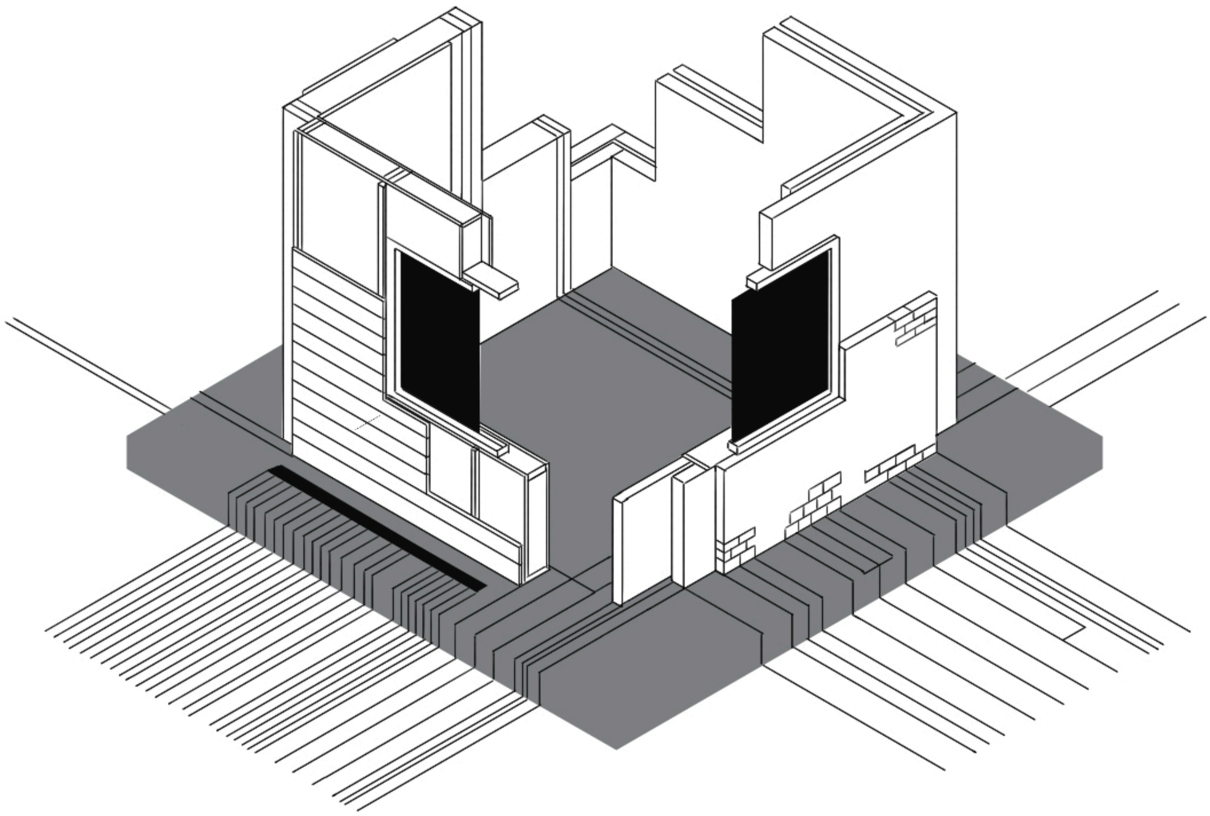
Dynamic Façade Design for Sustainability: A Computational Approach to Reducing Embodied and Operational Carbon in Façade Elements



Lars Vedder

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Abstract

This research examines how dynamic façade variables influence the embodied and operational carbon of mid- to high-rise residences during the early design phase, addressing growing environmental concerns from urban densification. By analyzing façade design and parametric architectural strategies, the study aims to identify sustainable solutions that minimize environmental impact while complying with regulatory standards.

A combination of literature review and computational simulations was used to evaluate different façade typologies. The literature review identified common façade systems and their carbon footprints, while a case study applied this knowledge to a realistic scenario. Using parametric modeling tools such as Grasshopper, energy simulations were conducted to assess carbon impacts. An optimization process then identified the most sustainable façade configurations, highlighting key trends and design considerations.

The findings reveal that material selection, façade design, and energy efficiency significantly impact the total carbon footprint of buildings. Among the façade types analyzed, aluminum unitized façades have the highest embodied carbon emissions due to the carbon-intensive nature of aluminum production. In contrast, prefabricated timber façades have the lowest embodied emissions, benefiting from a lower carbon footprint and carbon sequestration potential. Concrete façades fall in between, with their high weight contributing to greater embodied carbon despite lower emissions per kilogram. The relationship between window-to-wall ratio (WWR) and embodied carbon varies by material; a higher WWR increases emissions for aluminum and timber façades, whereas for concrete façades, it reduces embodied carbon as glass replaces carbon-intensive concrete elements.

Operational carbon emissions are highly dependent on façade orientation. North-facing façades require the most heating due to limited solar exposure, while south-facing façades benefit from passive solar heating but require more cooling. The most effective way to reduce operational carbon is by improving glazing insulation (lowering U-values), especially in colder orientations. Increasing the Rc-value of insulation has only a minor effect when WWR is high, as window heat transfer dominates. With an assumed 2% annual improvement in energy efficiency and grid decarbonization over a 75-year lifespan, operational carbon emissions are expected to decrease by 50%, making embodied carbon an increasingly dominant factor.

Considering both embodied and operational emissions, timber façades emerge as the most sustainable option, particularly when paired with optimized glazing and insulation values. Aluminum façades have the highest total carbon footprint, with embodied emissions accounting for nearly half of the total impact even in efficient configurations. Concrete façades present a unique trend, where reducing WWR can sometimes increase total emissions due to the high embodied carbon of concrete relative to glazing. These results emphasize the need for an integrated approach to façade design, balancing material selection, insulation levels, glazing performance, and orientation to minimize total carbon impact.

This study acknowledges several limitations, including reliance on a single simulation program, uncertainties in future energy grid decarbonization, and a limited range of material and façade options. Future research should explore additional materials, occupant behavior models, and renewable energy integration to enhance sustainability assessments. Further validation using multiple simulation methods, diverse climate models, and broader material databases would improve reliability and deepen understanding of façade performance across different environmental contexts.

Acknowledgement

As my two-year master's program at TU Delft comes to an end I reflect on the academic experiences I've learned. I am grateful for the knowledge and insights I obtained during this time, which shaped my personal development and will benefit me in my professional journey after the master's.

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Contents

1.

Introduction

1.1 Background

Population growth among people is a significant driving force behind environmental concerns such as global warming. Currently, 55% of the global population lives in cities, with that percentage expected to rise to 68% by 2050 (United Nations, May 16, 2018). This urban movement, along with a population prediction of 9.7 billion by 2050, increases demand for housing, deepening the concentration of structures within cities (United Nations, June 21, 2017).

This urban densification is predicted to have a significant impact on climate change, not only because of the built environment's energy demand over time, but also because the materials embodied and carbon. As of now, the building industry uses 35% of the world's resources, 40% of its energy, 12% of its drinking water, and almost 40% of its carbon emissions (Saint-Gobain, 22 August 2017).

The European Union is responsible for encouraging and putting in place mitigation measures to combat climate change. This effort includes developing energy reduction goals, as evidenced by the creation of the Climate Agreement (Arcadis, 2019). Some examples for the built environment are; Energieakkoord en de Europese richtlijn Energieprestatie van Gebouwen. The main objective of these regulations is to cut greenhouse gas emissions by 85-90% by 2050, thereby keeping the temperature rise below 2 degrees Celsius (European Parliament and Council of the European Union, 2010).

Dutch regulations require all new buildings to be Nearly Zero-Energy by 2020 (Rijksdienst van Ondernemend Nederland. (n.d.)). This means that since January 1, 2021, all building permit applications must meet the requirements for almost zero-energy buildings (Rijksdienst van Ondernemend Nederland. (n.d.)).

These regulations primarily account for energy use during the use of the buildings. However, as buildings become more energy efficient, embodied energy, which includes manufacture, transportation, construction, maintenance, and demolition/reuse, becomes increasingly important (Cabeza et al., 2014; Huang et al., 2018; Lolli et al., 2019).

These regulatory improvements have big effects on building industry. The Netherlands Enterprise Agency (Rijksdienst van Ondernemend Nederland) recommends evaluating energy performance during the early stages of design. This could also be applied to the embodied carbon.

Compared to operational emissions, and despite their growing importance, legislation tackling embodied GHG emissions is uncommon (J. Steinmann et al. 2022). It is now anticipated that embodied GHG emissions in construction around the world must be cut back by at least 40% by 2030 in order to reach a net-zero carbon emission balance by 2050, as required by the Paris Agreement on Climate Change (UNEP, 2021).

Despite progress in operational energy efficiency, embodied carbon emissions are overlooked often in research and policy. This gap makes it difficult to reach climate targets like those set by the Paris Agreement. As worldwide efforts to cut emissions rise, managing embodied carbon during a building's lifecycle becomes more and more important. This study hopes to fill this gap through using a computational approach to identify trends and improve embodied carbon reductions early in the design process.

1.2 Problem statement

While the global trend toward urbanization and vertical is increasing. the sustainability of mid to high-rise buildings is still a concern. Existing research shows an increasing worry about the environmental impact of tall structures, especially in terms of energy usage and carbon emissions. Studies by (Godoy-Shimizu et al., 2018). highlight the increased needs for resources and energy usage that are needed for higher structures. Recent research undertaken by the Energy Institute of the University College London supports this, indicating a significant increase in electricity demand, fossil fuel consumption, and CO2 emissions in high-rise structures over 20 floors (Godoy-Shimizu et al., 2018).

Although much attention has been given to operational energy efficiency, the embodied carbon in mid to high-rise buildings is often overlooked. Embodied carbon, which includes emissions from material production, transportation, construction, and lifecycle, is becoming more important as operational energy demand decreases. However, reducing one often increases the other: strategies to reduce embodied carbon, such as using lightweight materials, can increase operational energy requirements due to reduced insulation, whereas reducing operational carbon through advanced materials can increase embodied emissions from production. This trade-off challenges sustainable design, but little research has been conducted to investigate how early design decisions, especially those involving façade typologies, influence this balance. Understanding these relationships is necessary to finding effective strategies for reducing both embodied and operational carbon in mid to high-rise structures.

Mid- to high-rise structures face unique environmental challenges, such as variations in wind, air temperature, and daylight throughout their vertical span. These factors necessitate specific façade designs for energy efficiency and occupant comfort.

This study tries to address this gap by looking into the impact of integrated and dynamic façade designs on embodied carbon and energy in mid- to high-rise buildings. Using a computational approach, it aims to identify trends and optimize sustainable design strategies that balance embodied and operational carbon. By bridging this gap, the study helps to reduce the environmental impact of mid to high-rise buildings while remaining in line with global climate targets.

The difference between embodied carbon (Left) and operational carbon (right). ***Figure 1.1***

1.3 Research objective

The aim of this study is to investigate the impact of different façade typologies on the embodied carbon and energy performance of mid to high-rise structures, with a particular focus on the early design phase. It specifically addresses the trade-off between reducing embodied carbon and meeting operational carbon demands.

The study uses computational tools to determine how parametric and dynamic tactics influence this relationship in facade design. It examines common façade typologies in mid to high-rise buildings, identifying key parameters such as material selection, façade performance, and lifecycle impacts. The goal is to find trends and propose techniques or reducing both embodied and operational carbon.

By delivering practical and data-driven insights, the study hopes to help designers, contractors, and other stakeholders make educated decisions early in the building design process. These decisions can encourage the development of structures that are both energy-efficient and environmentally responsible, reducing the negative consequences of urban densification and helping to climate change mitigation.

1.4 Research questions

The aim of this research is to answer the following research question:

"How do dynamic façade variables influence the embodied and operational carbon of mid to high-rise residences during the early design phase, and what are the optimal combinations of these variables that minimize environmental impact while meeting regulatory standards?"

A number of sub-questions will help the project meet its goal of answering this main research question:

"What defines a mid to high-rise building, and what are the most common façade typologies used for such structures?"

"How do different façade materials impact the embodied energy and carbon footprint of mid- to high-rise buildings, considering production, transportation, and lifecycle stages?"

"What are the regulatory standards for façade design regarding embodied energy and carbon, and how do they compare to other building performance standards?"

"How is the integrated dynamic façade model developed, and how does its performance compare to traditional design software?"

v

1.5 Methodology

During the background research, several issues were identified: population growth, urban densification, and global warming. This led to the Paris Agreement and the Energy Accord, since then regulations have been implemented to achieve zero energy design during the building's operational phase. The next step in this process involves reducing the embodied carbon of buildings and their materials. This study addresses these issues through a literature review, followed by a simulation on a simple case study and finally a optimisation.

This study starts with a quantitative literature review to define the dimensions that characterize mid to high-rise buildings, considering both international standards and Dutch regulations. This phase establishes the definitions for mid to high-rise buildings by analysing existing literature and regulatory documents. It also involves identifying common façade typologies for these buildings using sources such as the SBR detail database and other government repositories.

After this, the review focuses on analysing the materials used in each identified façade typology, finding their embodied energy and carbon footprint during the production, transportation, and installation stages, using quantitative literature sources and databases like Edupack.

Furthermore, the study investigates existing regulatory criteria for façade design, emphasizing embodied energy and carbon, and compares these criteria to other building performance standards to ensure compliance and relevance.

Following the literature review, a case study is done to apply insights to a real-world scenario. A computational workflow is then developed to model the building's façade typologies, utilizing frameworks that integrate dynamic modelling tools to ensure accurate simulation of embodied carbon and operational carbon. Grasshopper along with some plugins, a parametric design tool, is used to simulate the energy and carbon performance of different façade typologies.

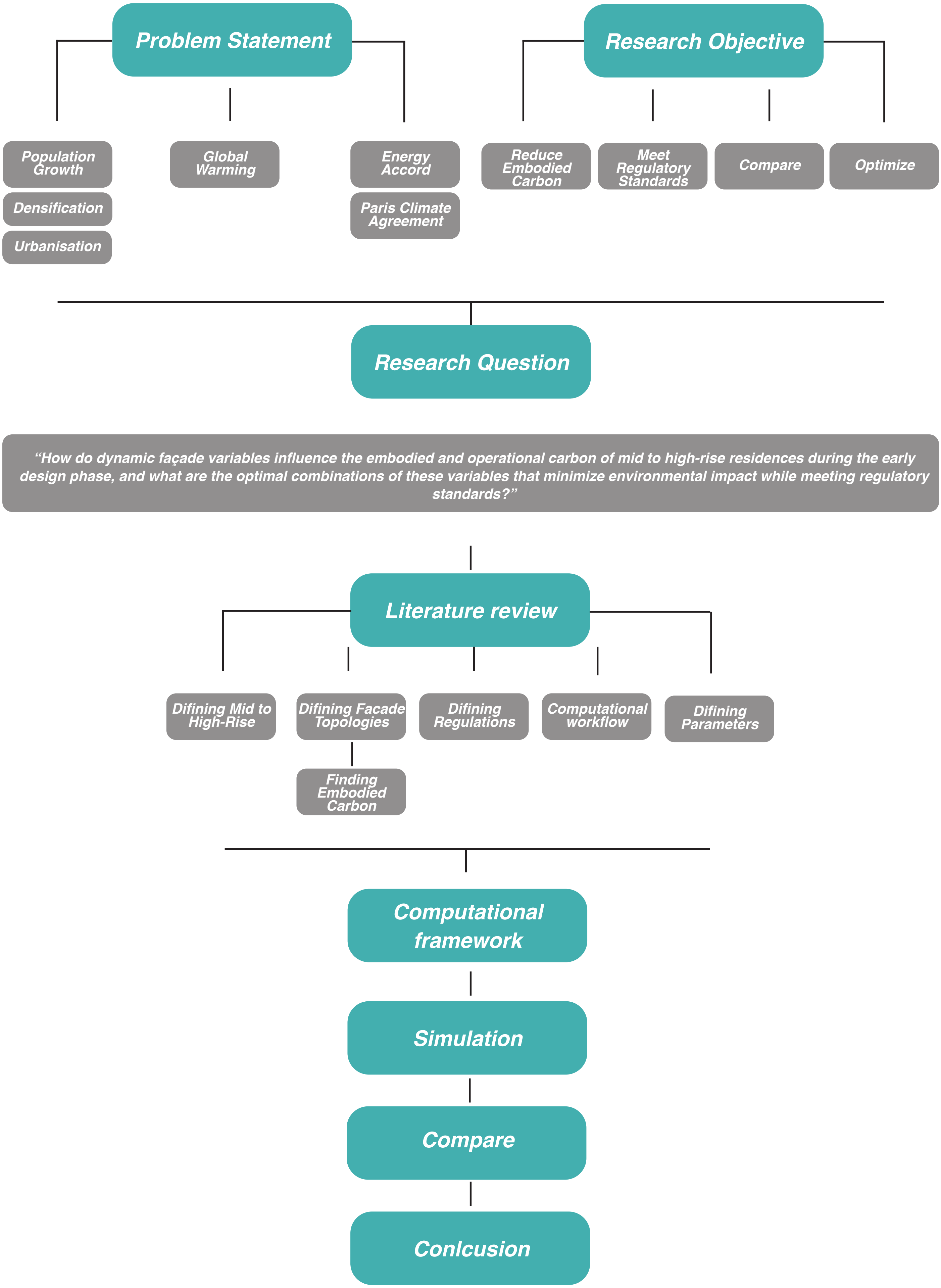
The final phase involves a n optimization study to identify the most sustainable façade designs. Optimization algorithms are implemented within the Grasshopper environment to explore various design alternatives, focusing on minimizing embodied energy and carbon while meeting regulatory standards. The performance of these optimized designs is analysed to determine the optimal combinations of façade materials and designs. The study evaluates these combinations against performance benchmarks and regulatory requirements, providing recommendations for architects, designers, and other stakeholders based on the optimized results. These recommendations aim to help the previously mentioned stake holders in the early design phases.

Summarizing, methodology combines literature review, regulatory analysis, case study, and computational simulation to comprehensively address the research question. By focusing on the embodied energy and carbon impacts of different façade typologies in mid to high-rise buildings, the study aims to contribute insights for sustainable architectural design. The findings will guide the development of energy-efficient, environmentally responsible buildings, aligning with global and national climate goals.

1.6 Relevance

This research aims to make a difference at a societal level but also at an academic level. Society wise it addresses the need to combat climate change by reducing the environmental impact of buildings, particularly in the context of urban densification, which significantly contributes to global carbon emissions. The goal of the thesis is an attempt to find sustainable design solutions that can reduce the carbon footprint of mid to high-rise buildings, in this way contributing to global climate goals. As urban populations rise, the need for sustainable housing alternatives becomes more important. This study encourages more sustainable urban development by giving practical data into how different façade designs could reduce embodied energy and carbon. Additionally, the study provides architects, designers, and contractors with concrete data and recommendations, helping them to make informed choices early in the design process.

Scientifically, the study attempts to fill the gap in the existing literature by concentrating on the embodied carbon implications and trade-offs of façade typologies in mid- to high-rise buildings. It tries to improve the existing knowledge in this field and proposes new strategies, such as the use of computational tools like Grasshopper for dynamic modelling which are fairly new. The use of optimization algorithms to discover sustainable façade designs tries to offer a new standard for minimizing environmental impact. This project aims to promote sustainable architecture and building science by providing significant insights and approaches for future studies and practical applications in the field.


Problem Statement
Population Growth
Densification
Urbanisation
Global Warming
Energy Accord
Paris Climate Agreement
Research Objective
Reduce Embodied Carbon
Meet Regulatory Standards
Compare
Optimize
Research Question
“How do dynamic façade variables influence the embodied and operational carbon of mid to high-rise residences during the early design phase, and what are the optimal combinations of these variables that minimize environmental impact while meeting regulatory standards?”
Literature review
Difining Mid to High-Rise
Difining Facade Topologies
Finding Embodied Carbon
Difining Regulations
Computational workflow
Difining Parameters
Computational framework
Simulation
Compare
Conlcusion

1.7 Boundary conditions

Geographic Scope
This study focuses on mid- to high-rise buildings in urban contexts, primarily in the Netherlands and the European Union. While worldwide insights can be obtained, the study focuses on local weather conditions and building techniques.

Building Type and Height
Mid- to high-rise buildings are defined as structures taller than 20 meters, with a focus on residential and mixed-use developments. Commercial and industrial buildings are excluded due to their specific energy requirements and façade designs.

Façade Typologies
The study assesses typical façade methods suitable for mid to high-rise structures, including element façades, prefab concrete, and wood frame construction (HSB). Experimental or niche designs are excluded.

Material Selection
The research simplifies material analysis by focusing on the important materials for example glass, steel, concrete, and wood. Smaller components and experimental materials weren't included to keep the focus on the most important elements.

Operational Carbon
The study includes energy demands for the façade, such as heating, cooling, and daylighting. Other operational considerations, such as water or waste management, are ignored unless they are directly related to façade performance.

Embodied Carbon
The study evaluates the embodied carbon from material manufacturing and transportation. To improve simplicity, other stages such as installation, demolition, and reuse have been simplified.

Regulatory Standards
The findings are consistent with Dutch and EU building rules and energy performance criteria. Non-EU regulations are cited solely for comparison.

Tools and Methods.
Simulations are carried out using Grasshopper and its plugins (for example, Ladybug/Honeybee), which are validated using other software. Traditional design approaches are provided solely for comparative purposes.

Timeframe
The study uses current design methods (up to 2025) and assumes a building lifespan of 75 years.

2.

Literature Review

2.1 Defining mid to high-rise and it's facades

Chapter 2.1 investigates the characteristics of a mid- to high-rise building and the most common façade typologies used. The goal is to provide an answer to the question: "What is the definition of mid to high-rise, and what are the most prevalent facade typologies that apply to mid to high-rise buildings?" By doing this, a simple foundation is laid for understanding how these buildings are defined and what their exteriors often look like.

2.1.1 Short History of Mid to High-Rise

Even before the middle ages there were ideas of constructing upward rather than outward. In Roman cities there were already some multi-story apartment complexes, then called "Insulae". They were common in Roman cities; some of them were as many as ten floors (Aldrete, 2004). In the middle ages rich families built defensive towers throughout medieval Europe, as the 97.2-meter Asinelli Tower in Bologna, Italy (Behrens-Abouseif, 1992).

Thanks to developments in steel frame construction and Elisha Otis's discovery of the safety elevator in 1857, the modern era of high-rises started in the late 1800s. These developments made high-rise buildings more feasible and practical and this way realistic. The Home Insurance Building in Chicago, completed in 1885, is often cited as the first skyscraper due to its ten-story height and steel frame construction (Petruzzello, 2022).

After these developments, New York City and Chicago were the two leading cities in the building of skyscrapers. Steel frames were used in the construction of Chicago's skyscrapers, such as the Rand McNally Building and the Wainwright Building (Peterson, 1950). In that time, skyscrapers in New York City, like the American Surety Building and the Flatiron Building, fought to be the tallest structures in the world (Peterson, 1986).

The Great Depression and World War II slowed skyscraper construction. However, post-war advancements led to iconic structures like the Empire State Building in New York, which held the title of the world's tallest building for 40 years after its completion in 1931 (Hoffmann, 1969). The Soviet Union's "Seven Sisters" in Moscow and other Eastern Bloc skyscrapers reflected a different architectural style known as Socialist Classicism (Ambrose, Harris & Stone, 2008).

Fazlur Rahman Khan's tubular structural systems transformed skyscraper design in the 1960s, enabling for larger and more diversified building designs (Peterson, 1950). The completion of Chicago's John Hancock Center and Willis Tower represented important developments (Hoffmann, 1969). The global trend has changed toward building supertall skyscrapers, with cities in Asia, the Middle East, and other countries joining the race. The Petronas Towers in Kuala Lumpur and Dubai's Burj Khalifa are prime examples of this trend (Emporis, 2015).

Figure 2.1

The Empire state building

2.1.2 Criticism of Mid to High-Rise

High-rise is expensive to build and maintain. Materials, construction, and the operational phase maintenance of buildings is more expensive than the maintenance of low-rise buildings (Ali & Al-Khodmany, 2012). Also, high-rise is often found in city centres where land values are high, making them economically viable primarily for office, commercial, and luxury residential usage, often eliminating cheap housing (Ali & Al-Khodmany, 2012). This makes High-rise buildings often appeal to high-income individuals and companies, which could worsen social hierarchies and gentrification by displacing lower-income residents and small businesses (Emporis, 2015).

Also, critics argue that these the tall buildings can disrupt the traditional urban fabric by overshadowing historical buildings and changing the character of neighbourhoods, resulting in the loss of human-scale environments (Peterson, 1950). Additionally, high-rise living may lead to isolated neighbourhoods with limited interaction at street level, producing a sense of split from the urban population (Ambrose, Harris & Stone, 2008). Visually, the worldwide style of high-rise buildings, defined by glass and steel façades, often results in homogeneity, reducing architectural variation and cultural identity (Petruzzello, 2022).

