humidity of the critical layer (Plywood) for Alternatives 7 and 8

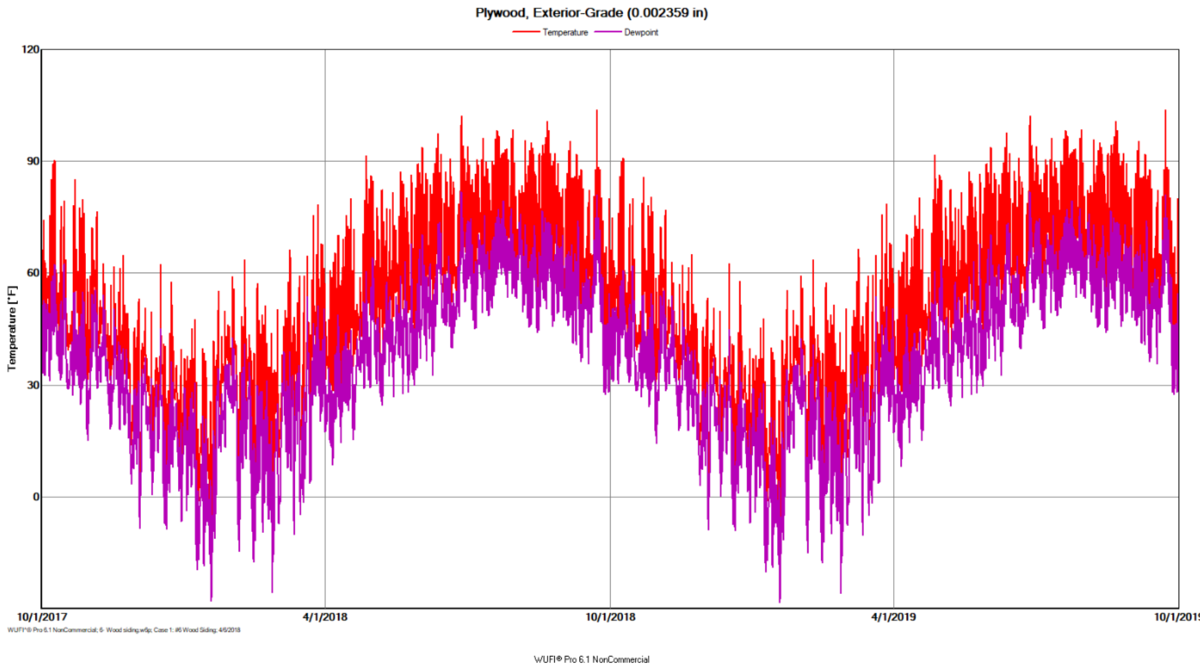


Figure A.33 Dew point of the critical layer (Plywood) for Alternatives 7 and 8

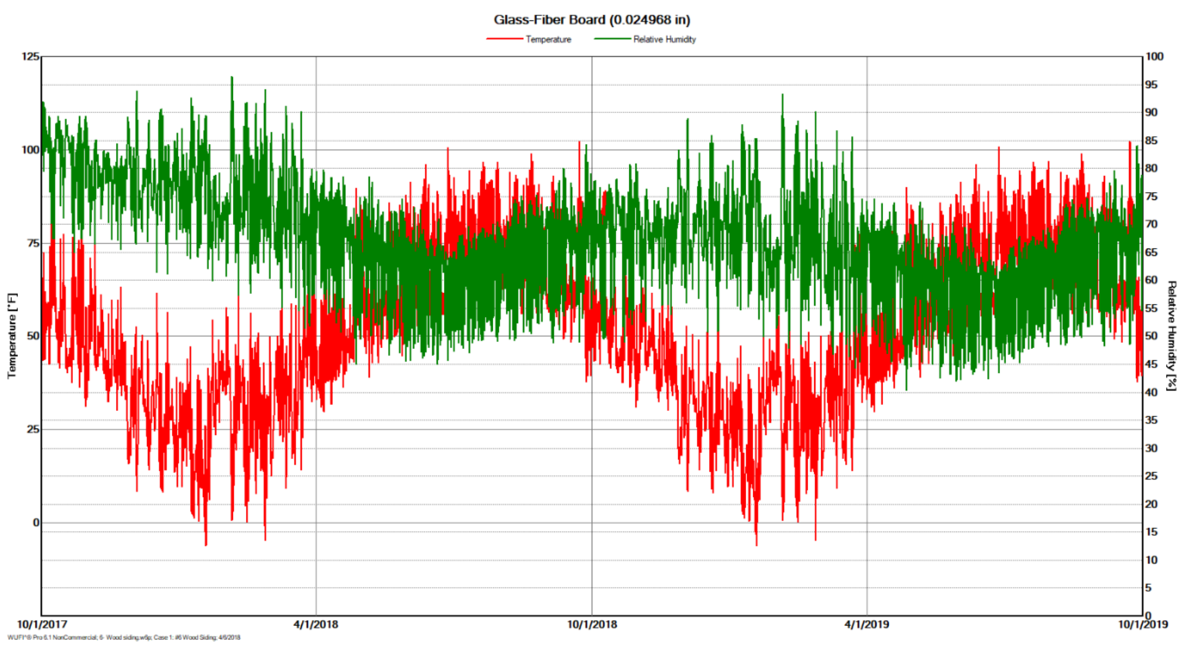


Figure A.34 Relative humidity of the critical layer (Glass fibre) for Alternatives 7 and 8

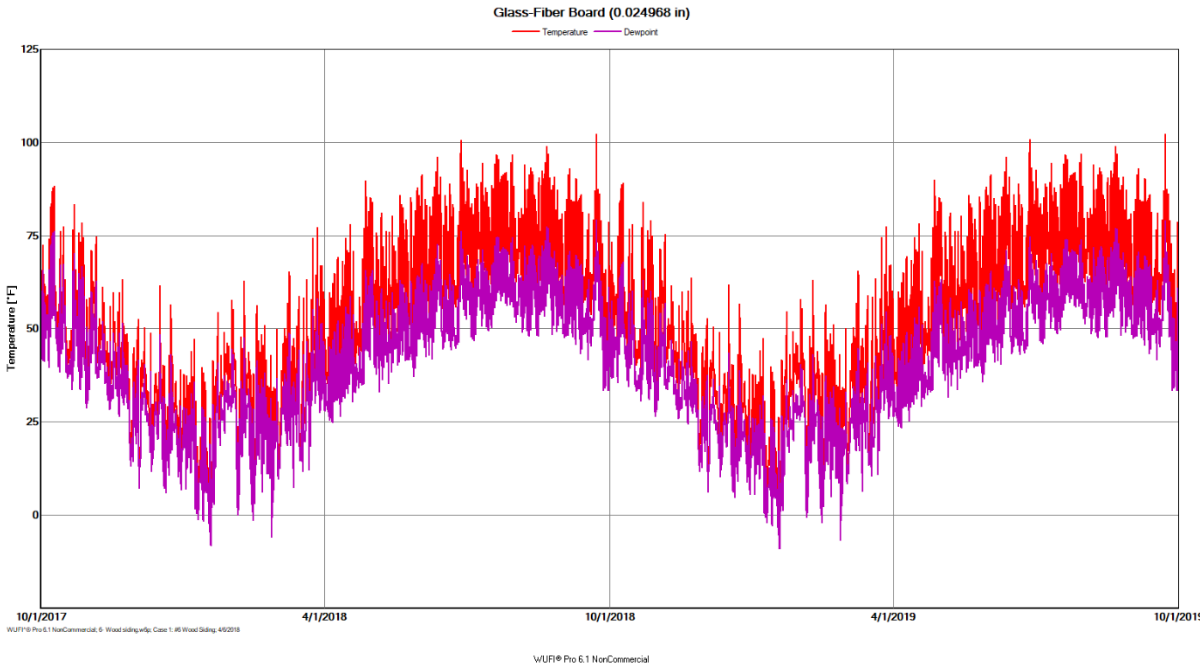


Figure A.35 Dew point of the critical layer (Glass fibre) for Alternatives 7 and 8

WALL ASSEMBLY 5: ALTERNATIVE 9 AND 10

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Acrylic Stucco	0.7874	5.9306
2	Spun Bonded Polyolefin Membrane (SBP)	0.0752	0.0
3	Gypsum Board (USA)	0.5	2.185
4	Glass-Fiber Board	6.0	0.0837
5	PE-Membrane 0,2 mm (sd = 87 m)	0.118	0.0
6	Gypsum Board (USA)	0.5	2.185

Figure A.36 Initial water content in different layers of Alternatives 9 and 10

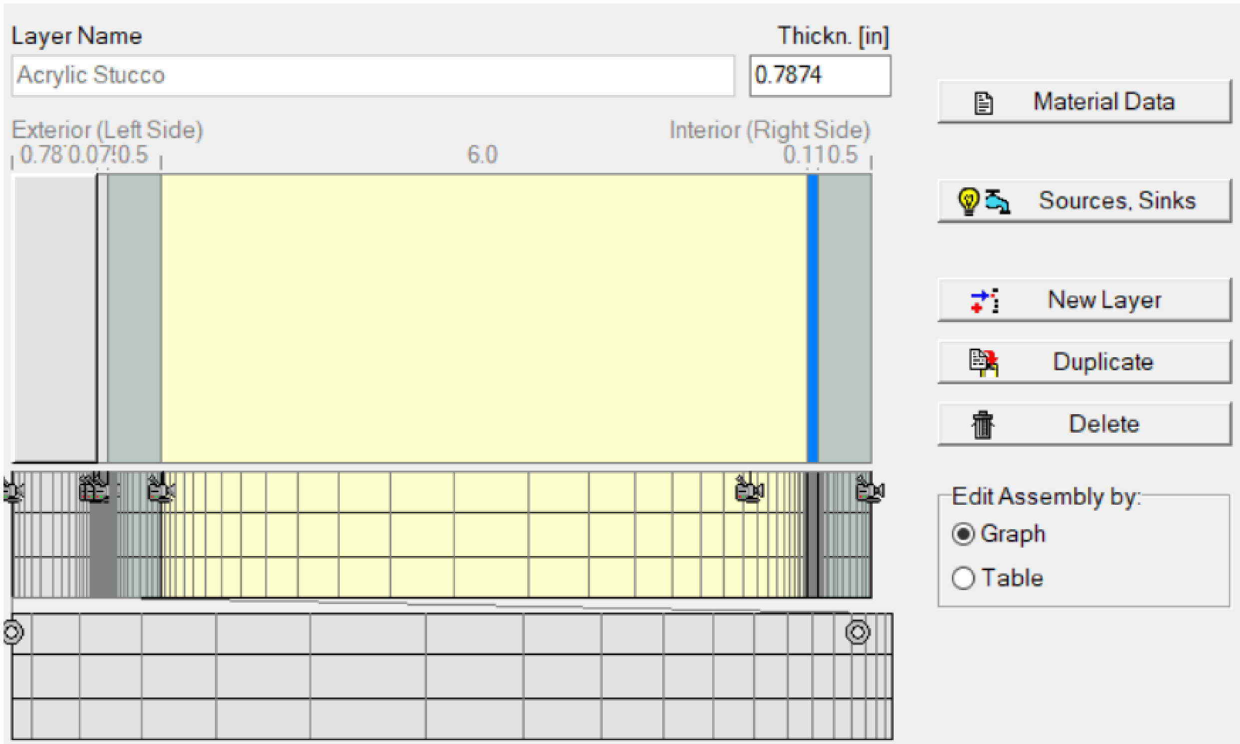


Figure A.37 Assembly layers of Alternatives 9 and 10

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.61	0.68	0.56	0.94

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Acrylic Stucco	5.93	8.84	5.76	13.31
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	1.07	0.49	2.18
Glass-Fiber Board	0.08	0.08	0.04	0.13
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.29	0.11	2.18

Figure A.38 Water content in different layers of Alternatives 9 and 10

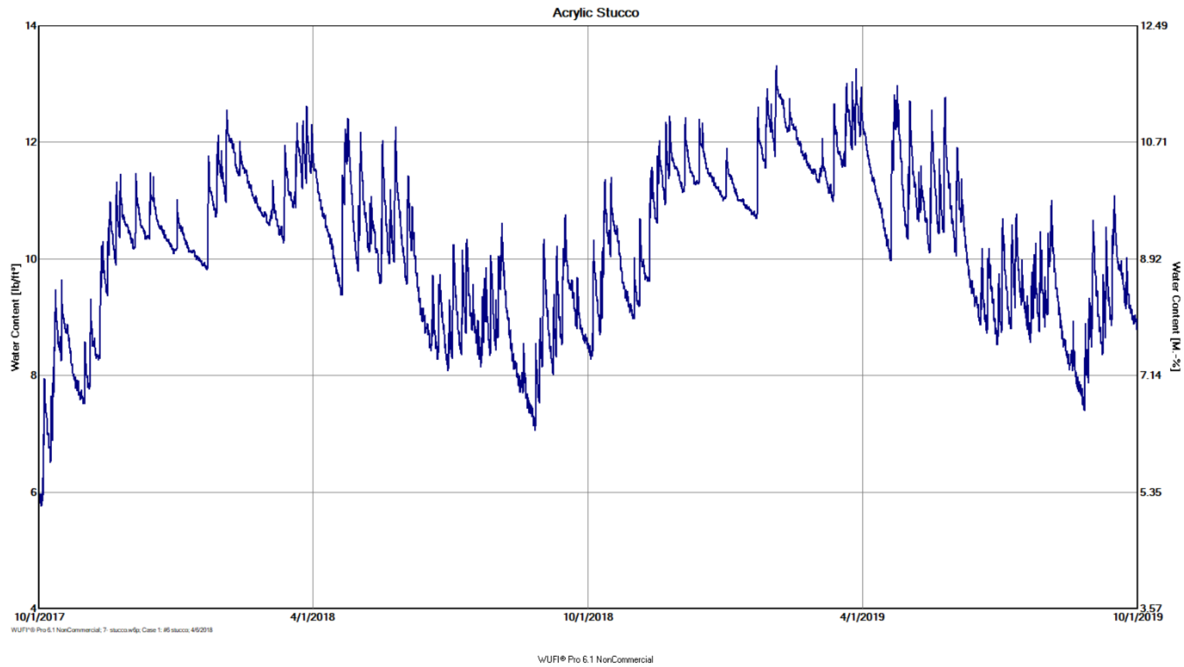


Figure A.39 Water content in Stucco layer for Alternatives 9 and 10 increases from 5.1% to 7.5%, (at max point 11.5%) which is much lower than 20%.

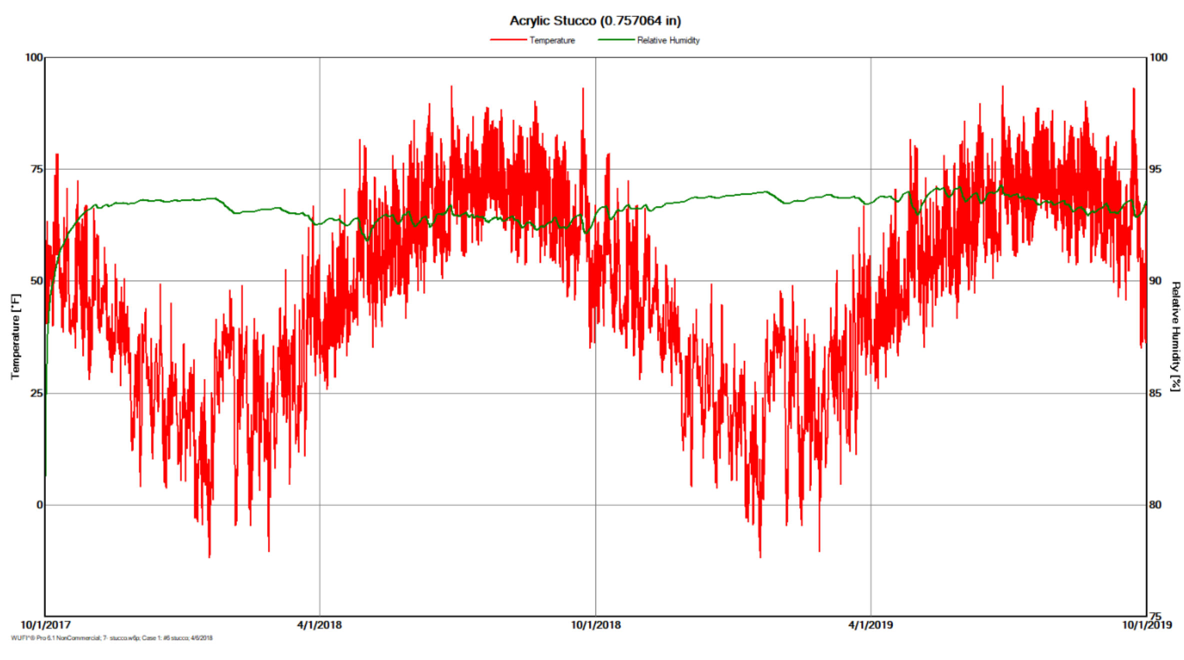


Figure A.40 Relative humidity of the critical layer (Stucco) for Alternatives 9 and 10

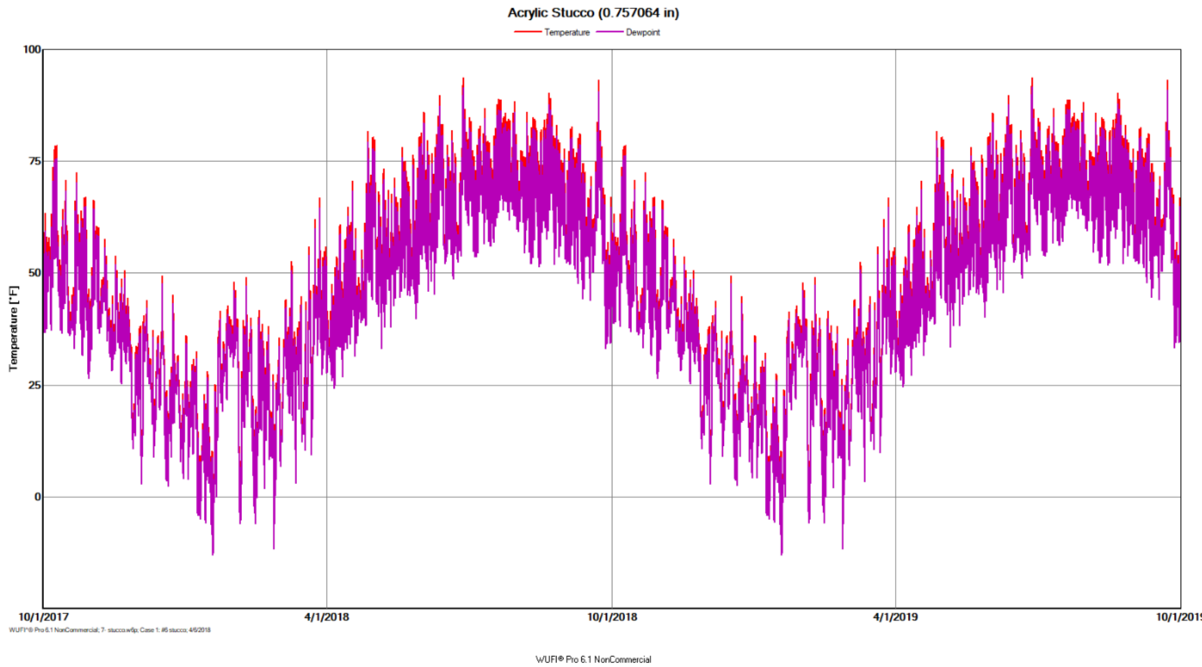


Figure A.41 Dew point of the critical layer (Stucco) for Alternatives 9 and 10

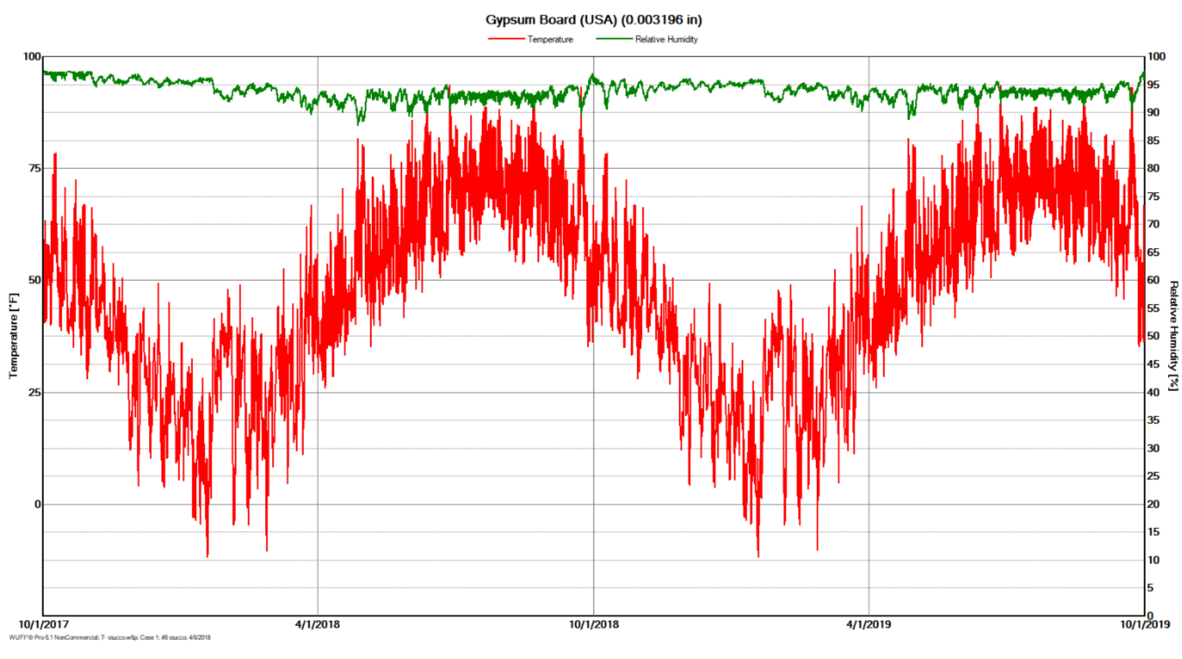


Figure A.42 Relative humidity of the critical layer (Gypsum) for Alternatives 9 and 10

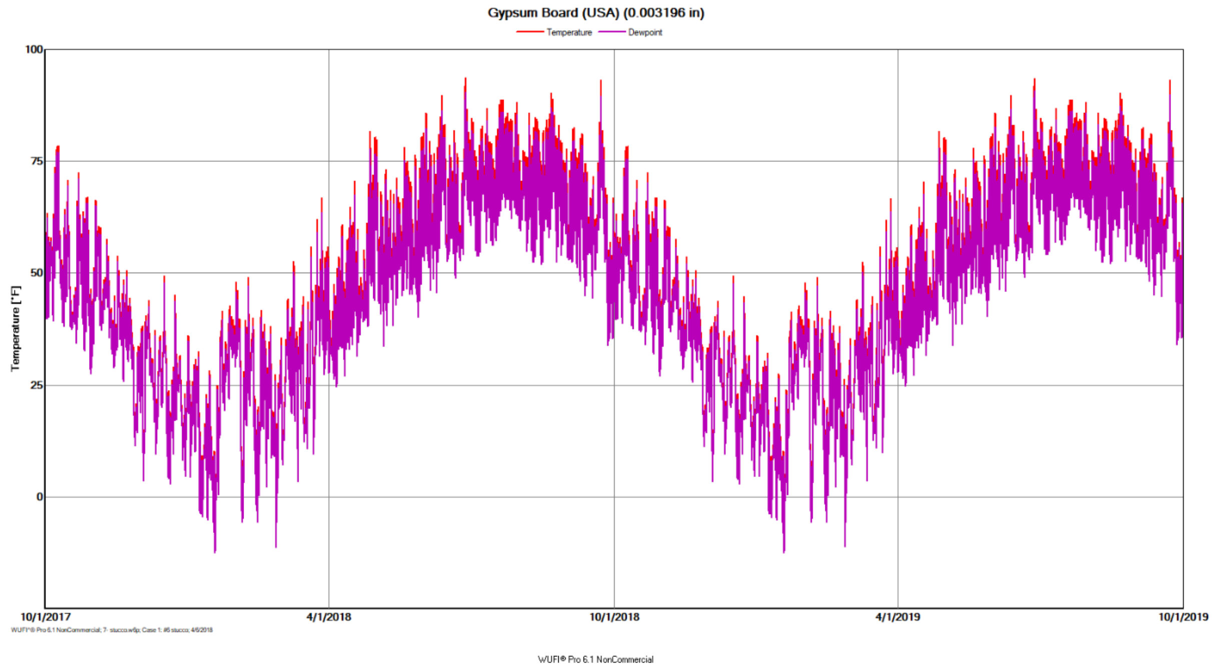


Figure A.43 Dew point of the critical layer (Gypsum) for Alternatives 9 and 10

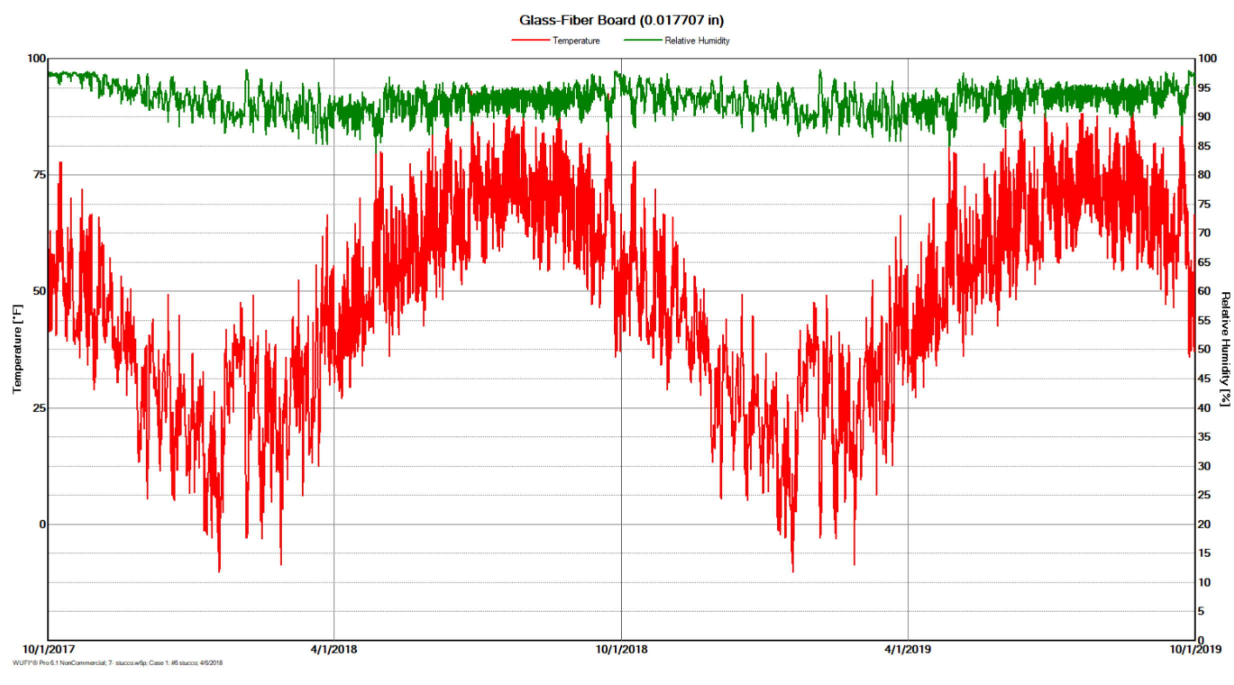


Figure A.44 Relative humidity of the critical layer (Glass fibre) for Alternatives 9 and 10

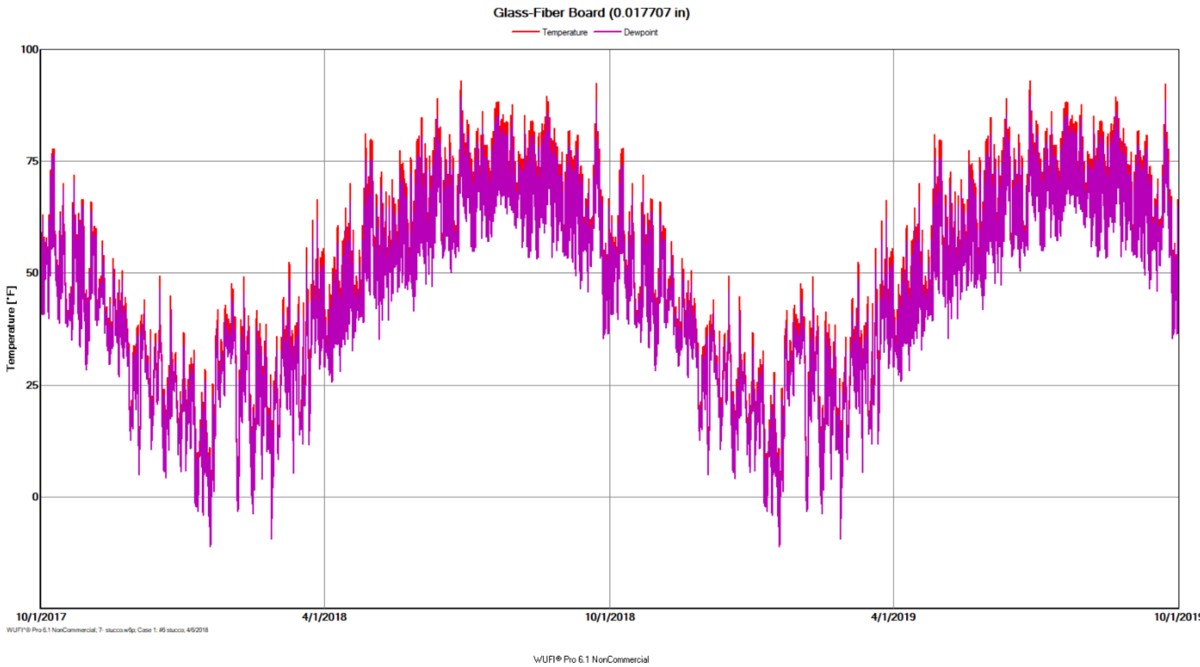


Figure A.45 Dew point of the critical layer (Glass fibre) for Alternatives 9 and 10