Furthermore, high-rise construction requires large amounts of steel, concrete, and glass, resulting in enormous embodied energy. Also, due to their size, huge buildings consume quite a lot of energy for heating, cooling, and lighting during the operational phase. The use of more mechanical equipment, such as elevators and HVAC systems, results in a bigger carbon footprint. Despite developments in energy-efficient technology, the overall environmental impact remains significant (Petruzzello, 2022).

2.1.3 Defenition

The definition of high-rise is a bit subjective and varies based on different criteria. The Council on Tall Buildings and Urban Habitat (CTBUH, 2010) defines a tall building using a few aspects. One aspect requires that a structure have at least 14 floors or be more than 50 meters high. However, according to the CTBUH, this definition can vary depending on the context of the building ; for example, a 14-story structure may not be considered high-rise in the Netherlands but not in cities such as Chicago or New York. CTBUH also highlights proportion as an important metric because buildings with a big footprint may not appear taller despite their height. Another norm is the use of integrated technologies for high-rise such as advanced vertical transportation systems and wind bracing. These also play a role in defining a tall building (CTBUH, 2010).

According to Emporis, the term “high-rise” is generally applied to buildings with 12 to 39 floors or those standing 35 to 100 meters tall (Emporis, 2015). A skyscraper, even bigger than high-rise, refers to buildings with over 40 floors and standing taller than 150 meters (Skyscraper, n.d.). Buildings exceeding 150 meters are classified as supertall, while those reaching 300 meters and above are megatall (CTBUH, 2019).

In the Netherlands, high-rise buildings are defined as those above 70 meters (Bouwbesluit, 2012). Additionally, low-rise buildings are typically under five stories, not requiring elevator use, while mid-rise buildings range between five and ten stories (Davies & Jokiniemi, 2008; Designing Buildings Wiki, 2019).

Summarizing, because of the varying definitions of ‘mid to high-rise,’ this study will use the following criteria: structures between 20 and 100 meters in height, or 5 to 40 stories, will be classed as mid to high-rise. Low-rise buildings are those that are under 20 meters or have fewer than 5 floors, whereas skyscrapers are those that are more than 100 meters tall.

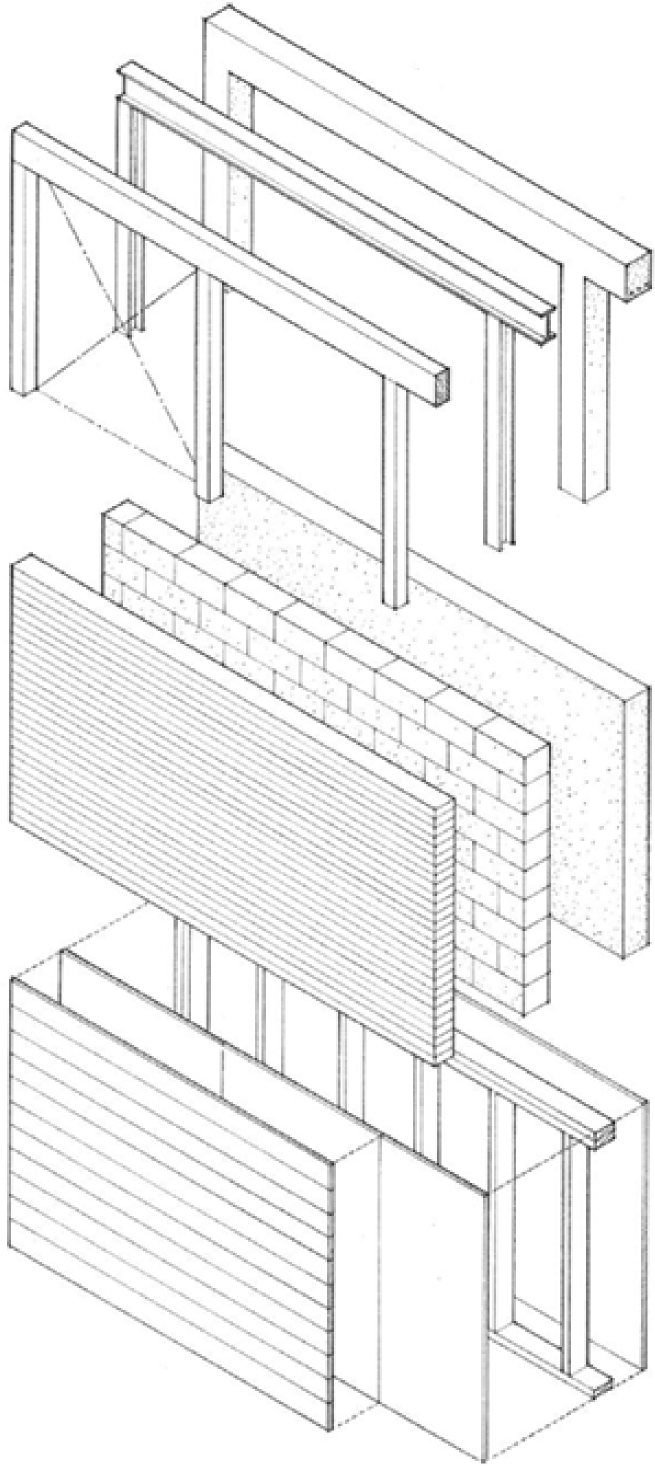
2.1.4 Facade Typlogies

Façade typologies play a significant role in building construction, influencing a structure's aesthetics, structural robustness, and functionality. In the past few decades, facade technologies have also changed quickly. This is because of stricter energy requirements, higher comfort levels expected by users, and more extreme weather events that are hard to predict because of climate change. Because of this change, different types of facades were developed, which will be discussed in this chapter.

In "Building Construction Illustrated" by Francis D.K. Ching, Three primary wall systems are identified by Ching: Structural Frames, Concrete and Masonry Bearing Walls, and Metal and Wood Stud Walls (Ching, 2014).

He starts with structural frames which can be made from concrete, steel or wood. Concrete frames are typically stiff and classified as fireproof, fire-resistant construction. Fireproof steel frames may use moment connections and require fireproofing to be classified as fire-resistant construction. Timber frames need to be braced or have shear planes for lateral stability. They also could be qualified as heavy timber construction if they are utilized with non-combustible, fire-resistive external walls and if the members fulfil the minimum size requirements stated in the building code. Steel and concrete frames can span bigger distances and support bigger loads than timber frames. . Structural frames can support and accept a range of non-bearing or curtain wall systems. The detailing of connections is crucial for structural and cosmetic reasons when the frame is left exposed (Ching, 2014).

Concrete and masonry bearing walls are already non-combustible constructions and they rely on their mass to carry loads. While concrete and masonry are robust in compression, they require reinforcement to withstand tensile stress. Wall design and construction rely heavily on the height-to-width ratio, lateral stability features, and precise



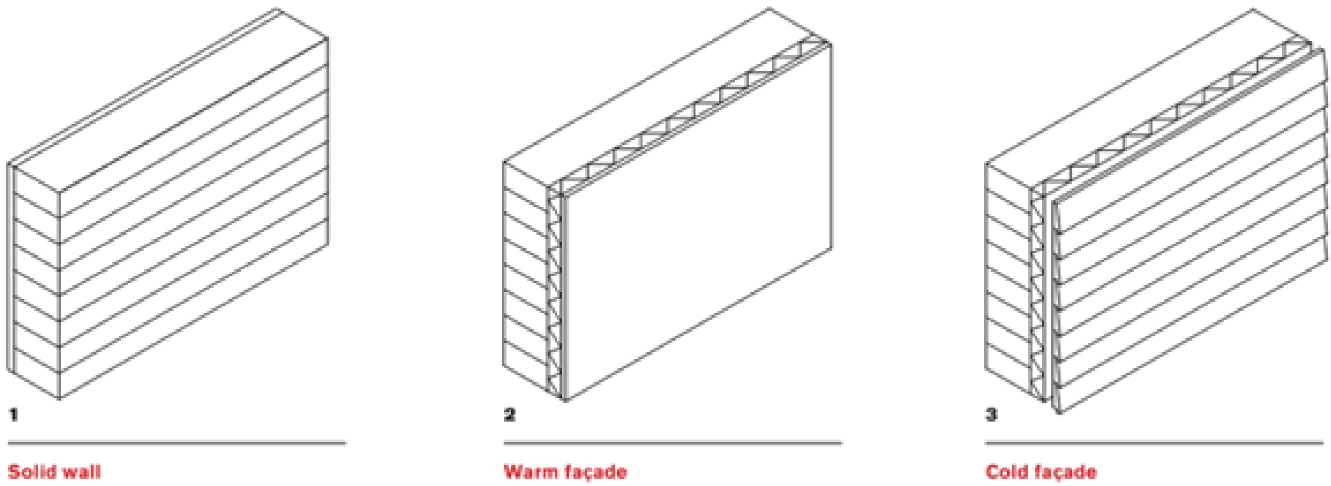
Three primary wall systems by Francis D.K. Ching (2014) ***Figure 2.2***

positioning of expansion joints (Ching, 2014).

Metal or wood studs of cold-formed metal or wood are typically spaced at 400 or 600 on centre; this spacing is related to the width and length of common sheathing materials. Studs primarily carry vertical loads while sheathing or diagonal bracing stiffens the plane of the wall. Cavities within the wall frame can be used to accommodate thermal insulation, vapor retarders, and the distribution of mechanical and electrical services. Additionally, stud framing can accept a variety of interior and exterior wall finishes. The fire-resistance rating of the wall assembly is often determined by the finish materials used. Stud wall frames may be assembled on-site or panelised off-site, offering flexibility in construction methods. This flexibility is further enhanced by the workability of relatively small pieces and the various means of fastening available (Ching, 2014).

In “Façades: Principles of Construction” by Ulrich Knaack, Tillmann Klein, Marcel Bilow, and Thomas Auer (2007), three primary façade types are detailed: solid walls, warm façades, and cold façades. Solid walls, made of materials like stone or brick, are both durable and simple. Warm façades feature a thermal insulation layer put directly to the surface, either outdoors or inside, with the outside insulation being weatherproof. Cold façades have a ventilated space between the outside protective layer and the thermal insulation, this allows moisture to evaporate so that the insulation materials keeps the necessary insulation properties (Knaack et al. 2007).

Summarizing, the evolution of facade typologies has impacted building construction, driven by increasing energy requirements, higher comfort standards, and climate change challenges. Structural frames, whether made of concrete, steel, or timber, offer versatile support for various non-bearing wall systems especially for mid to high-rise. On site built concrete and masonry bearing walls, are less suitable for high-rise structures due to their high mass and the need for reinforcement. Tough they are sometimes used as prefabricated elements. Similarly, the solid walls described in Principles of Construction, are impractical for high-rise applications because of their mass and shortcomings in todays’ energy requirements. In contrast, warm and cold facades provide effective insulation solutions, with cold facades having better moisture management through ventilation.



Three primary wall systems by In “Façades: Principles of Construction” by Ulrich Knaack

Figure 2.3

2.1.5 Mid to High-Rise Facade Typologies

Facade systems evolved during the Neoclassical era, when architects began to differentiate the functions of the wall: bearing, sealing, and light transmission. Technical developments allowed bigger window openings without the requirement for structural connections present in older buildings. Inner columns provided structural support, allowing the building's exterior envelope to function as an independent non-load-bearing structure. This innovation was a big step forward, allowing facades to prioritize design, light, and ventilation over structural needs (Knaack et al. 2007).

Modernism revolutionized architecture by completely liberating the facade from structural functions. Architects were no longer limited by the structural requirements of load-bearing walls, giving them the creative flexibility to design building envelopes that focused on expression and performance. Architectural features separated from the load-bearing structure, becoming vehicles for aesthetic and functional innovation. In post-World War II European tall buildings, facades were built as independent systems to improve both look and environmental performance (Pietrzak & Stefaska, 2019).

The most essential features for facade typologies utilized in mid to high-rise buildings are:

Non-Load Bearing Design

Modern facades are largely non-load bearing, which means they do not contribute to the building's stability. Instead, the principal structure of the building handles all load-bearing tasks. This design philosophy allows the facade to focus on more important functions including thermal insulation, weatherproofing, and light transmission. Non-load-bearing facades also offer greater design flexibility, allowing architects to experiment with new materials and forms.

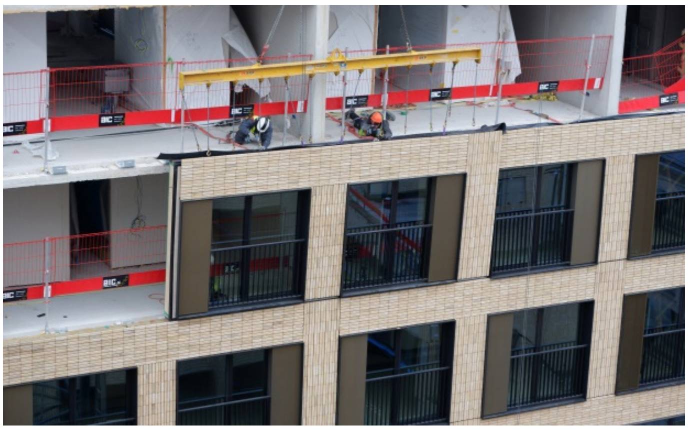
Prefabrication

Advances in prefabrication have completely transformed the construction of mid- to high-rise facades. Prefabricated facade components, such as curtain walls and precast panels, are made in controlled settings, resulting in uniform quality and reduced on-site labour. These methods shorten building schedules and reduce weather-related delays, making them perfect for the fast-paced nature of urban development.

Scalability

Scalability is an essential feature for currently used façade systems. Facades for high-rise structures must efficiently cover large vertical surfaces while retaining performance and cost effectiveness. Scalable solutions are designed to meet the demands of wide areas, such as wind loads and thermal insulation, without sacrificing aesthetic appeal or structural integrity.

Load bearing structure separate from facade. Facade ready to install. ***Figure 2.4***



Prefabricated masonry wall system. ***Figure 2.5***

2.1.6 Examples of non-load bearing façade typologies

Facade systems evolved in response to previously discussed advancements and requirements for mid to high-rise buildings. Starting with post and beam systems, then curtain walls, and finally element facades. These developments prioritized transparency, structural efficiency, and design flexibility, transforming facades into adaptable and self-sufficient architectural parts.

Post-and-Beam Facade

The post-and-beam façade was the first important success in isolating the building's external wall from its load-bearing structure, leading the way for modern buildings. This design combines storey-high vertical pillars and horizontal beams to provide a flexible framework. The voids between these structural parts are utilized for cladding, lighting, and ventilation, resulting in multifunctional facades. In addition to distributing wind loads and structural weight to the ground, post-and-beam façades meet a variety of functional needs. This method further divided the solid wall, increasing facade versatility and adaptability to architectural and environmental requirements (Knaack et al., 2007).

Post and Beam system, Delft University of Technology (Knaack et al., 2007) ***Figure 2.7***

Post Façade

Post façade systems are an early step in the history of building envelopes, using tie rods to sustain weights. These solutions are intended to improve structural transparency by increasing openness, making them ideal for building visually light and translucent structures. The key structural limitation in post systems is the maximum distance between posts, which must be carefully calculated to ensure stability. Storey-high poles are used to distribute loads straight to the ground, establishing a foundation for separating structural and envelope functions (Knaack et al., 2007).

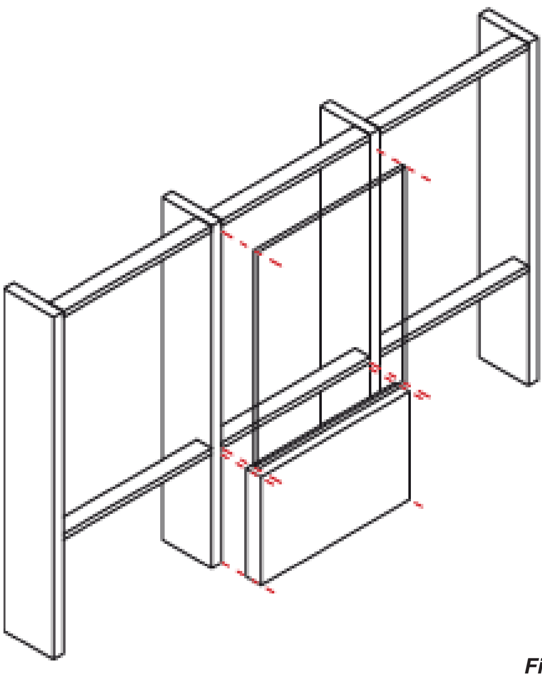


Figure 2.6 *Post and Beam system (Knaack et al., 2007)*

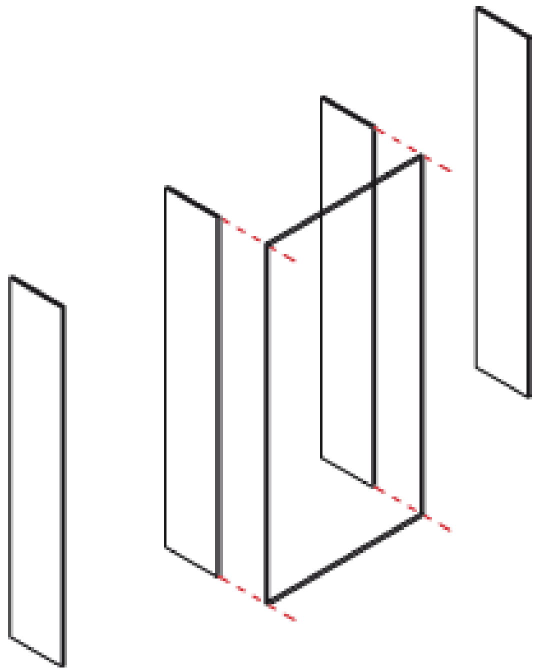
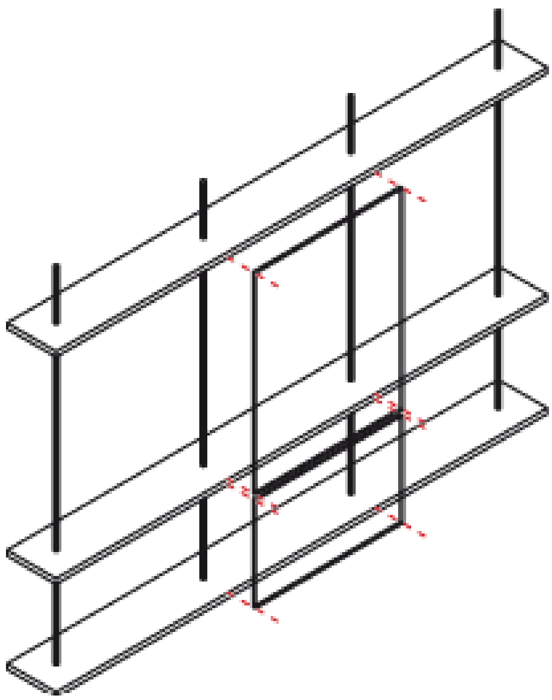


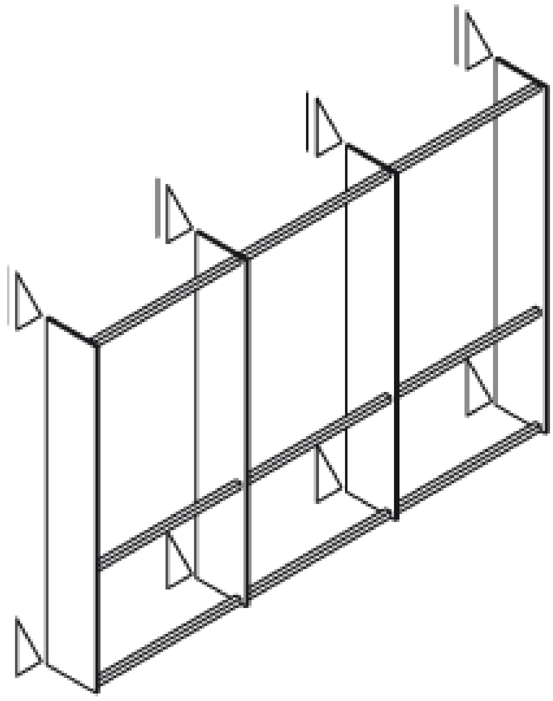
Figure 2.8 *Post system* (Knaack et al., 2007)

Beam Façade.
Beam façade systems originated as an alternative to post systems in which horizontal beams rather than vertical posts bear lateral loads. In this suspended façade design, vertical suspension systems and heavy-duty tie rods near the roof support the façade's weight. This setup reduces total structural mass and lowers the risk of buckling caused by vertical posts. Wind loads effectively travel to the ground through the beams, indicating a more efficient structural technique while keeping the openness required in modern building design (Knaack et al., 2007).



Beam system (Knaack et al., 2007) ***Figure 2.9***

Standing Post and Beam Façade
Standing post-and-beam façades are often made up of storey-high modules, which provide a modular method to facade building. However, these systems must handle the significant issue of post-buckling, which could threaten structural integrity. This system improved the post-and-beam idea, resulting in a more solid yet adaptable solution for high-rise applications and contributing to the continued evolution of façade technology (Knaack et al., 2007).



Standing post and beam system (Knaack et al., 2007) ***Figure 2.10***

Curtain Wall Façade.
The curtain wall façade is the result of these evolutionary steps, introducing a system that is largely independent of the building's primary construction. Curtain walls are suspended from the roof using tie rods and are intended to provide maximum design flexibility. This system provides for adjustable partitioning and the use of a variety of cladding or glazing alternatives, allowing architects to meet both aesthetic and practical objectives. Vertical and lateral stresses are transferred floor by floor, and specialized parts may accommodate larger spans, avoiding the buckling issues associated with previous systems. Curtain walls have transformed façade design by offering an economical, non-load-bearing envelope that improves architectural expression and building performance (Knaack et al., 2007).

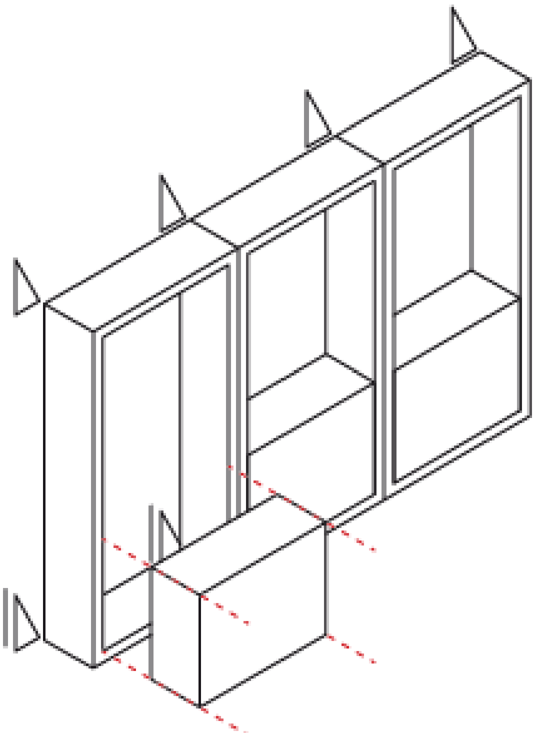


Figure 2.11

Curtain wall system (Knaack et al., 2007)

Curtain wall, federal center Chicago (Knaack et al., 2007)

Figure 2.12

System or Element Façade

The curtain walls that are often used can be classified into stick or unit systems. These elements can be prefabricated and assembled on-site, or full walls can be built off-site and installed as a whole. Prefabrication can have several advantages, including consistent quality, speedy assembly, and inexpensive on-site labor, but it's typically only used in special aplicattions such as high-rise buildings due to logistical demands, such as crane usage. System façades differ from post-and-beam systems by allowing complete prefabrication and minimal on-site labour (Knaack et al., 2007).

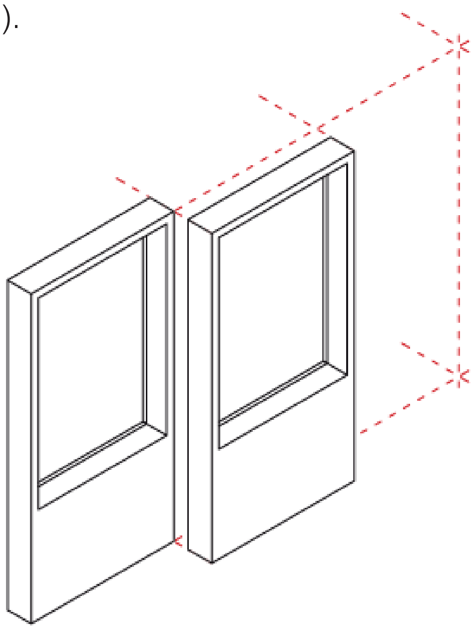


Figure 2.13

Element Facade (Knaack et al., 2007)

Element Facade, Westhaven Haus Frankfurt (Knaack et al., 2007)

Figure 2.14

advanced façade systems.
Beyond these common methods, there are more complicated façade styles that improve comfort and energy efficiency. These advanced systems include the following:

- **Double Façades:** These incorporate an additional glazing layer for ventilation or soundproofing, addressing issues such as noise, wind loads, and building height. Ventilation spans numerous storeys and is tailored to unique building requirements.
- **Second-Skin Façades:** These are simple to build and have an external glass layer with simple ventilation at the top and bottom. However, they are prone to overheating and provide limited temperature control.
- **Box-Window Façades:** These have storey-high sections with individual ventilation control. However, exhaust air might damage adjacent floors, necessitating staggered ventilation.
- **Corridor Façades:** These regulate ventilation and noise by using staggered air inlets, outlets, and vertical baffles, but are constrained by horizontal connections, which reduce baffle practicality.
- **Shaft-Box Façades:** By connecting box windows to multi-floor shafts, these systems improve thermal efficiency through stack effects, although they need sophisticated engineering.

While these advanced solutions improve building performance and sustainability, they require complex engineering and precise modeling.(Knaack et al. 2007). Therefore, they are beyond the scope of this thesis.

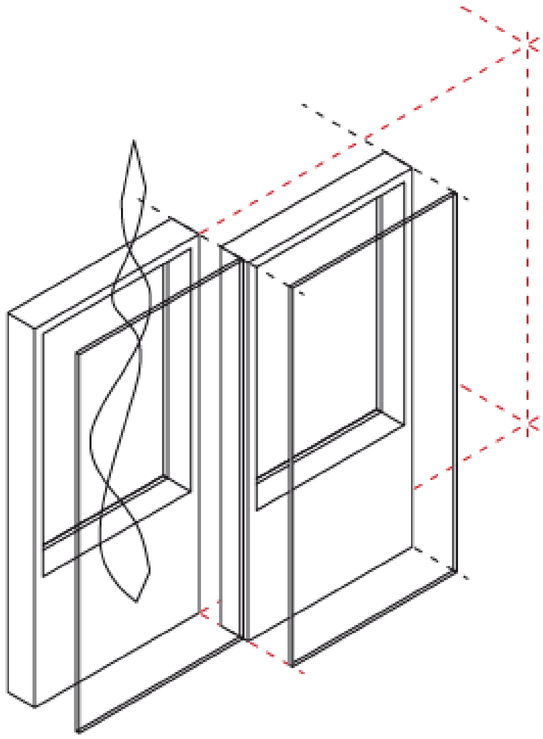


Figure 2.15
Double Facade (Knaack et al., 2007)

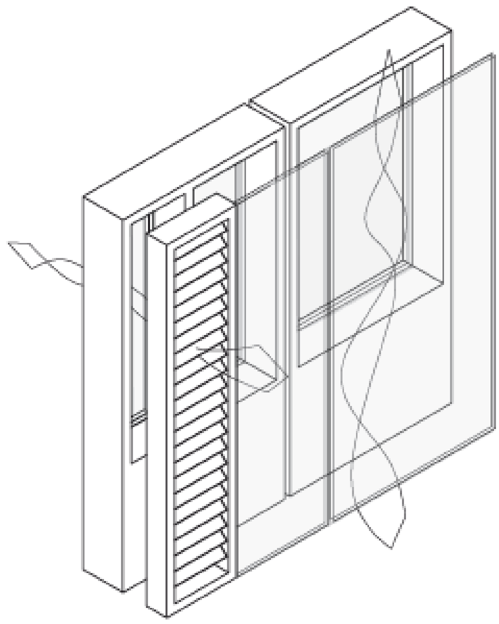


Figure 2.16
Alternating Facade (Knaack et al., 2007)

2.1.7 Façade typologies details analysis

To compare different façade classifications, a reference research was done using content from the SBR publishing website and details from architecture firms.

ISSO-SBR provides drawings and specifications for lots of façade typologies that meet Dutch building codes and performance standards. These tools are useful for architects, engineers, and contractors working in building design and construction. ISSO classifies façade typologies according to their building methods, materials, and utility.

In addition to these reference sources, extra information was obtained from architects, resulting in the creation of drawing details. These drawing details will be represented in a parametric and computational framework, allowing for the examination of various façade choices.

The chosen façade typologies required to meet the following requirements:

Non-Load Bearing Design
Most mid- to high-rise facades are non-load bearing, which means they do not contribute to the building's structural stability. The primary structure supports all loads, freeing up the façade to focus on thermal insulation, weatherproofing, and light transmission. This design philosophy also offers great versatility, allowing architects to experiment with new materials and forms.

Prefabrication
Prefabrication has changed façade construction, especially for mid- to high-rise structures. Prefabricated materials, such as curtain walls and concrete panels, are manufactured under controlled conditions, resulting in consistent quality and less on-site labour. This strategy reduces construction time and weather-related delays, making it ideal for mid to high-rise.

Based on these criteria, three typologies were chosen:

Timber Frame Element
Timber frame construction was chosen because of its lightweight nature and usage of bio-based components, which contribute to lower embodied carbon. This construction approach is becoming increasingly popular due to its sustainability and prefabrication capabilities, which allow for faster installation. The combination of an inner cavity wall and hardwood sheet materials makes it an appealing choice for eco-friendly construction projects.

Prefabricated Concrete Element.
Despite its high mass and projected high embodied carbon, precast concrete is widely employed in the Netherlands for mid-rise buildings. This material provides excellent thermal and acoustic performance while allowing for efficient prefabrication, resulting in speedy on-site assembly. Traditional Dutch building types sometimes combine concrete inner walls with brickwork.

Aluminium unitized facade.
Aluminium unitized facades offer substantial benefits in terms of scalability, building speed, and lightweight design. Because of its ease of assembly and versatility, this façade type is widely utilized in high-rise buildings. The method allows for enormous glass surfaces and provides a great degree of design flexibility and aesthetic appeal while meeting modern façade building regulations.

This thesis will model these façade systems in a computational. Following that, calculations will be undertaken to estimate the embodied carbon and operational carbon for each façade type, with an assessment of their environmental impact. The systems will then be optimized to reduce their environmental impact. The goal is to strike a balance between environmental performance, sustainability, and comfort.

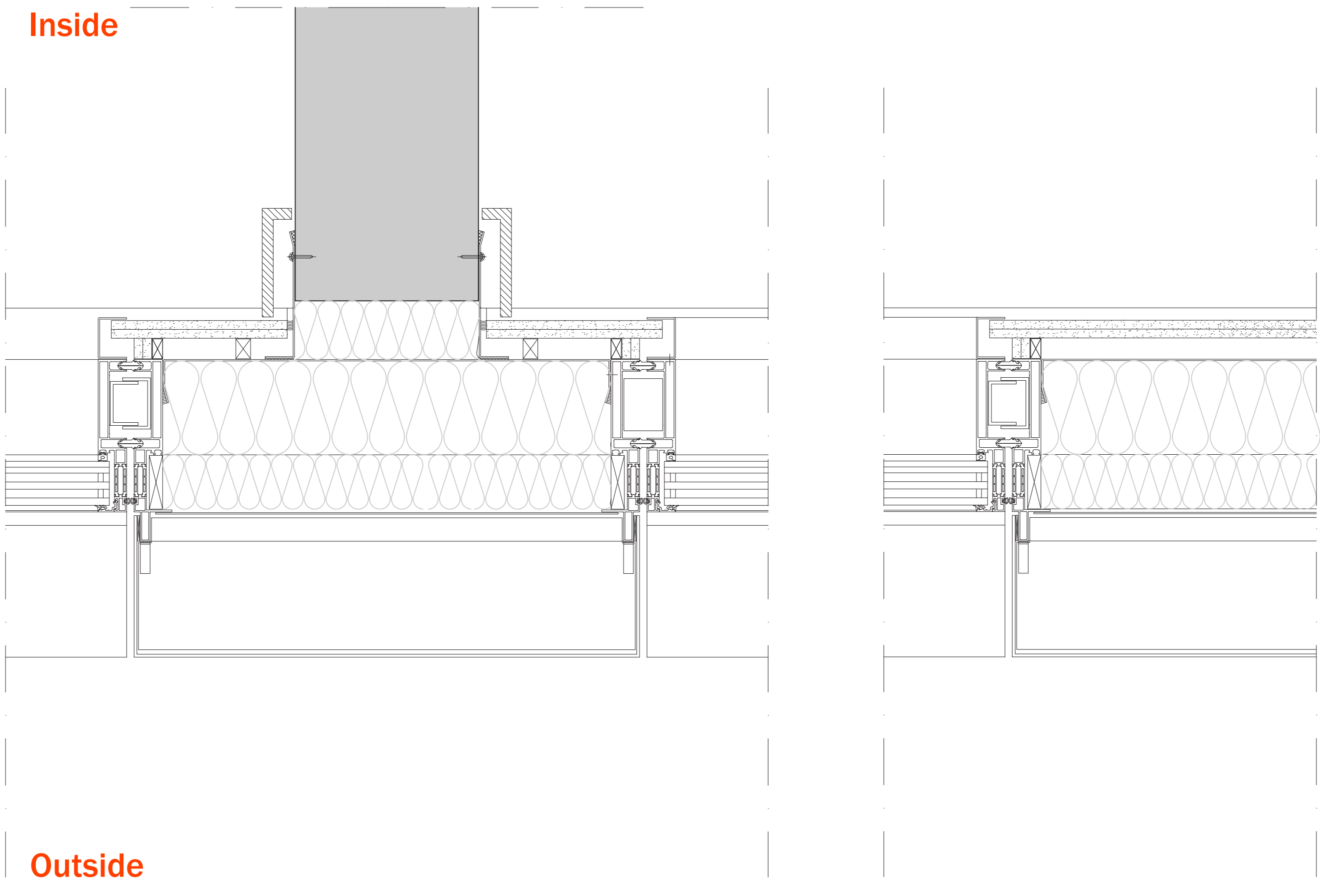


Figure 2.17

The Modernist render

Figure 2.x

Aluminium Element Facade
Horizontal details

Building: The modernist
Architect: MVRDV
Location: Rotterdam
Draftsman: Lars Vedder
Source: Frontwise Facades

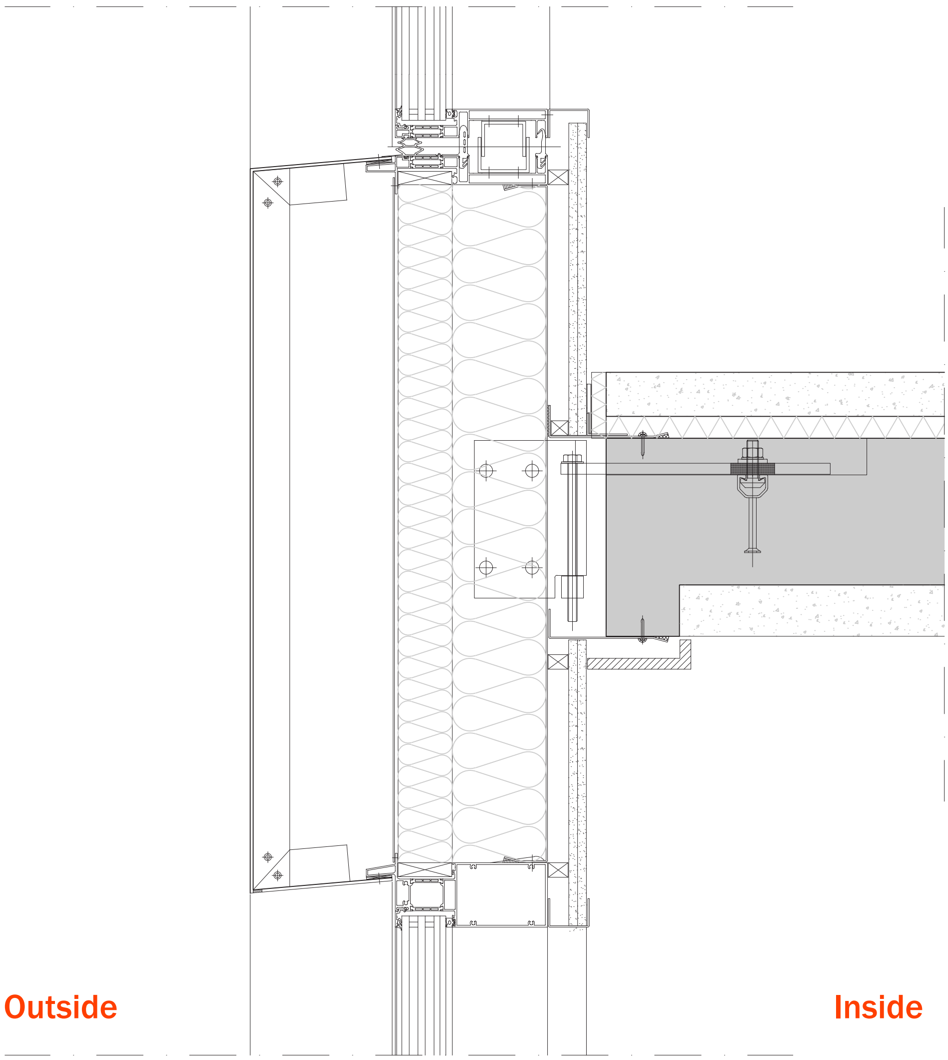


Figure 2.18

The Modernist render

Figure 2.x

Aluminium Element Facade Vertical Detail

Building: The modernist
Architect: MVRDV
Location: Rotterdam
Draftsman: Lars Vedder
Source: Frontwise Facades

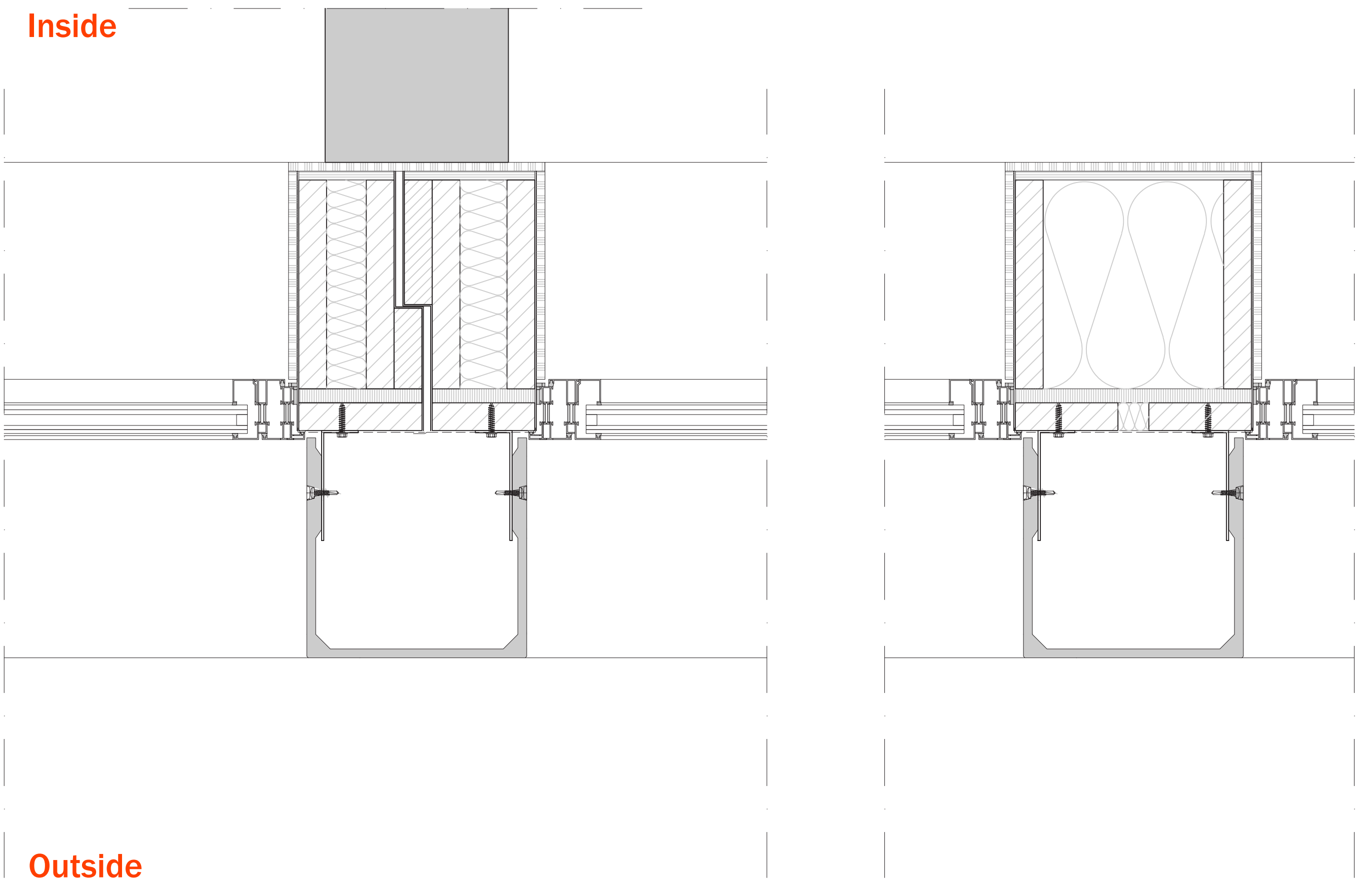


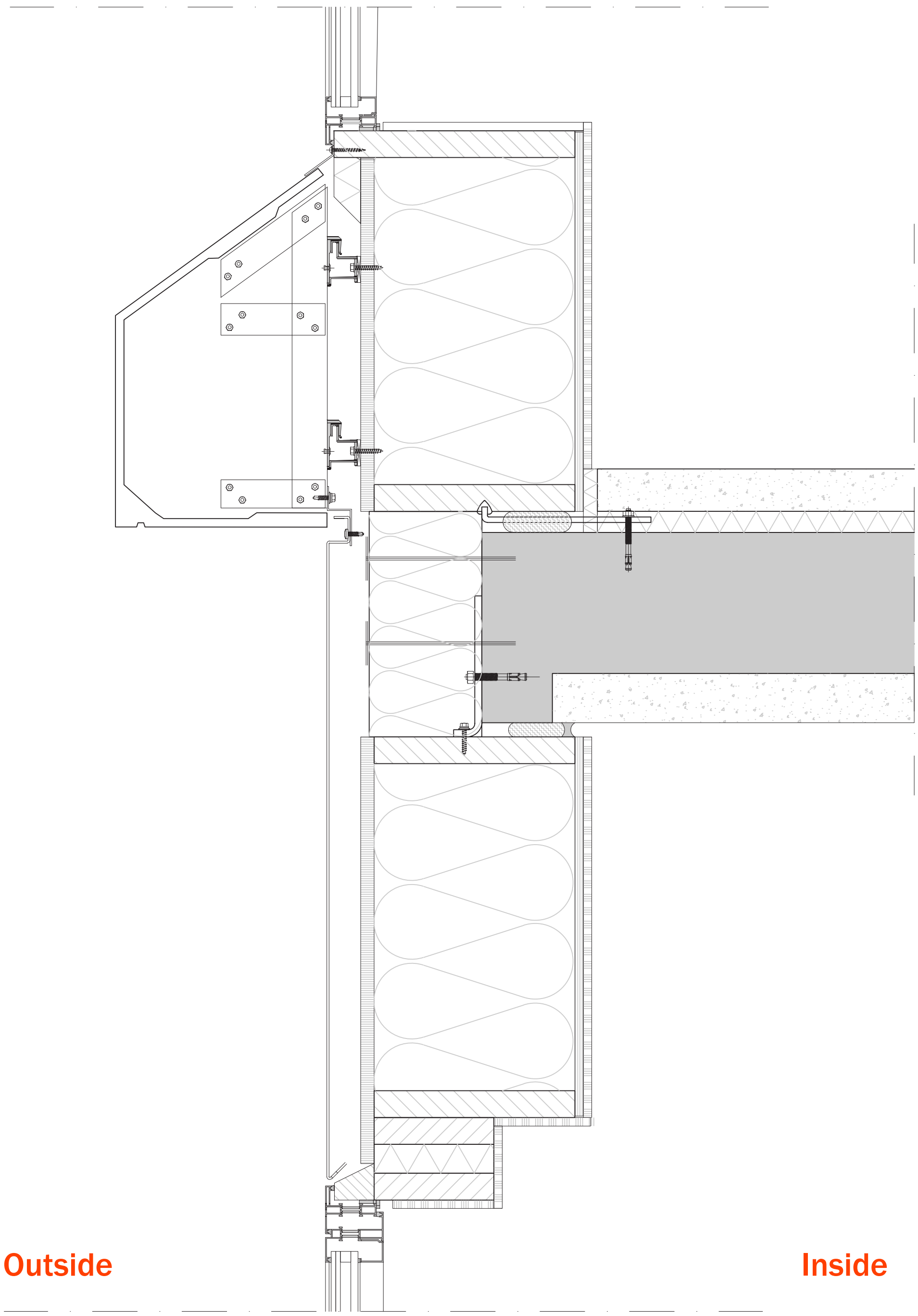
Figure 2.18

RDC VUMC render

Figure 2.x

Aluminium Element Facade Horizontal Details

Building: RDC VUMC
Architect: Atelier PRO
Location: Amsterdam
Draftsman: Lars Vedder
Source: Frontwise Facades



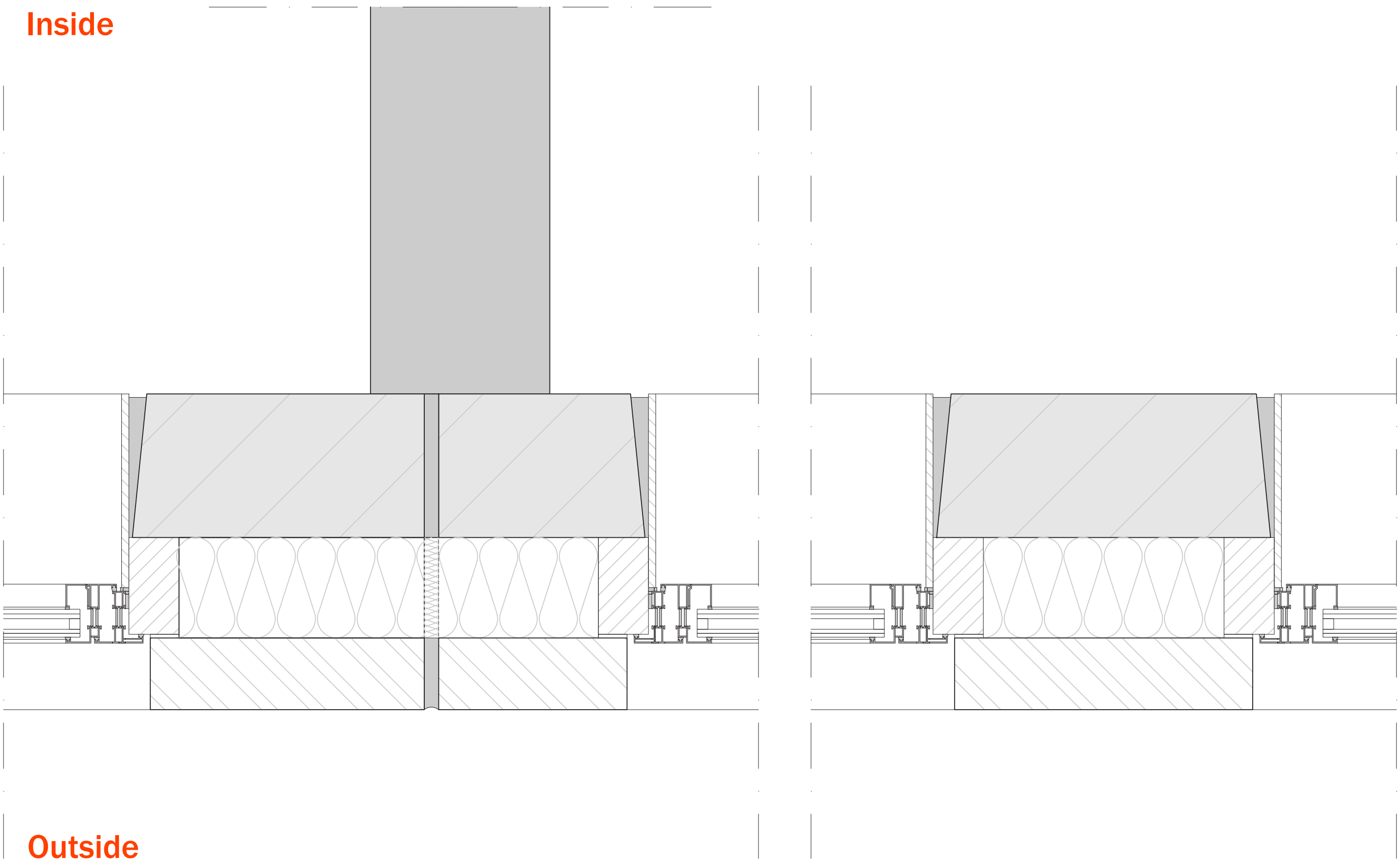
RDC VUMC render

Figure 2.18

Figure 2.x

Aluminium Element Facade Vertical Detail

Building: RDC VUMC
Architect: Atelier PRO
Location: Amsterdam
Draftsman: Lars Vedder
Source: Frontwise Facades



Vanzz Render

Figure 2.19

Figure 2.x

Aluminium Element Facade Horizontal Details

Building: Vanzz
Architect: Team V
Location: Amsterdam
Draftsman: Lars Vedder
Source: Frontwise Facades