WALL ASSEMBLY 6: ALTERNATIVE 11 AND 12

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Fibrecementboard	0.511811	2.185
2	Air Layer 25 mm	0.98425	0.0006
3	Spun Bonded Polyolefin Membrane (SBP)	0.03937	0.0
4	Plywood, Exterior-Grade	0.5	4.4386
5	Glass-Fiber Board	6.0	0.0837
6	PE-Membrane 0,2 mm (sd = 87 m)	0.11811	0.0
7	Gypsum Board (USA)	0.5	2.185

Figure A.46 Initial water content in different layers of Alternatives 11 and 12

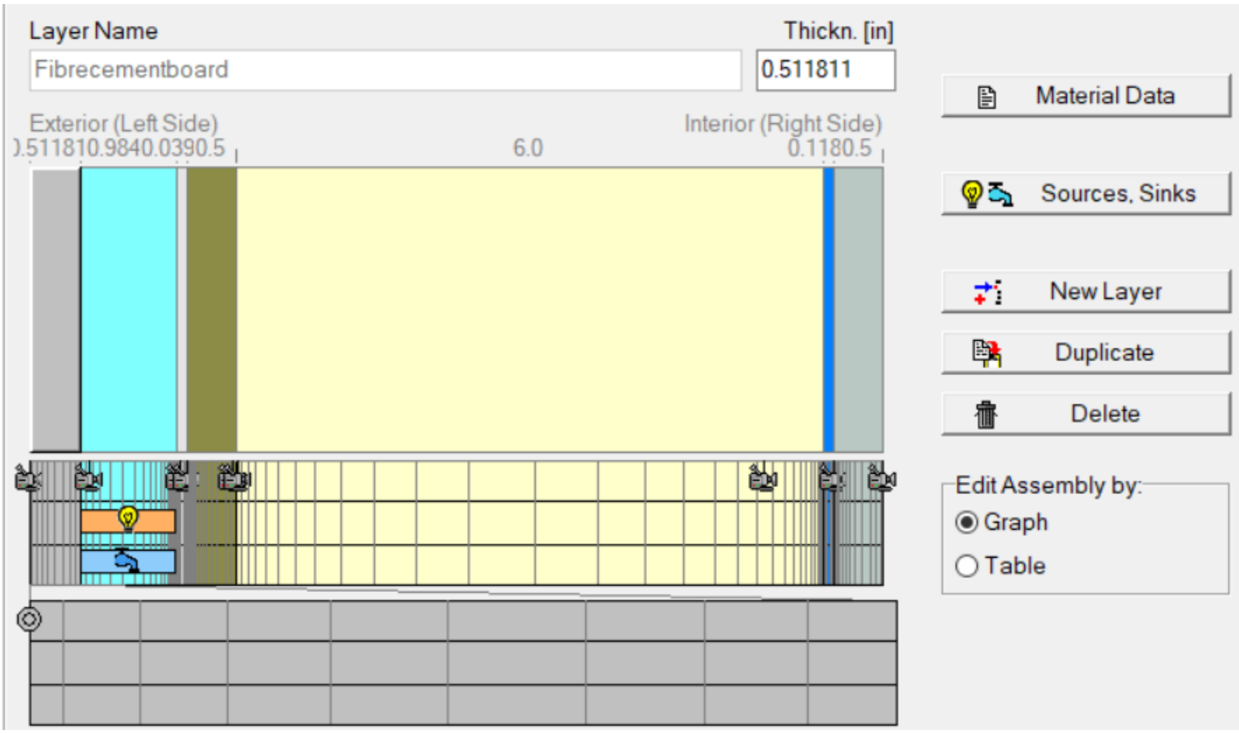


Figure A.47 Assembly layers of Alternatives 11 and 12

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	0.41	0.37	0.3	0.53

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Fibrecementboard	2.18	4.83	2.18	5.80
Air Layer 25 mm	0.00	0.05	0.00	0.24
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Plywood, Exterior-Grade	4.44	2.99	2.34	4.45
Glass-Fiber Board	0.08	0.05	0.03	0.09
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.28	0.11	2.18

Figure A.48 Water content in different layers of Alternatives 11 and 12

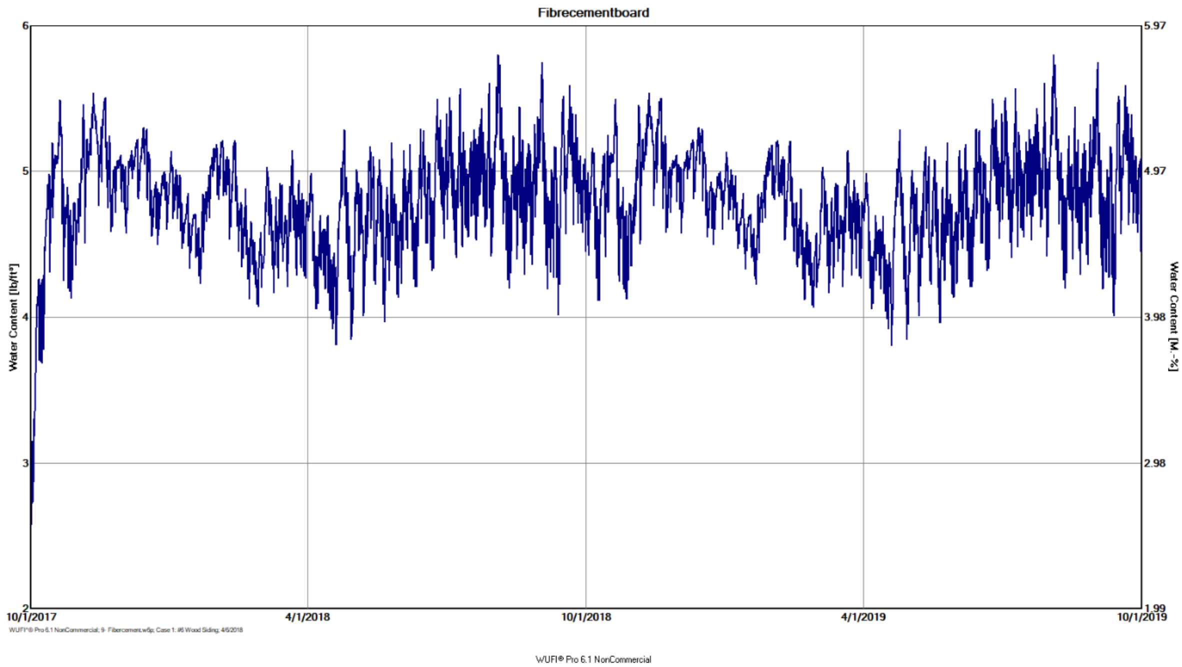


Figure A.49 Water content in Fibrecement layer for Alternatives 11 and 12 increases from 2 % to 4.5%, (at max point 5.5%) which is much lower than 20%.

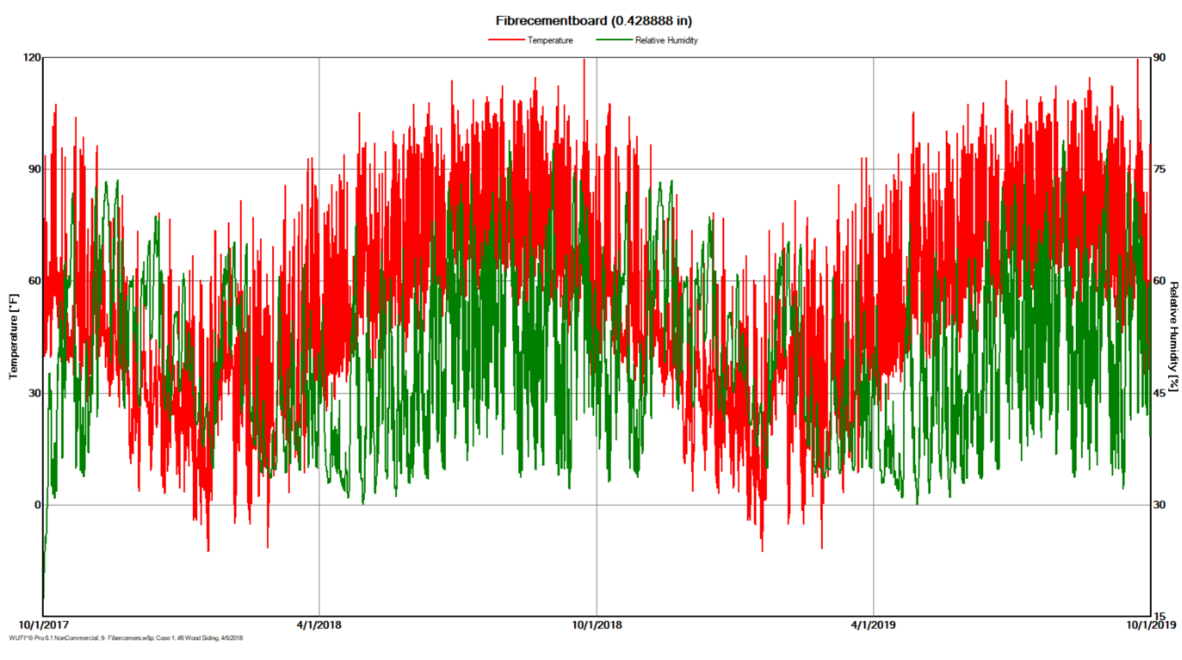


Figure A.50 Relative humidity of the critical layer (Fibrecement) for Alternatives 11 and 12

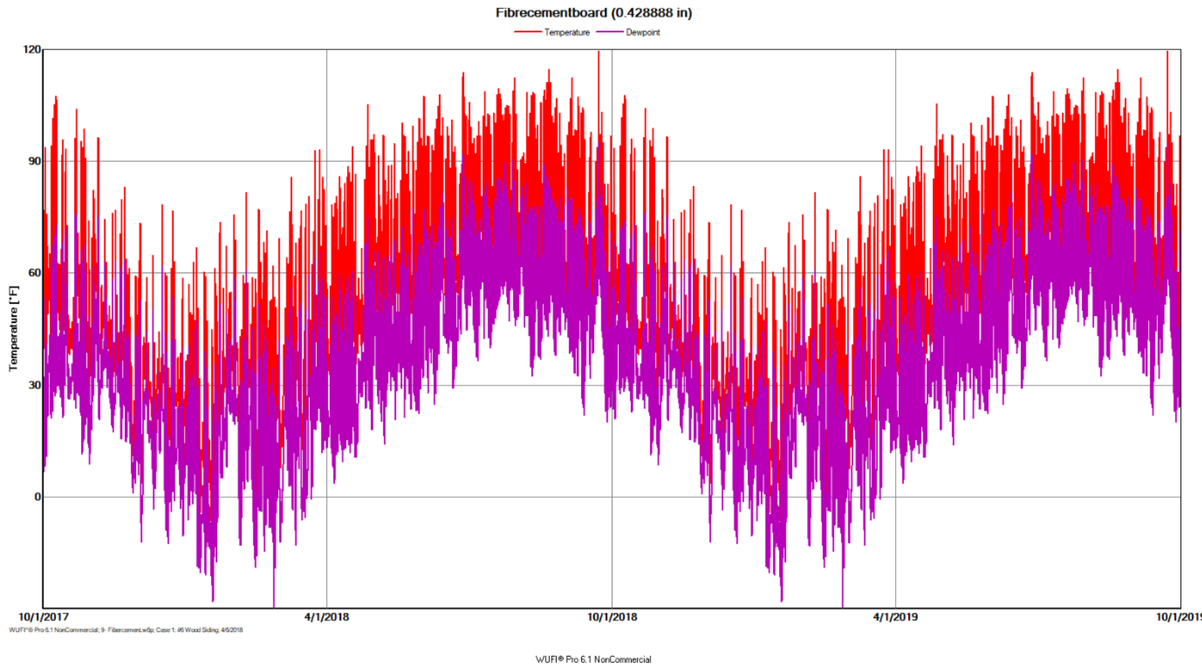


Figure A.51 Dew point of the critical layer (Fibrecement) for Alternatives 11 and 12

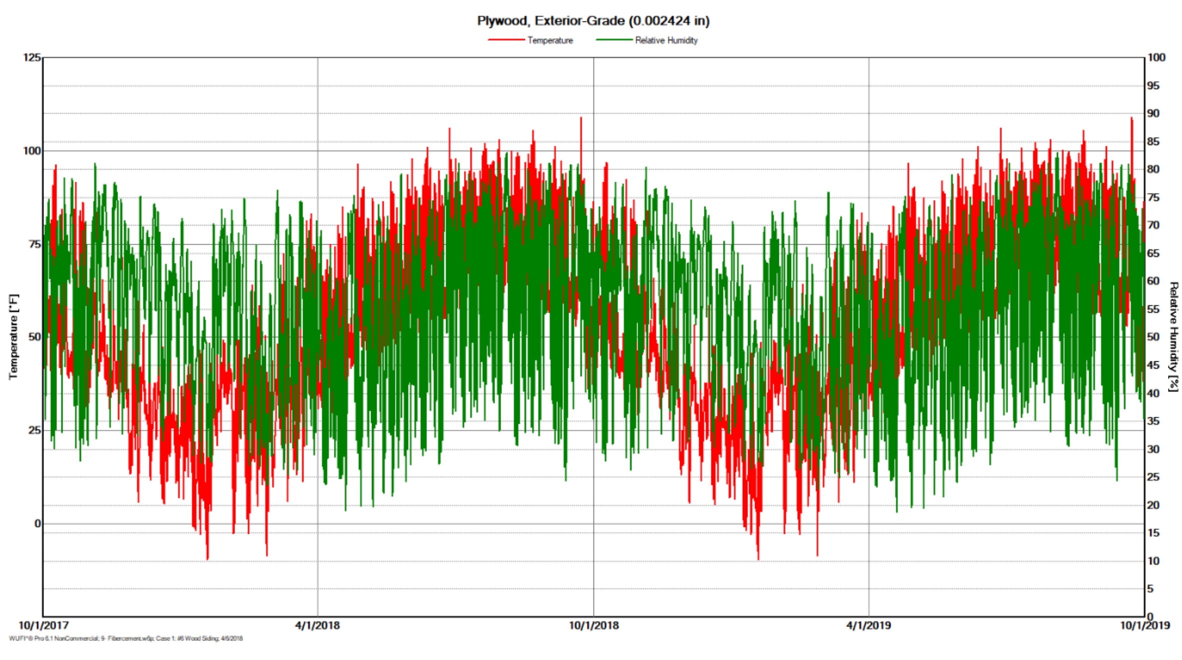


Figure A.52 52 Relative humidity of the critical layer (Plywood) for Alternatives 11 and 12

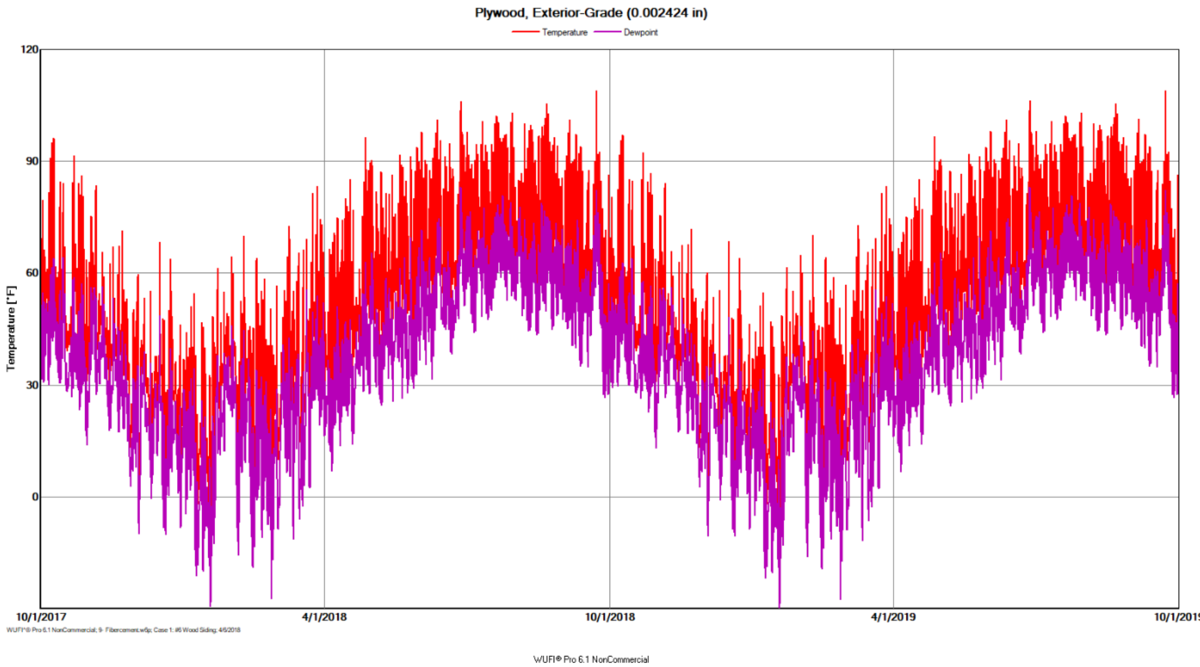


Figure A.53 Dew point of the critical layer (Plywood) for Alternatives 11 and 12

Figure A.54 Relative humidity of the critical layer (Glass fibre) for Alternatives 11 and 12

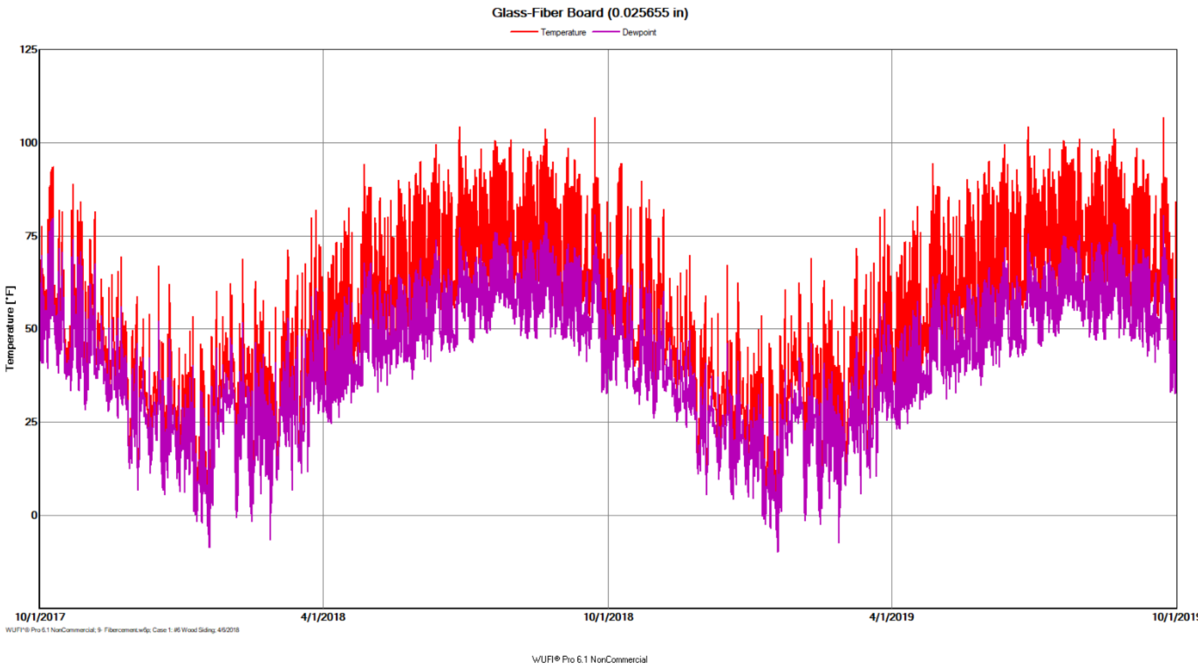


Figure A.55 Dew point of the critical layer (Glass fibre) for Alternatives 11 and 12

WALL ASSEMBLY 7: ALTERNATIVE 13 AND 14

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Brick (old)	3.93701	0.2085
2	Air Layer 40 mm	1.5748	0.117
3	Extruded Polystyrene Insulation	3.50394	0.008
4	PE-Membrane (Poly; 0.07 perm)	0.23622	0.000
5	Concrete Brick	8	3.2463
6	Interior Gypsum Board	0.49213	0.6243

Figure A.56 Initial water content in different layers of Alternatives 13 and 14

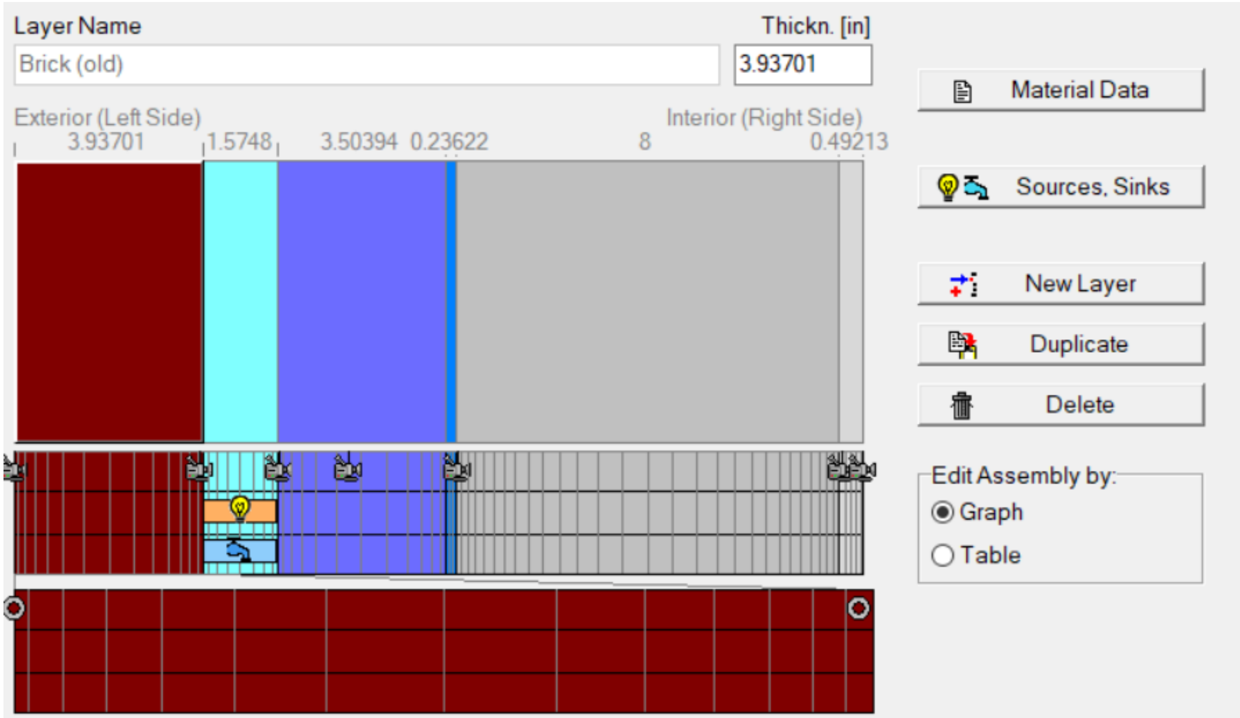


Figure A.57 Assembly layers of Alternatives 13 and 14

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	2.28	1.94	1.84	4.72

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Brick (old)	0.21	0.11	0.05	7.97
Air Layer 40 mm	0.12	0.04	0.01	0.56
Extruded Polystyrene Insulation	0.01	0.01	0.00	0.02
PE-Membrane (Poly; 0.07 perm)	0.00	0.00	0.00	0.00
Concrete Brick	3.25	2.83	2.72	3.25
Interior Gypsum Board	0.62	0.31	0.14	0.62

Figure A.58 Water content in different layers of Alternatives 13 and 14

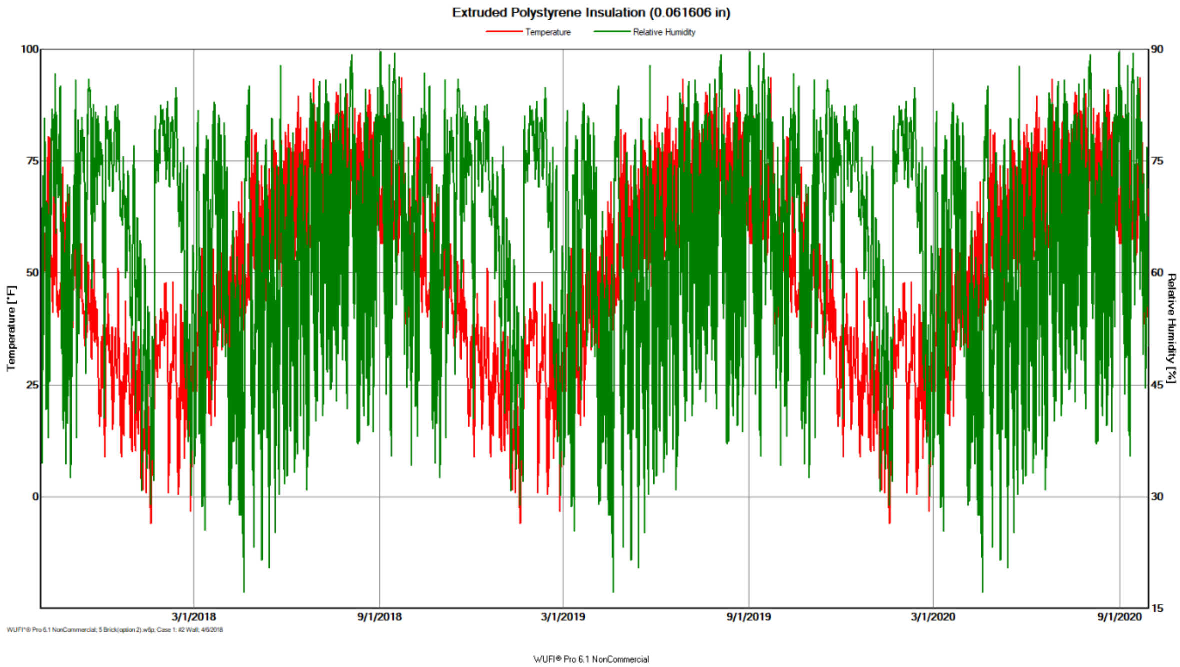


Figure A.59 Relative humidity of the critical layer (XPS) for Alternatives 13 and 14

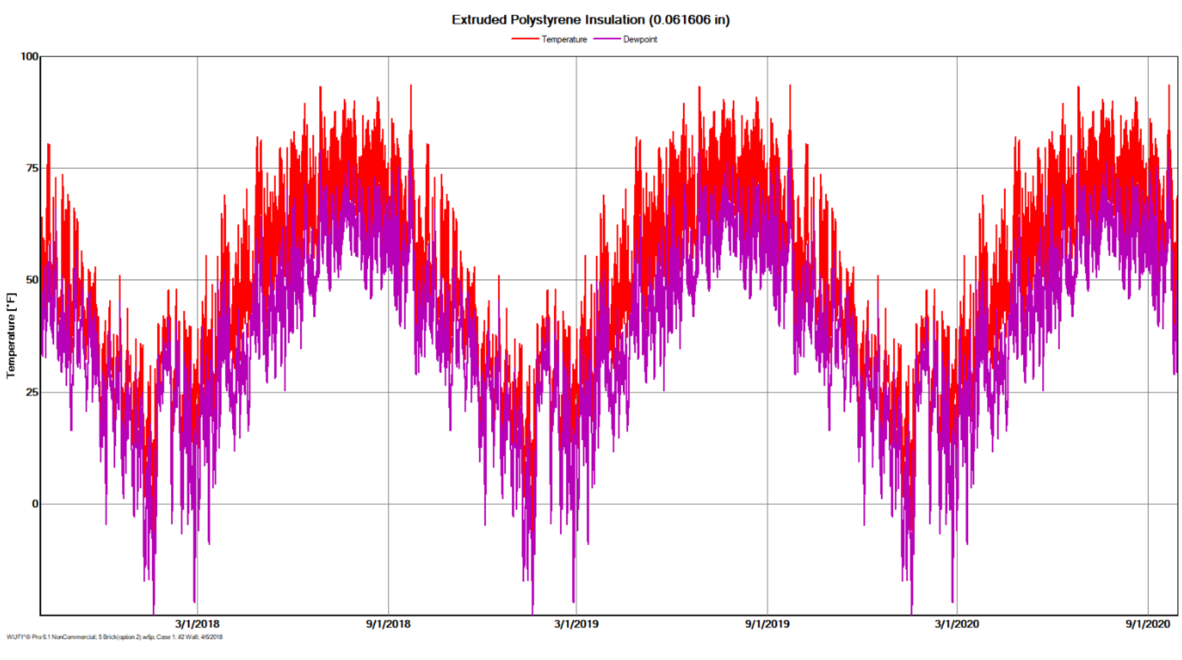


Figure A.60 Dew point of the critical layer (XPS) for Alternatives 13 and 14

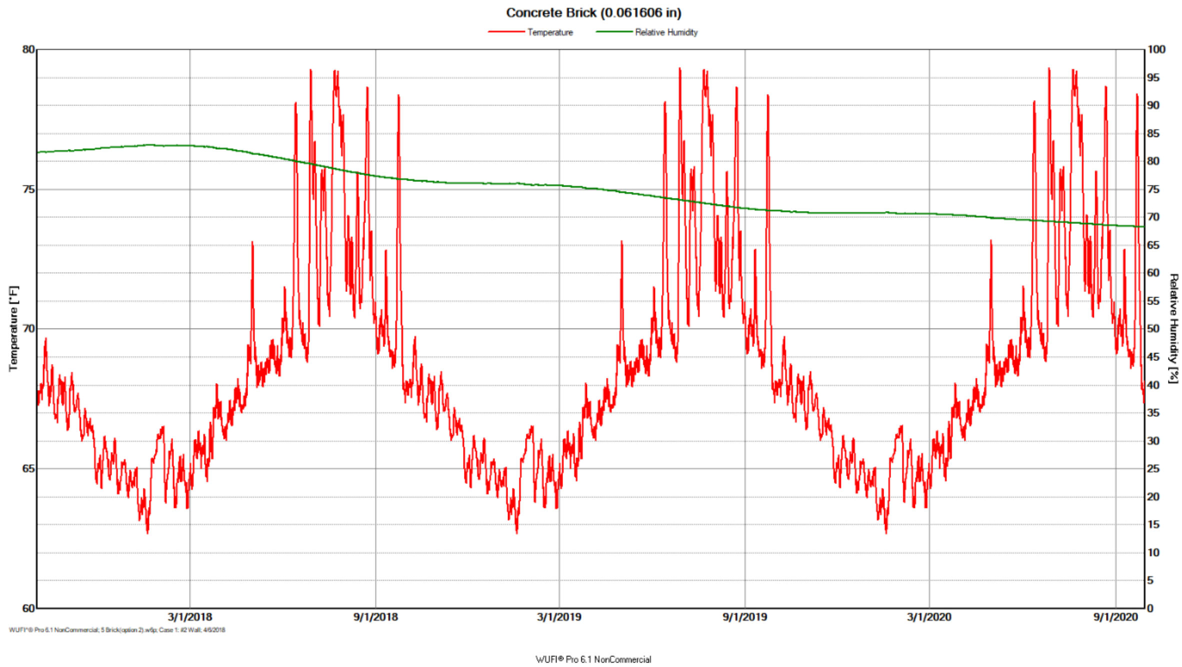


Figure A.61 Relative humidity of the critical layer (Concrete brick) for Alternatives 13 and 14

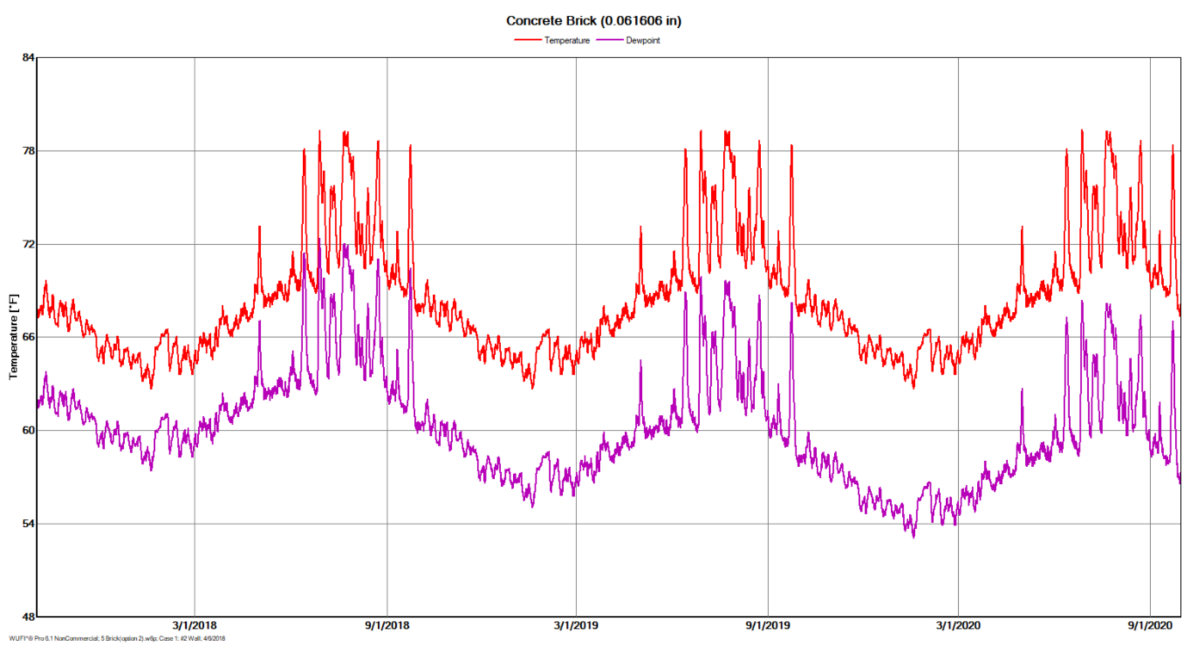


Figure A.62 Dew point of the critical layer (Concrete brick) for Alternatives 13 and 14

WALL ASSEMBLY 8: ALTERNATIVE 15 AND 16

Initial Water Content in Different Layers

No.	Material Layer	Thickn. [in]	Water Content [lb/ft³]
1	Acrylic Stucco	0.7874	5.9307
2	Spun Bonded Polyolefin Membrane (SBP)	0.07874	0.000
3	Extruded Polystyrene Insulation	4	0.0081
4	PE-Membrane 0,2 mm (sd = 87 m)	0.118	0.000
5	Gypsum Board (USA)	0.5	2.185
6	Concrete Brick	8	3.2462
7	Gypsum Board (USA)	0.5	2.185

Figure A.63 Initial water content in different layers of Alternatives 15 and 16

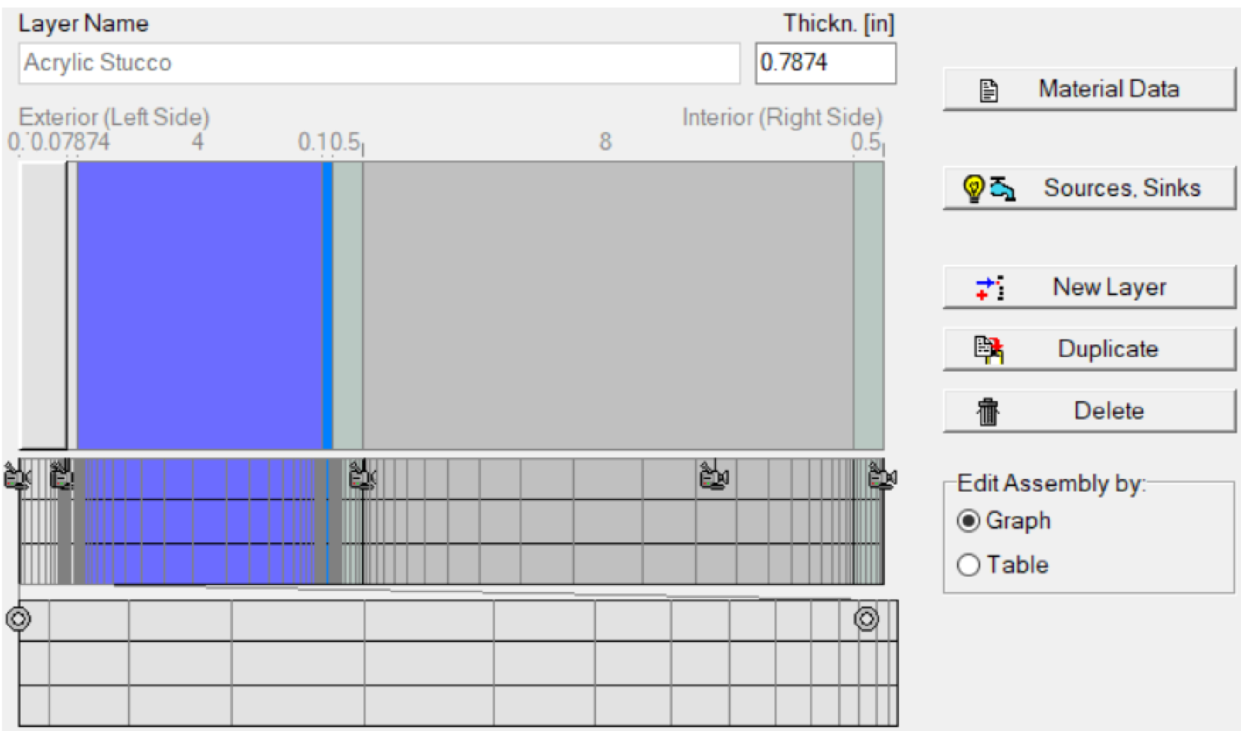


Figure A.64 Assembly layers of Alternatives 15 and 16

Water Content [lb/ft²]

	Start	End	Min.	Max.
Total Water Content	2.74	2.82	2.72	3.1

Water Content [lb/ft³]

Layer/Material	Start	End	Min.	Max.
Acrylic Stucco	5.93	9.50	5.63	13.46
Spun Bonded Polyolefin Membrane (SBP)	0.00	0.00	0.00	0.00
Extruded Polystyrene Insulation	0.01	0.04	0.01	0.05
PE-Membrane 0,2 mm (sd = 87 m)	0.00	0.00	0.00	0.00
Gypsum Board (USA)	2.18	0.46	0.46	2.18
Concrete Brick	3.25	3.23	3.23	3.38
Gypsum Board (USA)	2.18	0.34	0.29	2.18

Figure A.65 Water content in different layers of Alternatives 15 and 16

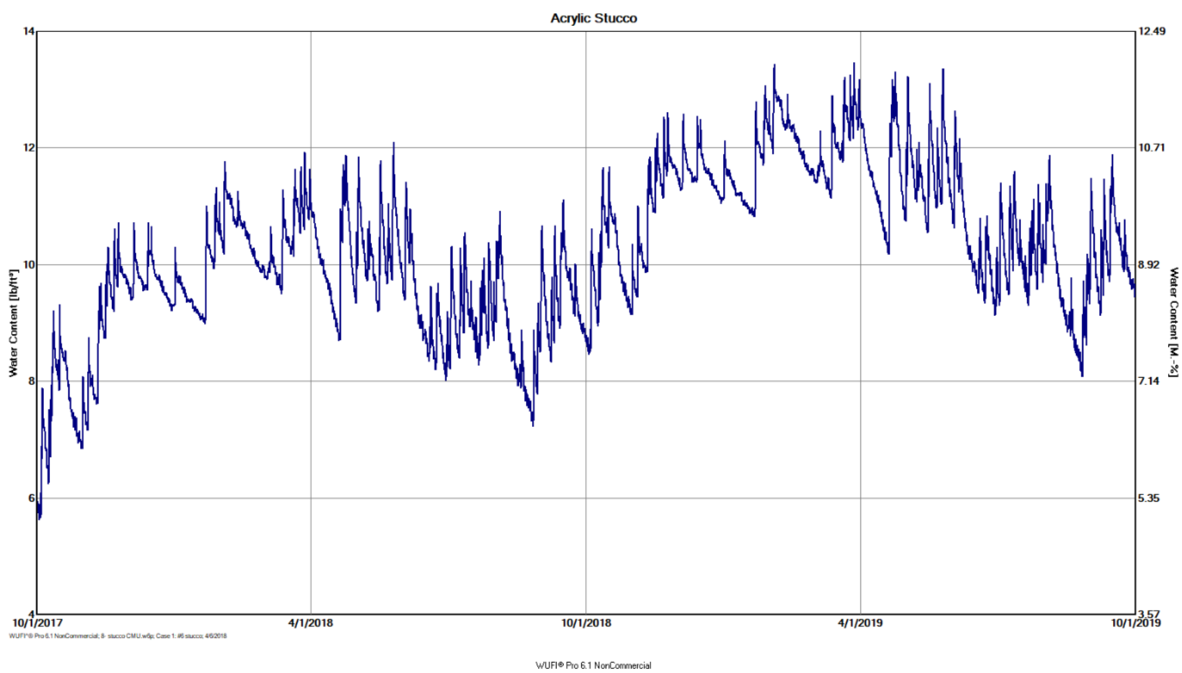


Figure A.66 Water content in Stucco layer for Alternatives 15 and 16 increases from 5 % to 8.75%, (at max point 11.8%) which is much lower than 20%.

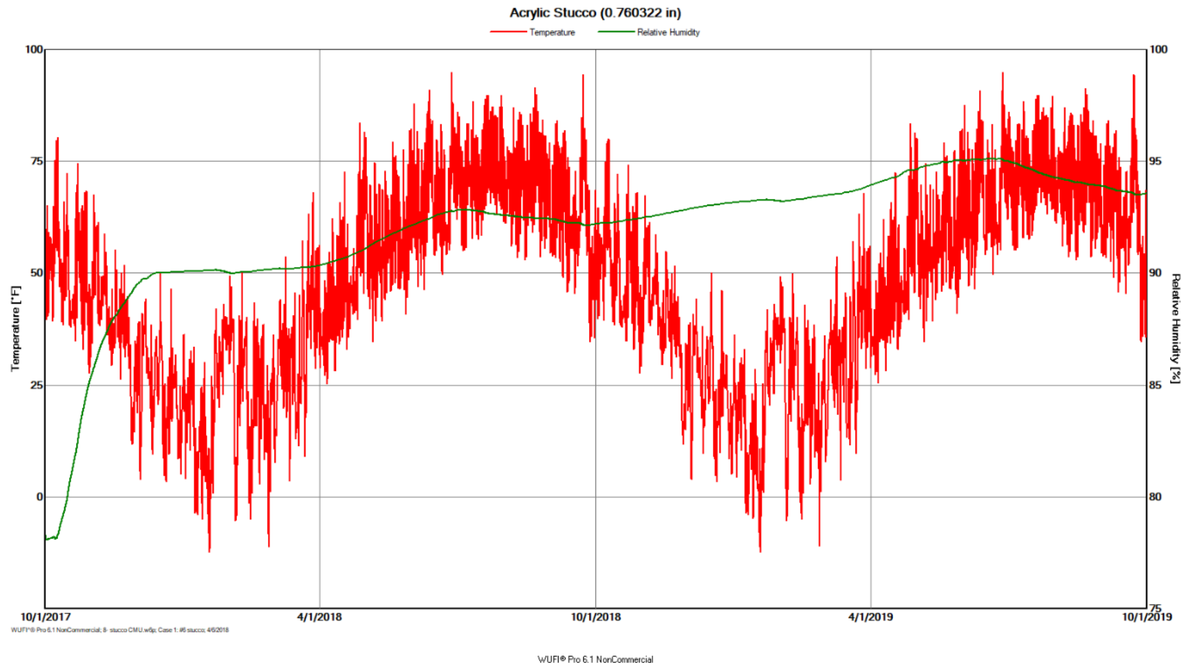


Figure A.67 Relative humidity of the critical layer (Stucco) for Alternatives 15 and 16

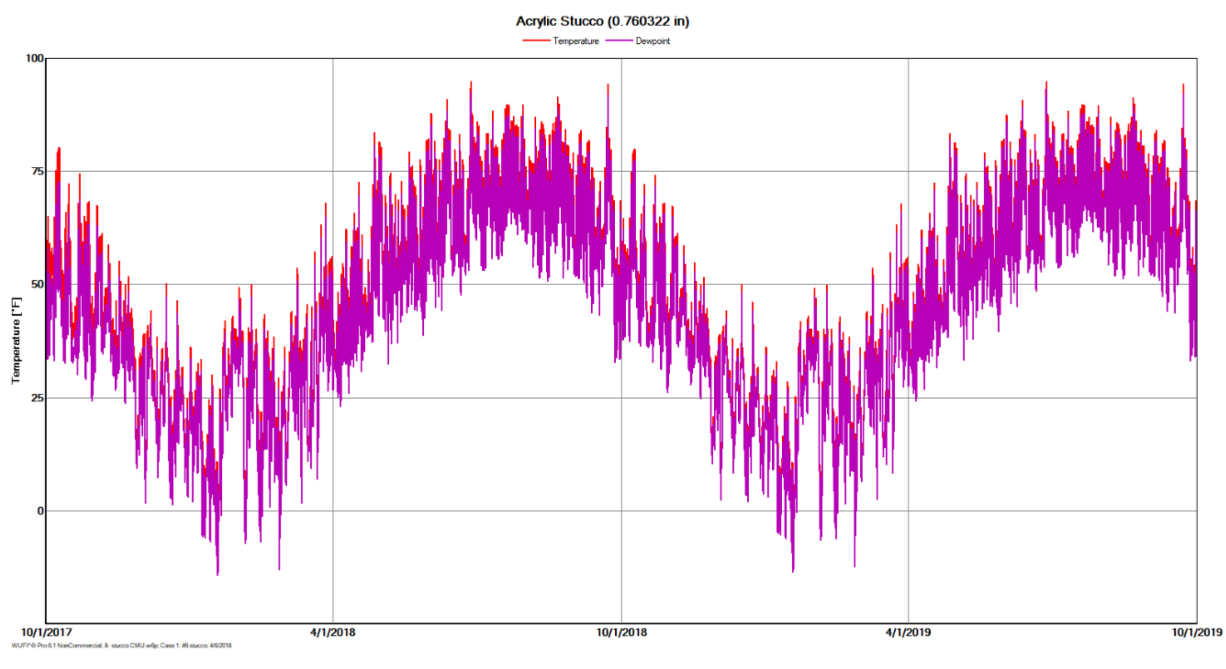


Figure A.68 Dew point of the critical layer (Stucco) for Alternatives 15 and 16

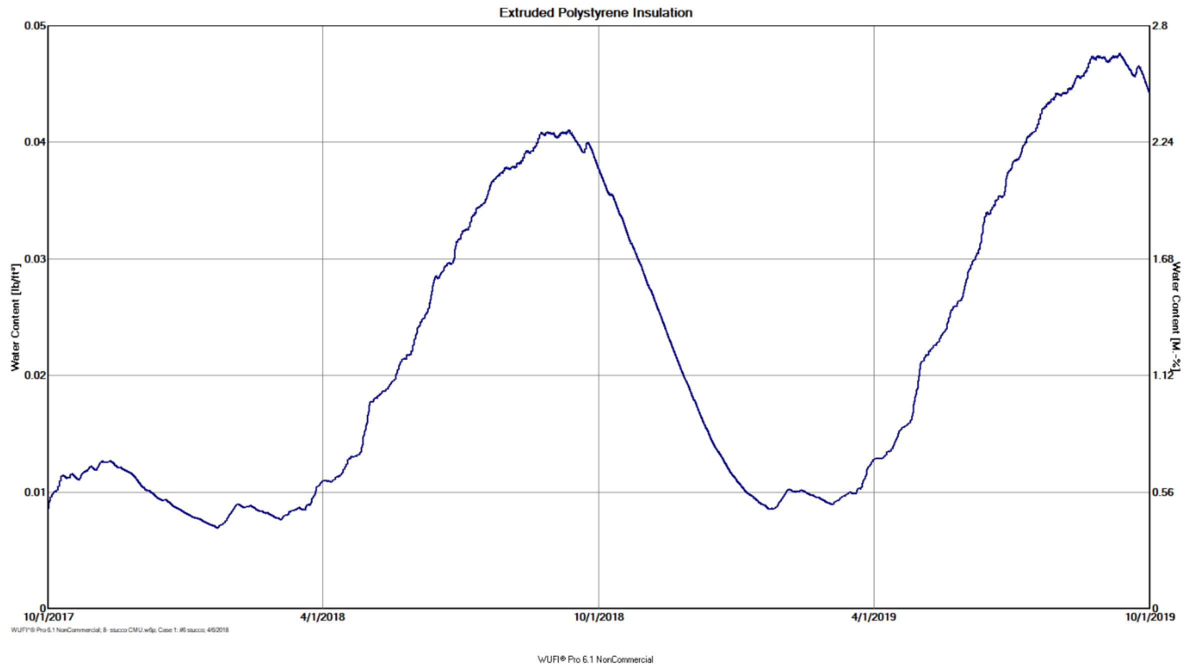


Figure A.69 Water content in Stucco layer for Alternatives 15 and 16 increases from 0.55 % to 2.5% which is much lower than 20%.

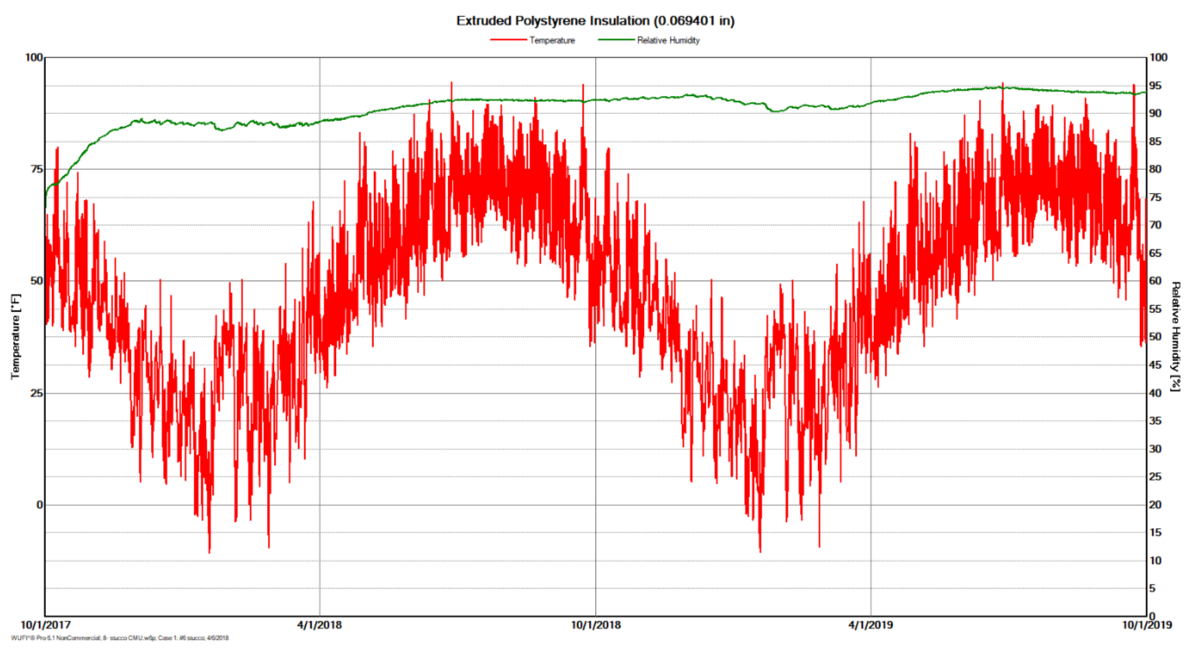


Figure A.70 Relative humidity of the critical layer (XPS) for Alternatives 15 and 16

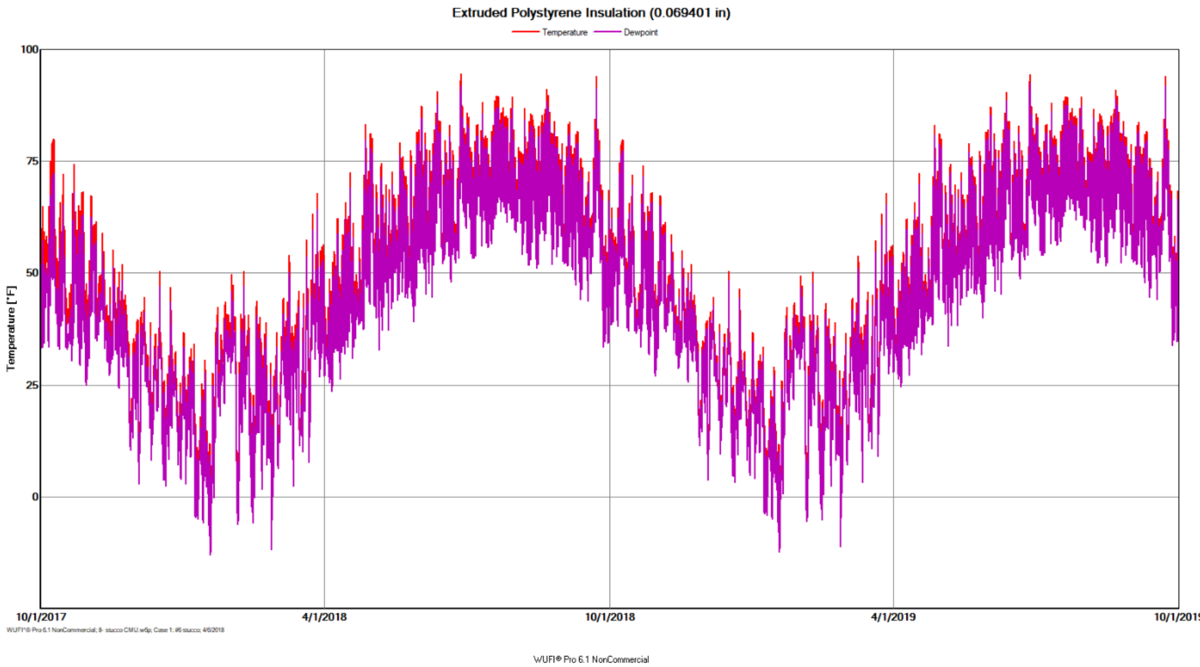


Figure A.71 Dew point of the critical layer (XPS) for Alternatives 15 and 16

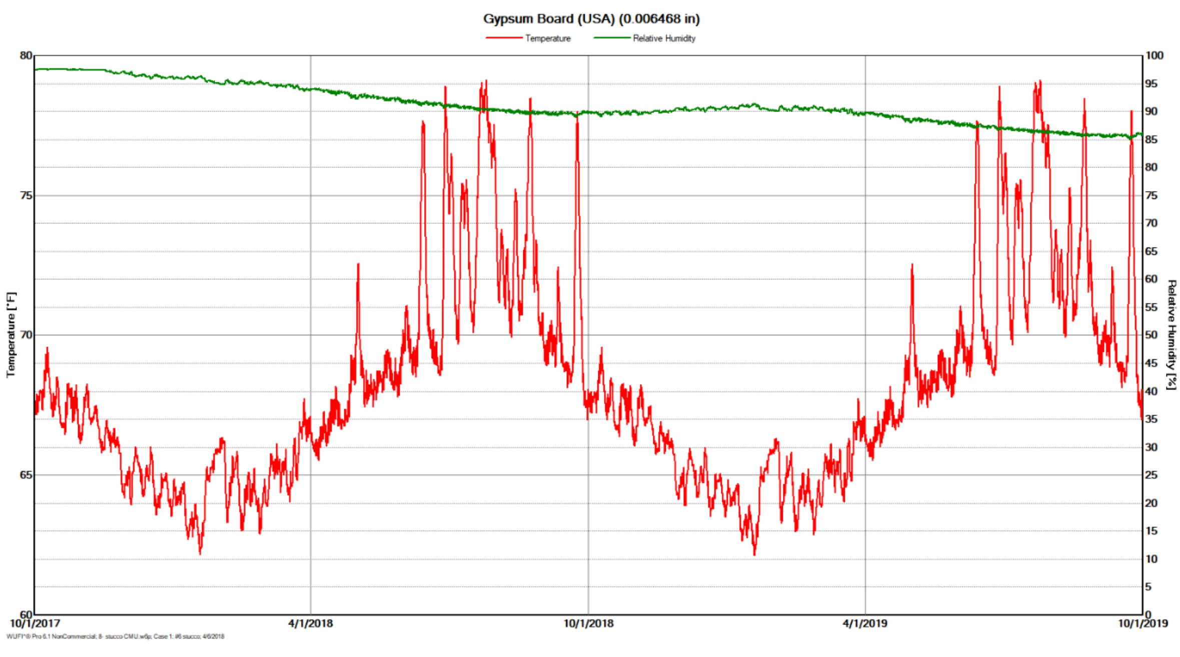


Figure A.72 Relative humidity of the critical layer (Gypsum) for Alternatives 15 and 16

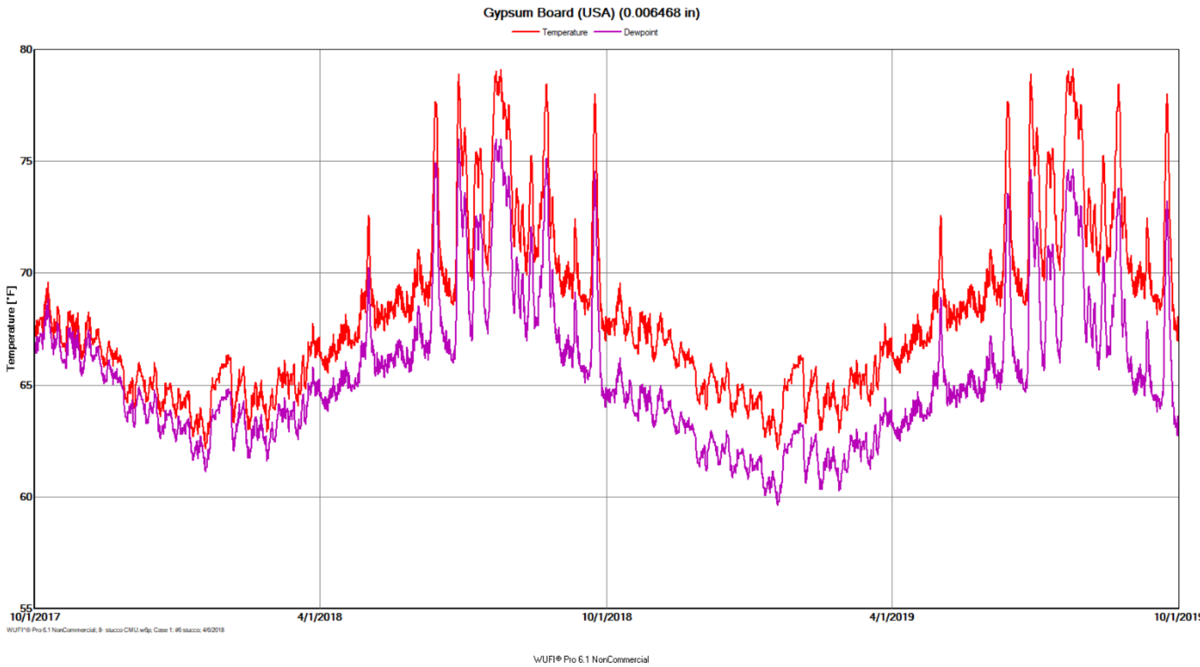


Figure A.73 Dew point of the critical layer (Gypsum) for Alternatives 15 and 16

APPENDIX B THERM and Window Simulation Results

The thermal analyses of the wall assemblies are presented. The indoor air temperature is 71˚ F (almost 22˚ C) and the outdoor air temperature is 23˚ F (-5˚ C).