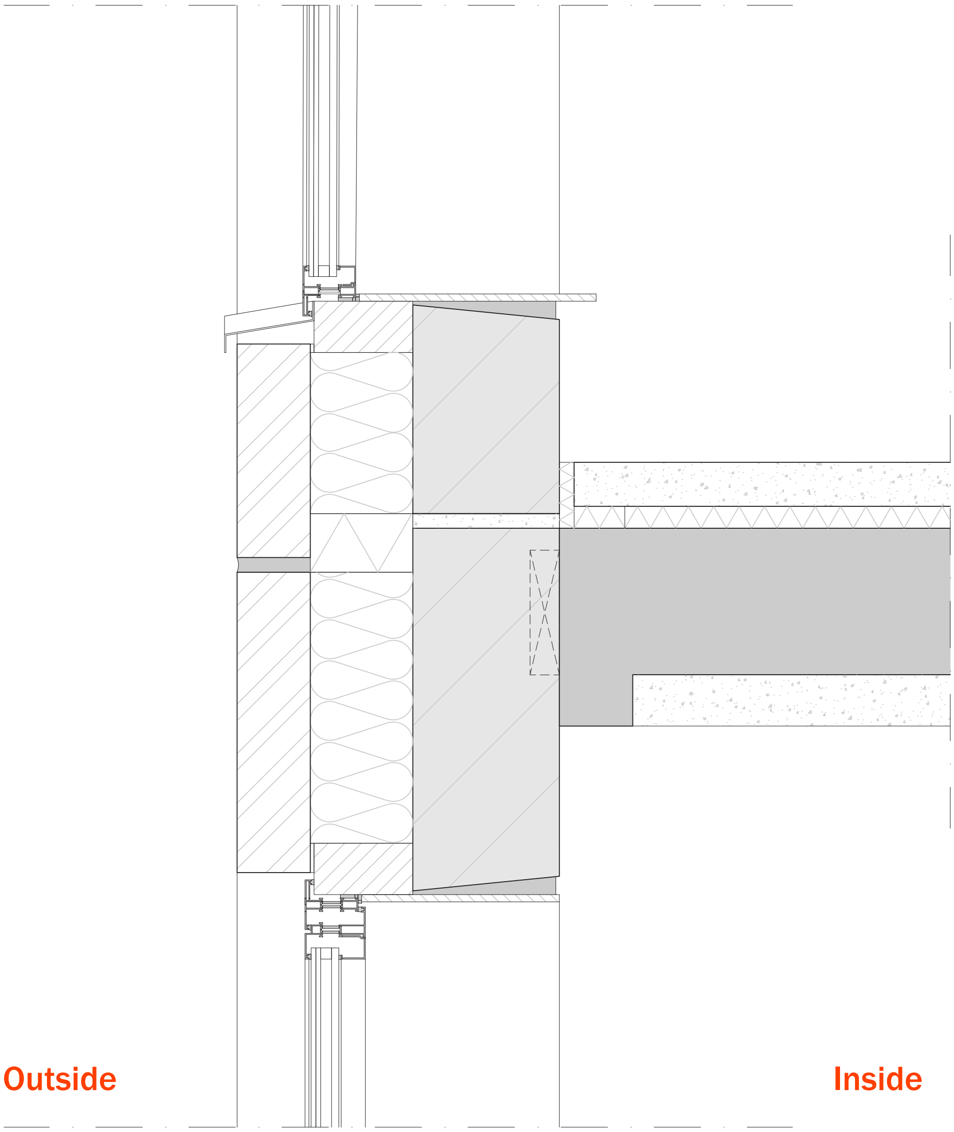


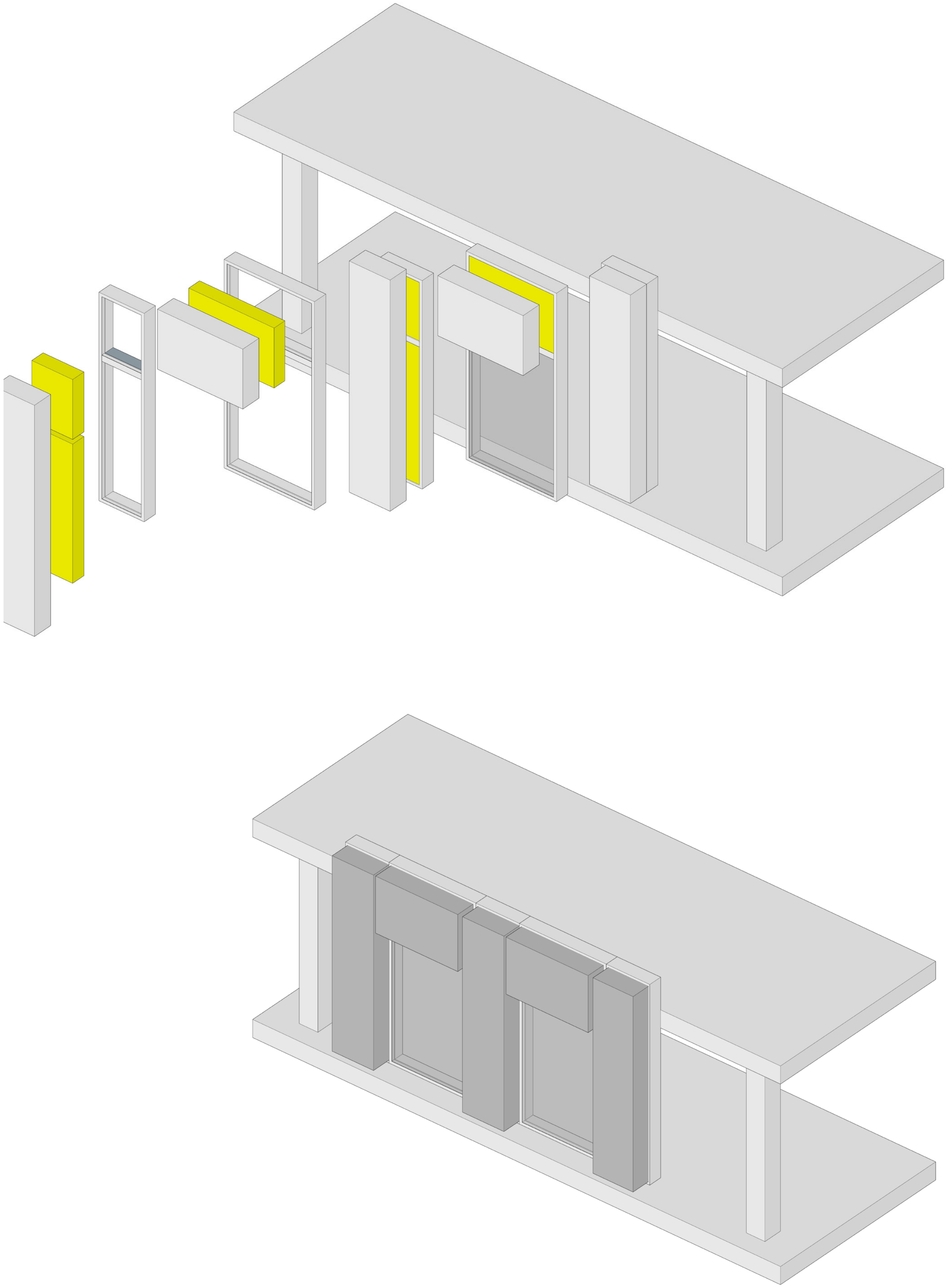
Figure 2.19

Vanzz Render

Figure 2.x

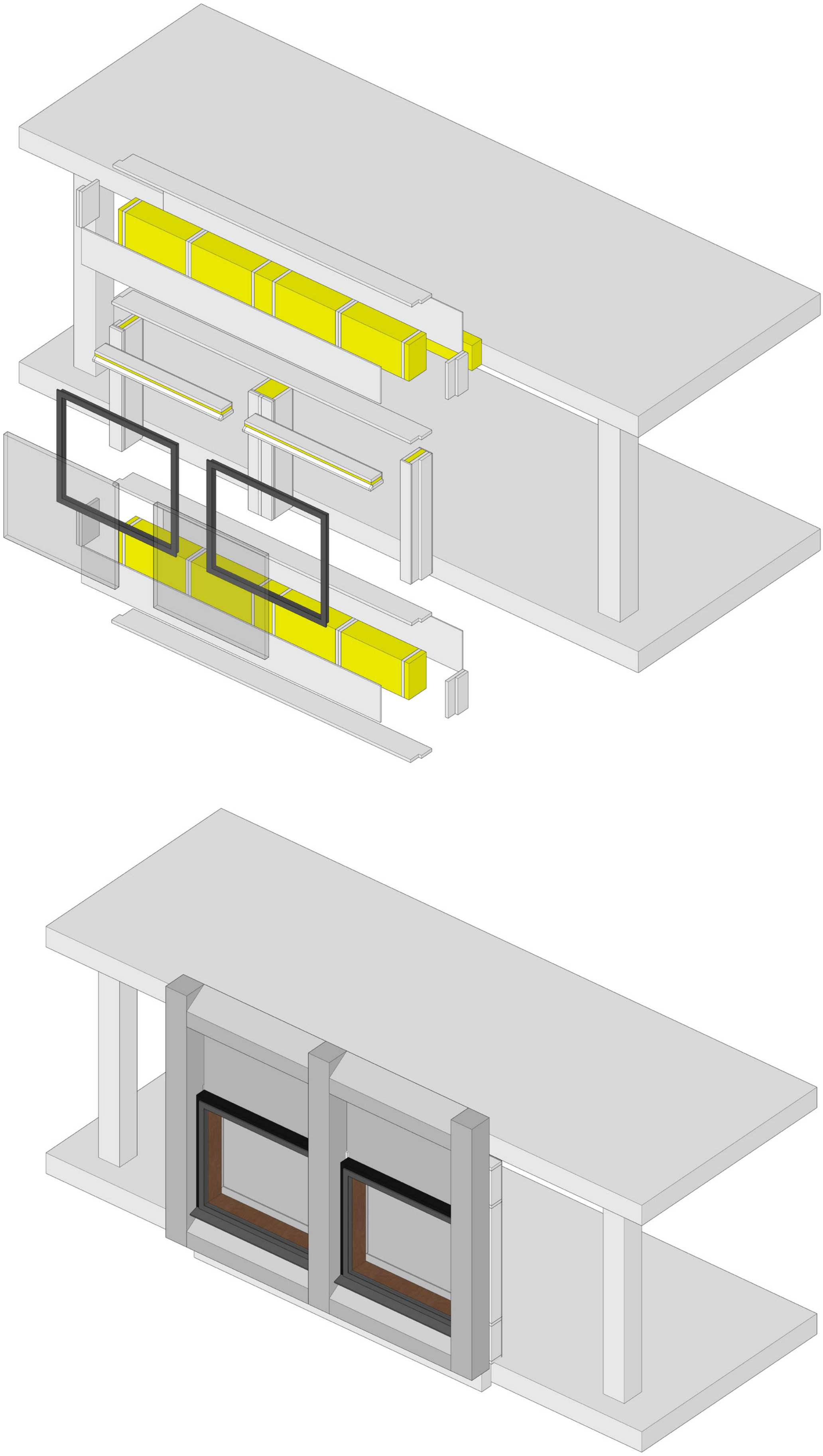
Aluminium Element Facade Vertical Detail

Building: Vanzz
Architect: Team V
Location: Amsterdam
Draftsman: Lars Vedder
Source: Frontwise Facades



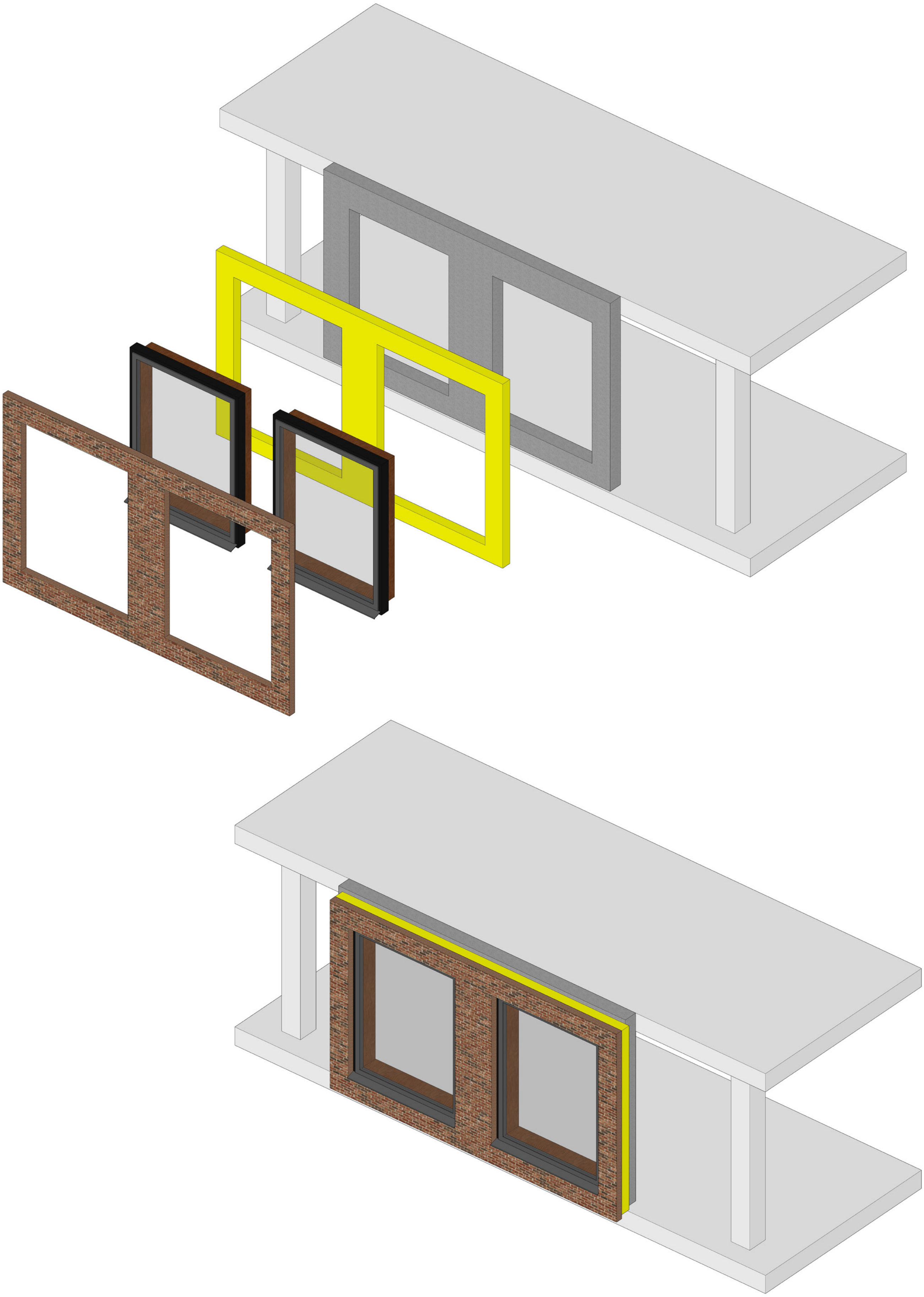
Aluminium Element Facade
3D + exploded view

Figure 2.20



HSB Element Facade
3D + exploded view

Figure 2.24



Prefab Concrete Element Facade
3D + exploded view

Figure 2.22

2.1.8 Conclusions

Façade systems are vast and diverse; the options for building design are nearly limitless, allowing different aesthetic or performance goals to be achieved through varying façade typologies.

The focus shifts to three widely used systems in the Netherlands after providing a broad overview of many essential façade typologies: element facades with an inner wall made of concrete, element facades with inner walls made of timber frames, and curtain walls with aluminum profiles. These systems are particularly interesting for their potential in prefabrication, providing advantages such as increased construction efficiency, consistent quality, improved sustainability, and scalability. Their non-load-bearing architecture enables customization and adaptation, making them suitable for a wide range of applications while reducing material costs and building time.

The chapter ends by discussing how the three façade typologies will be integrated into the computational framework. This approach will determine their embodied carbon, followed by optimization measures to reduce their environmental impact. This initiative is consistent with the overall goal of making mid- to high-rise building more sustainable and environmentally responsible.

Building on the review of façade systems, the next section depicts three distinct façade typologies in moddelled, each with unique structural, aesthetic, and functional qualities. Exploring various designs allows us to better grasp their unique advantages, such as energy efficiency, design flexibility, and cost-effectiveness, as well as potential drawbacks, such as maintenance issues, scalability constraints, and environmental impact. The visual representations will provide a better understanding of how these typologies might be utilized in different contexts, informing future design decisions.

2.2 Embodied and Operational Carbon

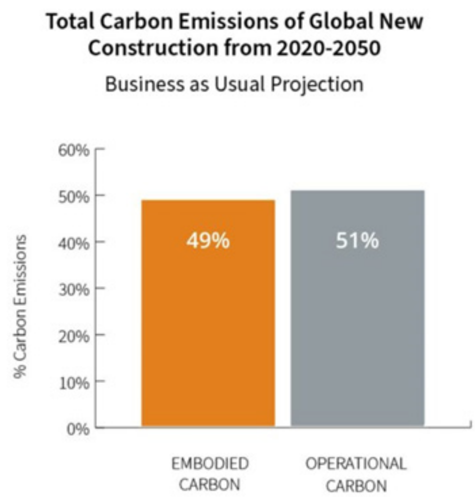
This chapter looks at how different façade materials affect the operational and embodied carbon of mid- to high-rise buildings. It will discuss how the choice of materials impacts sustainability, focusing on production, transportation, and disposal at the end of the building's life. By examining these factors, the chapter aims to show how façade materials contribute to the environmental impact of buildings.

2.2.1 Definitions

Operational carbon refers to the carbon dioxide (CO) emissions produced during the lifecycle of building materials and construction operations. This is taking into account the CO emissions from the collection of raw materials and processing, transportation to manufacturers, manufacturing building products and delivering resources to construction sites, and lastly the construction methods used to create the building.

In simple terms, embodied carbon is the carbon impact of a building or infrastructure project before it becomes operational. It also covers emissions from building maintenance and destruction, as well as garbage transportation and recycling.

Embodied carbon is different from operational carbon, this refers to emissions resulting from the energy used to run a building (heating, cooling, lighting, etc.). As operational carbon has been successfully been reduced due to legislation, embodied carbon now makes up a larger part of a building's total carbon footprint. The World Green Building Council notes that this shift makes reducing embodied carbon a key focus for lowering the construction industry's environmental impact. (Carbon Cure, 2024)

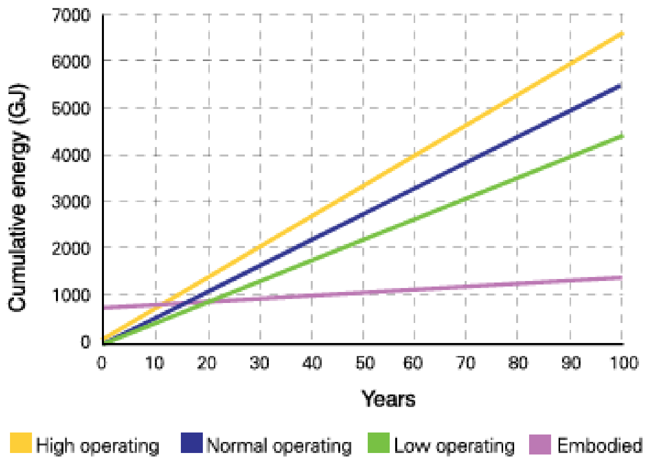


Emmisions, operational vs embodied (Carbon Cure, 2024) ***Figure 2.24***

The difference between embodied carbon (Left) and operational carbon (right). (Carbon Cure, 2024) ***Figure 2.23***

Embodied carbon is expected to account for nearly 50% of the total carbon footprint of new construction by 2050. In response, various organizations, including Architecture 2030, Structural Engineers 2050 Challenge (SE2050), the Carbon Leadership Forum, and the World Green Building Council, are working toward the goal of eliminating embodied carbon from buildings by 2050. (Carbon Cure, 2024)

Another example, research by the CSIRO found that the average household contains around 1,000 GJ of embodied energy in the materials used for its construction, equivalent to about 15 years of operational energy for an average home. Over a building's lifespan of 100 years, this could account for over 10% of its total energy use. Therefore, reducing embodied energy is a key factor in minimizing the overall environmental impact of buildings. (Crawford, 2020)



The balance between operational and embodied carbon (Milne & Reardon, n.d.) ***Figure 2.25***

As stated in the previous section, operational energy, measured in joules, is commonly brought up when discussing the energy consumption of buildings' operational phases.

Similar to operational carbon, operational energy refers to the overall amount of energy consumed by a building during its operational period, which includes heating, cooling, lighting, and other energy requirements. It is vital to emphasize that operational energy does not include the energy utilized in the manufacture or disposal of building materials, but rather the energy consumed while the building is in use and over its lifetime.

To further assess the environmental impact of operational energy, operational carbon is frequently estimated using the carbon emissions connected with the energy used. This is usually done by applying the national carbon intensity of the grid, which calculates the amount of CO emissions produced per unit of energy. Multiplying a building's total operating energy consumption by the carbon intensity factor of the local or national electrical grid provides an accurate estimate of CO emissions from energy use.

This approach creates a clear relationship between energy use and carbon emissions, offering an important statistic for assessing the sustainability of a building's operations. The carbon intensity of the grid varies based on the energy mix (renewable, fossil fuel, etc.) in a given region, emphasizing the importance of location when estimating the operational carbon of a building.

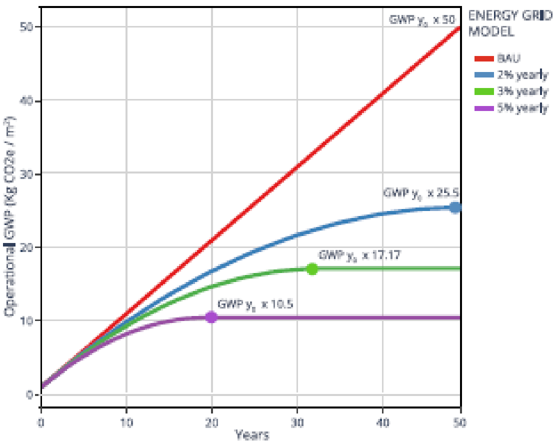
2.2.2 Carbon intensity

Operational carbon emissions have a direct link to the amount of energy consumed by a building during its operation, as well as the carbon intensity of the electricity grid that provides that energy.

For example, Méndez et al. (2022) used eGRID data to simulate operational carbon emissions over a 50-year period under various grid carbon intensity reduction scenarios. The study looked at four scenarios: one that assumed no change in carbon intensity (Business as Usual), and three others that projected annual reductions of 2%, 3%, and 5%. They calculated total operational GWP over time using an algorithm that included energy consumption intensity as well as annual grid carbon intensity. Their studies suggested that buildings might reach operational carbon neutrality in 50, 33, or 20 years, depending on the rate of grid decarbonization. This analysis illustrates the crucial necessity of reducing grid carbon intensity in reaching sustainability targets, as well as the growing importance of considering embodied carbon in facades.

In this study, a similar technique will be used, with a focus on the Dutch electrical grid. The carbon intensity of the Dutch grid, which reflects the Netherlands' energy mix and continuing decarbonization initiatives, will serve as the baseline for operational carbon calculations. Experimentation with different reduction ratios will follow simulation, allowing for a comparative investigation of alternative decarbonization scenarios.

By integrating national carbon intensity data and simulating potential reduction trajectories, this study attempts to analyse the operational carbon footprint of Dutch buildings and offer pathways to reach carbon neutrality in line with national and global sustainability targets.



Carbon intensity factors (Mendeze et al. 2022) **Figure 2.26**

2.2.3 Embodied data

When comparing embodied energy analysis results, it's important to be cautious. This applies to both assemblies and individual materials. For example, a concrete slab might have lower embodied energy than a timber floor if built using best practices. Be careful when comparing data from different manufacturers or sources, as calculation methods can vary greatly, sometimes leading to big differences in results. (Milne & Reardon, n.d.)

According to Milne & Reardon (n.d.), it's more important to follow general guidelines than to focus on exact numbers. You don't need precise figures to select materials that reduce embodied energy in a building. In general, the more processed a material is, the higher its embodied energy. The tables below provide typical values for some common materials.

These figures should be used with care because

- The embodied energy of a material can change depending on how far it's transported. A material used locally will have a different energy impact compared to one transported over a long distance.
- Recycled materials, like aluminium, have much lower embodied energy than those made from raw materials. Recycled aluminium can have less than 10% of the energy of new aluminium.
- High-value materials, such as stainless steel, are often recycled many times, which helps reduce their overall environmental impact.

EduPack
EduPack is an online tool that Delft University students can use to help them select materials and analyse their sustainability. It allows students to conduct eco audits by assessing the environmental impact of various materials used in construction and design projects. EduPack can be used by students to learn about the environmental impact of materials,

such as their embodied energy, carbon content, and recyclability. It's a handy tool for selecting materials that lower a project's environmental impact, enabling sustainable design in engineering and architecture. Example Applications according to Granta EduPack (2009):

Early Phase Design: Integrate eco factors into initial product design where adjustments are most cost-effective and impactful.
Minimize Eco-Costs: Reduce the embedded energy or carbon footprint of a product.
End-of-Life Issues: Identify potential problems with disposal or regulatory constraints.
Life Cycle Impact: Consider the full environmental impact of a product throughout its entire lifecycle.