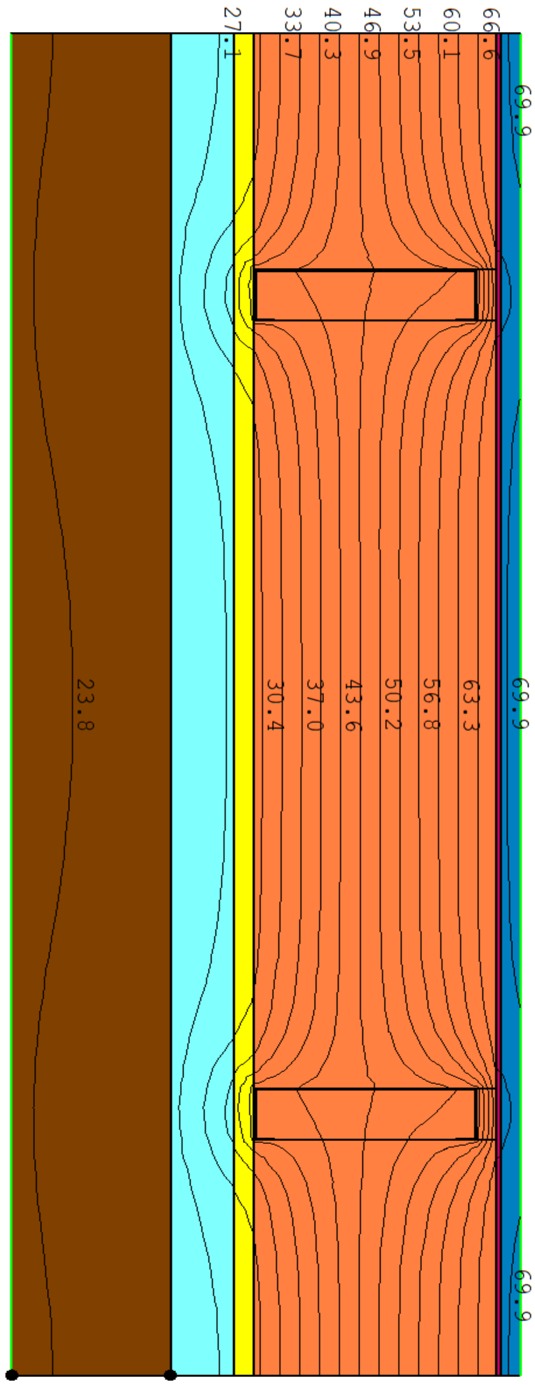


Figure B.1 Thermal analysis of wall assemblies with THERM, for alternatives 1 and 2

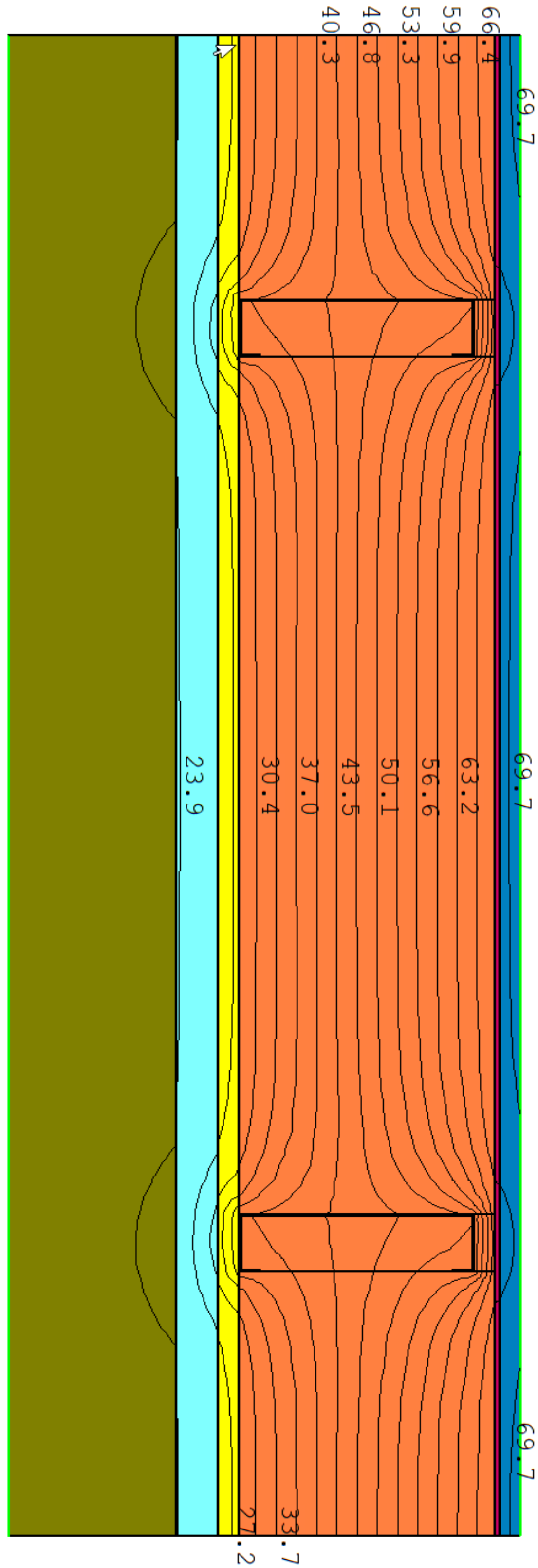


Figure B.2 Thermal analysis of wall assemblies with THERM, for alternatives 3 and 4

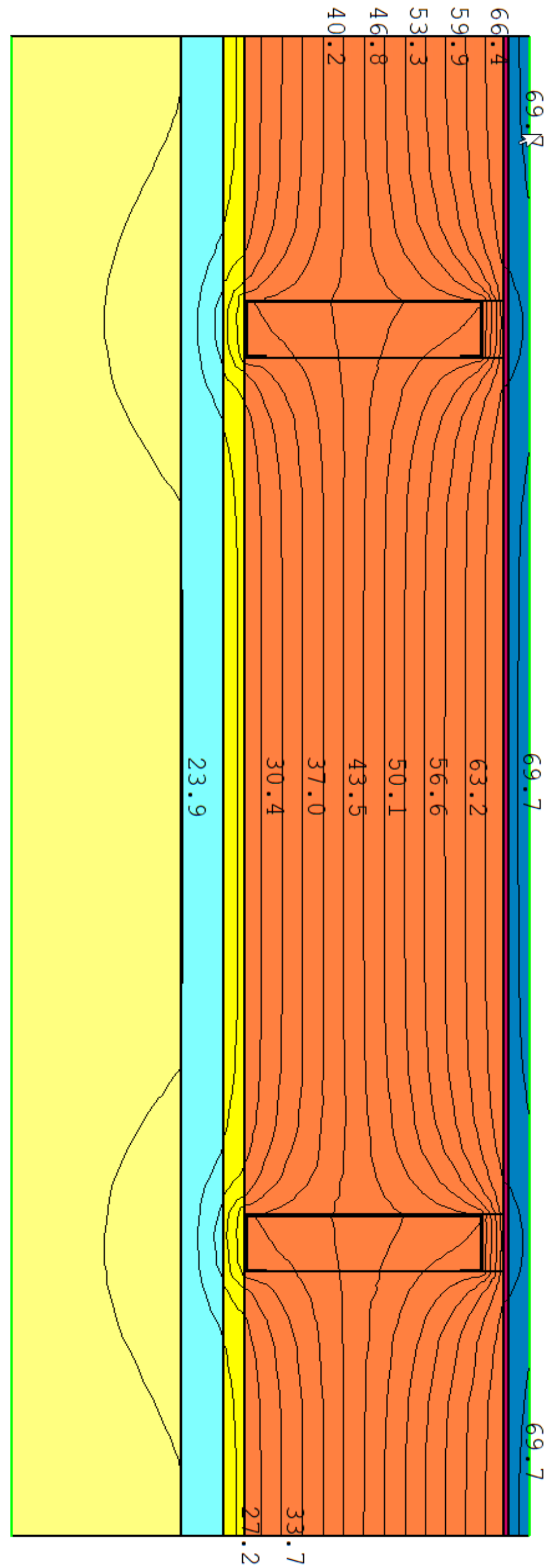


Figure B.3 Thermal analysis of wall assemblies with THERM, for alternatives 5 and 6

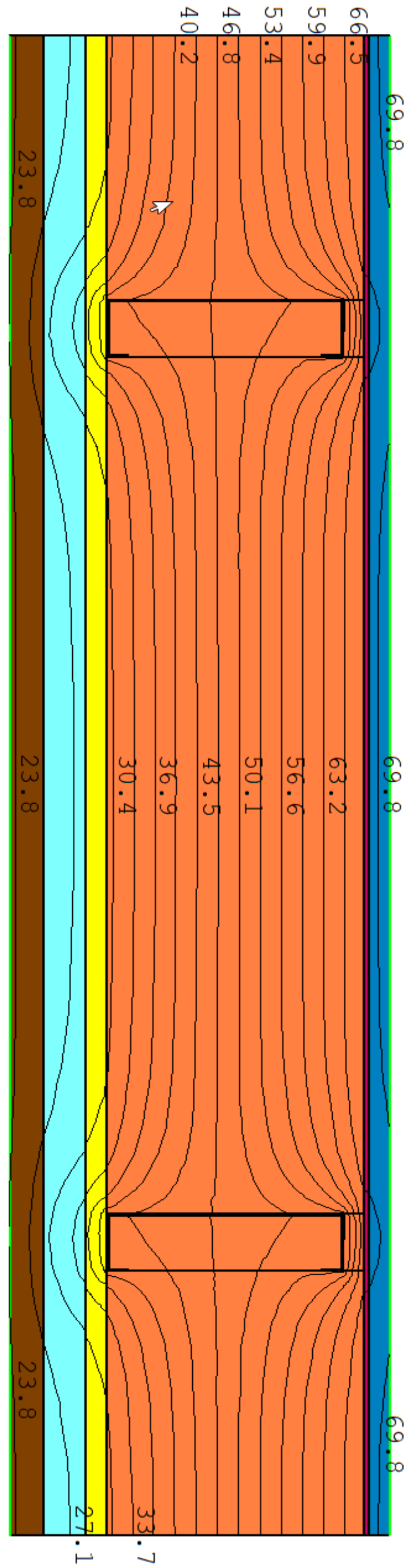


Figure B.4 Thermal analysis of wall assemblies with THERM, for alternatives 7 and 8

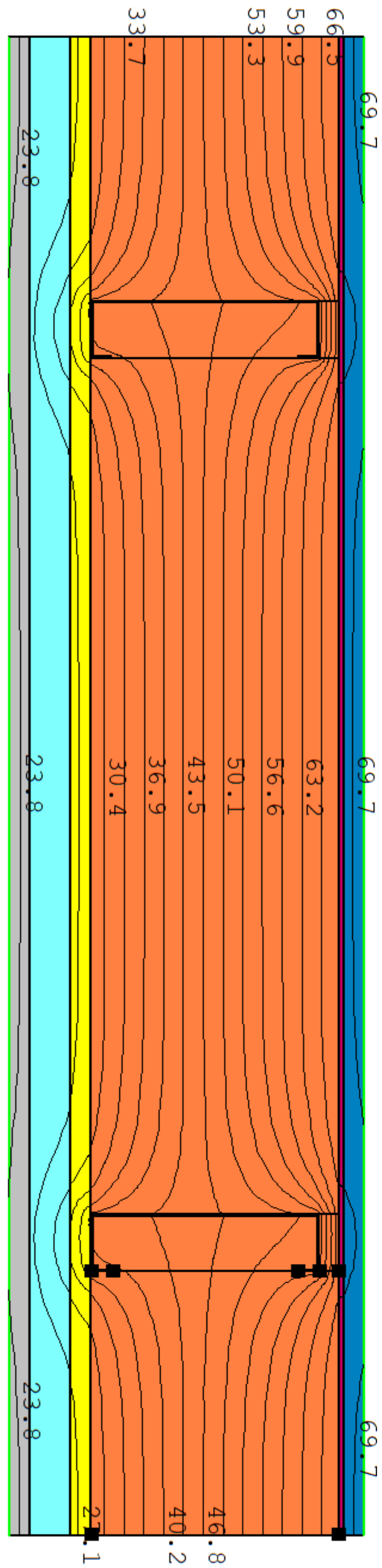


Figure B.5 Thermal analysis of wall assemblies with THERM, for alternatives 9 and 10

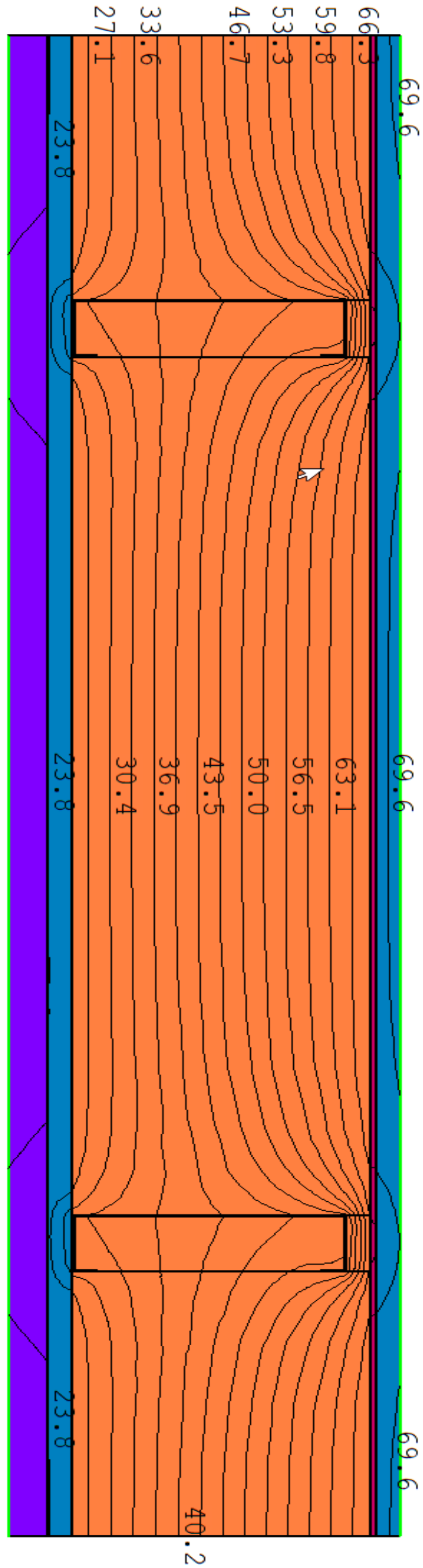


Figure B.6 Thermal analysis of wall assemblies with THERM, for alternatives 11 and 12

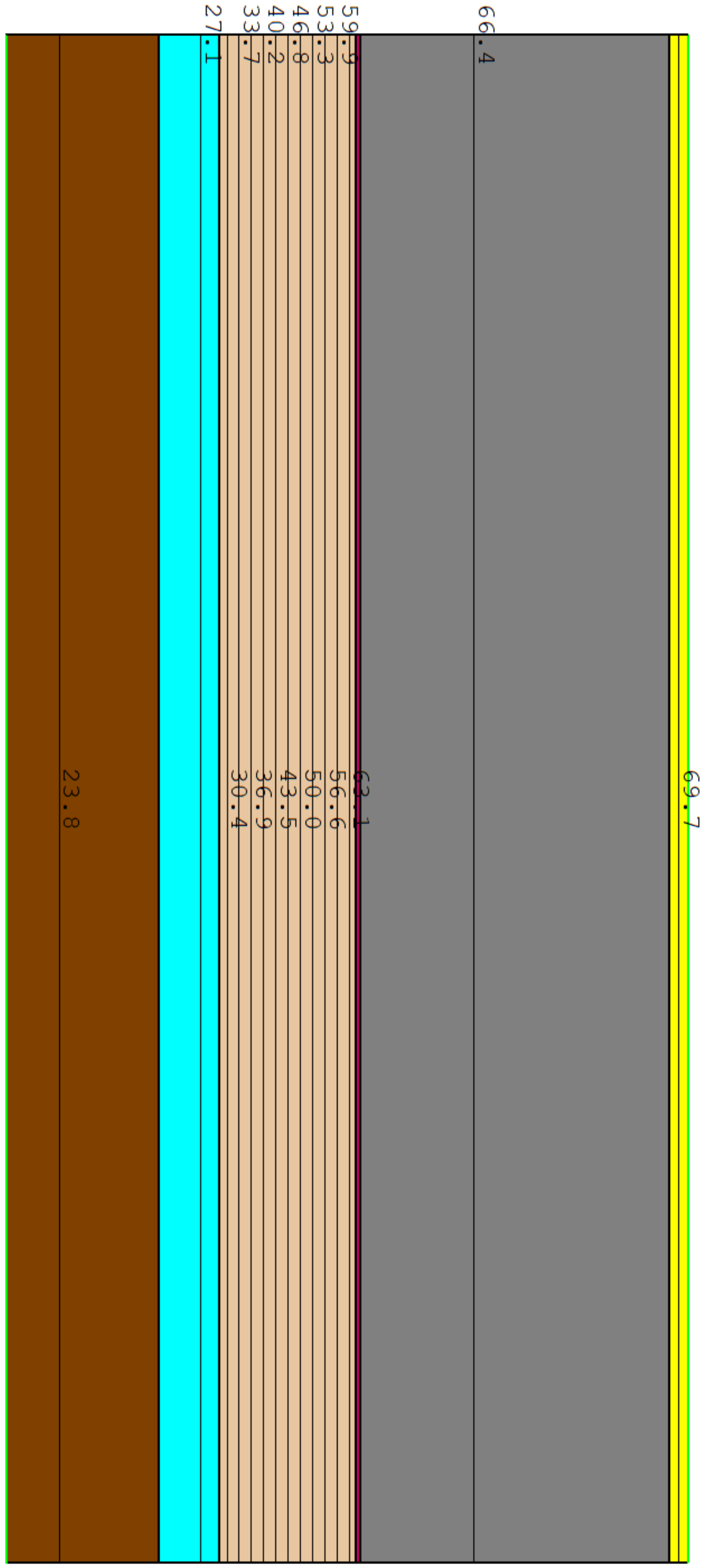


Figure B.7 Thermal analysis of wall assemblies with THERM, for alternatives 13 and 14

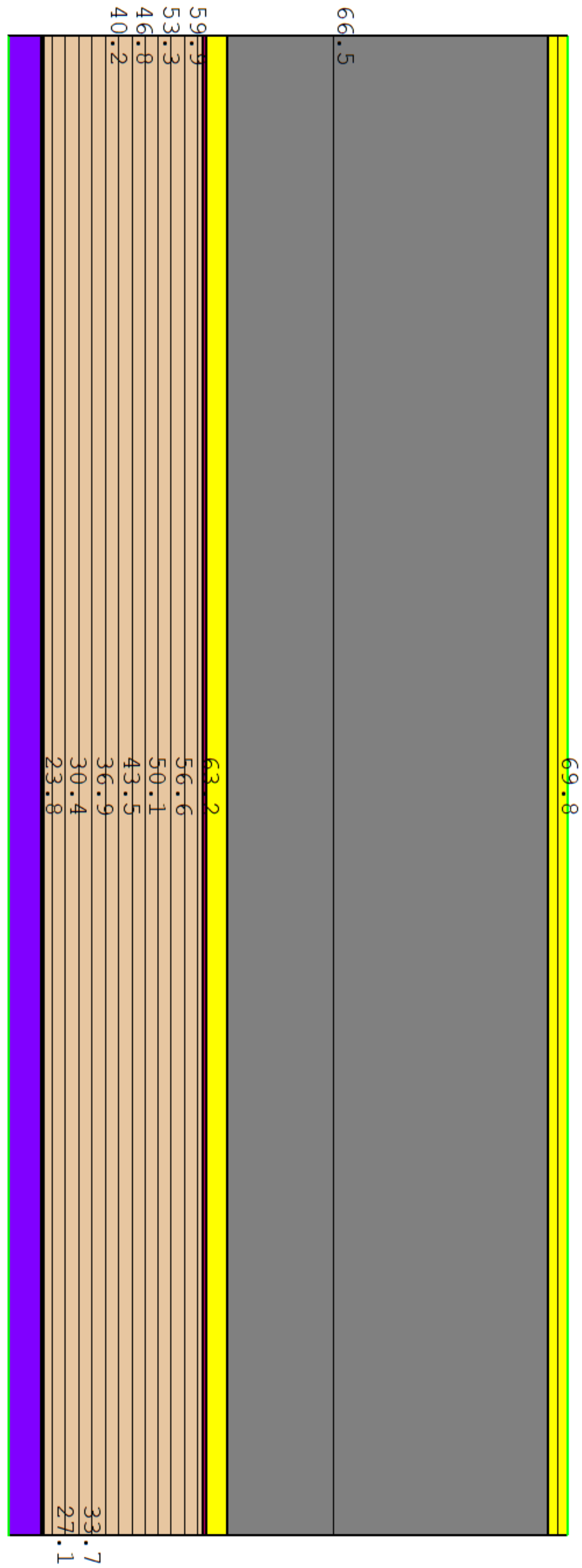


Figure B.8 Thermal analysis of wall assemblies with THERM, for alternatives 15 and 16

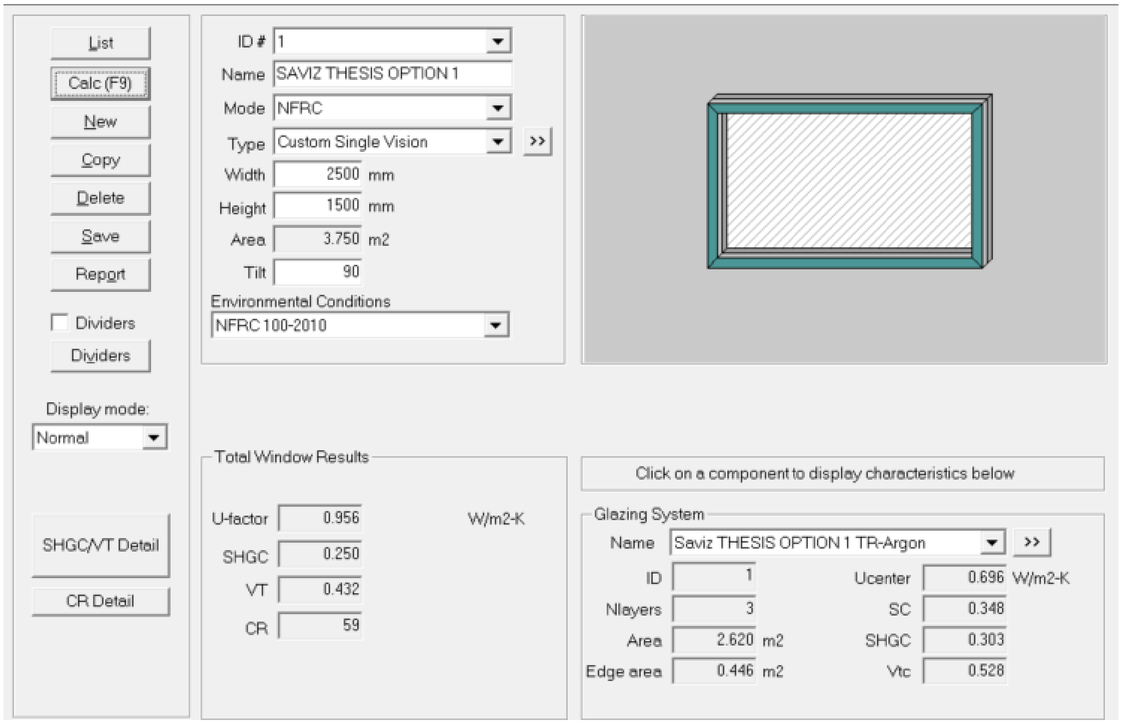


Figure B.9 Simulation results for triple pane window system, using Window 7.6, demonstrating the SHGC, VT and CR values and the overall U factor (equal to 1/R)

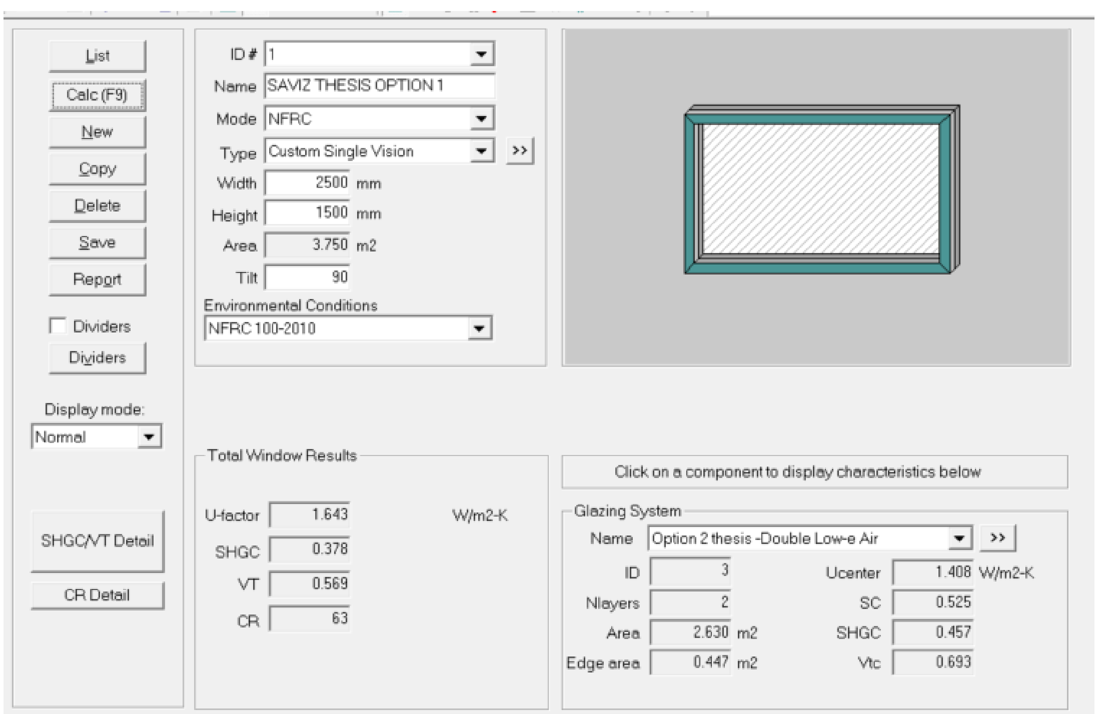
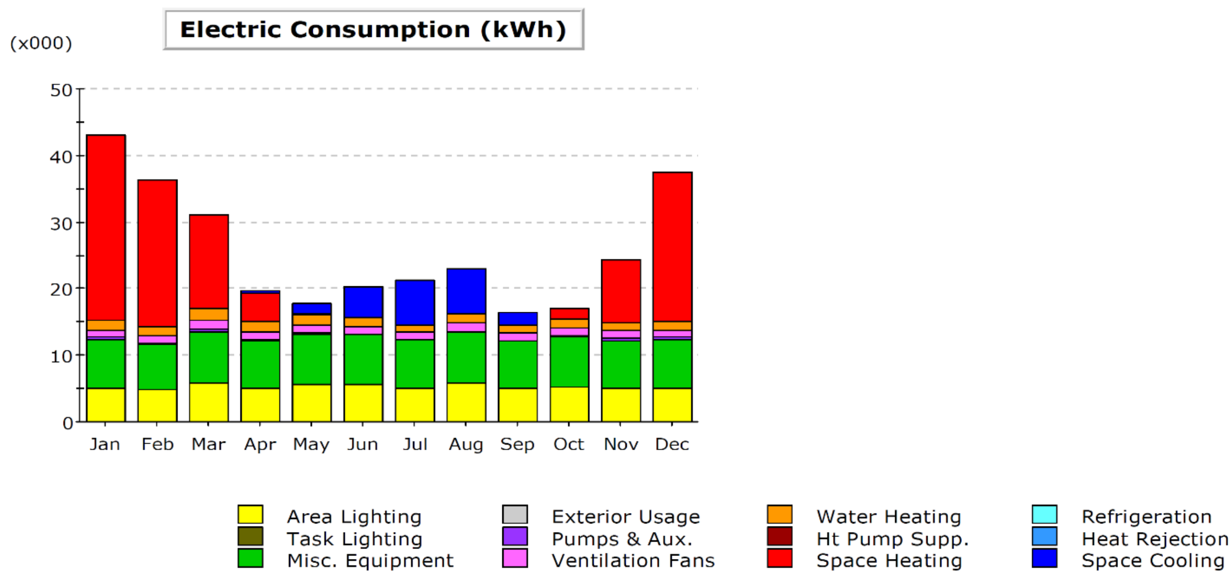