The Eco MaterialUniverse data module expands on the standard MaterialUniverse data for 3,700 materials by including additional eco-design information. This module provides details on:

Material Production:
Production energy, CO_2, NO_x, and SO_x emissions.

End of Life:
Recycling, down-cycling, disposal methods (biodegradation, incineration, landfill), recycling energy, recycling percentage, heat of combustion, and CO_2 emissions from combustion.

Sustainability:
Information on sustainability, possible substitutes, eco-indicator values, and EPS (Environmental Performance Score).
Material Processing Energy:
Energy required for melting, vaporizing, and deforming materials.

Bio-data:
Toxicity ratings, suitability for skin and food contact, and WEEE (Waste Electrical and Electronic Equipment) restrictions.

Geo-economic Data:
Annual world production, reserves, typical and minimum ore grades, and abundance in the Earth's crust.

According to Granta EduPack (2009) the tool can be used in two steps:

Step 1: Eco Auditing
Materials have a life cycle: production, use, and disposal. Each stage impacts the environment. By entering details about a product's composition, processing, use, transportation, and disposal into a simple form, the Eco Audit Tool in CES Selector estimates energy use and CO_2 emissions at each stage. The results are shown in easy-to-understand graphs and tables, helping you make better design choices early on.

Step 2: Optimizing Eco Impact
Once you know which stages have the most impact, you can adjust your design to reduce it. For example, if production is the biggest issue, choose materials with lower energy use. CES Selector helps you compare materials based on their environmental impact and performance. It also checks for recycling options and regulatory compliance. After selecting materials, use the Eco Audit Tool again to ensure that your changes improve the overall environmental impact.

2.2.4 Materials

Aluminium Element Facade							
Aluminium, wrought (6061, T4)							
	Properties				Avarage		Source
Density	2690	-	2730	kg/m^3	2710	kg/m^3	Edupack
Conductivity	221.2	-	229.9	W/m*C	225.55	W/m*C	Edupack
Spec heat	934	-	972	J/kg*C	953	J/kg*C	Edupack
Embodied carbon	7.47	-	8.6	Kg/kg	8.035	Kg/kg	Edupack
Recycle				✔			Edupack
biodegrade				✘			Edupack
Renewable resource				✘			
Carbon storage				✘			
Insulation (Fiberglass)							
	Properties				Avarage		Source
Density	12	-	48	kg/m^3	30	kg/m^3	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Conductivity	0.03	-	0.041	W/m*C	0.0355	W/m*C	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Spec heat	800	-	805	J/kg*C	802.5	J/kg*C	Edupack
Embodied carbon	2.42	-	2.66	Kg/kg	2.54	Kg/kg	Edupack
Recycle				✘			Edupack
biodegrade				✘			Edupack
Renewable resource				✘			Edupack
Carbon storage				✘			
Laminated Glass							
	Properties				Avarage		Source
Density	2440	-	2490	kg/m^3	2465	kg/m^3	Edupack
Conductivity	1.3	-	0.7	W/m*C	1	W/m*C	Edupack
Spec heat	600	-	1300	J/kg*C	950	J/kg*C	Edupack
Embodied carbon	0.666	-	0.742	Kg/kg	0.704	Kg/kg	Edupack
Recycle				✔			Edupack
biodegrade				✘			Edupack
Renewable resource				✘			Edupack
Carbon storage				✘			
Gypsum							
	Properties				Avarage		Source
Density	1.18	-	1.7	kg/m^3	1.44	kg/m^3	Edupack
Conductivity	0.4	-	0.6	W/m*C	0.5	W/m*C	Edupack
Spec heat	850	-	950	J/kg*C	900	J/kg*C	Edupack
Embodied carbon	2.09	-	2.31	Kg/kg	2.2	Kg/kg	Edupack
Recycle				✔			Edupack
biodegrade				✘			Edupack
Renewable resource				✘			Edupack
Carbon storage				✘			

HSB Element Facade							
Soft Wood							
	Properties				Avarage		Source
Density	440	-	600	kg/m^3	520	kg/m^3	Edupack
Conductivity	0.23	-	0.2	W/m*C	0.215	W/m*C	Edupack
Spec heat	1660	-	1710	J/kg*C	1685	J/kg*C	Edupack
Embodied carbon	0.229	-	0.253	Kg/kg	0.241	Kg/kg	Edupack
Recycle				✔			Edupack
biodegrade				✔			Edupack
Renewable resource				✔			Edupack
Carbon storage	800	-	1000	Kg/kg	900	Co2/m3	
Plywood							
	Properties				Avarage		Source
Density	700	-	800	kg/m^3	750	kg/m^3	Edupack
Conductivity	0.349	-	0.3	W/m*C	0.3245	W/m*C	Edupack
Spec heat	1660	-	1710	J/kg*C	1685	J/kg*C	Edupack
Embodied carbon	0.553	-	0.61	Kg/kg	0.5815	Kg/kg	Edupack
Recycle				✘			Edupack
biodegrade				✔			Edupack
Renewable resource				✔			Edupack
Carbon storage	250	-	350	Kg/kg	300	Co2/m3	

Aluminium, Wrought (6061, T4)							
	Properties				Avarage		Source
Density	2690	-	2730	kg/m^3	2710	kg/m^3	Edupack
Conductivity	221.2	-	229.9	W/m*C	225.55	W/m*C	Edupack
Spec heat	934	-	972	J/kg*C	953	J/kg*C	Edupack
Embodied carbon	7.47	-	8.6	Kg/kg	8.035	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			
Carbon storage				✗			

Insulation (Fiberglass)							
	Properties				Avarage		Source
Density	12	-	48	kg/m^3	30	kg/m^3	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Conductivity	0.03	-	0.041	W/m*C	0.0355	W/m*C	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Spec heat	800	-	805	J/kg*C	802.5	J/kg*C	Edupack
Embodied carbon	2.42	-	2.66	Kg/kg	2.54	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Laminated Glass							
	Properties				Avarage		Source
Density	2440	-	2490	kg/m^3	2465	kg/m^3	Edupack
Conductivity	1.3	-	0.7	W/m*C	1	W/m*C	Edupack
Spec heat	850	-	950	J/kg*C	900	J/kg*C	Edupack
Embodied carbon	0.666	-	0.742	Kg/kg	0.704	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Gypsum							
	Properties				Avarage		Source
Density	1.18	-	1.7	kg/m^3	1.44	kg/m^3	Edupack
Conductivity	0.4	-	0.6	W/m*C	0.5	W/m*C	Edupack
Spec heat	850	-	950	J/kg*C	900	J/kg*C	Edupack
Embodied carbon	2.09	-	2.31	Kg/kg	2.2	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Prefab Concrete Element Facade

Conncrete							
	Properties				Avarage		Source
Density	2200	-	2600	kg/m^3	2400	kg/m^3	Edupack
Conductivity	2.59	-	1.65	W/m*C	2.12	W/m*C	Edupack
Spec heat	835	-	1050	J/kg*C	942.5	J/kg*C	Edupack
Embodied carbon	0.119	-	0.13	Kg/kg	0.1245	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			
Carbon storage				✗			

Insulation (Fiberglass)							
	Properties				Avarage		Source
Density	12	-	48	kg/m^3	30	kg/m^3	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Conductivity	0.03	-	0.041	W/m*C	0.0355	W/m*C	https://www.shethinsulations.com/fiberglasswool-insulation-materials.html
Spec heat	800	-	805	J/kg*C	802.5	J/kg*C	Edupack
Embodied carbon	2.42	-	2.66	Kg/kg	2.54	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Brick							
	Properties				Avarage		
Density	1980	-	2070	kg/m^3	2025	kg/m^3	Edupack
Conductivity	0.8	-	0.4	W/m*C	0.6	W/m*C	Edupack
Spec heat	750	-	850	J/kg*C	800	J/kg*C	Edupack
Embodied carbon	0.239	-	0.264	Kg/kg	0.2515	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Brick							
	Properties				Avarage		
Density	1980	-	2070	kg/m^3	2025	kg/m^3	Edupack
Conductivity	0.8	-	0.4	W/m*C	0.6	W/m*C	Edupack
Spec heat	750	-	850	J/kg*C	800	J/kg*C	Edupack
Embodied carbon	0.239	-	0.264	Kg/kg	0.2515	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Aluminium, wrought (6061, T4)							
	Properties				Avarage		Source
Density	2690	-	2730	kg/m^3	2710	kg/m^3	Edupack
Conductivity	221.2	-	229.9	W/m*C	225.55	W/m*C	Edupack
Spec heat	934	-	972	J/kg*C	953	J/kg*C	Edupack
Embodied carbon	7.47	-	8.6	Kg/kg	8.035	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			
Carbon storage				✗			

Zink							
	Properties				Avarage		Source
Density	5710	-	7160	kg/m^3	6435	kg/m^3	Edupack
Conductivity	100	-	134	W/m*C	117	W/m*C	Edupack
Spec heat	394	-	480	J/kg*C	437	J/kg*C	Edupack
Embodied carbon	327	-	367	Kg/kg	347	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Soft Wood							
	Properties				Avarage		Source
Density	440	-	600	kg/m^3	520	kg/m^3	Edupack
Conductivity	0.23	-	0.2	W/m*C	0.215	W/m*C	Edupack
Spec heat	1660	-	1710	J/kg*C	1685	J/kg*C	Edupack
Embodied carbon	0.229	-	0.253	Kg/kg	0.241	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✓			Edupack
Renewable resource				✓			Edupack
Carbon storage	800	-	1000	Kg/kg	900	Co2/m3	

Glass							
	Properties				Avarage		Source
Density	2440	-	2490	kg/m^3	2465	kg/m^3	Edupack
Conductivity	1.3	-	0.7	W/m*C	1	W/m*C	Edupack
Spec heat	850	-	950	J/kg*C	900	J/kg*C	Edupack
Embodied carbon	0.666	-	0.742	Kg/kg	0.704	Kg/kg	Edupack
Recycle				✓			Edupack
biodegrade				✗			Edupack
Renewable resource				✗			Edupack
Carbon storage				✗			

Plywood							
	Properties				Avarage		Source
Density	700	-	800	kg/m^3	750	kg/m^3	Edupack
Conductivity	0.349	-	0.3	W/m*C	0.3245	W/m*C	Edupack
Spec heat	1660	-	1710	J/kg*C	1685	J/kg*C	Edupack
Embodied carbon	0.553	-	0.61	Kg/kg	0.5815	Kg/kg	Edupack
Recycle				✗			Edupack
biodegrade				✓			Edupack
Renewable resource				✓			Edupack
Carbon storage	250	-	350	Kg/kg	300	Co2/m3	

2.2.5 Operational data

To estimate the yearly operational energy demand for a building, the energy balance can be combined with local weather data. By integrating hourly or daily temperature variations, solar radiation levels, and other climate factors, a dynamic understanding of energy flows is achieved. This approach allows for a more accurate prediction of heating and cooling demands over an entire year, taking into account seasonal changes and variations in building performance. Using weather data in conjunction with the energy balance equation ensures that calculations reflect real-world conditions, enabling optimized design and energy efficiency.

Energy balance

Theoretical energy demand for space heating and cooling is largely determined by the building's physical properties, the climate in which the building is located, and its occupants (Linden, 2016). The European standard (ISO13790:2008) defines the energy demand for heating and cooling as: The heat to be supplied to, or removed from, a conditioned space to maintain the desired temperature over a period of time (Linden, 2016). The heat balance, also known as the energy balance, forms the basis for determining the energy demand of a building. The heat balance of a space consists of all the heat flows entering or leaving the space (Linden, 2016)

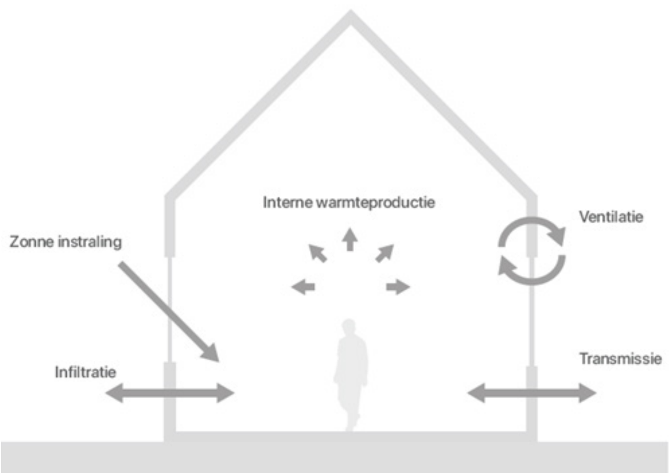


Figure 2.27

Energy balance

By combining the previously mentioned heat flows, the energy demand can be determined using the heat balance equation:

Qtrans + Qvent + Qinf + Qsol + Qint = Qneed

Which is described as follows to demonstrate a balance:

Qtrans + Qvent + Qinf + Qsol + Qint – Qneed = 0

Transmission

Qtrans as part of the heat balance is determined by the building envelope. Building envelope means the border between indoor and outdoor climate. Seen in an energy perspective, its primary function is to maintain a consistent indoor climate by protecting against a variety of exterior climate variables such as wind, low temperatures, solar heat, and moisture. The building envelope usually consists of floor, wall, façade, and roof elements. Each one of them has its specific material composition, and thus each may affect the energy flow differently.

The energy flow for transmission is calculated using the formula:

- Qtrans = U * A * (Te - Ti)

Where:

- U = Heat transfer coefficient (W/m²K)
- A = Surface area (m²)
- Te = Outside temperature (°C)
- Ti = Inside temperature (°C)

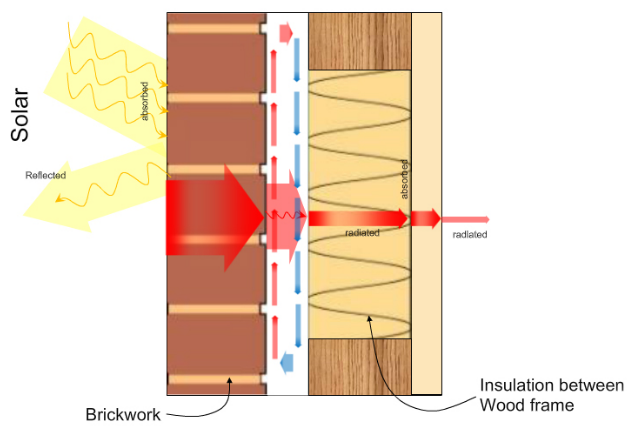


Figure 2.28

Influence of U-values

Ventilation & Infiltration

Although ventilation and infiltration are distinct energy flows, they are considered equivalent because both involve energy loss or gain caused by air movement into and out of the building (Linden, 2016). The primary purpose of ventilation is to supply fresh air to provide a comfortable and healthy indoor air quality for the occupants.

Infiltration refers to the air that unintentionally flows into a building through gaps and cracks in the building envelope. In conventional homes, infiltration was part of the incoming fresh air to the indoor spaces. In more modern buildings, infiltration values are minimized as much as possible, and fresh air is supplied through controlled ventilation systems (admin, 2015).

Ventilation and infiltration are calculated using the following formulas:

- Qvent = Vvent * p * cp * (Te - Ti)
- Qinf = Vinf * p * cp * (Te - Ti)

Where:

- Vvent = Ventilation airflow rate (m^3/s)
- Vinf = Infiltration airflow rate (m^3/s)
- p = Density of air (~1.2 kg/m^3)
- cp = Specific heat capacity of air (~1000 J/kgK)
- Te = Outside temperature (°C)Ti = Inside t emperature (°C)
- Ti = Inside temperature (°C)

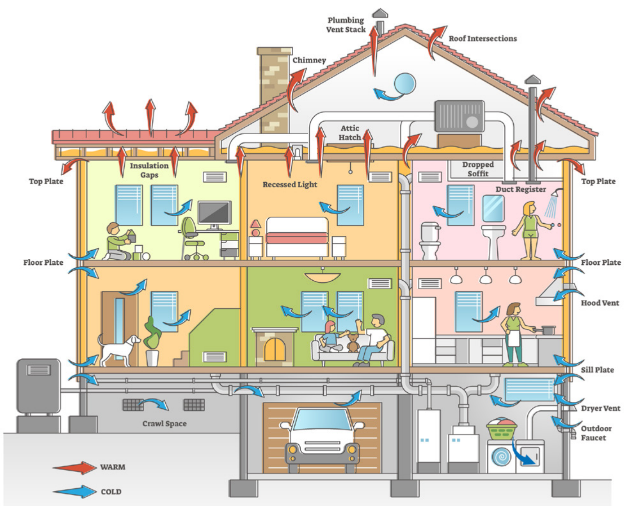


Figure 2.29

Ventilation & Infiltration

Internal heat gains

The internal heat load is the sum of all heat-generating elements within a building. It is defined as follows:

- Qint = Qpeople + Qlighting + Qappliances

Where:

- Qpeople = Heat generated by occupants (W)
- Qlighting = Heat from lighting (W)
- Qappliances = Heat from household appliances (W)

For people, the heat is produced by metabolism. This is highly dependent on the activities that the individuals are performing; the higher the metabolism, the more heat is generated. Lighting and equipment produce heat when electricity is converted into the end use of the electrical device. The heat load from lighting and equipment can be minimized by increasing efficiency or reducing total usage.

Figure 2.30

Runner under heat camera

Heat transfer through solar radiation

Solar heat gain is defined as the energy that enters the building as solar radiation. This energy is converted into heat through absorption. For this solar heat gain, only the heat that enters the interior through transparent materials is considered. In the case of residential buildings, this primarily occurs through windows. In architectural designs, windows are a crucial element for achieving quality in terms of comfort and aesthetics. At the same time, windows have one of the greatest impacts on energy transfer in a building.

The calculation of solar heat gain is defined by the following formula:

- Qsol = Aglass * Qsun * zta / g

Where:
- Aglass = Area of glass (m^2)
- Qsun = Solar radiation intensity (W/m^2)
- zta = Solar heat gain coefficient
- g = Glazing factor

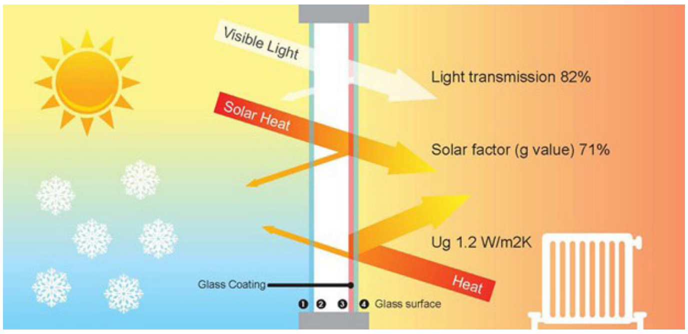


Figure 2.31

Influence of G and U value in glass

2.2.5 Conlcusions

This chapter studied how different façade materials impact the embodied energy and carbon footprint of mid- to high-rise buildings, considering production, transportation, and lifecycle stages. By addressing the research sub question, "How do façade materials contribute to the embodied energy and carbon footprint of buildings?", the analysis highlighted the following insights:

Embodied Carbon

Embodied carbon accounts for the emissions produced during the lifecycle of materials, including raw material extraction, processing, transportation, manufacturing, and end-of-life disposal or recycling. The chapter emphasized that more processed materials and those transported over long distances have higher embodied energy and carbon, whereas recycled materials can significantly lower the impact.

Operational Carbon

Operational carbon refers to the emissions generated from energy consumption during a building's lifecycle. The operational impact of a façade can be determined through an annual energy balance, which calculates energy flows related to heat transfer, ventilation, and solar heat gain. By integrating building physics and climate data, the operational carbon footprint can be estimated over the lifespan of the façade, considering the regional electricity grid's carbon intensity and potential future decarbonization trends.

In conclusion, façade materials significantly influence a building's overall carbon footprint by impacting both embodied and operational carbon. A lifecycle-based analysis enables the identification of sustainable materials and design strategies to minimize environmental impact. Through this framework, future decisions on façade material selection can align with global sustainability targets, ensuring reductions in embodied and operational carbon footprints and supporting the transition to net-zero buildings.

2.3 Regulations

This chapter addresses regulatory guidelines for façade design, with a focus on embodied energy and carbon. As sustainability becomes more important in construction, knowing how these façade rules interact with total building performance can be important. The chapter tries to understand how standards like the Bouwbesluit, BENG, MPG, and EPC affect the footprint of buildings. By studying these relationships, the chapter shows how façade regulations contribute to sustainability and suggests ways to improve alignment with larger environmental goals.

2.3.1 Bouwbesluit

The Dutch Building Decree, called Bouwbesluit 2012, is a set of legal requirements for building and renovation projects in the Netherlands. It ranges from safety and health to energy efficiency and usability. This is to ensure that buildings meet their performance in terms of load-bearing capacity, fire safety, insulation, ventilation, and accessibility.

The Dutch Building Decree (Bouwbesluit, 2012) has specified various requirements with respect to safety, health, usability, energy efficiency, and environmental concerns. Some of the key requirements for the facades I came across are listed below:

1. Strength and Stability

Structural Safety: The facade must have sufficient strength and stability to withstand loads such as wind pressure, its own weight, and (in some cases) snow load, without the risk of collapse. These requirements are based on standards like the Eurocodes.

2. Fire Safety

Fire Resistance: Facades must meet fire resistance requirements, meaning the facade should be able to resist fire for a certain period, depending on the building's function and the location of the facade (e.g., between different fire compartments).

Fire Spread: The facade must provide adequate protection against fire spreading to neighbouring buildings. This is regulated by the rules concerning the distance between buildings and the fire resistance of the facade.

Cladding: Facade cladding must meet certain fire classification standards, especially for taller buildings. Stricter requirements apply to buildings higher than 13 meters.

3. Daylight and Ventilation

Daylight Access: Facades must allow sufficient daylight into habitable rooms. This is assessed based on the daylight factor and a minimum glass area (10% of the usable area of a habitable room).

Ventilation: Facades must include openings to provide adequate ventilation, particularly in habitable rooms, kitchens, toilets, and bathrooms.

4. Thermal Insulation and Energy Performance

Thermal Insulation (Rc-value): Facades must meet insulation requirements to limit energy loss. The minimum Rc-value for thermal insulation of facades is 4.7 m^2K/W (since 2021), ensuring buildings are energy-efficient.

Airtightness: The facade must be airtight to prevent unnecessary airflows that could increase energy use and worsen indoor climate.

5. Waterproofing

Rain and Waterproofing: The facade must be designed and constructed to prevent water from penetrating indoors. This means facades must be resistant to rain infiltration and moisture ingress from the air or ground (groundwater).

These requirements are aimed at ensuring the safety, sustainability, and comfort of buildings. The Building Decree also refers to NEN standards for specific technical specifications and guidelines for construction

In conclusion, the most important parts of the Bouwbesluit for mid to high-rise and high-performance buildings include fall and fall-through protection, ensuring windows and facade openings prevent falls, crucial due to the building height. This can impact the glass for example. Thermal insulation requires facades to meet a minimum Rc-value of 4.7 m^2K/W to reduce energy loss and ensure energy efficiency. Cladding is expected to comply with fire classification standards, especially for buildings over 13 meters high. Finally, daylight access askes that facades can provide enough daylight to the building, with a minimum glass area of 10% of the usable room surface for the user's comfort (Bouwbesluit, 2012).

2.3.2 EPC & BENG

Since the oil crisis of 1973, insulation requirements for new homes have been implemented in the Netherlands. Initially, this was done through the (model) building regulations of the Association of Dutch Municipalities (VGN). Over the years, these regulations were gradually tightened. On October 1, 1992, these technical provisions, which only included minimum requirements for heat transmission losses in the building envelope, were incorporated into the Bouwbesluit (van de Griendt & de Vries, 2016).

Functie	1995	1998	2000	2006	2013	2015
Woonfunctie	1,4	1,2	1,0	0,8	0,6	0,4
Kantoorfunctie	-	-	1,6	1,5	1,1	0,8
Sportfunctie	-	-	2,2	1,8	1,8	0,9
Bijeenkomstfunctie	-	-	2,4	2,2	2,0	1,1
Celfunctie	-	-	2,2	1,9	1,8	1,0
Gezondheidszorgfunctie met bedgebied	-	-	3,8	3,6	2,6	1,8
Logiesfunctie in logiesgebouw	-	-	2,1	1,9	1,8	1,0
Onderwijsfunctie	-	-	1,5	1,4	1,3	0,7
Winkelfunctie	-	-	3,5	3,4	2,6	1,7

Different EPC scores trough the years. (Handelbouwadvies, n.d.)

Figure 2.32

Partly due to the United Nations Climate Treaty of 1992, the Energy Performance Standard was included in the Bouwbesluit in 1995. Since then, energy performance has been expressed in the so-called Energy Performance Coefficient (EPC).

The Energy Performance Coefficient (EPC) of a home expresses its energy efficiency. A value of 1.0 represents the average performance of a house in 1990. A home with an EPC of 0.6, therefore, uses only 60% of the energy that a similar home would have used twenty years ago. The table below shows the development of the EPC requirement for residential buildings over time.