Figure B.10 Simulation results for double pane window system, using Window 7.6, demonstrating the SHGC, VT and CR values and the overall U factor (equal to 1/R)

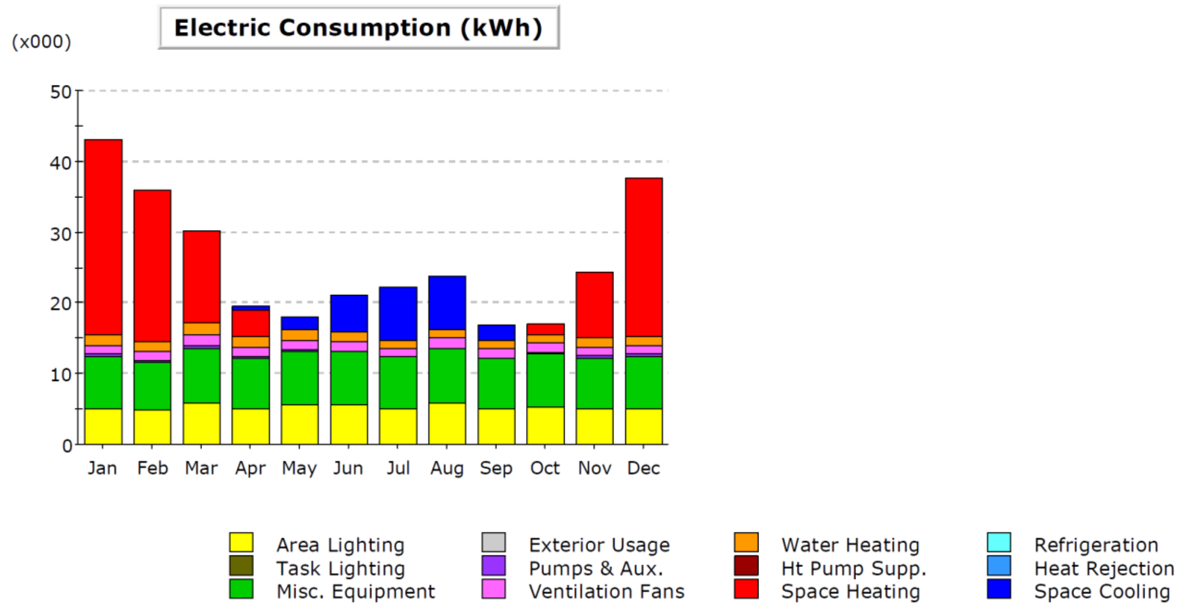
APPENDIX C eQUEST Simulation Results



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.40	1.57	4.69	6.72	6.91	1.91	-	-	-	22.18
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.74	21.93	14.11	4.28	0.15	0.00	-	-	0.00	1.72	9.51	22.24	101.69
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.14	1.08	1.31	1.14	1.25	1.25	1.14	1.31	1.14	1.19	1.14	1.14	14.20
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	42.98	36.25	31.06	19.71	17.71	20.33	21.29	23.04	16.37	17.07	24.38	37.38	307.57

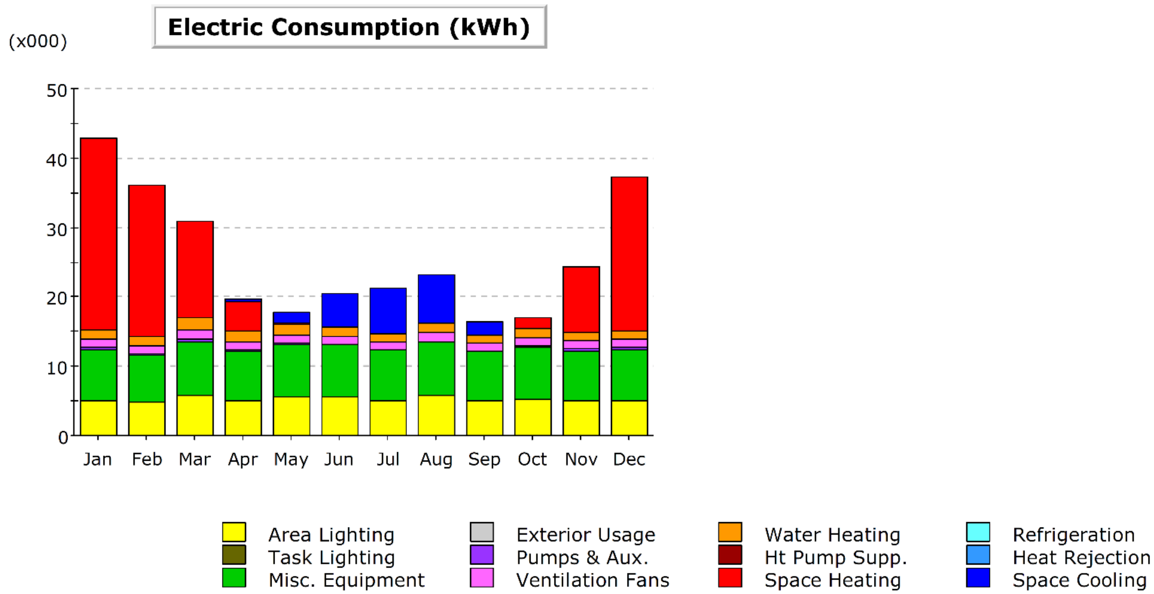
Figure C.1 Detailed annual energy consumption: Alternative 1



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.46	1.80	5.30	7.42	7.56	2.17	-	-	-	24.70
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.78	21.45	13.11	3.82	0.11	-	0.00	-	0.00	1.53	9.40	22.47	99.68
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.23	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.26	1.20	1.45	1.26	1.39	1.39	1.26	1.45	1.26	1.33	1.26	1.26	15.80
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.14	35.90	30.21	19.43	18.05	21.09	22.12	23.84	16.76	17.01	24.39	37.74	309.67

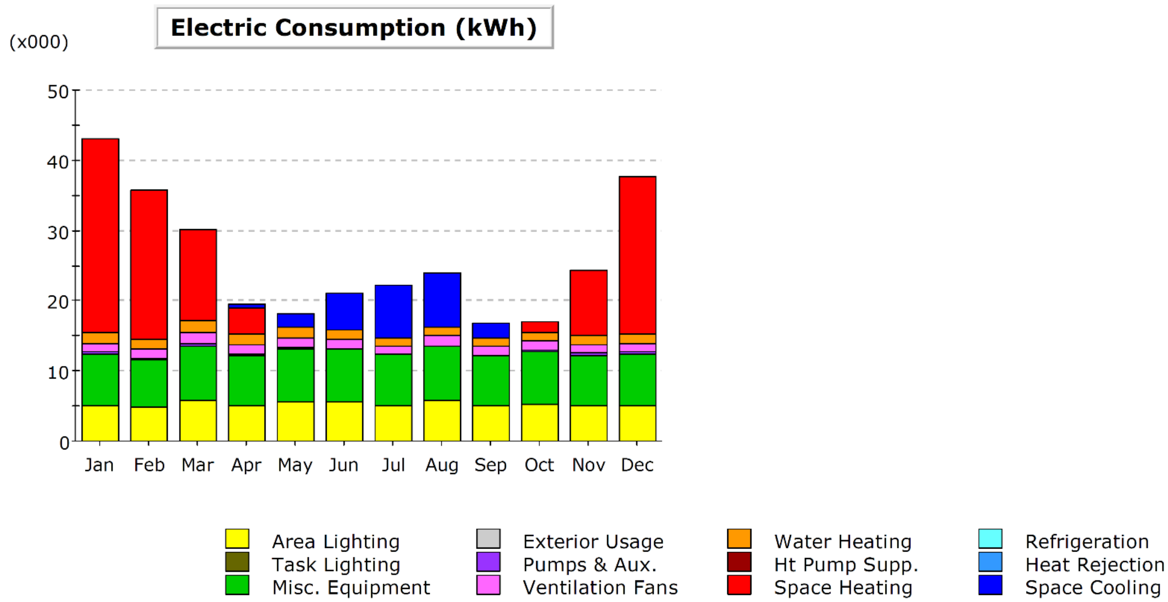
Figure C.2 Detailed annual energy consumption: Alternative 2



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.40	1.58	4.72	6.75	6.94	1.92	-	-	-	22.32
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.69	21.85	14.01	4.23	0.14	0.00	-	0.00	0.00	1.70	9.48	22.20	101.31
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.14	1.08	1.31	1.14	1.25	1.25	1.14	1.31	1.14	1.20	1.14	1.14	14.24
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	42.92	36.18	30.97	19.67	17.72	20.38	21.33	23.07	16.38	17.05	24.35	37.34	307.36

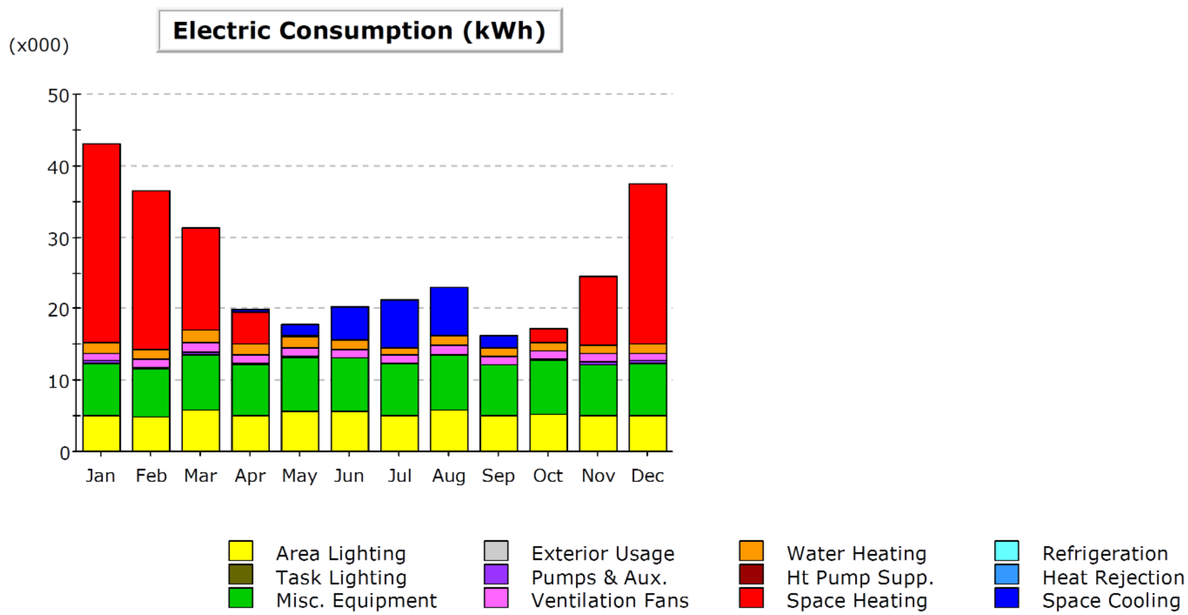
Figure C.3 Detailed annual energy consumption: Alternative 3



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.47	1.83	5.33	7.45	7.58	2.18	-	-	-	24.84
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.66	21.30	12.98	3.80	0.13	-	0.00	0.00	0.00	1.56	9.37	22.40	99.21
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.23	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.28	1.22	1.47	1.28	1.41	1.41	1.28	1.47	1.28	1.34	1.28	1.28	15.99
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.04	35.77	30.10	19.44	18.11	21.13	22.17	23.88	16.79	17.06	24.38	37.68	309.53

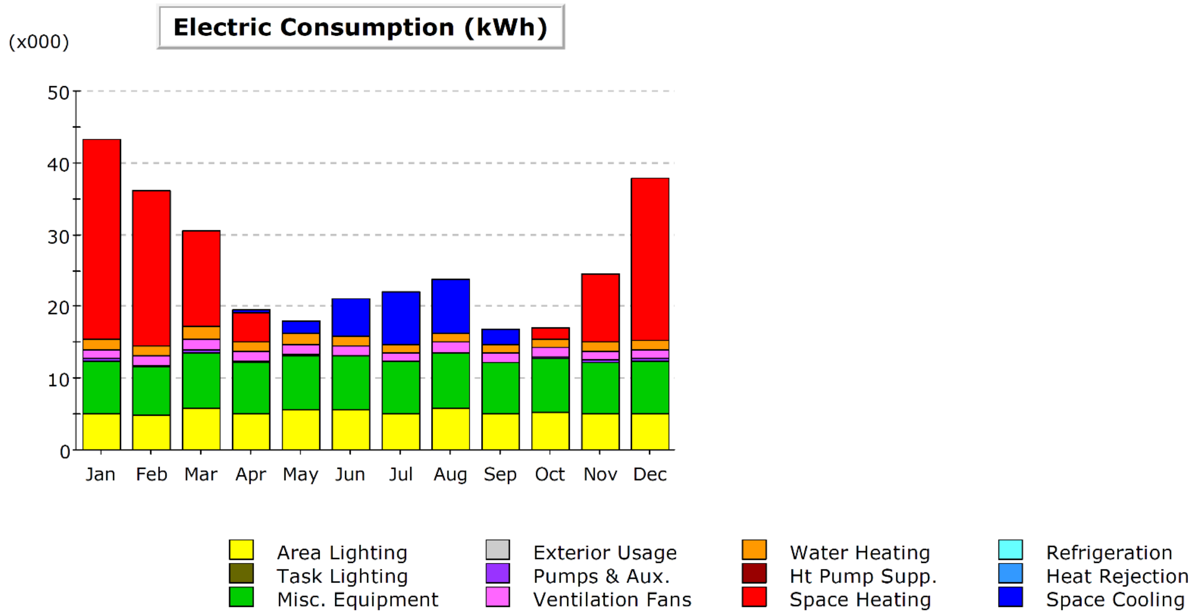
Figure C.4 Detailed annual energy consumption: Alternative 4



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.39	1.53	4.60	6.61	6.81	1.85	-	-	-	21.79
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.91	22.16	14.38	4.39	0.16	-	-	-	0.00	1.81	9.65	22.38	102.85
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.13	1.07	1.30	1.13	1.24	1.24	1.13	1.30	1.13	1.19	1.13	1.13	14.12
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.14	36.48	31.32	19.80	17.69	20.24	21.18	22.93	16.31	17.15	24.51	37.51	308.27

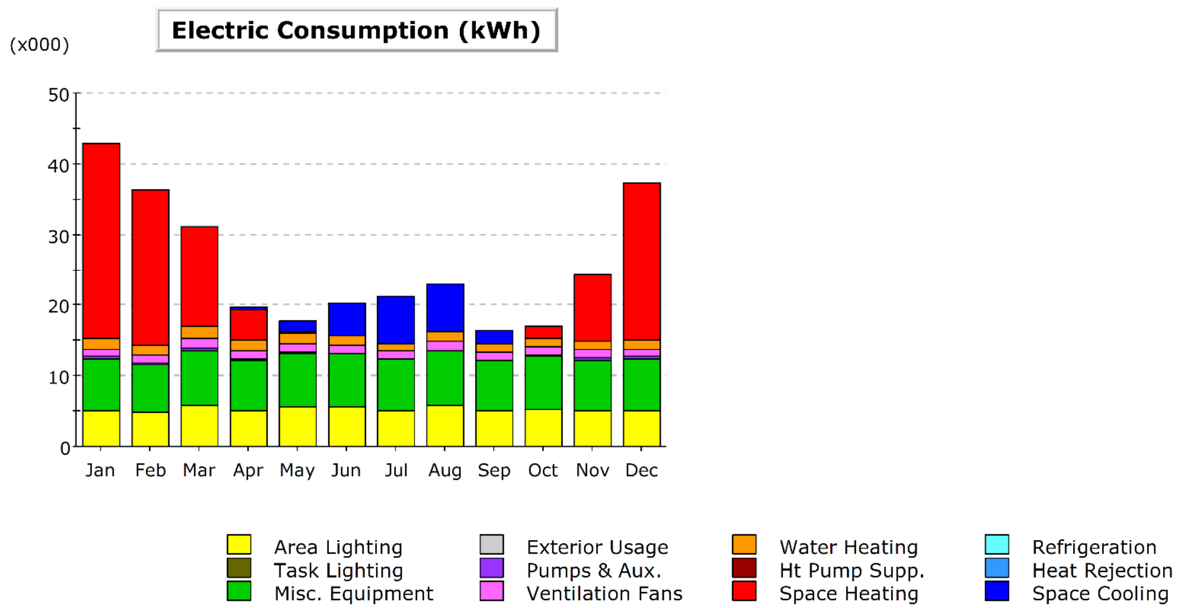
Figure C.5 Detailed annual energy consumption: Alternative 5



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.45	1.76	5.21	7.32	7.45	2.12	-	-	-	24.31
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.95	21.67	13.36	3.92	0.13	0.00	-	-	0.00	1.60	9.53	22.61	100.76
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.26	1.20	1.45	1.26	1.38	1.38	1.26	1.45	1.26	1.32	1.26	1.26	15.72
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.30	36.11	30.45	19.52	18.02	20.99	22.01	23.72	16.70	17.07	24.52	37.87	310.29

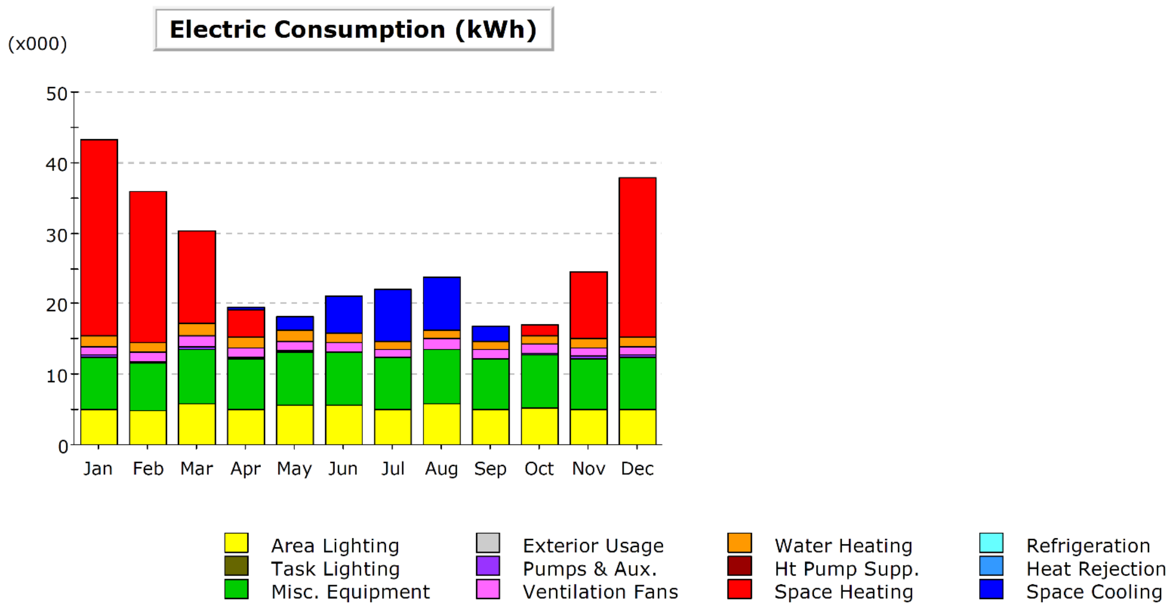
Figure C.6 Detailed annual energy consumption: Alternative 6



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.40	1.55	4.65	6.66	6.86	1.88	-	-	-	21.99
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.69	21.91	14.12	4.28	0.15	-	-	-	0.00	1.73	9.50	22.18	101.57
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.13	1.07	1.30	1.13	1.24	1.24	1.13	1.30	1.13	1.19	1.13	1.13	14.14
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	42.92	36.23	31.07	19.70	17.69	20.29	21.23	22.99	16.34	17.08	24.36	37.31	307.20

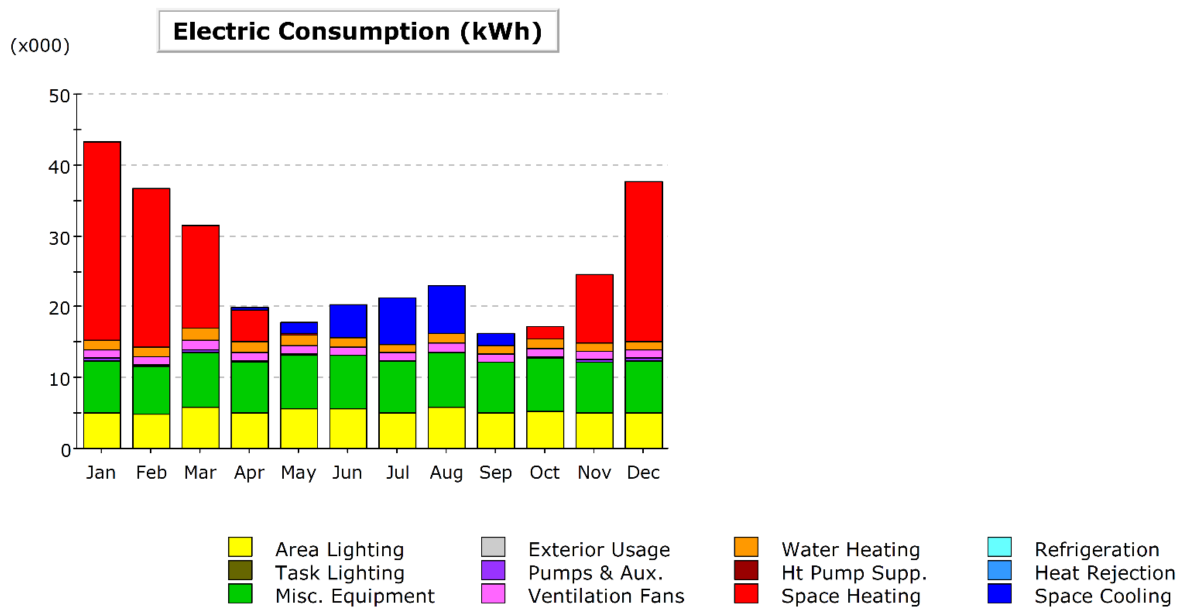
Figure C.7 Detailed annual energy consumption: Alternative 7



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.46	1.79	5.26	7.37	7.49	2.15	-	-	-	24.51
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.82	21.51	13.20	3.87	0.12	-	-	-	0.00	1.58	9.45	22.50	100.05
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.27	1.21	1.46	1.27	1.40	1.40	1.27	1.46	1.27	1.34	1.27	1.27	15.90
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.18	35.96	30.31	19.49	18.05	21.06	22.08	23.79	16.74	17.07	24.45	37.78	309.96

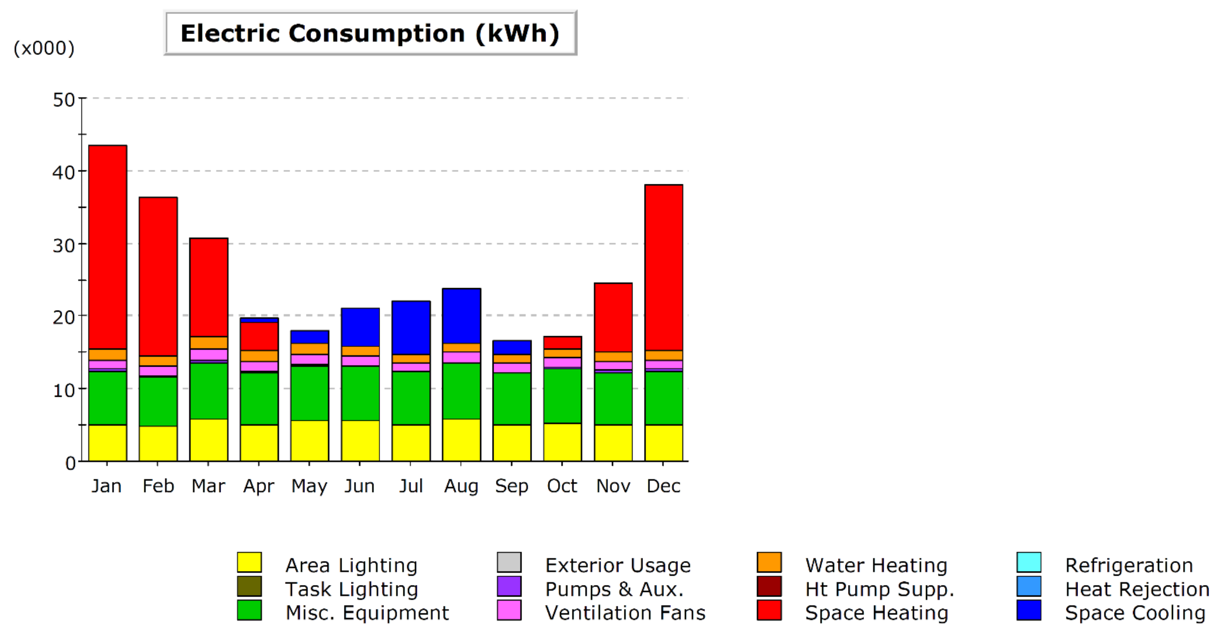
Figure C.8 Detailed annual energy consumption: Alternative 8



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.39	1.53	4.58	6.59	6.77	1.84	-	-	-	21.71
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.06	22.28	14.53	4.47	0.18	-	-	-	0.01	1.88	9.74	22.50	103.63
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.14	1.08	1.31	1.14	1.25	1.25	1.14	1.31	1.14	1.20	1.14	1.14	14.23
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.29	36.61	31.48	19.89	17.71	20.23	21.17	22.91	16.31	17.23	24.61	37.64	309.07

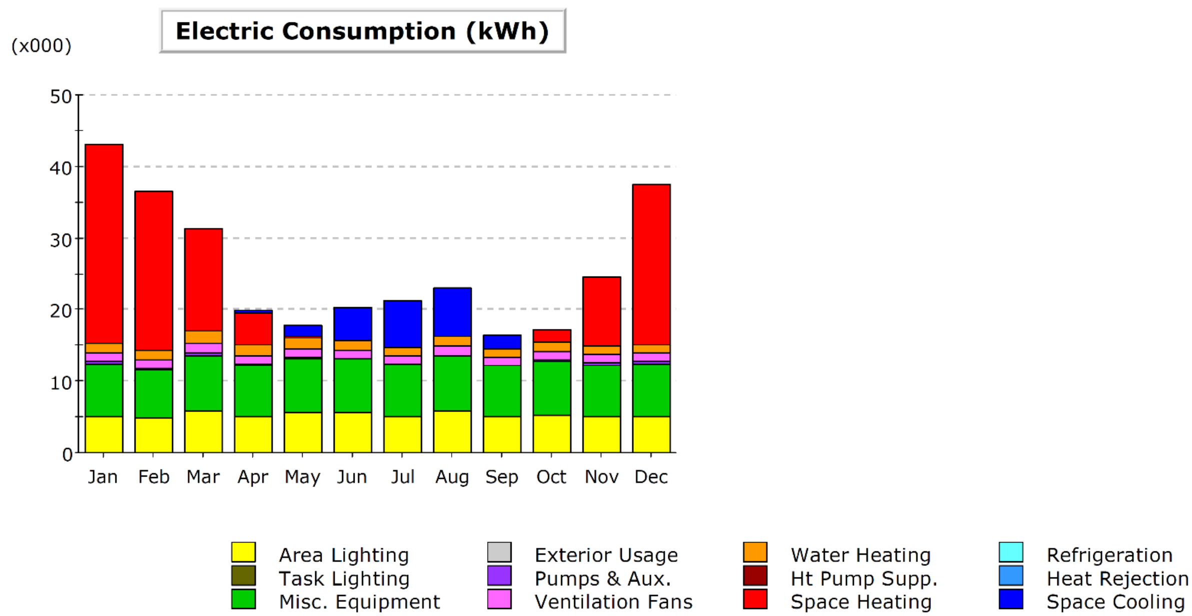
Figure C.9 Detailed annual energy consumption: Alternative 9



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.45	1.76	5.19	7.29	7.43	2.10	-	-	-	24.22
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.09	21.80	13.51	3.99	0.13	0.00	-	-	0.00	1.66	9.61	22.73	101.52
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.27	1.20	1.46	1.27	1.39	1.39	1.27	1.46	1.27	1.33	1.27	1.27	15.83
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.45	36.25	30.61	19.60	18.03	20.98	21.99	23.71	16.69	17.15	24.61	38.00	311.06

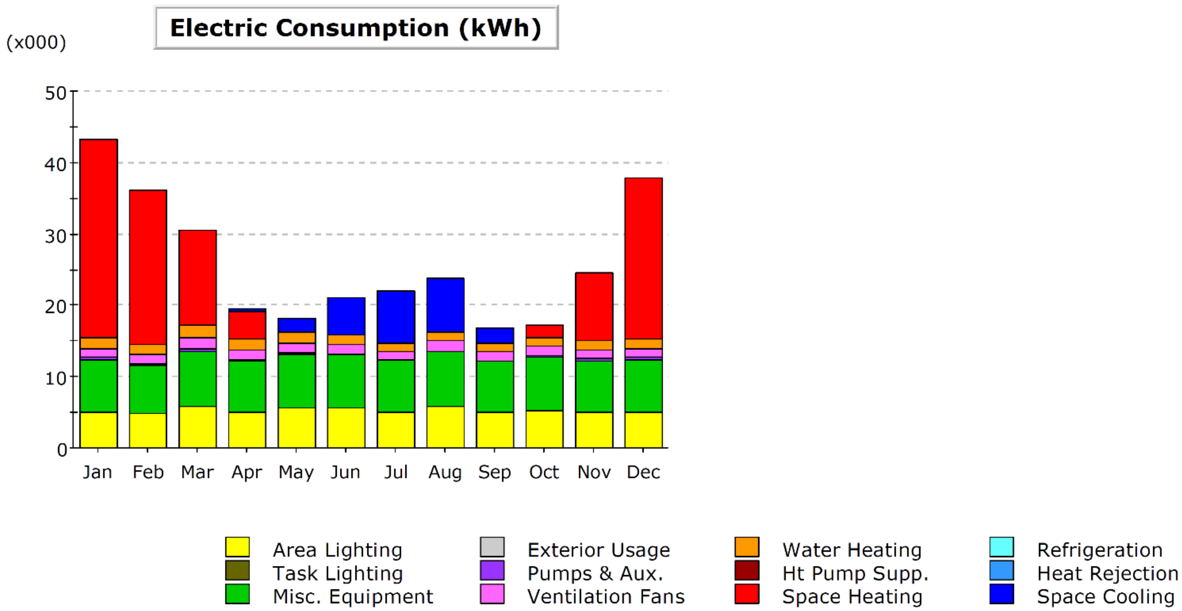
Figure C.10 Detailed annual energy consumption: Alternative 10



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.40	1.55	4.62	6.64	6.82	1.87	-	-	-	21.90
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.88	22.09	14.32	4.38	0.16	-	-	-	0.01	1.82	9.62	22.35	102.63
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.15	1.09	1.32	1.15	1.26	1.26	1.15	1.32	1.15	1.20	1.15	1.15	14.34
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.13	36.42	31.28	19.82	17.72	20.28	21.22	22.97	16.34	17.18	24.50	37.49	308.37

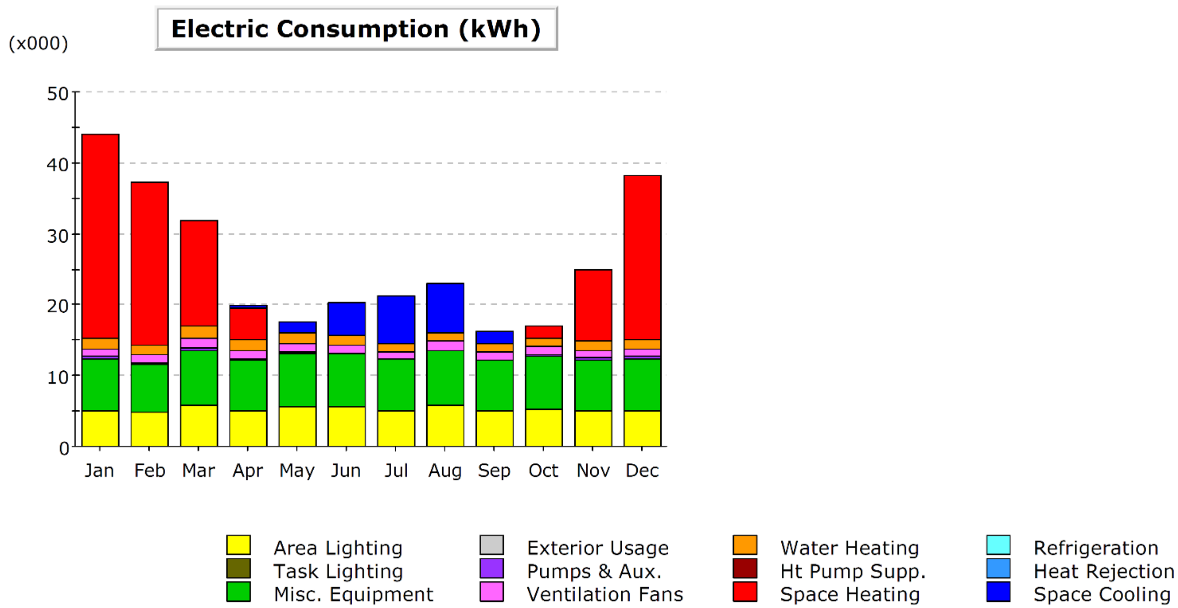
Figure C.11 Detailed annual energy consumption: Alternative 11



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.46	1.78	5.23	7.35	7.47	2.13	-	-	-	24.42
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.91	21.61	13.32	3.92	0.13	-	-	-	0.00	1.61	9.50	22.58	100.57
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.27	1.21	1.47	1.27	1.40	1.40	1.27	1.47	1.27	1.34	1.27	1.27	15.93
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.28	36.07	30.42	19.54	18.05	21.03	22.06	23.77	16.73	17.11	24.51	37.85	310.43

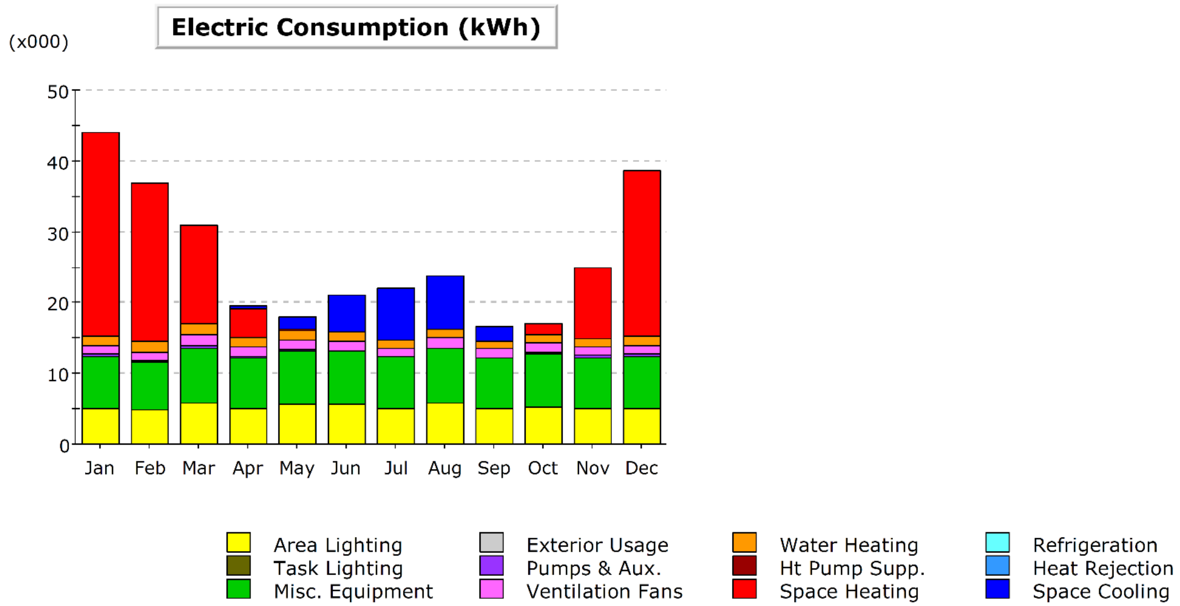
Figure C.12 Detailed annual energy consumption: Alternative 12



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.38	1.50	4.67	6.72	6.90	1.86	-	-	-	22.01
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.80	22.90	14.87	4.56	0.14	-	-	0.00	0.00	1.76	10.08	23.14	106.23
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.10	1.04	1.26	1.10	1.21	1.21	1.10	1.26	1.10	1.15	1.10	1.10	13.72
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	43.99	37.19	31.77	19.92	17.59	20.27	21.25	22.99	16.28	17.07	24.90	38.23	311.47

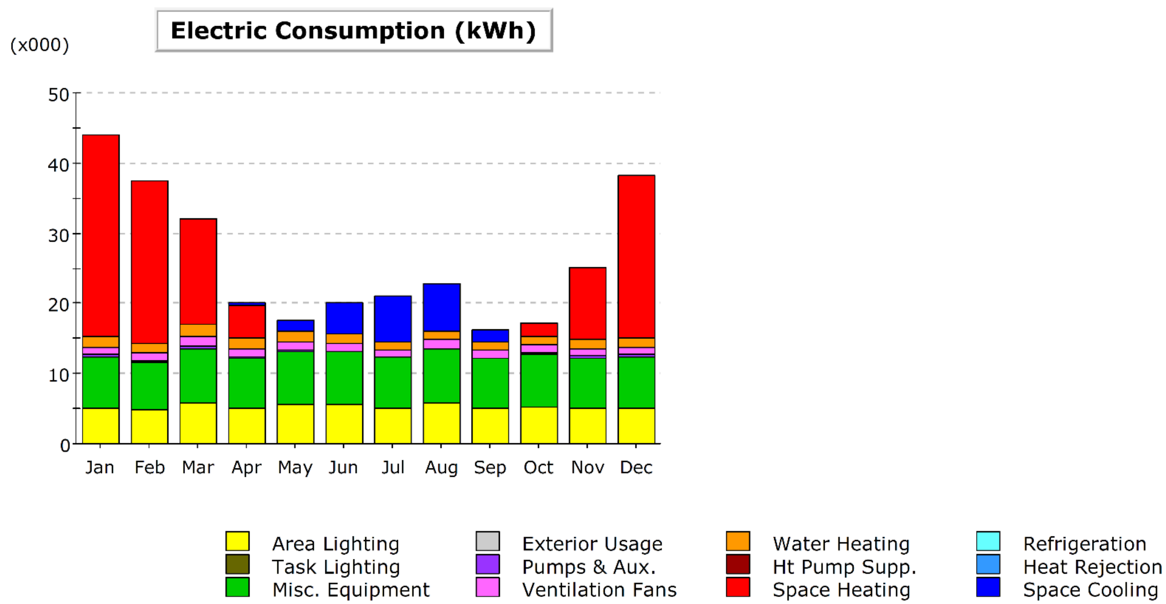
Figure C.13 Detailed annual energy consumption: Alternative 13



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.44	1.72	5.25	7.40	7.55	2.11	-	-	-	24.46
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.79	22.39	13.79	4.04	0.10	0.00	0.00	0.00	-	1.52	9.89	23.32	103.83
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.23	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.22	1.16	1.40	1.22	1.34	1.34	1.22	1.40	1.22	1.28	1.22	1.22	15.20
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	44.10	36.79	30.83	19.59	17.91	20.98	22.05	23.78	16.64	16.95	24.84	38.53	312.99

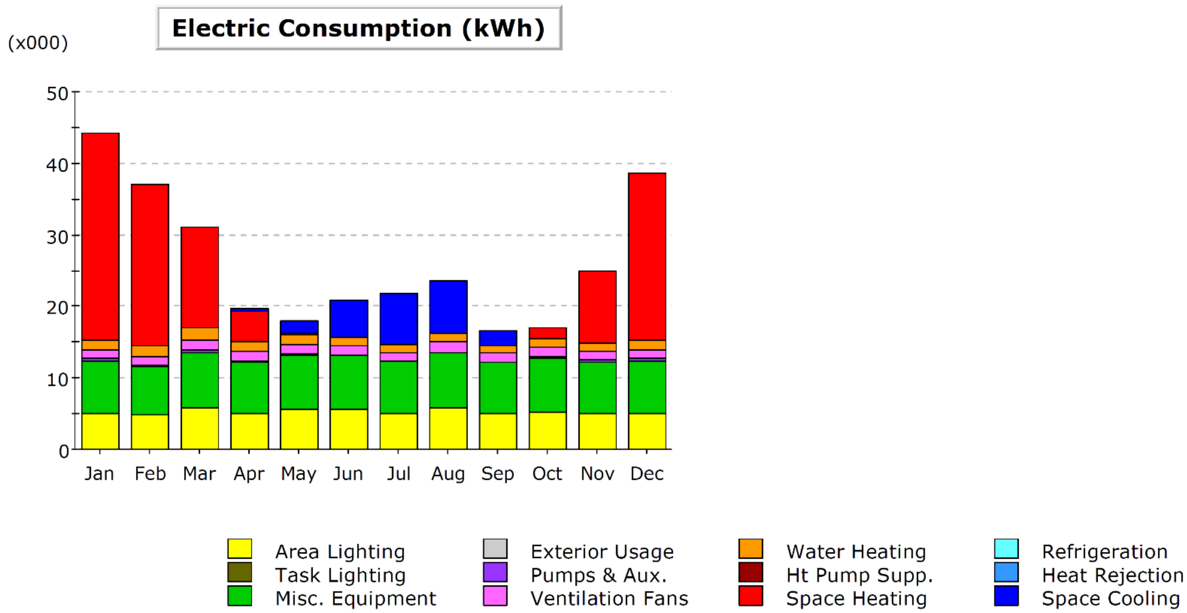
Figure C.14 Detailed annual energy consumption: Alternative 14



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.36	1.45	4.51	6.52	6.72	1.78	-	-	-	21.35
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.92	23.14	15.22	4.71	0.16	-	-	-	0.00	1.90	10.22	23.21	107.48
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.09	1.04	1.25	1.09	1.20	1.20	1.09	1.25	1.09	1.14	1.09	1.09	13.63
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	44.11	37.42	32.12	20.06	17.56	20.11	21.05	22.80	16.20	17.20	25.04	38.30	311.96

Figure C.15 Detailed annual energy consumption: Alternative 15



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	0.42	1.68	5.10	7.21	7.37	2.04	-	-	-	23.83
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.96	22.65	14.14	4.20	0.12	0.00	0.00	-	0.00	1.65	10.06	23.45	105.23
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	1.43	1.40	1.69	1.45	1.46	1.34	1.14	1.24	1.08	1.19	1.23	1.33	15.98
Vent. Fans	1.21	1.15	1.39	1.21	1.33	1.33	1.21	1.39	1.21	1.27	1.21	1.21	15.10
Pumps & Aux.	0.37	0.34	0.37	0.27	0.13	0.02	0.00	0.01	0.07	0.24	0.33	0.37	2.51
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	7.25	6.73	7.83	7.14	7.64	7.53	7.25	7.83	7.14	7.45	7.14	7.25	88.21
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	5.04	4.78	5.75	5.03	5.52	5.51	5.04	5.75	5.03	5.28	5.03	5.04	62.80
Total	44.27	37.05	31.17	19.72	17.87	20.83	21.86	23.59	16.57	17.07	25.00	38.66	313.65

Figure C.16 Detailed annual energy consumption: Alternative 16

APPENDIX D Life Cycle Assessment (LCA) Results

Table D.1 Detailed LCA measure table by life cycle stages: Alternative 1

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	5.32E+03	4.12E+01	4.69E+00	1.36E+00	9.69E-05	3.48E+02	7.23E+04	5.95E+04	5.65E+04
	Transport	6.73E+01	6.94E-01	3.63E-02	4.30E-02	2.47E-09	2.20E+01	9.79E+02	9.78E+02	9.77E+02
	Total	**5.39E+03**	**4.19E+01**	**4.73E+00**	**1.41E+00**	**9.69E-05**	**3.70E+02**	**7.33E+04**	**6.05E+04**	**5.75E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	2.31E+02	2.06E+00	2.48E-01	8.62E-02	6.91E-07	3.90E+01	2.92E+03	2.55E+03	2.49E+03
	Transport	2.69E+02	3.03E+00	1.40E-01	1.88E-01	1.00E-08	9.70E+01	3.85E+03	3.85E+03	3.84E+03
	Total	**5.00E+02**	**5.09E+00**	**3.88E-01**	**2.74E-01**	**7.01E-07**	**1.36E+02**	**6.77E+03**	**6.40E+03**	**6.34E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.68E+03	2.07E+01	1.56E+00	8.06E-01	8.89E-05	1.63E+02	3.56E+04	2.66E+04	2.60E+04
	Replacement Transport	1.02E+02	1.09E+00	5.68E-02	6.77E-02	3.94E-09	3.47E+01	1.49E+03	1.49E+03	1.48E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.78E+03**	**2.18E+01**	**1.62E+00**	**8.73E-01**	**8.89E-05**	**1.98E+02**	**3.71E+04**	**2.80E+04**	**2.75E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.70E+02	1.46E+00	1.38E-01	4.83E-02	2.42E-08	2.26E+01	3.55E+03	3.47E+03	3.33E+03
	Transport	6.37E+01	6.12E-01	3.39E-02	3.80E-02	2.22E-09	1.93E+01	9.28E+02	9.28E+02	9.26E+02
	Total	**3.33E+02**	**2.07E+00**	**1.72E-01**	**8.64E-02**	**2.64E-08**	**4.19E+01**	**4.48E+03**	**4.40E+03**	**4.26E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.76E+03	-3.17E+01	-3.22E+00	-5.44E-01	-2.09E-07	-2.48E+02	-4.58E+04	-4.54E+04	-4.55E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.76E+03**	**-3.17E+01**	**-3.22E+00**	**-5.44E-01**	**-2.09E-07**	**-2.48E+02**	**-4.58E+04**	**-4.54E+04**	**-4.55E+04**
TOTAL EFFECTS	**A to C**	**9.01E+03**	**7.09E+01**	**6.91E+00**	**2.64E+00**	**1.87E-04**	**7.45E+02**	**1.22E+05**	**9.93E+04**	**9.56E+04**
	A to D	**3.25E+03**	**3.92E+01**	**3.68E+00**	**2.09E+00**	**1.86E-04**	**4.97E+02**	**7.59E+04**	**5.38E+04**	**5.01E+04**

Table D.2 Detailed LCA measure table by life cycle stages: Alternative 2

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	4.57E+03	3.48E+01	4.24E+00	1.17E+00	6.83E-05	3.03E+02	6.26E+04	5.20E+04	4.91E+04
	Transport	5.97E+01	6.14E-01	3.21E-02	3.81E-02	2.18E-09	1.95E+01	8.67E+02	8.67E+02	8.66E+02
	Total	**4.63E+03**	**3.54E+01**	**4.27E+00**	**1.21E+00**	**6.83E-05**	**3.22E+02**	**6.35E+04**	**5.29E+04**	**5.00E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	2.31E+02	2.06E+00	2.48E-01	8.62E-02	6.91E-07	3.90E+01	2.92E+03	2.55E+03	2.49E+03
	Transport	2.51E+02	2.83E+00	1.30E-01	1.76E-01	9.29E-09	9.07E+01	3.59E+03	3.59E+03	3.59E+03
	Total	**4.82E+02**	**4.90E+00**	**3.78E-01**	**2.62E-01**	**7.00E-07**	**1.30E+02**	**6.51E+03**	**6.14E+03**	**6.08E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	1.88E+03	1.42E+01	1.09E+00	6.14E-01	6.02E-05	1.16E+02	2.54E+04	1.86E+04	1.82E+04
	Replacement Transport	7.44E+01	7.93E-01	4.13E-02	4.91E-02	2.86E-09	2.52E+01	1.08E+03	1.08E+03	1.08E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**1.96E+03**	**1.49E+01**	**1.14E+00**	**6.63E-01**	**6.02E-05**	**1.41E+02**	**2.65E+04**	**1.96E+04**	**1.93E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.30E+02	1.28E+00	1.23E-01	4.42E-02	2.04E-08	2.09E+01	3.05E+03	2.97E+03	2.85E+03
	Transport	6.12E+01	5.88E-01	3.26E-02	3.66E-02	2.13E-09	1.86E+01	8.92E+02	8.91E+02	8.90E+02
	Total	**2.91E+02**	**1.87E+00**	**1.55E-01**	**8.07E-02**	**2.25E-08**	**3.94E+01**	**3.94E+03**	**3.86E+03**	**3.74E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.89E+03	-2.65E+01	-2.73E+00	-4.59E-01	-1.74E-07	-2.08E+02	-3.83E+04	-3.81E+04	-3.84E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.89E+03**	**-2.65E+01**	**-2.73E+00**	**-4.59E-01**	**-1.74E-07**	**-2.08E+02**	**-3.83E+04**	**-3.81E+04**	**-3.84E+04**
TOTAL EFFECTS	**A to C**	**7.36E+03**	**5.71E+01**	**5.94E+00**	**2.22E+00**	**1.29E-04**	**6.33E+02**	**1.00E+05**	**8.25E+04**	**7.91E+04**
	A to D	**2.46E+03**	**3.06E+01**	**3.21E+00**	**1.76E+00**	**1.29E-04**	**4.25E+02**	**6.21E+04**	**4.44E+04**	**4.07E+04**

Table D.3 Detailed LCA measure table by life cycle stages: Alternative 3 and 5

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	4.60E+03	2.77E+01	7.96E+00	1.25E+00	9.55E-05	2.98E+02	6.98E+04	5.00E+04	4.69E+04
	Transport	1.40E+02	1.44E+00	7.48E-02	8.91E-02	5.07E-09	4.56E+01	2.04E+03	2.04E+03	2.04E+03
	Total	**4.74E+03**	**2.91E+01**	**8.04E+00**	**1.34E+00**	**9.55E-05**	**3.44E+02**	**7.19E+04**	**5.20E+04**	**4.89E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.54E+02	9.95E-01	3.51E-01	5.83E-02	4.65E-07	2.46E+01	2.46E+03	1.76E+03	1.70E+03
	Transport	3.33E+02	3.92E+00	1.80E-01	2.42E-01	1.32E-08	1.25E+02	4.77E+03	4.77E+03	4.76E+03
	Total	**4.87E+02**	**4.91E+00**	**5.31E-01**	**3.00E-01**	**4.78E-07**	**1.50E+02**	**7.23E+03**	**6.52E+03**	**6.46E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.74E+03	2.12E+01	1.60E+00	8.14E-01	8.89E-05	1.67E+02	3.91E+04	2.99E+04	2.94E+04
	Replacement Transport	1.07E+02	1.14E+00	5.92E-02	7.05E-02	4.10E-09	3.62E+01	1.55E+03	1.55E+03	1.55E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.85E+03**	**2.23E+01**	**1.66E+00**	**8.84E-01**	**8.89E-05**	**2.04E+02**	**4.07E+04**	**3.15E+04**	**3.09E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.65E+02	1.40E+00	1.37E-01	4.45E-02	2.40E-08	2.05E+01	3.49E+03	3.40E+03	3.27E+03
	Transport	3.41E+01	3.28E-01	1.82E-02	2.04E-02	1.19E-09	1.04E+01	4.97E+02	4.97E+02	4.96E+02
	Total	**3.00E+02**	**1.73E+00**	**1.55E-01**	**6.49E-02**	**2.52E-08**	**3.09E+01**	**3.99E+03**	**3.90E+03**	**3.76E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.76E+03	-3.17E+01	-3.22E+00	-5.44E-01	-2.09E-07	-2.48E+02	-4.58E+04	-4.54E+04	-4.55E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.76E+03**	**-3.17E+01**	**-3.22E+00**	**-5.44E-01**	**-2.09E-07**	**-2.48E+02**	**-4.58E+04**	**-4.54E+04**	**-4.55E+04**
TOTAL EFFECTS	**A to C**	**8.37E+03**	**5.81E+01**	**1.04E+01**	**2.59E+00**	**1.85E-04**	**7.28E+02**	**1.24E+05**	**9.39E+04**	**9.01E+04**
	A to D	**2.61E+03**	**2.64E+01**	**7.16E+00**	**2.05E+00**	**1.85E-04**	**4.80E+02**	**7.80E+04**	**4.85E+04**	**4.45E+04**

Table D.4 Detailed LCA measure table by life cycle stages: Alternative 4 and 6

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	3.84E+03	2.13E+01	7.51E+00	1.06E+00	6.68E-05	2.53E+02	6.01E+04	4.25E+04	3.95E+04
	Transport	1.33E+02	1.36E+00	7.05E-02	8.41E-02	4.78E-09	4.30E+01	1.93E+03	1.93E+03	1.93E+03
	Total	**3.97E+03**	**2.26E+01**	**7.58E+00**	**1.15E+00**	**6.68E-05**	**2.96E+02**	**6.21E+04**	**4.44E+04**	**4.14E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.54E+02	9.95E-01	3.51E-01	5.83E-02	4.65E-07	2.46E+01	2.46E+03	1.76E+03	1.70E+03
	Transport	3.15E+02	3.72E+00	1.70E-01	2.30E-01	1.24E-08	1.19E+02	4.51E+03	4.51E+03	4.50E+03
	Total	**4.70E+02**	**4.72E+00**	**5.21E-01**	**2.88E-01**	**4.77E-07**	**1.44E+02**	**6.97E+03**	**6.26E+03**	**6.20E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	1.94E+03	1.46E+01	1.14E+00	6.22E-01	6.02E-05	1.21E+02	2.89E+04	2.19E+04	2.15E+04
	Replacement Transport	7.88E+01	8.39E-01	4.37E-02	5.19E-02	3.02E-09	2.66E+01	1.14E+03	1.14E+03	1.14E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.02E+03**	**1.54E+01**	**1.18E+00**	**6.74E-01**	**6.02E-05**	**1.47E+02**	**3.01E+04**	**2.31E+04**	**2.27E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.26E+02	1.22E+00	1.21E-01	4.03E-02	2.02E-08	1.88E+01	2.98E+03	2.90E+03	2.79E+03
	Transport	3.16E+01	3.04E-01	1.68E-02	1.89E-02	1.10E-09	9.60E+00	4.61E+02	4.61E+02	4.60E+02
	Total	**2.58E+02**	**1.52E+00**	**1.38E-01**	**5.92E-02**	**2.13E-08**	**2.84E+01**	**3.44E+03**	**3.36E+03**	**3.25E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.89E+03	-2.65E+01	-2.73E+00	-4.59E-01	-1.74E-07	-2.08E+02	-3.83E+04	-3.81E+04	-3.84E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.89E+03**	**-2.65E+01**	**-2.73E+00**	**-4.59E-01**	**-1.74E-07**	**-2.08E+02**	**-3.83E+04**	**-3.81E+04**	**-3.84E+04**
TOTAL EFFECTS	**A to C**	**6.72E+03**	**4.43E+01**	**9.42E+00**	**2.17E+00**	**1.28E-04**	**6.16E+02**	**1.03E+05**	**7.71E+04**	**7.35E+04**
	A to D	**1.83E+03**	**1.78E+01**	**6.69E+00**	**1.71E+00**	**1.27E-04**	**4.08E+02**	**6.42E+04**	**3.91E+04**	**3.52E+04**