Since January 1, 2021, all new construction, whether residential or commercial, must comply with the nearly energy-neutral building (BENG) requirements when applying for building permits. BENG, which stands for "nearly energy-neutral building," derives from the Energy Agreement for Sustainable Growth and the European EPBD directive.
Just as the EPC calculation the energy performance of a new building indicates how energy-efficient the residential or commercial building is.

The three BENG indicators according to the Rijkdienst van Ondernemend Nederland (2017):

BENG 1

The first indicator, BENG 1, measures a building's energy demand. The formula is: ""The maximum energy demand in kWh per square meter of usable floor area per year (kWh/m²/yr)" . This indicates the quantity of energy that a building requires annually, considering factors such as design, insulation, solar gain, building orientation, and thermal mass. The thermal envelope, or the building's exterior, plays a crucial role in retaining or blocking heat. Better thermal envelopes reduce energy needs, with detached homes typically showing different results compared to terraced houses due to variations in their thermal envelopes.

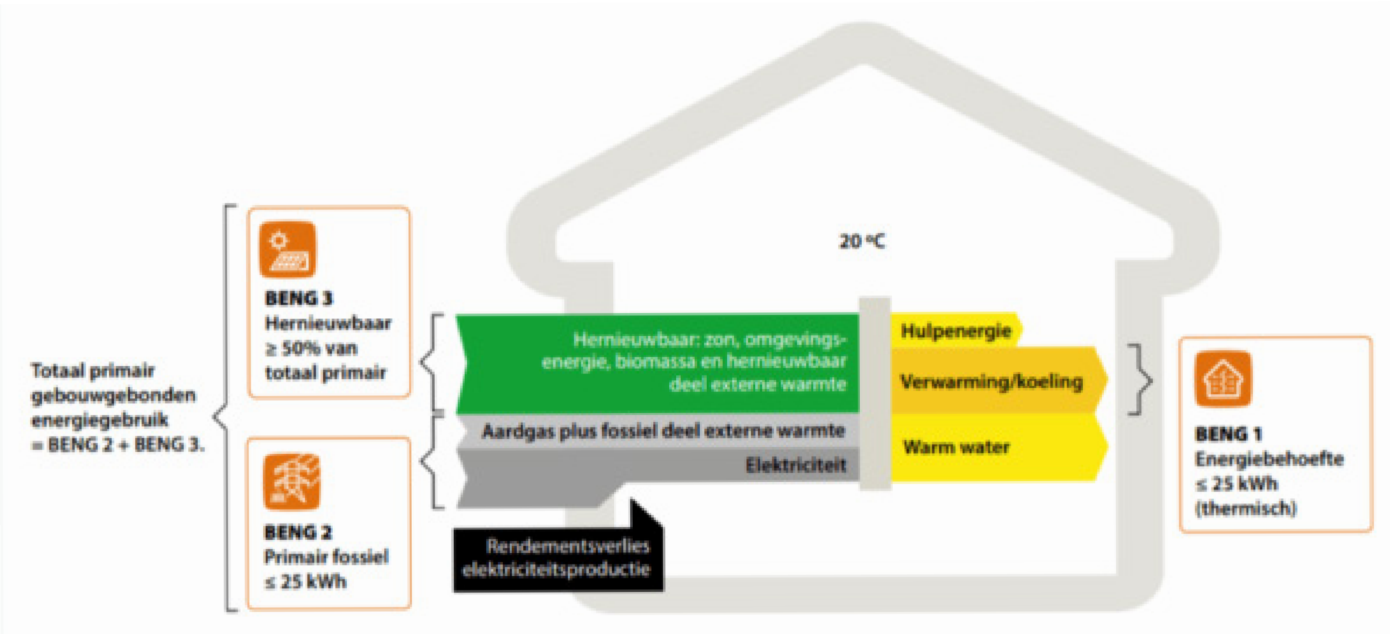


Figure 2.33

Beng (bouwbesluit 2012)

BENG 2

also measures energy consumption in kWh per m^2 per year but focuses on primary fossil energy. The formula is: "The maximum primary fossil energy use in kWh per square meter of usable floor area per year (kWh/m^2/yr)". This includes energy for heating, hot water, cooling, and ventilation. For commercial buildings, it also covers lighting and humidity control.

BENG 3

The third indicator, BENG 3, measures the percentage of renewable energy produced by the building: "The percentage of renewable energy (%)". This reflects the building's self-generated renewable energy, such as from solar panels.

This measures the energy the building generates itself, such as through solar panels. High-rise buildings are assessed differently from low-rise buildings because there is relatively less surface area available for solar panels to cover the large building area.

A building must meet all three requirements simultaneously. It is not possible to compensate for a low score in one indicator with a higher score in another. However, there are connections between the three indicators. For example, a home that requires less energy for heating and cooling often uses less primary fossil energy. Similarly, a home that generates more renewable energy reduces its dependence on fossil fuels.

The major difference with the former EPC and the new BENG is that EPC gives only one value concerning the energy performance of a building. Within that single value, one area with a poor score may be balanced against an area with a higher score. Under BENG, these kinds of compensations are no longer valid; hence, it provides a more transparent and correct view of real energy consumption by a building. One last important thing to note is that the EPC and the BENG both focus on energy, but says nothing about comfort and health.

2.3.3 MPG

The MPG (Environmental Performance of Buildings) is an important measure of a building's sustainability. The lower the MPG, the more sustainable the material usage. The environmental performance of building materials will increasingly become a key factor in the overall environmental impact of a building. The MPG serves as an objective tool in the design process and can be used in a Program of Requirements to document the outcome of a design process.

For example, using recycled carpet gives a building a sustainable appearance and serves as an important communication tool. However, an MPG calculation shows that the sustainability of the floor beneath the carpet has a much greater impact on the environmental load (Rijkdienst van Ondernemend Nederland, 2017).

For which buildings is an environmental performance calculation required?

- Buildings with a primary function of residential or office space
- Ancillary functions in office buildings.

For which buildings is an environmental performance calculation not required?

- Offices that are part of a building with other functions besides an office function
- Buildings with a maximum lifespan of 15 years at the same location.

Calculating Environmental Impact

The environmental impact of matewrials can be calculated using an MPG calculation. As energy consumption in buildings continues to decrease due to stricter energy performance standards, the MPG of a building is becoming an increasingly important measure of sustainability. It is important to note that measures beneficial for BENG (Nearly Zero Energy Building) indicators may negatively affect the MPG, and vice versa. For instance, thicker insulation or solar panels improve energy performance but worsen the MPG. The environmental impact of producing solar cells is high, increasing the MPG. However, since solar cells generate electricity, they reduce EP2 (primary fossil energy use). Over their lifespan, solar cells produce enough energy to offset the environmental impact of their production.

To determine the environmental impact of a single material, a Life Cycle Assessment (LCA) is conducted. The LCA must be carried out by a qualified expert. The LCA results in 11 indicators for the environmental impact of a product. These 11 indicators are combined into one value: the shadow costs. As of January 1, 2025, this will expand to 19 indicators (Rijkdienst van Ondernemend Nederland, 2017).

The environmental information data collection by the NMD Foundation is based on a set of impact categories and a determination method given in the European standard EN15804. Up to 2019, this set consisted of 11 impact categories, referred to as ‘set A1’ since the revision in 2012 (EN15804+A1). In the revision of the standard from 2019, a new set was presented: ‘set A2’ according to EN15804+A2.

Starting from 1st January 2021, the obligation to provide two sets of environmental data was introduced to the NMD: one set based on EN15804+A1 (set 1) and one set based on

Milieu-impactcategorie	Indicator	Eenheid
Uitputting van abiotische grondstoffen, ex fossiele energiedragers	ADP-elementen	kg antimoon
Uitputting van fossiele energiedragers	ADP-brandstof [7]	kg antimoon
Klimaatverandering	GWP-100j	kg CO_2
Ozonlaagaantasting	ODP	kg CFC 11
Fotochemische oxidantvorming	POCP	kg etheen
Verzuring	AP	kg SO_2
Vermesting	EP	kg $(PO_4)^{3-}$
Humaan-toxicologische effecten	HTP	kg 1,4 dichloorbenzeen
Ecotoxicologische effecten, aquatisch (zoetwater)	FAETP	kg 1,4 dichloorbenzeen
Ecotoxicologische effecten, aquatisch (zeewater)	MAETP	kg 1,4 dichloorbenzeen
Ecotoxicologische effecten, terrestrisch	TETP	kg 1,4 dichloorbenzeen

Figure 2.34

Old MPG indicators

Milieu-impactcategorie	Indicator	Eenheid
Klimaatverandering - totaal	GWP-totaal	kg C02-eq.
Klimaatverandering – fossiel	GWP-fossiel	kg C02-eq.
Klimaatverandering – biogeen	GWP-biogeen	kg C02-eq.
Klimaatverandering - landgebruik en verandering in landgebruik	GWP-luluc	kg C02-eq.
Ozonlaagaantasting	ODP	kg CFC11-eq.
Verzuring	AP	mol H+-eq.
Vermesting zoetwater	EP-zoetwater	Kg P-eq.
Vermesting zeewater	EP-zeewater	kg N-eq.
Vermesting land	EP-land	mol N-eq.
Smogvorming	POCP	kg NMVOC-eq.
Uitputting van abiotische grondstoffen mineralen en metalen	ADP-mineralen&metalen	kg Sb-eq.
Uitputting van abiotische grondstoffen fossiele brandstoffen	ADP-fossiel	MJ, net cal. val.
Watergebruik	WDP	m3 world eq. deprived
Fijnstof emissie	Ziekte door PM	Ziekte-incidentie
Ioniserende straling	Humane blootstelling	kBq U235-eq.
Ecotoxiciteit (zoetwater)	CTU ecosysteem	CTUe
Humane toxiciteit, carcinogeen	CTU humaan	CTUh
Humane toxiciteit, non-carcinogeen	CTU humaan	CTUh
Landgebruik gerelateerde impact / bodemkwaliteit	Bodemkwaliteitsindex	Dimensieloos

Figure 2.35

New MPG indicators

EN15804+A2 (set 2). According to the plan that's still pending parliamentary approval- the MPG calculations will shift from 1st July 2025 onwards to the new A2 set. This A2 set, EN15804+A2, comprises 19 environmental impact categories (Nationale Milieu Database, n.d.).

Life Cycle Assessment (LCA) evaluates the environmental impacts of a product, service, or process throughout its life cycle. While the specific "11 indicators" can vary depending on the framework or guidelines used (e.g., ISO 14040/14044 or specific software/ tools), the following are commonly assessed environmental indicators:

Global Warming Potential (GWP): Measures greenhouse gas emissions contributing to climate change, expressed as CO equivalents (COe).

Acidification Potential (AP): Assesses emissions of sulfur dioxide (SO) and nitrogen oxides (NO), which can lead to acid rain and soil acidification, expressed as SO equivalents.

Eutrophication Potential (EP): Evaluates nutrient emissions (e.g., nitrogen and phosphorus) causing algal blooms and oxygen depletion in water bodies, expressed as phosphate equivalents (PO^3).

Ozone Depletion Potential (ODP): Considers substances that degrade the ozone layer, such as chlorofluorocarbons (CFCs), expressed as CFC-11 equivalents.

Photochemical Ozone Creation Potential (POCP): Also called smog formation, it measures emissions of volatile organic compounds (VOCs) and nitrogen oxides that form ground-level ozone, expressed as ethylene equivalents.

Abiotic Resource Depletion (Fossil Fuels): Tracks the consumption of non-renewable energy sources like coal, oil, and gas.

Abiotic Resource Depletion (Minerals and Metals): Measures the extraction of non-renewable minerals and metals from the Earth.

Water Depletion: Evaluates the consumption of freshwater resources.

Land Use: Assesses impacts related to the occupation and transformation of land, such as deforestation and habitat loss.

Human Toxicity Potential: Measures the potential harm of chemical emissions to humans, including both cancer and non-cancer effects.

Ecotoxicity Potential: Evaluates the toxic effects of chemical emissions on ecosystems, including aquatic and terrestrial environments.

Calculation Rules

The Environmental Cost Indicator (MKI) of a building is the sum of the shadow costs of all materials used in the building. This also includes materials that will be replaced during the building's lifespan. The total sum is then divided by the building's lifespan and by the gross floor area (GFA). The MPG is expressed in shadow costs per m^2 GFA per year. The lifespan is assumed to be 75 years for residential buildings and 50 years for office buildings.

To calculate the MPG, every material in a design must be identified, and the quantity used must be determined. While many software packages can use a standard product list, actual calculation of accurate MPG takes a tremendous amount of time. The structural elements most contributing to the MPG are the foundations, facades, floors, and installations- often reaching 60% up to 80%-depending heavily on the geometry and the installation concept (Rijkdienst van Ondernemend Nederland, 2017).

2.3.4 Conclusions

Summarizing. This chapter tries to understand regulatory guidelines for façade design, focusing on embodied energy and carbon. It examines the Dutch Bouwbesluit 2012, which sets legal standards and preconditions for safety, energy efficiency, and usability, and also covers the EPC and BENG frameworks for energy performance. BENG evaluates a building's energy demand, fossil fuel usage, and renewable energy generation, emphasizing sustainability. The MPG assesses material usage and environmental impact, considering life cycle assessments. While improving energy performance can negatively impact the MPG, both are essential for building sustainability. The chapter highlights the importance of aligning regulations with environmental goals.

The most important takeaways for the integration into computational frameworks include:

Safety from bouwbesluit: Fall and fall-through protection needs to be considered for façades, which should especially apply to high-rise buildings, as this needs to affect glass specifications.

Energy Efficiency : Thermal insulation demands that a façade must have at least an Rc-value of 4.7 m^2K/W for reduced energy losses.

Fire safety from bouwbesluit: cladding needs to comply with fire classification standards above 13 meters building height.

Daylight Access from bouwbesluit: Facades are required to provide adequate daylight to habitable rooms. This is evaluated using the daylight factor and by ensuring that the glazing area is at least 10% of the room's usable floor area.

Energy demand trough BENG: measures a building's energy demand. The formula is: "The maximum energy demand in kWh per square meter of usable floor area per year ($kWh/m^2/yr$)".

Sustainability trough MPG : MPG assesses material impact, expressed in LCA costs per m^2 per year, with a focus on a 75-year lifespan for residential buildings and 50 years for offices.

Limitations : comfort and health factors are not taken into account in the EPC and BENG.

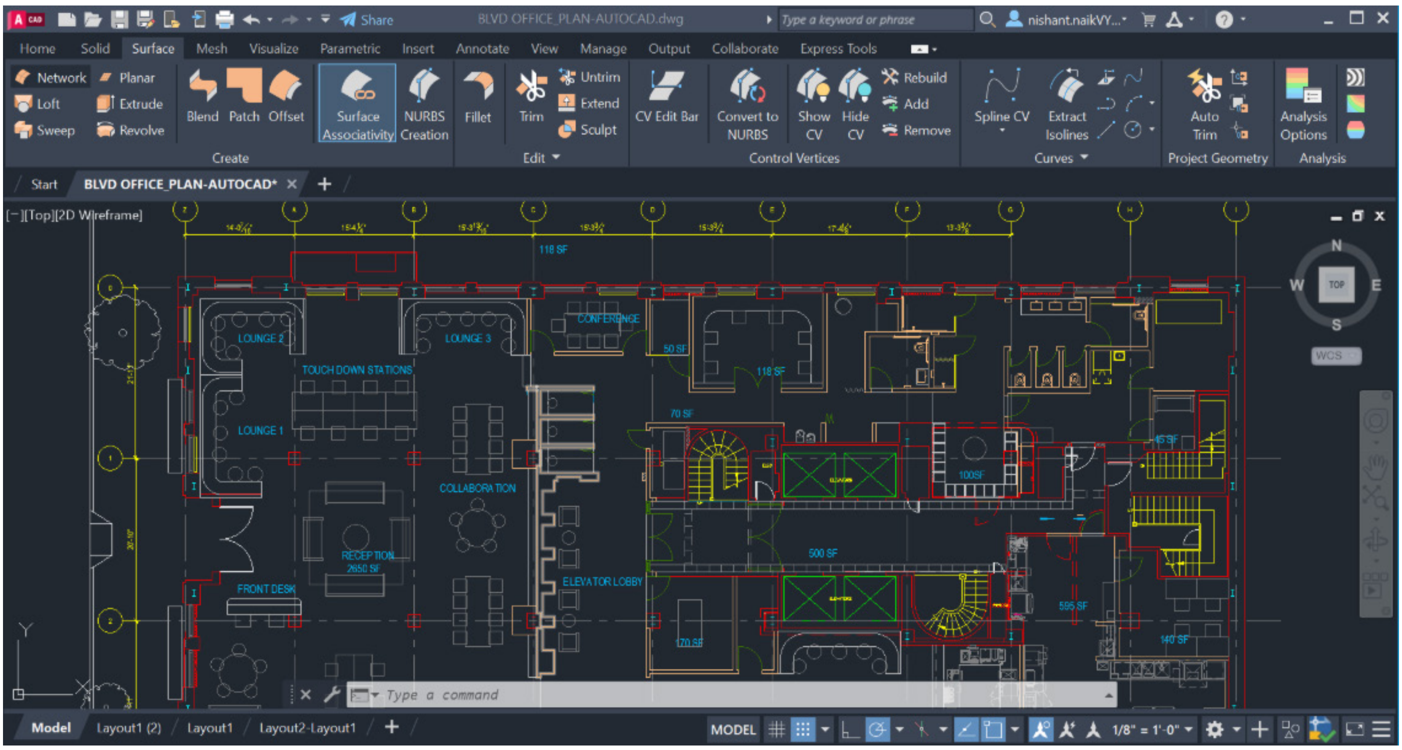
2.4 Computational design

Simulating building performance needs technical expertise in design, engineering, construction, operations, and management. The goal is to predict a building's behaviour from design to demolition using different disciplines including as physics, mathematics, material science, and human behaviour. The idea of developing performance simulation algorithms and forecasts stretches back several decades and the area is constantly evolving. Recent improvements in building simulation settings demonstrate the incorporation of research findings into current design and construction methods. (Malkawi, 2004)
This chapter tries to investigate how this dynamic model compares to traditional software, assessing its effective it is in predicting and optimizing building performance across various contexts. The goal of studying the development and performance of dynamic models is to show how they help make modern building practices more efficient and sustainable.

2.4.1 Definitions

This section of the review highlights important concepts and methodologies that are key to the field of computer-aided design. A few examples include Traditional software, parametric and computational design, visual programming languages, integrated dynamic models, Building Information Modelling (BIM), and Building Performance Simulation (BPS). The section provides a basis for understanding in the advancement of building practices in the modern general buildings culture today.

Traditional software (CAD & BIM)
Computer-Aided Design (CAD) software has been important in the architecture, engineering, and construction industries for decades. Traditional CAD systems have helped designers create, modify, analyse, and optimize designs. These systems produce detailed drawings and specifications, improving precision and efficiency compared to manual



Autocad interface (Architzer, 2025)

Figure 2.36

drafting. Some Important characteristics of traditional CAD systems include:

- 2D and 3D Drafting: Create and visualize both two-dimensional and three-dimensional models.
- Precision and Accuracy: Tools for exact measurements and adjustments.
- Documentation: Generate comprehensive documentation such as plans, elevations, sections, and details.
- Interoperability: Support various file formats and integrate with other software for seamless collaboration.

Traditional CAD mainly focuses on representing a building's geometry but cannot simulate or predict how it will perform in real life. This limitation has led to the development of more advanced methods that include performance analysis early in the design process.

Building Information Modelling (BIM) is a digital model of a building's physical and functional features. It acts as a shared resource for information, helping with decisions throughout the building's life, from design to demolition. Some features of BIM include:

- Integrated Data: Combines 3D building models with detailed information about each part.
- Collaboration: Allows architects, engineers, contractors, and owners to work together using one model.
- Visualization: Creates 3D models to better communicate ideas and spot problems before construction starts.
- Lifecycle Management: Supports the building's entire life, improving efficiency and reducing costs over time.

Unlike traditional CAD, BIM handles more detailed building data, allowing better analysis and decision-making.

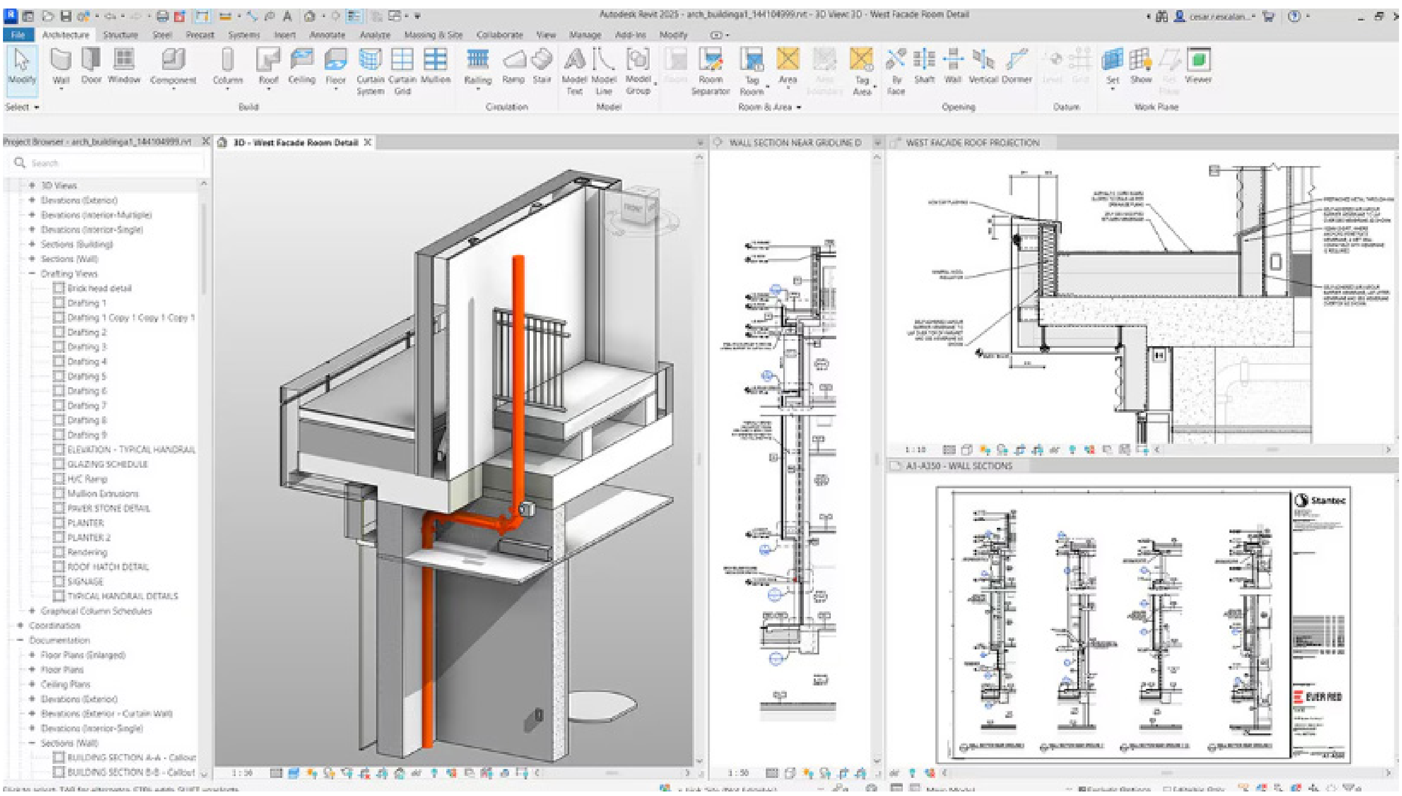


Figure 2.37

Revit interdace (Autodesk, 2025)

Building Performance simulation (BPS)

Building Performance Simulation (BPS) refers to the use of computer-based models to predict and evaluate the performance of buildings in terms of energy consumption, indoor environmental quality, and other critical factors. BPS tools enable designers to assess various design alternatives and their impact on a building's performance, promoting more informed decision-making.

Building Performance Simulation (BPS) is defined in this research as the scientific prediction of specific building performances using mathematical models based on fundamental physical principles. BPS relies on computer-controlled calculations and is considered essential for supporting and assessing the design of high-performing buildings (Malkawi, 2004).

The use of BPS enables the design team to make informed decisions during the exploration of architectural expressions and concepts throughout the design phases. Providing project-specific data on design performance can help improve the quality of the design (Negendahl, 2016).