Table D.5 Detailed LCA measure table by life cycle stages: Alternative 7

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	3.71E+03	2.77E+01	2.98E+00	1.28E+00	9.43E-05	3.15E+02	5.56E+04	4.31E+04	4.04E+04
	Transport	4.88E+01	5.12E-01	2.64E-02	3.18E-02	1.82E-09	1.63E+01	7.09E+02	7.08E+02	7.07E+02
	Total	**3.75E+03**	**2.82E+01**	**3.01E+00**	**1.32E+00**	**9.43E-05**	**3.31E+02**	**5.63E+04**	**4.38E+04**	**4.11E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	7.92E+01	6.57E-01	5.20E-02	4.03E-02	2.87E-07	1.43E+01	1.39E+03	9.98E+02	9.58E+02
	Transport	1.40E+02	1.81E+00	7.21E-02	1.12E-01	5.56E-09	5.84E+01	1.97E+03	1.97E+03	1.96E+03
	Total	**2.19E+02**	**2.46E+00**	**1.24E-01**	**1.52E-01**	**2.93E-07**	**7.27E+01**	**3.35E+03**	**2.96E+03**	**2.92E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	3.21E+03	2.59E+01	3.03E+00	1.09E+00	8.91E-05	2.89E+02	4.70E+04	3.58E+04	3.52E+04
	Replacement Transport	1.31E+02	1.40E+00	7.26E-02	8.66E-02	5.04E-09	4.44E+01	1.90E+03	1.90E+03	1.89E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**3.34E+03**	**2.73E+01**	**3.10E+00**	**1.17E+00**	**8.91E-05**	**3.34E+02**	**4.89E+04**	**3.77E+04**	**3.71E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.62E+02	1.35E+00	1.34E-01	4.12E-02	2.38E-08	1.88E+01	3.43E+03	3.35E+03	3.21E+03
	Transport	1.67E+01	1.60E-01	8.87E-03	9.95E-03	5.81E-10	5.05E+00	2.43E+02	2.43E+02	2.42E+02
	Total	**2.78E+02**	**1.51E+00**	**1.43E-01**	**5.12E-02**	**2.44E-08**	**2.39E+01**	**3.67E+03**	**3.59E+03**	**3.45E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-7.66E+03	-3.17E+01	-3.21E+00	-5.43E-01	-2.09E-07	-2.48E+02	-4.57E+04	-4.54E+04	-4.54E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-7.66E+03**	**-3.17E+01**	**-3.21E+00**	**-5.43E-01**	**-2.09E-07**	**-2.48E+02**	**-4.57E+04**	**-4.54E+04**	**-4.54E+04**
TOTAL EFFECTS	**A to C**	**7.59E+03**	**5.95E+01**	**6.38E+00**	**2.69E+00**	**1.84E-04**	**7.61E+02**	**1.12E+05**	**8.81E+04**	**8.46E+04**
	A to D	**-7.00E+01**	**2.78E+01**	**3.17E+00**	**2.15E+00**	**1.83E-04**	**5.14E+02**	**6.65E+04**	**4.27E+04**	**3.92E+04**

Table D.6 Detailed LCA measure table by life cycle stages: Alternative 8

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	2.95E+03	2.13E+01	2.53E+00	1.10E+00	6.56E-05	2.70E+02	4.59E+04	3.56E+04	3.30E+04
	Transport	4.11E+01	4.32E-01	2.22E-02	2.68E-02	1.53E-09	1.37E+01	5.97E+02	5.97E+02	5.96E+02
	Total	**2.99E+03**	**2.18E+01**	**2.55Ez00**	**1.12E+00**	**6.56E-05**	**2.84E+02**	**4.65E+04**	**3.62E+04**	**3.36E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	7.92E+01	6.57E-01	5.20E-02	4.03E-02	2.87E-07	1.43E+01	1.39E+03	9.98E+02	9.58E+02
	Transport	1.22E+02	1.61E+00	6.21E-02	9.95E-02	4.85E-09	5.21E+01	1.71E+03	1.71E+03	1.71E+03
	Total	**2.01E+02**	**2.27E+00**	**1.14E-01**	**1.40E-01**	**2.92E-07**	**6.64E+01**	**3.09E+03**	**2.71E+03**	**2.66E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.41E+03	1.93E+01	2.56E+00	8.94E-01	6.04E-05	2.42E+02	3.68E+04	2.78E+04	2.73E+04
	Replacement Transport	1.03E+02	1.10E+00	5.71E-02	6.80E-02	3.96E-09	3.49E+01	1.49E+03	1.49E+03	1.49E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.52E+03**	**2.04E+01**	**2.62E+00**	**9.62E-01**	**6.04E-05**	**2.77E+02**	**3.83E+04**	**2.93E+04**	**2.88E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.22E+02	1.17E+00	1.19E-01	3.71E-02	2.00E-08	1.71E+01	2.92E+03	2.85E+03	2.73E+03
	Transport	1.42E+01	1.36E-01	7.55E-03	8.47E-03	4.94E-10	4.30E+00	2.07E+02	2.06E+02	2.06E+02
	Total	**2.36E+02**	**1.30E+00**	**1.26E-01**	**4.56E-02**	**2.05E-08**	**2.14E+01**	**3.13E+03**	**3.05E+03**	**2.94E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-6.80E+03	-2.65E+01	-2.71E+00	-4.57E-01	-1.74E-07	-2.07E+02	-3.83E+04	-3.80E+04	-3.82E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-6.80E+03**	**-2.65E+01**	**-2.71E+00**	**-4.57E-01**	**-1.74E-07**	**-2.07E+02**	**-3.83E+04**	**-3.80E+04**	**-3.82E+04**
TOTAL EFFECTS	**A to C**	**5.94E+03**	**4.57E+01**	**5.42E+00**	**2.27E+00**	**1.26E-04**	**6.49E+02**	**9.10E+04**	**7.13E+04**	**6.80E+04**
	A to D	**-8.54E+02**	**1.92E+01**	**2.70E+00**	**1.81E+00**	**1.26E-04**	**4.41E+02**	**5.27E+04**	**3.33E+04**	**2.98E+04**

Table D.7 Detailed LCA measure table by life cycle stages: Alternative 9

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	3.86E+03	2.69E+01	3.62E+00	1.20E+00	9.56E-05	2.65E+02	5.43E+04	4.40E+04	4.09E+04
	Transport	5.78E+01	6.27E-01	3.13E-02	3.88E-02	2.19E-09	2.00E+01	8.39E+02	8.39E+02	8.38E+02
	Total	**3.92E+03**	**2.75E+01**	**3.65E+00**	**1.24E+00**	**9.56E-05**	**2.85E+02**	**5.52E+04**	**4.49E+04**	**4.18E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.02E+02	7.74E-01	1.13E-01	4.61E-02	4.19E-07	1.60E+01	1.49E+03	1.25E+03	1.21E+03
	Transport	1.57E+02	1.76E+00	8.70E-02	1.09E-01	6.18E-09	5.60E+01	2.27E+03	2.27E+03	2.26E+03
	Total	**2.59E+02**	**2.53E+00**	**2.00E-01**	**1.55E-01**	**4.25E-07**	**7.20E+01**	**3.75E+03**	**3.52E+03**	**3.47E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	3.01E+03	2.27E+01	3.33E+00	8.74E-01	8.98E-05	1.98E+02	4.28E+04	3.34E+04	3.28E+04
	Replacement Transport	1.66E+02	1.78E+00	9.18E-02	1.11E-01	6.38E-09	5.67E+01	2.41E+03	2.41E+03	2.41E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**3.17E+03**	**2.45E+01**	**3.42E+00**	**9.84E-01**	**8.98E-05**	**2.55E+02**	**4.52E+04**	**3.59E+04**	**3.52E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.54E+02	1.22E+00	1.37E-01	3.30E-02	2.35E-08	1.44E+01	3.31E+03	3.22E+03	3.08E+03
	Transport	3.27E+01	3.14E-01	1.74E-02	1.95E-02	1.14E-09	9.91E+00	4.76E+02	4.76E+02	4.75E+02
	Total	**2.86E+02**	**1.53E+00**	**1.54E-01**	**5.25E-02**	**2.46E-08**	**2.43E+01**	**3.79E+03**	**3.70E+03**	**3.56E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.49E+03	-3.18E+01	-3.25E+00	-5.48E-01	-2.09E-07	-2.49E+02	-4.59E+04	-4.56E+04	-4.58E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.49E+03**	**-3.18E+01**	**-3.25E+00**	**-5.48E-01**	**-2.09E-07**	**-2.49E+02**	**-4.59E+04**	**-4.56E+04**	**-4.58E+04**
TOTAL EFFECTS	**A to C**	**7.64E+03**	**5.61E+01**	**7.42E+00**	**2.43E+00**	**1.86E-04**	**6.36E+02**	**1.08E+05**	**8.79E+04**	**8.40E+04**
	A to D	**2.14E+03**	**2.44E+01**	**4.17E+00**	**1.88E+00**	**1.86E-04**	**3.87E+02**	**6.20E+04**	**4.24E+04**	**3.82E+04**

Table D.8 Detailed LCA measure table by life cycle stages: Alternative 10

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	3.10E+03	2.05E+01	3.17E+00	1.01E+00	6.69E-05	2.20E+02	4.46E+04	3.66E+04	3.35E+04
	Transport	5.02E+01	5.46E-01	2.71E-02	3.38E-02	1.90E-09	1.74E+01	7.28E+02	7.28E+02	7.27E+02
	Total	**3.15E+03**	**2.11E+01**	**3.19E+00**	**1.05E+00**	**6.69E-05**	**2.37E+02**	**4.54E+04**	**3.73E+04**	**3.43E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.02E+02	7.74E-01	1.13E-01	4.61E-02	4.19E-07	1.60E+01	1.49E+03	1.25E+03	1.21E+03
	Transport	1.39E+02	1.56E+00	7.70E-02	9.66E-02	5.47E-09	4.98E+01	2.01E+03	2.01E+03	2.00E+03
	Total	**2.41E+02**	**2.34E+00**	**1.90E-01**	**1.43E-01**	**4.24E-07**	**6.57E+01**	**3.49E+03**	**3.26E+03**	**3.21E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.21E+03	1.62E+01	2.86E+00	6.82E-01	6.12E-05	1.52E+02	3.26E+04	2.55E+04	2.50E+04
	Replacement Transport	1.38E+02	1.48E+00	7.62E-02	9.19E-02	5.30E-09	4.72E+01	2.01E+03	2.01E+03	2.00E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.35E+03**	**1.77E+01**	**2.94E+00**	**7.74E-01**	**6.12E-05**	**1.99E+02**	**3.46E+04**	**2.75E+04**	**2.70E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.14E+02	1.04E+00	1.22E-01	2.89E-02	1.96E-08	1.27E+01	2.81E+03	2.72E+03	2.60E+03
	Transport	3.02E+01	2.90E-01	1.61E-02	1.80E-02	1.05E-09	9.16E+00	4.40E+02	4.40E+02	4.39E+02
	Total	**2.44E+02**	**1.33E+00**	**1.38E-01**	**4.69E-02**	**2.07E-08**	**2.19E+01**	**3.25E+03**	**3.16E+03**	**3.04E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.63E+03	-2.66E+01	-2.76E+00	-4.62E-01	-1.74E-07	-2.08E+02	-3.85E+04	-3.82E+04	-3.86E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.63E+03**	**-2.66E+01**	**-2.76E+00**	**-4.62E-01**	**-1.74E-07**	**-2.08E+02**	**-3.85E+04**	**-3.82E+04**	**-3.86E+04**
TOTAL EFFECTS	**A to C**	**5.99E+03**	**4.24E+01**	**6.46E+00**	**2.01E+00**	**1.29E-04**	**5.23E+02**	**8.67E+04**	**7.12E+04**	**6.75E+04**
	A to D	**1.36E+03**	**1.58E+01**	**3.70E+00**	**1.55E+00**	**1.28E-04**	**3.15E+02**	**4.82E+04**	**3.29E+04**	**2.88E+04**

Table D.9 Detailed LCA measure table by life cycle stages: Alternative 11

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	3.91E+03	2.84E+01	4.19E+00	1.26E+00	9.78E-05	2.71E+02	5.29E+04	4.18E+04	3.90E+04
	Transport	5.86E+01	6.17E-01	3.16E-02	3.83E-02	2.18E-09	1.96E+01	8.52E+02	8.51E+02	8.50E+02
	Total	**3.97E+03**	**2.90E+01**	**4.22E+00**	**1.30E+00**	**9.78E-05**	**2.90E+02**	**5.38E+04**	**4.27E+04**	**3.98E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.03E+02	7.76E-01	1.74E-01	4.09E-02	6.38E-07	1.13E+01	1.23E+03	9.68E+02	9.13E+02
	Transport	1.48E+02	1.97E+00	7.41E-02	1.21E-01	5.83E-09	6.37E+01	2.06E+03	2.06E+03	2.05E+03
	Total	**2.51E+02**	**2.74E+00**	**2.48E-01**	**1.62E-01**	**6.44E-07**	**7.50E+01**	**3.29E+03**	**3.03E+03**	**2.97E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.89E+03	2.22E+01	3.13E+00	8.55E-01	8.98E-05	1.78E+02	4.15E+04	3.23E+04	3.16E+04
	Replacement Transport	1.18E+02	1.28E+00	6.52E-02	7.92E-02	4.55E-09	4.07E+01	1.72E+03	1.72E+03	1.71E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**3.01E+03**	**2.35E+01**	**3.19E+00**	**9.34E-01**	**8.98E-05**	**2.19E+02**	**4.32E+04**	**3.40E+04**	**3.34E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.62E+02	1.35E+00	1.34E-01	4.12E-02	2.38E-08	1.88E+01	3.43E+03	3.35E+03	3.21E+03
	Transport	2.09E+01	2.01E-01	1.11E-02	1.25E-02	7.29E-10	6.34E+00	3.05E+02	3.05E+02	3.04E+02
	Total	**2.83E+02**	**1.55E+00**	**1.45E-01**	**5.37E-02**	**2.46E-08**	**2.51E+01**	**3.74E+03**	**3.65E+03**	**3.52E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.74E+03	-3.17E+01	-3.21E+00	-5.43E-01	-2.09E-07	-2.48E+02	-4.57E+04	-4.54E+04	-4.54E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.74E+03**	**-3.17E+01**	**-3.21E+00**	**-5.43E-01**	**-2.09E-07**	**-2.48E+02**	**-4.57E+04**	**-4.54E+04**	**-4.54E+04**
TOTAL EFFECTS	**A to C**	**7.51E+03**	**5.68E+01**	**7.81E+00**	**2.45E+00**	**1.88E-04**	**6.09E+02**	**1.04E+05**	**8.34E+04**	**7.96E+04**
	A to D	**1.77E+03**	**2.52E+01**	**4.60E+00**	**1.91E+00**	**1.88E-04**	**3.62E+02**	**5.83E+04**	**3.80E+04**	**3.42E+04**

Table D.10 Detailed LCA measure table by life cycle stages: Alternative 12

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	3.15E+03	2.20E+01	3.74E+00	1.08E+00	6.91E-05	2.26E+02	4.33E+04	3.43E+04	3.16E+04
	Transport	5.10E+01	5.37E-01	2.74E-02	3.33E-02	1.89E-09	1.71E+01	7.41E+02	7.40E+02	7.39E+02
	Total	**3.20E+03**	**2.26E+01**	**3.76E+00**	**1.11E+00**	**6.91E-05**	**2.43E+02**	**4.40E+04**	**3.51E+04**	**3.23E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	1.03E+02	7.76E-01	1.74E-01	4.09E-02	6.38E-07	1.13E+01	1.23E+03	9.68E+02	9.13E+02
	Transport	1.30E+02	1.77E+00	6.41E-02	1.09E-01	5.13E-09	5.75E+01	1.80E+03	1.80E+03	1.80E+03
	Total	**2.33E+02**	**2.55E+00**	**2.38E-01**	**1.50E-01**	**6.43E-07**	**6.88E+01**	**3.03E+03**	**2.77E+03**	**2.71E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.09E+03	1.56E+01	2.66E+00	6.63E-01	6.11E-05	1.32E+02	3.13E+04	2.43E+04	2.38E+04
	Replacement Transport	9.05E+01	9.80E-01	4.97E-02	6.07E-02	3.47E-09	3.12E+01	1.31E+03	1.31E+03	1.31E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.18E+03**	**1.66E+01**	**2.71E+00**	**7.24E-01**	**6.11E-05**	**1.63E+02**	**3.26E+04**	**2.56E+04**	**2.51E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	2.22E+02	1.17E+00	1.19E-01	3.71E-02	2.00E-08	1.71E+01	2.92E+03	2.85E+03	2.73E+03
	Transport	1.84E+01	1.77E-01	9.80E-03	1.10E-02	6.42E-10	5.59E+00	2.68E+02	2.68E+02	2.68E+02
	Total	**2.41E+02**	**1.34E+00**	**1.29E-01**	**4.81E-02**	**2.07E-08**	**2.27E+01**	**3.19E+03**	**3.11E+03**	**3.00E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.88E+03	-2.65E+01	-2.71E+00	-4.57E-01	-1.74E-07	-2.07E+02	-3.83E+04	-3.80E+04	-3.82E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.88E+03**	**-2.65E+01**	**-2.71E+00**	**-4.57E-01**	**-1.74E-07**	**-2.07E+02**	**-3.83E+04**	**-3.80E+04**	**-3.82E+04**
TOTAL EFFECTS	**A to C**	**5.86E+03**	**4.31E+01**	**6.84E+00**	**2.03E+00**	**1.31E-04**	**4.97E+02**	**8.28E+04**	**6.66E+04**	**6.31E+04**
	A to D	**9.81E+02**	**1.66E+01**	**4.13E+00**	**1.57E+00**	**1.31E-04**	**2.90E+02**	**4.46E+04**	**2.86E+04**	**2.49E+04**

Table D.11 Detailed LCA measure table by life cycle stages: Alternative 13

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	7.38E+03	5.21E+01	7.08E+00	1.90E+00	1.10E-04	4.84E+02	9.69E+04	8.39E+04	7.93E+04
	Transport	6.72E+01	6.99E-01	3.61E-02	4.33E-02	2.47E-09	2.22E+01	9.76E+02	9.76E+02	9.74E+02
	Total	**7.44E+03**	**5.28E+01**	**7.11E+00**	**1.94E+00**	**1.10E-04**	**5.06E+02**	**9.79E+04**	**8.48E+04**	**8.03E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	4.78E+02	3.54E+00	4.98E-01	1.65E-01	1.73E-06	7.54E+01	5.84E+03	5.56E+03	5.44E+03
	Transport	3.27E+02	3.26E+00	1.77E-01	2.02E-01	1.18E-08	1.03E+02	4.76E+03	4.76E+03	4.75E+03
	Total	**8.05E+02**	**6.80E+00**	**6.75E-01**	**3.67E-01**	**1.74E-06**	**1.78E+02**	**1.06E+04**	**1.03E+04**	**1.02E+04**
USE (B2, B4 & B6)	Replacement Manufacturing	2.68E+03	2.07E+01	1.56E+00	8.06E-01	8.89E-05	1.63E+02	3.56E+04	2.66E+04	2.60E+04
	Replacement Transport	1.02E+02	1.09E+00	5.68E-02	6.77E-02	3.94E-09	3.47E+01	1.49E+03	1.49E+03	1.48E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.78E+03**	**2.18E+01**	**1.62E+00**	**8.73E-01**	**8.89E-05**	**1.98E+02**	**3.71E+04**	**2.80E+04**	**2.75E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	3.55E+02	2.71E+00	1.56E-01	1.27E-01	2.79E-08	6.43E+01	4.82E+03	4.75E+03	4.61E+03
	Transport	1.10E+02	1.06E+00	5.88E-02	6.60E-02	3.85E-09	3.35E+01	1.61E+03	1.61E+03	1.61E+03
	Total	**4.65E+02**	**3.78E+00**	**2.15E-01**	**1.93E-01**	**3.18E-08**	**9.78E+01**	**6.43E+03**	**6.36E+03**	**6.22E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.07E+03	-3.08E+01	-2.83E+00	-4.98E-01	-2.09E-07	-2.39E+02	-4.40E+04	-4.37E+04	-4.19E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.07E+03**	**-3.08E+01**	**-2.83E+00**	**-4.98E-01**	**-2.09E-07**	**-2.39E+02**	**-4.40E+04**	**-4.37E+04**	**-4.19E+04**
TOTAL EFFECTS	**A to C**	**1.15E+04**	**8.53E+01**	**9.62E+00**	**3.37E+00**	**2.01E-04**	**9.80E+02**	**1.52E+05**	**1.30E+05**	**1.24E+05**
	A to D	**6.42E+03**	**5.45E+01**	**6.79E+00**	**2.88E+00**	**2.00E-04**	**7.41E+02**	**1.08E+05**	**8.59E+04**	**8.23E+04**

Table D.12 Detailed LCA measure table by life cycle stages: Alternative 14

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	6.62E+03	4.58E+01	6.63E+00	1.71E+00	8.14E-05	4.39E+02	8.72E+04	7.64E+04	7.19E+04
	Transport	5.96E+01	6.19E-01	3.19E-02	3.84E-02	2.18E-09	1.96E+01	8.65E+02	8.65E+02	8.63E+02
	Total	**6.68E+03**	**4.64E+01**	**6.66E+00**	**1.75E+00**	**8.14E-05**	**4.59E+02**	**8.81E+04**	**7.73E+04**	**7.28E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	4.78E+02	3.54E+00	4.98E-01	1.65E-01	1.73E-06	7.54E+01	5.84E+03	5.56E+03	5.44E+03
	Transport	3.09E+02	3.06E+00	1.67E-01	1.90E-01	1.11E-08	9.68E+01	4.51E+03	4.50E+03	4.50E+03
	Total	**7.87E+02**	**6.61E+00**	**6.65E-01**	**3.55E-01**	**1.74E-06**	**1.72E+02**	**1.03E+04**	**1.01E+04**	**9.94E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	1.88E+03	1.42E+01	1.09E+00	6.14E-01	6.02E-05	1.16E+02	2.54E+04	1.86E+04	1.82E+04
	Replacement Transport	7.44E+01	7.93E-01	4.13E-02	4.91E-02	2.86E-09	2.52E+01	1.08E+03	1.08E+03	1.08E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**1.96E+03**	**1.49E+01**	**1.14E+00**	**6.63E-01**	**6.02E-05**	**1.41E+02**	**2.65E+04**	**1.96E+04**	**1.93E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	3.15E+02	2.53E+00	1.40E-01	1.23E-01	2.41E-08	6.26E+01	4.31E+03	4.25E+03	4.13E+03
	Transport	1.08E+02	1.04E+00	5.75E-02	6.45E-02	3.77E-09	3.27E+01	1.57E+03	1.57E+03	1.57E+03
	Total	**4.23E+02**	**3.57E+00**	**1.98E-01**	**1.87E-01**	**2.79E-08**	**9.53E+01**	**5.88E+03**	**5.82E+03**	**5.70E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.21E+03	-2.56E+01	-2.34E+00	-4.13E-01	-1.74E-07	-1.99E+02	-3.65E+04	-3.63E+04	-3.48E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.21E+03**	**-2.56E+01**	**-2.34E+00**	**-4.13E-01**	**-1.74E-07**	**-1.99E+02**	**-3.65E+04**	**-3.63E+04**	**-3.48E+04**
TOTAL EFFECTS	**A to C**	**9.85E+03**	**7.15E+01**	**8.66E+00**	**2.95E+00**	**1.43E-04**	**8.68E+02**	**1.31E+05**	**1.13E+05**	**1.08E+05**
	A to D	**5.64E+03**	**4.59E+01**	**6.32E+00**	**2.54E+00**	**1.43E-04**	**6.69E+02**	**9.43E+04**	**7.65E+04**	**7.29E+04**

Table D.13 Detailed LCA measure table by life cycle stages: Alternative 15

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	**kg CO2 eq**	**kg SO2 eq**	**kg PM2.5 eq**	**kg N eq**	**kg CFC-11 eq**	**kg O3 eq**	**MJ**	**MJ**	**MJ**
PRODUCT (A1 to A3)	Manufacturing	6.08E+03	3.92E+01	6.17E+00	1.82E+00	1.09E-04	4.25E+02	8.31E+04	7.15E+04	6.68E+04
	Transport	6.57E+01	7.08E-01	3.54E-02	4.39E-02	2.47E-09	2.25E+01	9.53E+02	9.52E+02	9.51E+02
	Total	**6.15E+03**	**3.99E+01**	**6.21E+00**	**1.87E+00**	**1.09E-04**	**4.47E+02**	**8.40E+04**	**7.24E+04**	**6.77E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	3.58E+02	2.33E+00	3.72E-01	1.30E-01	1.46E-06	5.36E+01	4.62E+03	4.42E+03	4.31E+03
	Transport	2.55E+02	2.68E+00	1.39E-01	1.66E-01	9.58E-09	8.49E+01	3.70E+03	3.70E+03	3.69E+03
	Total	**6.13E+02**	**5.00E+00**	**5.11E-01**	**2.95E-01**	**1.47E-06**	**1.39E+02**	**8.32E+03**	**8.12E+03**	**8.00E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	3.01E+03	2.27E+01	3.33E+00	8.74E-01	8.98E-05	1.98E+02	4.28E+04	3.34E+04	3.28E+04
	Replacement Transport	1.66E+02	1.78E+00	9.18E-02	1.11E-01	6.38E-09	5.67E+01	2.41E+03	2.41E+03	2.41E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**3.17E+03**	**2.45E+01**	**3.42E+00**	**9.84E-01**	**8.98E-05**	**2.55E+02**	**4.52E+04**	**3.59E+04**	**3.52E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	3.49E+02	2.62E+00	1.59E-01	1.21E-01	2.77E-08	6.12E+01	4.74E+03	4.66E+03	4.52E+03
	Transport	8.19E+01	7.88E-01	4.36E-02	4.90E-02	2.86E-09	2.49E+01	1.19E+03	1.19E+03	1.19E+03
	Total	**4.31E+02**	**3.41E+00**	**2.02E-01**	**1.70E-01**	**3.05E-08**	**8.60E+01**	**5.93E+03**	**5.86E+03**	**5.72E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-5.10E+03	-3.09E+01	-2.86E+00	-5.02E-01	-2.09E-07	-2.40E+02	-4.41E+04	-4.38E+04	-4.22E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-5.10E+03**	**-3.09E+01**	**-2.86E+00**	**-5.02E-01**	**-2.09E-07**	**-2.40E+02**	**-4.41E+04**	**-4.38E+04**	**-4.22E+04**
TOTAL EFFECTS	**A to C**	**1.04E+04**	**7.28E+01**	**1.03E+01**	**3.32E+00**	**2.00E-04**	**9.27E+02**	**1.43E+05**	**1.22E+05**	**1.17E+05**
	A to D	**5.26E+03**	**4.20E+01**	**7.48E+00**	**2.82E+00**	**2.00E-04**	**6.88E+02**	**9.94E+04**	**7.84E+04**	**7.45E+04**

Table D.14 Detailed LCA measure table by life cycle stages: Alternative 16

	LCA Measures	Global Warming Potential	Acidification Potential	HH Particulate	Eutrophication Potential	Ozone Depletion Potential	Smog Potential	Total Primary Energy	Non-Renewable Energy	Fossil Fuel Consumption
	Unit	kg CO2 eq	kg SO2 eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg O3 eq	MJ	MJ	MJ
PRODUCT (A1 to A3)	Manufacturing	5.32E+03	3.28E+01	5.72E+00	1.64E+00	8.00E-05	3.80E+02	7.34E+04	6.40E+04	5.94E+04
	Transport	5.80E+01	6.28E-01	3.12E-02	3.89E-02	2.18E-09	2.00E+01	8.42E+02	8.41E+02	8.40E+02
	Total	**5.38E+03**	**3.34E+01**	**5.75E+00**	**1.68E+00**	**8.00E-05**	**4.00E+02**	**7.42E+04**	**6.48E+04**	**6.02E+04**
CONSTRUCTION PROCESS (A4 & A5)	Construction-Installation Process	3.58E+02	2.33E+00	3.72E-01	1.30E-01	1.46E-06	5.36E+01	4.62E+03	4.42E+03	4.31E+03
	Transport	2.37E+02	2.48E+00	1.29E-01	1.54E-01	8.88E-09	7.87E+01	3.44E+03	3.44E+03	3.43E+03
	Total	**5.95E+02**	**4.81E+00**	**5.01E-01**	**2.83E-01**	**1.47E-06**	**1.32E+02**	**8.06E+03**	**7.86E+03**	**7.74E+03**
USE (B2, B4 & B6)	Replacement Manufacturing	2.21E+03	1.62E+01	2.86E+00	6.82E-01	6.12E-05	1.52E+02	3.26E+04	2.55E+04	2.50E+04
	Replacement Transport	1.38E+02	1.48E+00	7.62E-02	9.19E-02	5.30E-09	4.72E+01	2.01E+03	2.01E+03	2.00E+03
	Operational Energy Use Total	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**2.35E+03**	**1.77E+01**	**2.94E+00**	**7.74E-01**	**6.12E-05**	**1.99E+02**	**3.46E+04**	**2.75E+04**	**2.70E+04**
END OF LIFE (C1 to C4)	De-construction, Demolition, Disposal & Waste Processing	3.10E+02	2.44E+00	1.43E-01	1.17E-01	2.39E-08	5.95E+01	4.23E+03	4.16E+03	4.04E+03
	Transport	7.95E+01	7.64E-01	4.23E-02	4.75E-02	2.77E-09	2.41E+01	1.16E+03	1.16E+03	1.16E+03
	Total	**3.89E+02**	**3.21E+00**	**1.85E-01**	**1.64E-01**	**2.66E-08**	**8.36E+01**	**5.39E+03**	**5.32E+03**	**5.20E+03**
BEYOND BUILDING LIFE (D)	BBL Material	-4.24E+03	-2.57E+01	-2.37E+00	-4.16E-01	-1.74E-07	-1.99E+02	-3.67E+04	-3.64E+04	-3.50E+04
	BBL Transport	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Total	**-4.24E+03**	**-2.57E+01**	**-2.37E+00**	**-4.16E-01**	**-1.74E-07**	**-1.99E+02**	**-3.67E+04**	**-3.64E+04**	**-3.50E+04**
TOTAL EFFECTS	**A to C**	**8.71E+03**	**5.91E+01**	**9.38E+00**	**2.90E+00**	**1.43E-04**	**8.15E+02**	**1.22E+05**	**1.05E+05**	**1.00E+05**
	A to D	**4.48E+03**	**3.34E+01**	**7.01E+00**	**2.48E+00**	**1.43E-04**	**6.15E+02**	**8.56E+04**	**6.90E+04**	**6.51E+04**

APPENDIX E Survey Results

The participant responses to determine the interaction indices among 11 sets of decision criteria:

In your professional opinion, to what extent does decreasing the WEIGHT of a facade panel improve the ENVIRONMENTAL IMPACTS in terms of embodied energy, waste residue, CO2 emissions, etc. ?