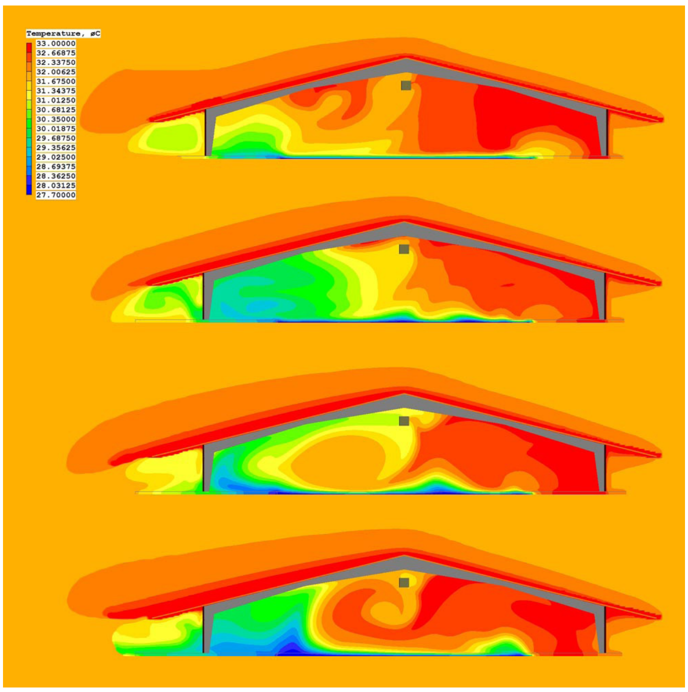


Figure 2.38

Building performance simulation (BPS)

The use of BPS for demonstrating building performance is not a new concept in itself. However, there has been an increasing use of BPS in recent years. This is because of stricter requirements created by new regulations or an increasing demand for high-performing buildings from the market, particularly in the context of sustainability (Negendahl, 2016).

Computational and parametric design

Parametric design has, in a short time, opened the door to groundbreaking new possibilities for design methodologies and their corresponding architectural designs (Harding, Joyce, Shepherd, & Williams, 2013). Today, it is well established within the so-called "computational design" community. Parametric design does not explicitly include the role of computation (calculations) or the type of process the designer uses it for. It simply means design as "a process where a problem is described using variables" (Hudson, 2010). Similarly, the term generative just describes something "with the power or function of generating, producing, or reproducing". Both terms can be applied to most, if not all, design processes.

Computational design encompasses a range of methodologies that use algorithms and computational processes to enhance design creativity and efficiency. It involves the application of advanced computational techniques to generate, analyse, and optimize complex designs. Parametric design, a subset of computational design, utilizes parameters and algorithms to control and manipulate design elements. This approach allows for the creation of flexible and adaptable models where changes to input parameters automatically update the design.

Within the domain of computer science, the process of applying an algorithm to input data to obtain an output is called computation ("Wolfram|Alpha," n.d.). In this research, computation is defined as the process of applying an algorithm to input to obtain output (that is, step-by-step procedures designed to solve a problem or complete a task) and their practical implementation in a computer program. Parametric design is defined in this research as "a design process in which a description of a problem is formulated using variables" (Hudson, 2010).

In mathematics, a graph is an abstract construction consisting of objects (nodes), some pairs of which are connected by links (edges). If the edges of the graph have a corresponding direction, the graph is a directed graph. The so-called directed graph is the fundamental data structure on which the most popular parametric modelling environments, such as McNeel's Grasshopper, Bentley's Generative Components, and Autodesk's Dynamo, are based. Within these parametric modelling environments, the user constructs components via a graphical interface, which are relationally connected with each other through wires. In this way, the directed graph is constructed. According to Davis, these environments are referred to as Visual Programming Languages (VPL). The main characteristics of parametric design include:

- Flexibility: Enables designers to explore multiple design variations quickly by adjusting parameters.
- Efficiency: Reduces the time and effort required to make changes, as the model updates automatically based on predefined rules and relationships.
- Optimization: Facilitates the exploration of optimal design solutions by analysing various scenarios and performance criteria.
- Integration: Combines geometric design with performance analysis, allowing for more holistic and sustainable solutions

"Conventional CAD systems focus design attention on the representation of the artifact being designed. Currently industry attention is on systems in which a designed artifact is represented parametrically, that is, the representation admits rapid change of design dimensions and structure. Parameterization increases complexity of both designer task and interface as designers must model not only the artifact being designed, but a conceptual structure that guides variation. (Aish & Woodbury, 2005) "

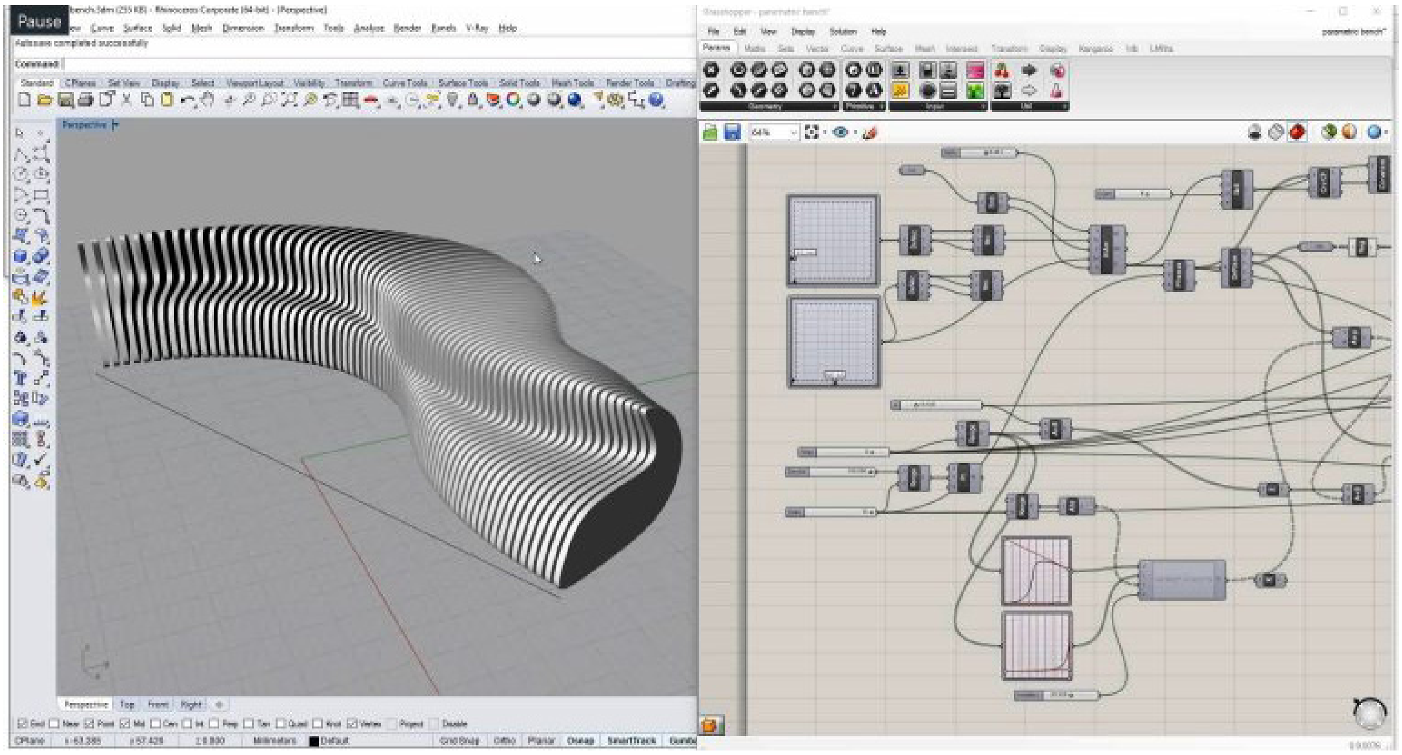


Figure 2.39

Rhino interface (Autodesk, 2025)

The integrated dynamic model

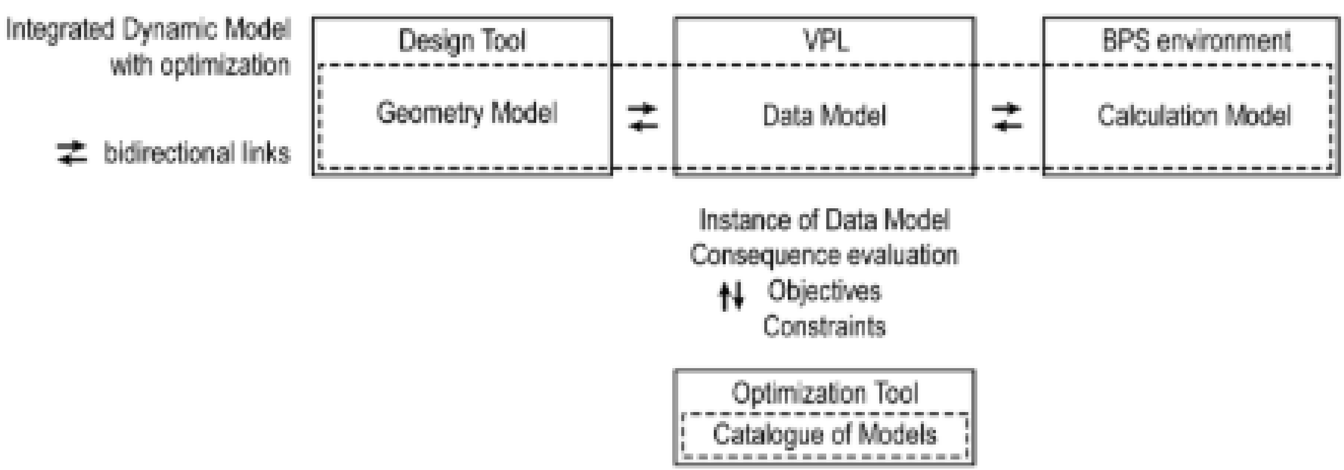
In a review, Negendahl (2016) describes an integrated dynamic model as a special type of distributed model that combines a geometric design tool that is directly connected to a visual programming language (VPL), which is also linked to a building performance simulation (BPS) system. The connection between these parts is called middleware and can be controlled by the simulation software, the building designer, both of them, or another person who isn't defined.

Visual programming languages (VPLs) like Grasshopper, Dynamo, GenerativeComponents, Digital Project, and Yeti are tools that designers, engineers and architects can use to automate the creation of forms. These VPLs allow design variables to remain flexible and adjustable (parametric), making it easy to use compared to traditional programming languages like Java or RhinoScript. Because VPLs work in real-time with design software, the connection between them is considered "dynamic," similar to how Zhai (2003) explains connections between building performance simulation (BPS) tools. Additionally, this integrated dynamic model approach can be used for evaluating multiple aspects of a design's performance, which is why it's considered "integrated," as described by Citherlet et al. (2001).

Sometimes, visual programming languages (VPLs) could be seen as design tools because they heavily rely on geometric modelling features. However, they are different from traditional CAD tools because VPLS are also able to handle non-geometric data and allow users to create their own algorithms (Negendahl, 2015a). VPLs are connected both ways with one or more design tools, such as Rhino, Revit, and MicroStation (Bentley, 2014), and they have real-time access to these tools' functions. VPLs linked to design tools can manage the exchange of geometric data, unlike BIM (Building Information Modelling), which focuses more on attribute-based data (Davis and Peters, 2013).

Optimization

Optimization can be described as a computer-driven process that involves changing user-defined values, known as design variables (x), to find solutions that depend on these variables. It is necessary to know that optimizing only works if it's clearly stated by the user what variables the computer can change and which functions or objectives it should focus on. In the early design stages, relevant variables might include building volume, window geometry, or façade type's. The design variables define a cost function F (x) that needs to be minimized or maximized, and are most likely subject to various sorts of constraints (Negendahl, 2016).



Integrated dynamic model (Negendahl, 2016)

Figure 2.40

2.4.2 Why computational design

"The truth of sustainable design is that approximately 80% of the design decisions that influence a building's energy performance are made by the architect in the early design stages, the remaining 20% are made by engineers at the later stages of design." (Solar Heating & Cooling Programme, 2010).

Most experts believe that decisions made during the early design stage have the biggest effect on the final design output. However, few building designs have been backed by early stage performance evaluations in areas of building energy consumption and interior environment (Augenbroe, 2002; Kanters et al., 2014).

In this part, the focus is on understanding why energy use, indoor environment, embodied energy, and embodied carbon are usually not considered together in the early stages of building design. The introduction of "parametric modelling" and the idea of using dynamic models to integrate these factors will be explored for a more complete understanding of building sustainability.
NL is using many types of incentives and regulatory methods to improve building energy performance; a few examples are:

- Energie-investeringsaftrek: This incentive allows businesses to deduct a percentage of their investment costs in energy-saving equipment and sustainable energy from their taxable profits. It encourages companies to invest in energy-efficient technologies and renewable energy sources.
- BENG (Bijna EnergieNeutrale Gebouwen): As of 2021, all new buildings in the Netherlands must comply with the BENG standards, which require buildings to have very low energy consumption, make extensive use of renewable energy, and meet strict requirements for insulation and energy performance. This regulation aims to significantly reduce the energy use and carbon footprint of new buildings.
- Investeringssubsidie duurzame energie en energiebesparing: This subsidy provides financial support to homeowners, businesses, and nonprofit organizations for the purchase of renewable energy systems such as solar panels, heat pumps, and biomass boilers, promoting the adoption of sustainable energy solutions.
- Energielabel C verplichting voor kantoorgebouwen: y 2023, all office buildings in the Netherlands must have the minimum energy label C. This rule encourages property owners to improve the energy efficiency of their buildings to meet with the norm, hence enhancing total building performance.

Most European countries have these incentives and they can be seen as "distant future goals," which are good ideas but hard for all countries to follow equally (Laustsen et al., 2011). Countries are at different stages of meeting these less strict requirements. For example, "nearly zero energy buildings" (NZEBs), or in the Netherlands BENG, are required by 2021 for all buildings and by 2019 for public buildings (Sutherland et al., 2013). The "Energy Efficiency Obligation" asks each country to save 1.5% of annual energy sales through efficiency measures. Countries like Germany and Denmark often set higher goals. The "20-20-20" targets aim for 20% cuts in emissions, 20% renewable energy, and 20% better energy efficiency by 2020 (European Parliament, 2009).

Also, many architectural studios and consulting engineers claim to be pioneers in sustainable design, often showing their design concepts online. However, there is a substantial gap between these objectives and the actual buildings built over the last decade. Building codes alone are insufficient (Laustsen et al., 2011) to ensure high-performance buildings, and 30% of modern buildings do not provide a healthy indoor environment (EPA, 1991). One issue is cost; clients may choose lower construction expenses to long-term operational expenditures. However, the issue is more complex than simply client preferences.

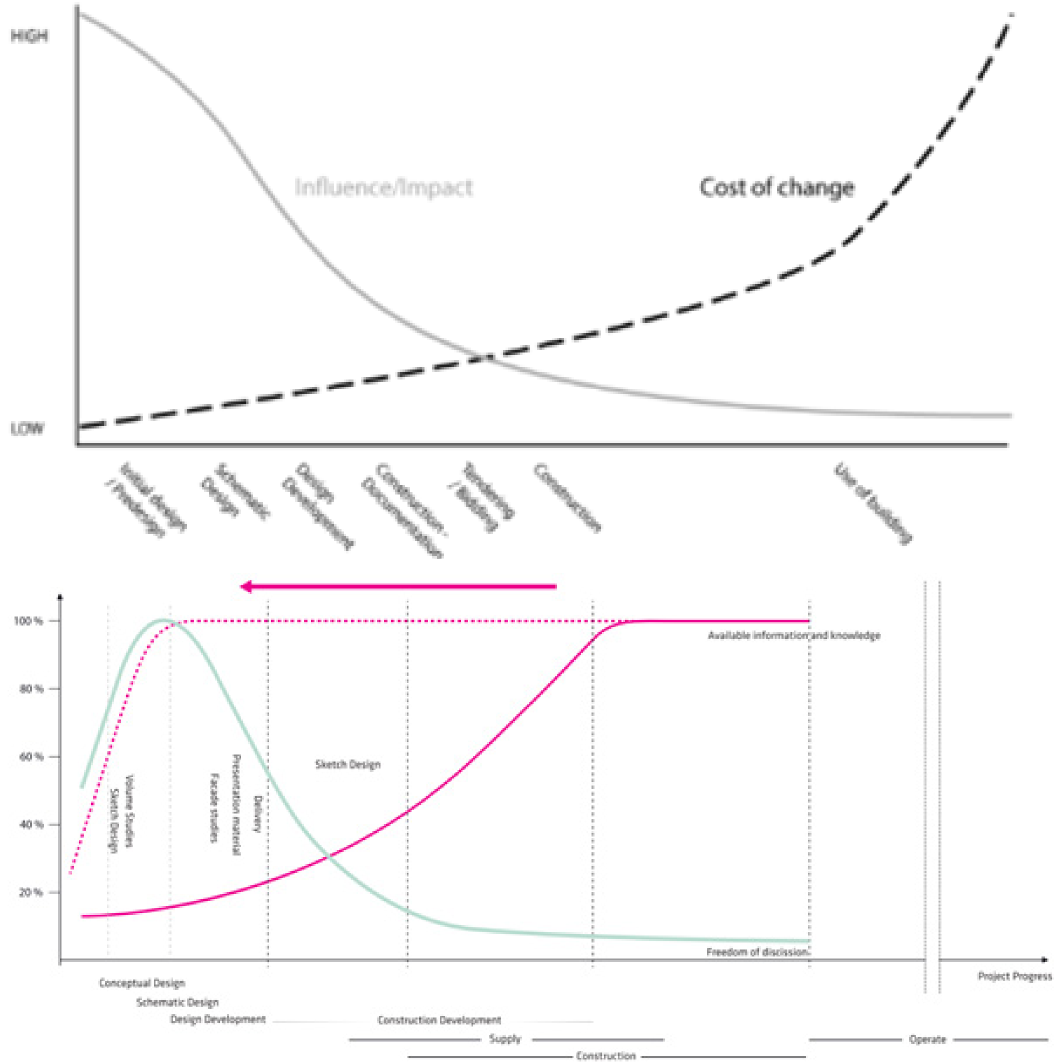
The cost of change

It's surprising that evaluations of life-cycle costs, energy use, and indoor environments are often left out of the early design stage in most building projects. These analyses are seen as costly because they require time and human resources, unlike physical upgrades like better ventilation or more insulation. Clients need to be convinced that these evaluations have value and can improve the building. They should invest wisely to make their buildings more efficient, green, and healthy in the most cost-effective way.

Often, the cheapest and best ways to improve a building are overlooked. One way to understand this is by looking at the cost of changes during design.MacLeamy (2013) explains that changes are expensive, but they cost less if made early in the design stage. Reducing changes early on can lower overall costs. MacLeamy's main point is to "contain changes as early in the design stage as possible." This means investing in thorough evaluations early to achieve cost-effective, high-performance building designs.

"In theory, a parametric model helps lower the cost of change if the manipulation of the model's parameters and explicit functions rebuilds the geometry with less effort than would otherwise be required from a designer." (Davis, 2013)

Parametric modelling not only reduces the cost of changes but also transforms the design process. It is used to analyse aspects from building envelopes and forms to materials and structures inspired by nature (Courtney L. Fromberg et al., 2015). Eastman (2011) notes



Different EPC scores trough the years. (Handelbouwadvies, n.d.)

Figure 2.41

that architectural expertise often relies on "rules of thumb" from past experiences. Parametric objects can incorporate this knowledge to create more precise solutions. Davis (2013) argues that instead of making early decisions to avoid costly changes later, parametric modelling allows for delaying critical decisions until they are better understood. This approach lowers the cost of changes, making the design process more flexible and efficient. By front-loading changes as suggested by Paulson (1976) and MacLeamy (2013), the cost and complexity of design alterations can be minimized (Davis 2013).

2.4.3 Optimization

Optimization in building design can range from manual and heuristic methods to fully automated processes. In this thesis, optimization is focused on computer-automated building performance optimization during the early design stage, making it a non-heuristic process. However, heuristic methods can still be useful in both early and later design stages. These approaches can also work with dynamic models, and combining parametric modelling with automated building performance analysis is an important part of Consequence-Based Design using dynamic models. The main advantage of computer-automated optimization is its ability to quickly solve complex problems.

Computer-automated optimization refers to using automated simulations and processes, such as generating variations in geometry, materials, and systems. Building on the information in given in this chapter, this section discusses how optimization can help designers by providing important building performance insights in the early design stage. Optimization is most effective when combined with integrated dynamic models. Making them useful for optimizing buildings to meet High-Performance Building standards. However, while these models are more effective than other tools available today, including qualitative objectives in the process remains a challenge (Negendahl, 2016).

Early Design Stage Optimization
"One of the problems with optimization is that not everything is captured by the fitness function" (Davis et al., 2014).

Current research almost never includes architectural design in the optimization process. Methods that handle non-quantifiable objectives, like aesthetics, are often based on heuristic approaches. As a result, optimizing building design that considers "architectural concerns" remains a relatively unexplored area (Negendahl, 2016). This is something to be careful of when using dynamic models.

When optimization is used in the early design stage, it tends to focus heavily on measurable, performance-based objectives. This is because most available optimization methods today mostly addresses the building performance, often involving pre- and post-processing steps to integrate design and performance optimization.

This process involves first defining clear objectives and boundaries (pre-process) and then selecting the best design alternatives (post-process) (Mora et al., 2008). As mentioned in before, early building design is complex, with many interacting quantitative and qualitative goals. In optimization, some objectives are hard to measure, and those that can be measured often require specific pre-processing rules unique to the project. Currently, human evaluations cannot be included in computer-automated optimization, so human input must occur in the pre- or post-process or both (Negendahl, 2016).

Pre-processing the mix of qualitative and quantitative objectives, along with their interactions, is complicated. As a result, optimization usually focuses on measurable (quantitative) objectives, and often only one or a few are chosen for building design optimization.

Optimization Algorithms
Designers today have many optimization algorithms to choose from. Here's a small overview of some popular algorithms. These algorithms can be used with integrated dynamic models through special tools or plugins like Galapagos, Octopus, and Goat, or with general tools like MATLAB.
Types of Optimization Algorithms
There are two main types of optimization algorithms: deterministic and stochastic.

Deterministic Algorithms: These methods use precise, systematic approaches. They are often slower but more reliable for finding exact solutions because they don't get stuck in local optima. Examples include brute force search methods, where all possible solutions are tested, and direct pattern search methods.

- Heuristic Search: Involves manually adjusting parameters and running simulations until the best solution is found. It's like trial and error.
- Complete Enumeration: Tests all possible solutions, which can be time-consuming.
- Random Search: Uses random sampling to find solutions and is sometimes called brute force.

Stochastic Algorithms: These methods use randomness to explore potential solutions. They can be faster and more flexible but don't guarantee finding the perfect solution. They might also be less predictable. Evolutionary algorithms, like Genetic Algorithms (GAs) and Simulated Annealing (SAs), fall into this category.

While many of these algorithms are relevant to dynamic modeling and optimization in design, more complex and advanced algorithms fall beyond the scope of this thesis. The focus remains on those most applicable and feasible within the context of this research.

Constraints
Some constraints on variables are needed for optimization as some conditions will have to be satisfied. Especially for the case of multivariate optimization, constraints serve towards fulfilling several needs.

If a constraint is placed on a dependent variable, if it is not complied with, a "penalty" or dedication function is utilized to the objective function. For instance, if thermal comfort is a focus of building design and one comfort criterion is not met then a high penalty in terms of adding cost to function such as the Percent of PPD can be imposed.

Another approach that is frequently employed is the use of Barrier functions that place a 'penalty' to the cost function where a certain variable moves toward the limit of the prescribed range. But Boundary functions should be approached carefully since they can be complicated due to the inability to properly set the limit. Some penalties do not exceed the limit but since they are too low, they create constraints on the optimization process causing problems to the entire optimization process.

Penalty approaches are common methods of accommodating multiple criteria within a single optimization task. Consequence entails violation of the set of tolerable limits and addressing equality requirements . In contrast to features such as Barrier functions, Penalty functions impose a positive penalty cost over the objective function once a constraint is saturated. These penalties become stiffer with increase in the violation of the regimes, that is it becomes increasingly for breaking any of the rule (Negendahl, 2016).

Optimization in Research and Practice
In practice, building performance optimization is not implemented most of the times during the early design phase (Kataras, 2010). The majority of research activity is targeted at later stages of design, considering some basic design features that are influential in

performance or applies optimization in areas that have no direct bearing on performance, such as form generation. Also, early design stage studies tend to concern simple forms of buildings, which constrains any relation to complex design processes (Negendahl, 2016).

Criteria for the Optimization Approach

As mentioned before, using optimization algorithms in the early design stage can be very useful for designers. Hermund (2009) warns that focusing too much on systematic optimization and reducing creative iterations could negatively impact architectural quality: "Linear working methods that promote the reduction of the creative loops in favour of systemic optimization is one topic that must be addressed by architects. Relying on one integrated model (referring to IFC- and gbXML-models) could mean an eventual loss of control with real value of the architectural quality: to create meaningful and beautiful spaces for real people."

Despite these concerns, the advantages of optimization can outweigh the loss of artistic control, especially if designers actively manage and oversee the process (Caldas and Norford, 2001). Therefore, the criteria for using optimization focus on improving support during the early design stage. This involves:

- Assisting rather than fully automating design
- Quickly generating integrated solutions
- Reducing the time needed for analysis and evaluation
- Helping in selecting the best design alternatives

2.4.4 Conclusions

This chapter explored the research question: "How is the integrated dynamic façade model developed, and how does its performance compare to traditional design software?" The findings illustrate that integrated dynamic façade models, combined with optimization techniques, significantly enhance early design processes compared to traditional methods.