47 responses

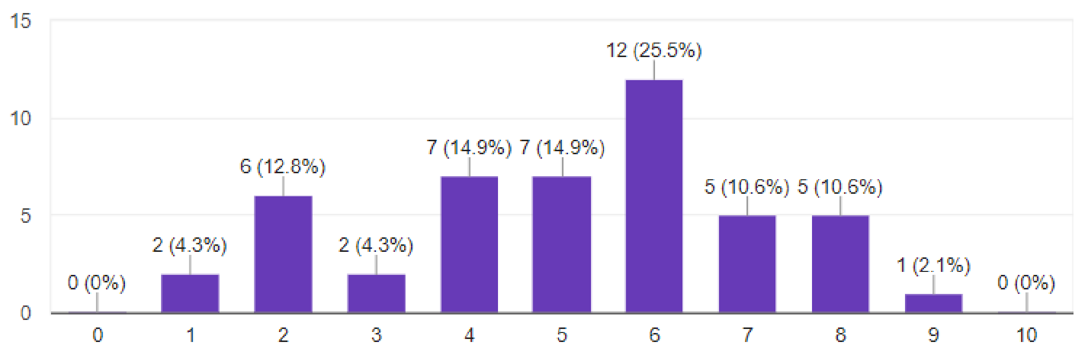


Figure E.1 Participant responses for determining the interaction between c_2 and c_5.

There were no outliers and all responses were accepted.

To what extent does decreasing the WEIGHT of a facade panel improve the EASE OF CONSTRUCTION of the facade system in terms of labour-hours needed and their user-friendliness?

46 responses

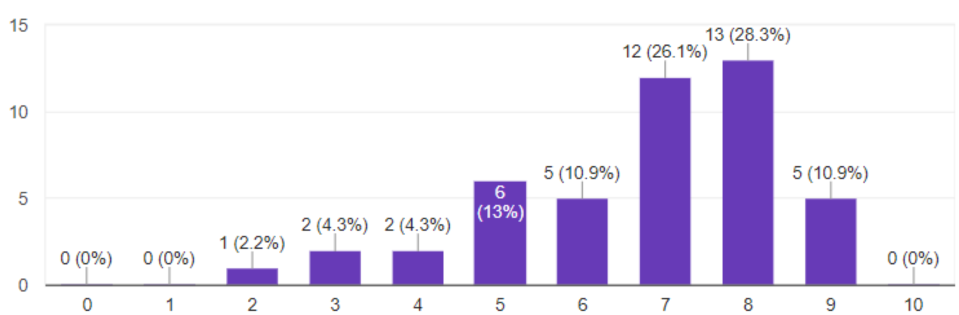


Figure E.2 Participant responses for determining the interaction between c_2 and c_6.

The input value 2 was an outlier and was not considered.

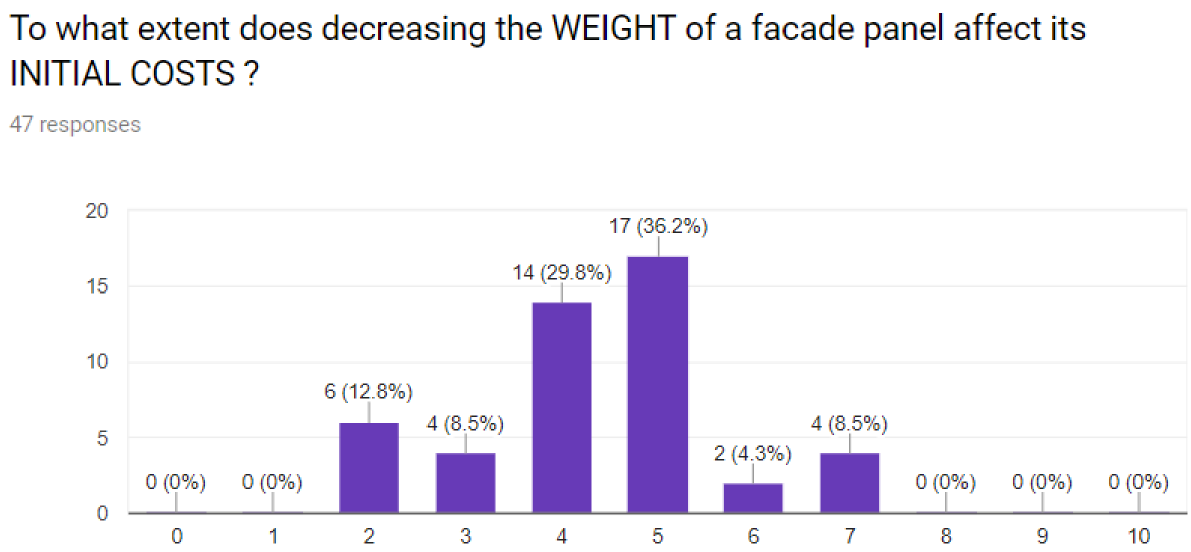


Figure E.3 Participant responses for determining the interaction between c_2 and c_8.

The inputs for 2 and 7 (10 responses) were outliers and were not considered.

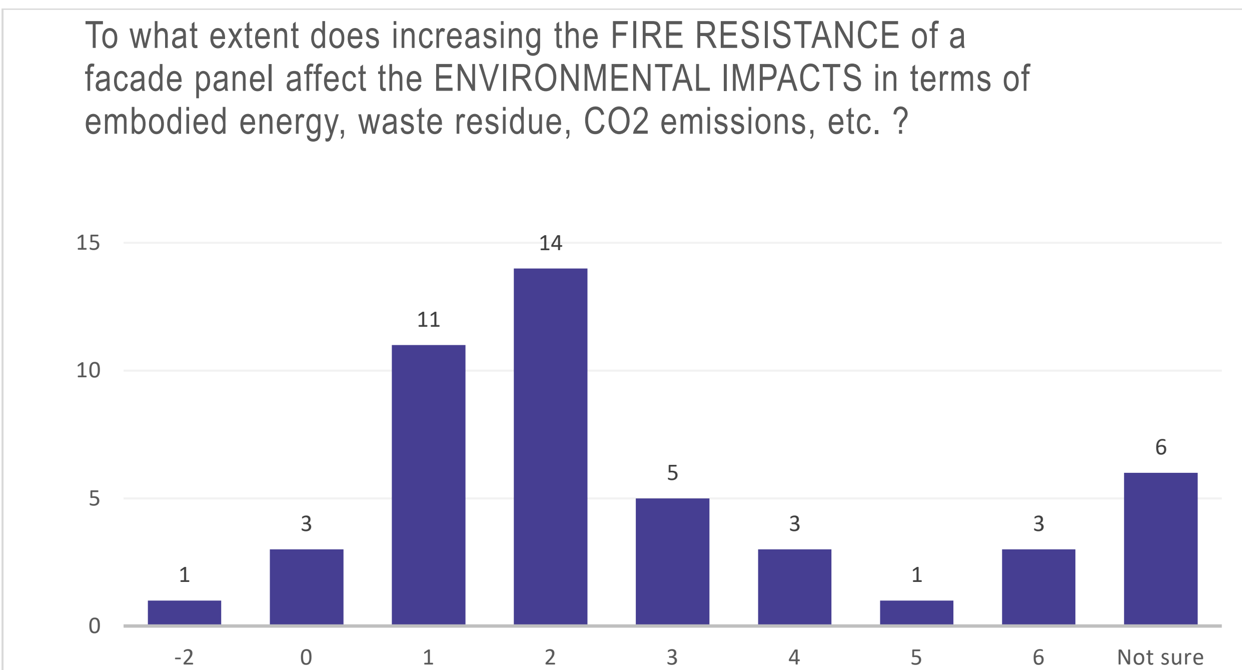


Figure E.4 Adjusted participant responses for determining the interaction between c_3 and c_5.

41 responses were considered.

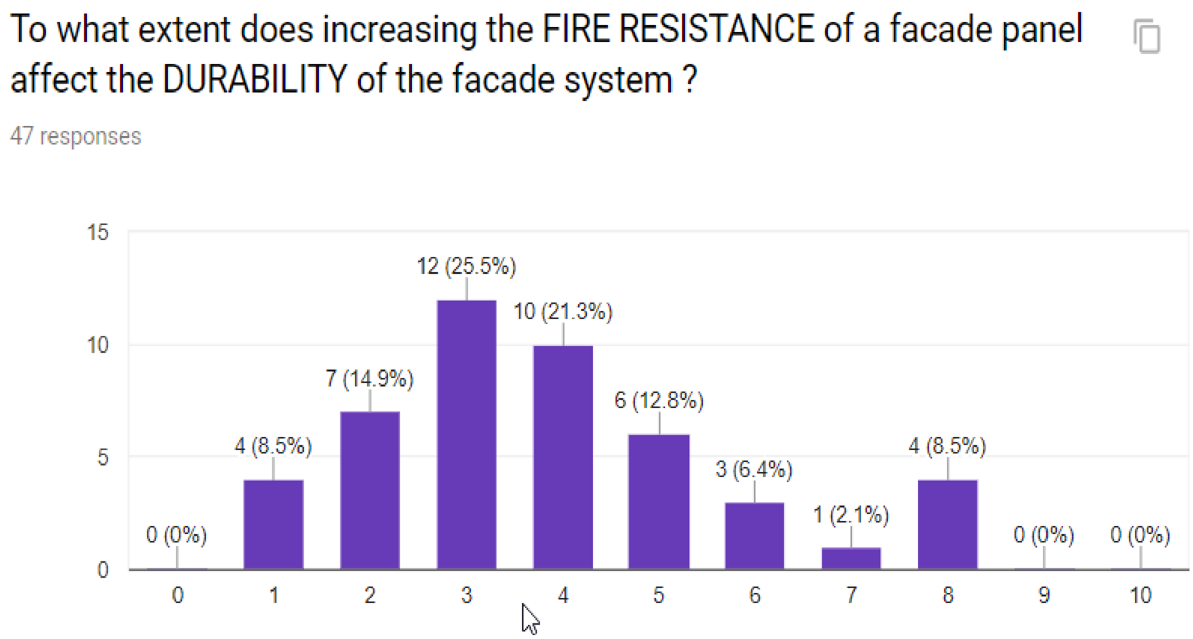


Figure E.5 Adjusted participant responses for determining the interaction between c_3 and c_7.

All responses were accepted and there were no outliers.

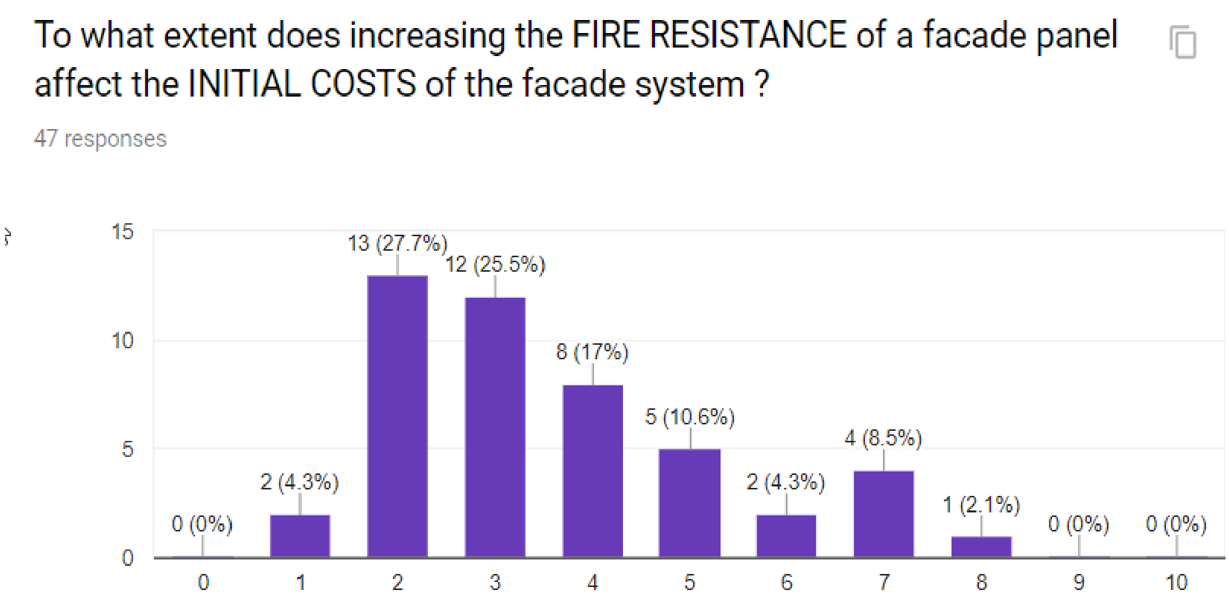


Figure E.6 Adjusted participant responses for determining the interaction between c_3 and c_8.

All responses were accepted and there were no outliers.

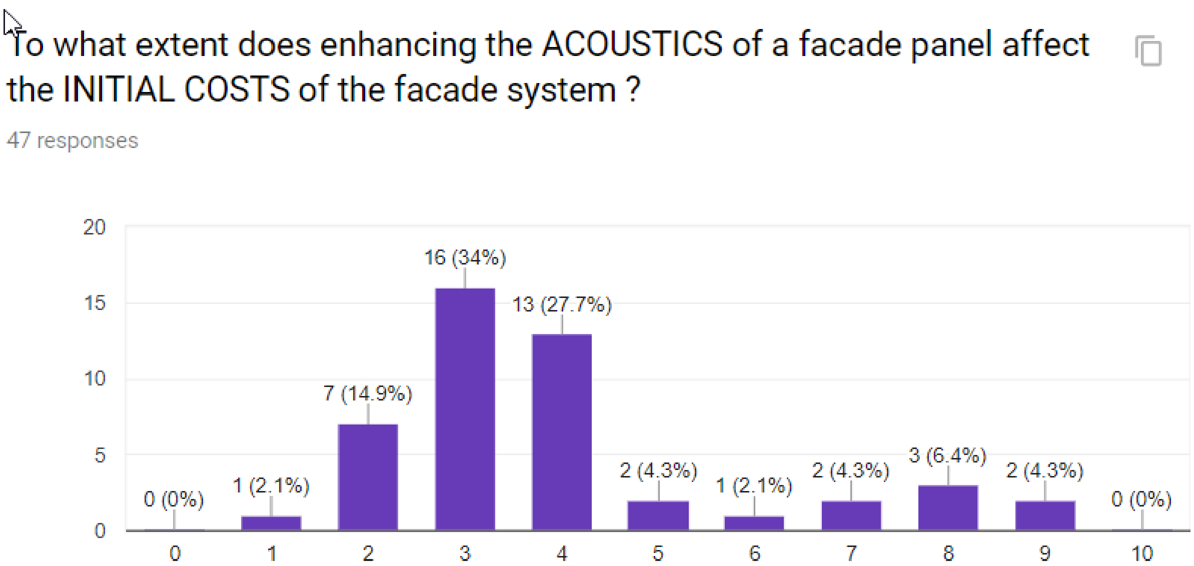
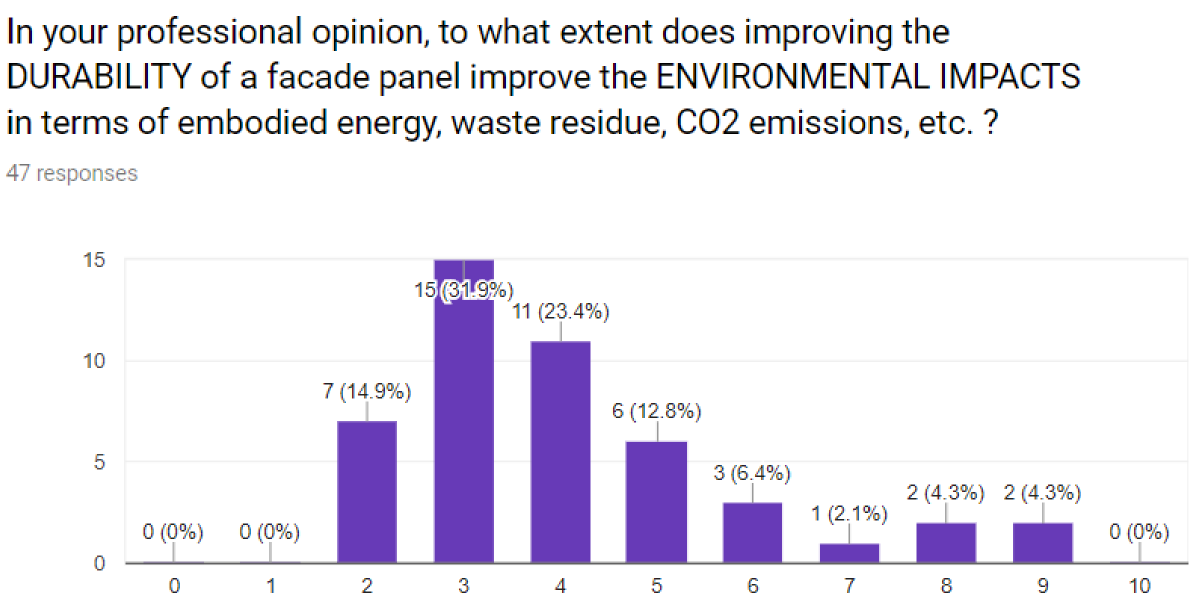


Figure E.7 Adjusted participant responses for determining the interaction between c_4 and c_8.

The inputs for 1, 6,7,8 and 9 (9 responses) were outliers and were not considered.



s

Figure E.8 Adjusted participant responses for determining the interaction between c_5 and c_7.

The inputs for 9 (2 responses) were outliers and were not considered.

In your professional opinion, to what extent will decreasing the ENVIRONMENTAL IMPACTS of a facade panel (embodied energy, waste residue, CO2 emissions, etc.), affect its initial costs?

47 responses

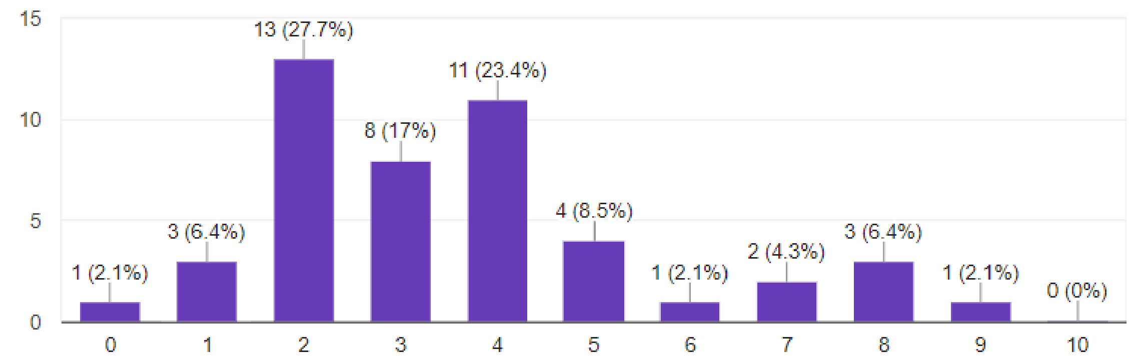


Figure E.9 Adjusted participant responses for determining the interaction between c_5 and c_8.

The inputs for 8 and 9 (4 responses) were outliers and were not considered.

In your professional opinion, to what extent does increasing the EASE OF CONSTRUCTION factor in facades, affect its initial costs?

47 responses

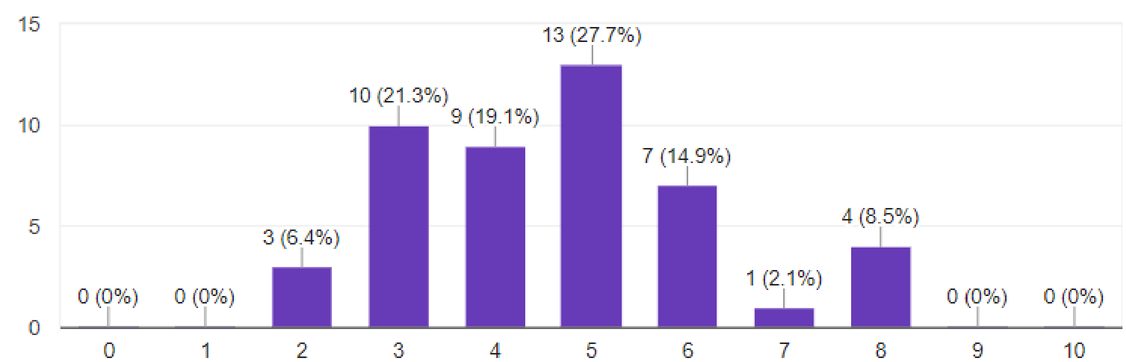


Figure E.10 Adjusted participant responses for determining the interaction between c_6 and c_8.

There were no outliers and all responses were accepted.

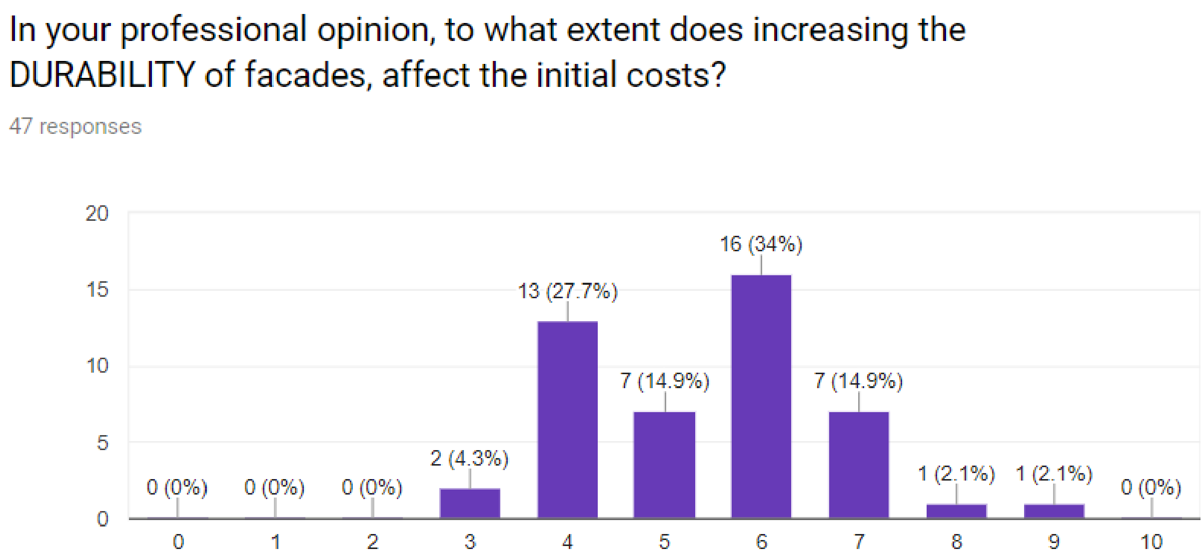


Figure E.11 Adjusted participant responses for determining the interaction between c_7 and c_8.

There were no outliers and all responses were accepted. Final results of the questionnaire are demonstrated in Table 6.1

APPENDIX F MATLAB Codes for Extracting Fuzzy Measures

Preferences (if any)

```
function [Pref, Input] = Preferences ()
  Input = importdata('Pref.csv');
  [W,L] = eig(Input);
  Pref = W(:,1)/sum(W(:,1));
end
```

Weighted correlation function by: Francesco Pozzi

```
function R = weightedcorrs(Y, w)

ctrl = isvector(w) & isreal(w) & ~any(isnan(w)) & ~any(isinf(w)) & all(w > 0);
if ctrl
 w = w(:) / sum(w);
else
 error('Check w: it needs be a vector of real positive numbers with no infinite or nan values!')
end
ctrl = isreal(Y) & ~any(isnan(Y)) & ~any(isinf(Y)) & (size(size(Y), 2) == 2);
if ~ctrl
 error('Check Y: it needs be a 2D matrix of real numbers with no infinite or nan values!')
end
ctrl = length(w) == size(Y, 1);
if ~ctrl
 error('size(Y, 1) has to be equal to length(w)!')
end

[T, N] = size(Y);                          % T: number of observations; N: number of variables
temp = Y - repmat(w' * Y, T, 1);           % Remove mean (which is, also, weighted)
temp = temp' * (temp .* repmat(w, 1, N));  % Covariance Matrix (which is weighted)
temp = 0.5 * (temp + temp');               % Must be exactly symmetric
R = diag(temp);                            % Variances
R = temp ./ sqrt(R * R');                  % Matrix of Weighted Correlation Coefficients
```

All mu

```
function [J, Es, VE, CVE ] = Comp_J(C, Ind, show)

  Corr = C( Ind, Ind );
  Es   = sort( eig( Corr ),1, 'descend' );
  VE   = Es/ sum( ( Es ) );
  CVE  = cumsum(VE);
  J    = sum( Es( Es < 1) ) + length( Es( Es >= 1) );
  if( show )
     Corr, Es, VE, CVE, J;
  end
end

function Ind = i2Ind( i, L_C, Temp_C)
  % Temp_C = 1:L_C; % pass this please for performance
  Ind   = Temp_C( de2bi( i-1, L_C ) == 1 );
end

function i = Ind2i( Ind, L_C)
  Temp_C = zeros(1,L_C);
  Temp_C(Ind) = true;
```

```
   i = bi2de( Temp_C)+1;
end

% [ mu_i, J_i, Es_i, VE_i, CVE_i ]
function mu = All_mu(C, show)
   L_C = length(C);
   Temp_C = 1:L_C;
   mu_c = Comp_J(C, 1:L_C,show);
   mu = {};
   for i = 1: 2^ L_C
      Ind   = i2Ind( i, L_C, Temp_C );
      assert( i == Ind2i(Ind, L_C), 'The index conversion went wrong. Please check' );
      [J, Eig, VE, CVE ] = Comp_J(C, Ind, 0); % do not display! this is too much.

      % we have to add 1!!!!!
      mu{i} = {J/mu_c, J, Eig, VE, CVE};
   end
end
```

nchoosek

```
function Mat = nchoosek_Mat( N )
% nchoosek matrix to make calculation faster.
   Mat = ones(N,N+1)*NaN;
   for k = 0:N-1
      Mat(N,k+1)   = nchoosek(N,k);
      Mat(N-1,k+1) = nchoosek(N-1,k);
   end
   Mat(N,N+1) = nchoosek(N,N);
End
```

Shapely importance

```
function S_imp = Shapley_importance_simple( N, mu, nchoosek_Mat )
%Shapley_importance
   h = waitbar(0,'Shapley Importance: Please wait...');
   S_imp = zeros(1,N);
   for i = 1:N
      S_imp(i) = Shapley_importance_fast( i, mu, nchoosek_Mat );
      waitbar( i/N);
   end
   close(h);
   assert( abs(sum( S_imp ) - 1) < .0001, 'The total of Shapley Importance should be 1.' );
end
```

Shapely interactions

```
function S_int = Shapley_interaction_simple( N, mu, nchoosek_Mat )
   %Shapley_interaction
   S_int = zeros(N,N);
   h = waitbar(0,'Shapley Interaction: Please wait...');
   for i = 1:N
      for j = i+1:N
         S_int(i,j) = Shapley_interaction_fast( i, j, mu, nchoosek_Mat );
         S_int(j,i) = S_int(i,j);
      end
      waitbar( i/N);
   end
   close(h)
   % assert( abs(sum( sum( S_int ) ) - 1 )  < .0001, 'The total of Shapley interaction should be 1.' );
   sum( S_int);
end
```

Choquet function

```
function C = Choquet_simple( Scores, mu, show )
  % Choquet
  [M,N] = size(Scores);
  C = zeros(1,M);
  for i = 1:M
    c_i = Scores(i,:);
    C(i) = Choquet( c_i, mu, show );
  end
end
```

Final run

```
% N = 15; % criteria
% M = 16; % alternative
Scores = importdata('Data jan 27.csv')';
show = 0;
% ======================
[M,N] = size(Scores);

% C = corrcoef(A);
S_imp_pref = Preferences();
y = ones(M,1);
Corr = weightedcorrs(Scores, y);

% all Mu. pass 1 to see the main eigenvalues.
mu = All_mu(Corr, show );
sprintf('done with mu')

% nchoosek matrix
Mat = nchoosek_Mat( N );
sprintf('done with nchoosek')

%Shapley_importance
S_imp = Shapley_importance_simple( N, mu, Mat );
sprintf('done with Shapley Importance')

%Shapley_interaction
S_int = Shapley_interaction_simple( N, mu, Mat );
A_Scaled = Scores;
Choq = Choquet_simple( A_Scaled, mu, show );
```