Performance Comparison to Traditional Methods

Integrated dynamic and parametric models outperform traditional design tools by allowing for multi-objective performance optimization early in the design cycle. Traditional tools commonly lack the ability to integrate energy use, embodied carbon, and other simulation tools such as indoor environmental quality into a single environment, resulting in a fragmented manner of working and the need to return to prior iterations of design.

Parametric Modelling

Parametric modelling enables rapid prototyping and flexible changes to building design. Parametric tools lower the cost of change by incorporating design logic into the model while also providing designers with iterative feedback. This results in a more dynamic and informed design process than traditional static methods.

Optimization as a Design Tool.

Optimization was described as the process of adjusting design factors to obtain optimal solutions within given limits. This strategy, when used early in the design process, aids in the identification of cost-effective and high-performance solutions that are consistent with the principles of sustainable architecture.

Optimization Algorithms

The chapter described a variety of optimization techniques, including deterministic (e.g., Newtonian and direct pattern search methods) and stochastic approaches (e.g., genetic algorithms and simulated annealing). In this thesis, deterministic methods, particularly complete enumeration, will be used. This method systematically examines all possible solutions, allowing for a thorough investigation of the design space and the exact identification of optimal solutions. When deterministic methodologies are integrated into dynamic models, they can provide a full performance analysis and inform early design decisions.

Challenges and Considerations
Despite its benefits, optimization has several limitations. It frequently prioritizes quantitative objectives over qualitative ones, such as aesthetics and human-centered design, necessitating human intervention throughout the pre- and post-processing stages. Balancing methodical o

Concluding, To produce adaptive, performance-driven designs, an integrated dynamic façade model uses parametric modeling and advanced optimization techniques, including deterministic algorithms such as complete enumeration. Unlike typical design software, these models allow for:

- Enhanced flexibility and adaptability,
- Faster iteration cycles,
- Integration of sustainability metrics from the outset, and better support for early-stage decision-making.

Traditional tools frequently rely on sequential processes and fixed parameters, but dynamic models excel at managing complexity and multi-objective optimization. By employing complete enumeration in this thesis, the model ensures a thorough examination of design options, enhancing its potential to deliver high-performance, sustainable building designs. Thus, the integrated dynamic façade approach not only enhances building performance but also better matches with sustainable design objectives than traditional methods.

2.5 Dynamic Variables and Their Influence on Building Performance

This chapter investigates the effect of dynamic façade variables on the embodied and operational carbon of mid- to high-rise structures. The sub-question that guides this chapter is: “How do dynamic variables influence the embodied and operational carbon of mid- to high-rise buildings?” The chapter examines numerous factors such as thermal performance, shading, and flexibility to demonstrate how these elements contribute to the energy efficiency and sustainability of building designs. This study aims to establish how dynamic variables might improve building performance during the early design phase while minimizing environmental impact.

To analyse these effects, dynamic variables are categorized into three groups:

2.5.10 Façade-Related Factors
Includes thermal properties, glazing, shading, structural performance, air tightness, and façade-integrated energy systems, affecting both embodied and operational energy.

2.5.20 Environment-Related Factors – Covers urban context, wind, temperature variations, solar exposure, and overshadowing, influencing site adaptation, heat gain/loss, and ventilation.

2.5.30 Building-Related Factors – Encompasses energy generation, HVAC strategies, ventilation, and material choices, impacting system efficiency, energy loads, and lifecycle carbon footprint.

2.5.10 Facade-Related factors

2.5.11 Thermal Properties

The heat balance, especially the transmission is heavily affected by the thermal properties of the material used in the façade. The heat losses in the material have to be compensated by heating the building. Ensuring the building is well isolated can save a lot of energy.

the building skin can outperform external climate conditions by choosing materials with specific properties. These materials’ thermal qualities are determined by three energy-related characteristics:

Thermal conductivity Lambda (), measured in W/mK, represents a material’s thermal conductivity, indicating how easily heat transfers through it regardless of thickness. Lower values signify slower heat flow and improved insulation performance.

Thermal resistance (R-value) is given in m^2.K/W and provides the material’s resistance to heat flow through its surface area. The given thermal resistance can be used for opaque elements of façades, such as external walls. In multilayered materials, the overall R-value is the sum of the thermal resistivity of each layer. A high R-value means better insulation. However, the R-value only accounts for heat transfer via conduction, excluding convection and radiation.

Thermal transmittance (U-value), measured in W/m².K, reflects how much heat passes through a material. A lower U-value means less heat transfer, signifying better insulation. Unlike the R-value, the U-value takes into consideration all three heat transmission modes: conduction, convection, and radiation.

According to the Bouwbesluit 2012, the external envelope must have a minimum R-value of 3.5 m²K/W (Bouwbesluit, 2012). For windows, doors, and frames, the maximum permitted U-value is 1.65 W/m²K (Rijksoverheid, 2012). The Lente Akkoord (2019), a government initiative, suggests initial R-values of 5, 7, and 8 m²K/W for floors, walls, and roofs, respectively (Lente Akkoord, 2019).

Figure 2.42

Thermal photo of a rowhouse

2.5.12 Window to Wall Ratio

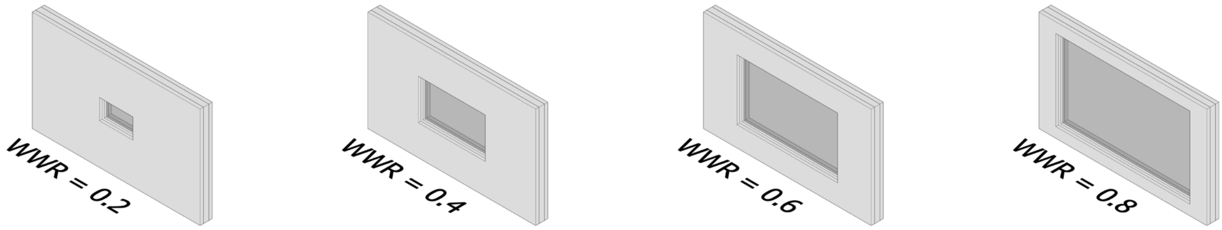
The Window to Wall Ratio (WWR) has an important role in controlling a building's energy efficiency, thermal performance, and overall comfort. Simply put, it is the percentage of a window area with respect to wall area, and handling this ratio well is important in terms of sunlight, heat, and natural light control indoors. While a high WWR can improve daylighting and reduce the need for artificial lighting, it can also reduce space for energy-generating systems like solar panels and increase heat loss or gain, making temperature regulation more difficult.

According to Raji, Tenpierik, and van den Dobbelsteen (2017), a WWR of 20-30% is optimum in temperate climates without the use of any shading devices. However, Goia et al. (2013) found that adding external shading allows a higher ratio of 35-45% to perform well. The optimal WWR varies based on factors like the building's orientation and thermal performance and can go up to 60% with high-performance glazing and shading. Beyond that, higher ratios increase heat transmission through the windows, which can raise energy use by as much as 10%. For daylighting and visual comfort, Ochoa et al. (2012) recommend window ratios between 50% and 70%, striking a balance between brightness and energy efficiency.

Steemers (2002) adds that WWR should be adjusted for not only orientation but also building height. On lower floors, nearby buildings may block sunlight, while upper floors get more direct sunlight, increasing the risk of overheating. In London, Steemers (2002) found that ground floors benefit from a WWR of 38%, while taller buildings should reduce it to 25% as height increases to control solar heat gain.

Additionally, changes in WWR not only impact operational energy but also embodied carbon, which depends heavily on the materials used. If the closed portions of a facade have high embodied carbon, reducing window size can be more efficient. However, if the window materials themselves have a higher relative embodied carbon footprint, it becomes more sustainable to keep windows smaller to minimize their environmental impact.

In summary, WWR is a vital element in building design that requires careful consideration of climate, building orientation, height, and technologies like glazing and shading. Windows significantly impact a building's carbon and energy footprint because of their influence on heating, cooling, and lighting needs. While larger windows can improve natural light and reduce artificial lighting,



Window to wall ratio's (Vedder, 2025)

Figure 2.43

they can also compromise thermal efficiency. Additionally, WWR affects both operational energy and embodied carbon, meaning the sustainability of different facade materials plays a crucial role in determining the ideal ratio. Striking the right balance in WWR, tailored to each facade and floor, is key to optimizing energy use, comfort, and environmental impact.

2.5.13 Glazing

Glazing choice and influence are closely related to the window-to-wall ratio. Together, these factors should optimize the daylight factor and provide views to the outside while maintaining indoor temperatures. Four important parameters in selecting glazing are the U-value, SHGC/g-value, g-value, and VLT.

- U-value [W/m²K] - Heat transmission coefficient
- SHGC/g-value - Solar heat gain coefficient
- VLT [%] - Visible light transmission
- LSG - Light to solar gain ratio

Heat Transmission Coefficient (U-Value)

The U-value measures heat transfer through a building component and is the opposite of the R-value, which represents a material's resistance to heat flow across a given thickness. A lower U-value indicates less heat loss, while a higher R-value indicates better insulation. The U-value is commonly used for rating windows and doors, while R-value is used for insulation materials. In the Netherlands, the Bouwbesluit specifies a

$$U = 1/R \quad [5]$$

$$R = r_e + r_{glass} + r_{cavity} + r_{glass} + r_i \quad [6]$$

$$r = d/\lambda \quad [7]$$

$$\lambda = a + r + t \quad [8]$$

The heat resistances for inside and outside are standardized in the dutch regulations and are:

re=0.04 m²K/W
ri=0.13 m²K/W

U-value [W/m²K] = heat transmission coefficient
R-value [m²K/W] = thermal resistance
d [m] = thickness of the material
λ [W/mK] = thermal conductivity of the material

a=absorption coefficient
r=reflection coefficient
t=transmission coefficient

Glazing formula's

Figure 2.44

maximum U-value of 1.65 W/m²K for windows (Bouwbesluit, 2012).

Solar Heat Gain Coefficient (SHGC)

The SHGC, also known as the g-value, defines how much solar radiation passes through glazing into a building. It varies between 0 and 1, where 1 means that 100% of solar energy is transmitted, while 0 denotes that none is transmitted. For example, single-pane glass has an SHGC of 0.8, which means that it transmits 80% of solar heat and reflects 20%. The SHGC can be very important as it affects energy efficiency. High SHGC glazing results in increasing summer cooling loads but when there is a low SHGC glazed window requires heat gain during winter. An optimal SHGC balance is needed to minimize both heating and cooling demands throughout the year. This can be reduced by using techniques like colour tints, reflective coatings, and low-e coatings can reduce the SHGC.

Visible Light Transmittance (VLT)

VLT (Visible Light Transmittance) refers to the percentage of visible light that travels through glazing, which affects visual comfort. VLT is expressed as a percentage, and the higher the VLT value, the more light the building allows in; the value of 0% then indicates that no light is transmitted

Light to Solar Gain Ratio (LSG)

The light-to-solar gain ratio (LSG) describes the relationship between a glazing's visual light transmittance (VLT) and solar heat gain coefficient (SHGC). A higher LSG value indicates that the glass allows enough of natural light, decreasing the need for artificial lighting and limiting undesired heat input.

LSG=VLT/SHGC

LSG - light to solar gain ratio
VLT [%] - visible light transmittance
SHGC - solar heat gain coefficient

Figure 2.45

Glazing formula's formula's

Energy efficiency highly depends on the balancing of glazing properties. According to Lang (2009), in the US, poor choices of glazing result in wasting 25-35% of a building's energy consumption. The use of multi-pane systems such as double- and triple-glazing is common in achieving better insulation. Gaps between the glass panes can be be filled with various insulating gasses like air, argon, and krypton. By doing so, for example, double glazing with argon can achieve the U-value of 1.2 W/m^{2}K, and triple-glazed units with krypton lower it to 0.6 W/m^{2}K (Schittich, 2006). Doubling or tripling does also influence the g-value. Standard double glazing has a g-value of about 60%, dropping to 50% for triple glazing, and down to 40% with solar-selective coatings (Schittich, 2006).

In temperate climates, the its important to minimize winter heat loss while optimizing passive solar heat gains. A lower U-value reduces heat loss, but a higher U-value can allow for beneficial heat gains, although this can lead to overheating in summer.
VT depends upon the kind of glazing, number of panes, and coatings. Clear glass normally will have higher VT than the coated and tinted glass types. Some glazing is spectrally selective, offering limited heat transfer while allowing enough daylight. Coatings like Low-E has been very effective in temperate climates. It reduces solar heat gain in summer and heat loss during winter.

Some examples:

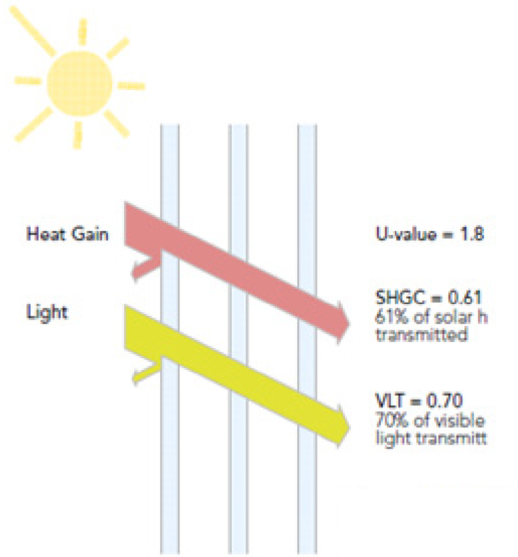


Figure 2.46

Glass properties

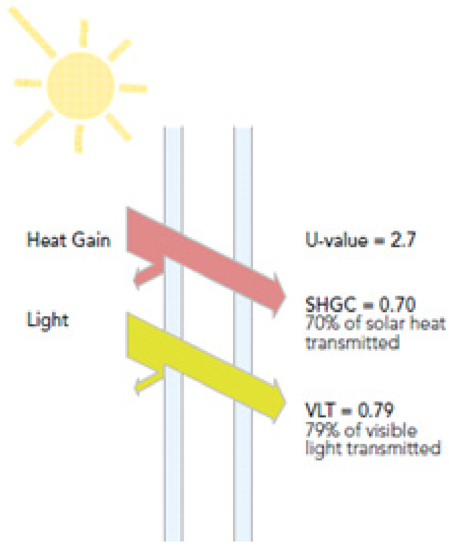


Figure 2.47

Glass properties

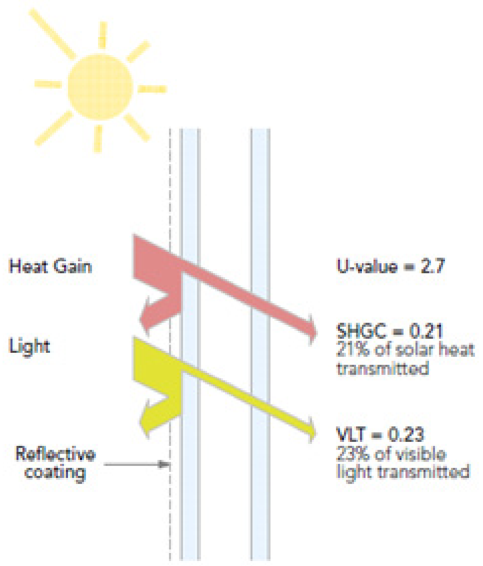


Figure 2.48

Glass properties

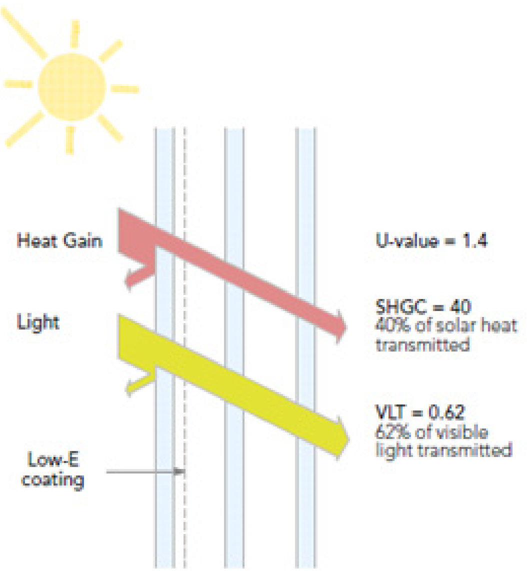


Figure 2.49

Glass properties

Laminated Glazing
Source: Efficient Windows Collaborative, n.d

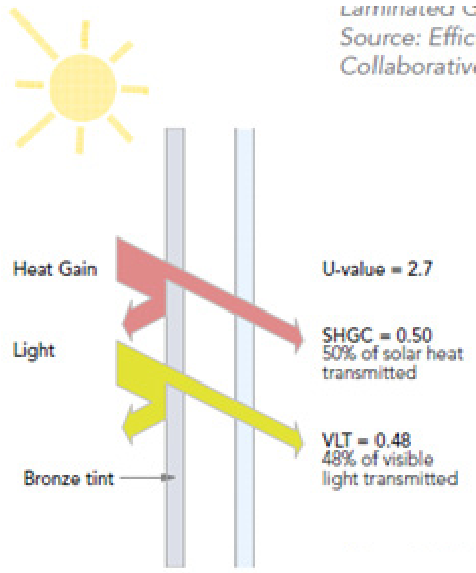


Figure 2.50

Glass properties

2.5.14 Air Tightness

According to Sherman and Chan (2004), a building's airtightness aids in preventing the entry of heat, moisture, and air through gaps, leaks, and cracks. It can be especially important in high-rise buildings to avoid pressure differentials created by strong winds on upper floors. Airtightness not only lowers energy use but also improves indoor air quality. Reduced air exchange between the interior and outdoor environments does add the need for an effective ventilation system that provides fresh air circulation while minimizing heat loss, which affects both cooling and heating demands.

In the Netherlands, NEN 2687:1989 specifies the requirements for energy-efficient building design. According to Nieman (2020), an air permeability rate of 0.3 to 0.6 $dm^3/s.m^2$ indicates good airtightness quality in class 2 buildings.

2.5.15 Additional Façade Considerations

Aside from the parameters used in the simulations discussed in this chapter, other façade-related factors influence both embodied and operational carbon. Shading, adaptability, material selection, structural qualities, energy generation, acoustic performance, safety glass, fire protection, and ventilation via the façade all have an impact on embodied and operational carbon. While these aspects were eliminated from the primary simulations due to complexity, their significance is recognized. The appendix contains a more extensive review of their possibilities for future study and improved simulation models.

Shading devices limit solar heat gain, improve comfort, and reduce cooling requirements. Exterior treatments such as overhangs and louvers effectively block sunlight, whereas dynamic solutions can maximize daylight management. Orientation-based shading is the most effective, with horizontal devices for south-facing façades and vertical systems for east/west orientation.

Adaptability and Modularity Improve efficiency and sustainability by allowing for changes, material recycling, and upgrading in accordance with circular construction concepts.

Material Selection and Lifecycle Impact has an impact on both embodied carbon and durability. Key considerations include recyclability (e.g., aluminum, glass), low-carbon alternatives , and long-lasting materials such as anodized metal.

Energy generation using façade-integrated photovoltaics (BIPV) optimizes renewable energy utilization, particularly in high-rise structures with limited roof space. Monocrystalline and polycrystalline PV panels have varied efficiencies, which contribute to overall building performance.

Ventilation Through the Façade improves indoor air quality and thermal comfort by using operable windows, double-skin façades, and pressure-balanced systems. These technologies help to manage airflow, minimize reliance on mechanical ventilation, and boost energy efficiency.

Safety Glass and Fire Safety is essential for occupant safety in mid to -highrise. Laminated and tempered glass improve impact resistance, and fire-rated glazing enhances fire safety by containing flames and smoke while retaining visibility and structural integrity.

2.5.20 Environment-Related factors

2.5.21 Site Surroundings

The different type of urban area can have an important role on a building's relative height and interaction with the surrounding environment. Tall nearby structures can overshadow facades, this leads to less solar gain. Also nearby strucres can obstruct wind. Low-rise locations have less interferences. As a result, the lower and upper levels of high-rises have different conditions.

For example, Ellis and Torcellini (2005) found that heating and cooling demand increased from the lowest to the highest floors of a Manhattan office tower, owing mostly to overshadowing by surrounding structures. Additionally, research reveal that building height can cause a 2.5-fold increase in energy use, compared to 2.0 from system efficiency or user behavior. The surrounding urban context alone could explain a 10% difference in energy performance (Godoy-Shimizu et al., 2018).

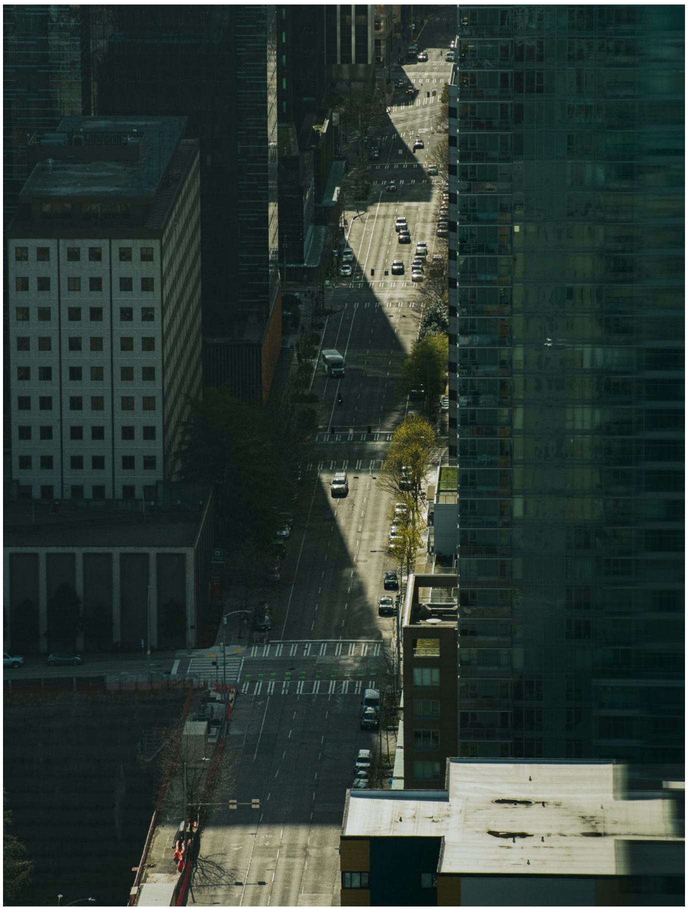


Figure 2.51

Buildings completely overshadowed

2.5.22 Orientation

The direction of a building effects solar exposure, which affects energy performance. Proper orientation can increase solar energy production and daylight access while reducing cooling demands. According to studies, daylight availability is determined by height and orientation, with nearby buildings having an impact on performance. (Godoy-Shimizu et al., 2018). To achieve the best outcomes, orientation should be consistent with the building's layout, compactness, and envelope elements.

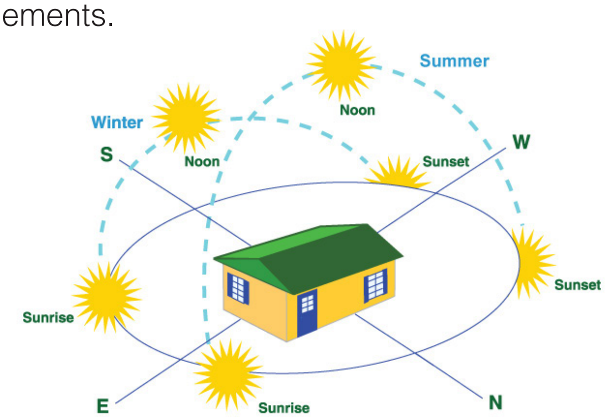


Figure 2.52

Building orientation

2.5.33 Environmental Parameters in High-Rise Buildings

As the building height increases, problems like temperature variation, wind pressure, and direct sun and daylight variation, affecting energy usage and comfort (Godoy-Shimizu et al., 2018).

Temperature variation occurs when outdoor air temperature decreases with altitude, affecting insulation and HVAC loads. I did not take this variation into account, though, to simplify the simulation.

Wind pressure increases in higher floors, influencing infiltration rates and energy demand. As much as this condition influences building performance, it was not considered in the simulation to keep things simple.
Direct sun and daylight exposure is greater at upper levels, reducing the need for artificial lighting but increasing cooling demand. Rather than incorporating these climatic differences into the simulation, I distinguished mid- and high-rise buildings based on design strategies and detailing. A more detailed discussion of these environmental influences can be found in the appendix.

2.5.30 Building-Related factors

2.5.31 Floor Plan Layout

The organization of the floor plans has an important effect on building geometry as well as heat input and loss through the envelope. The geometric type, plan depth, plan-to-wall ratio (floor height), and function/occupancy distribution are all important considerations.

Deeper floor layouts, for example, may reduce the amount of façade surface area exposed to external factors, potentially reducing heat loss while limiting natural daylight access. Meanwhile, a well-designed plan layout can assist distribute heat more evenly and influence energy efficiency by catering to the diverse needs of various building functions and occupancy levels.

2.5.32 Compactness

A building's compactness ratio is the ratio of its external surface (envelope area) to total volume (Raji et al., 2017). Studies demonstrate that when compactness rises, energy usage lowers. This is found to be true in hot and cold climes. Raji et al. (2017) discovered that energy-efficient designs have a 1:1 and 3:1 compactness ratio, which correspond to square and rectangle forms, respectively.

Compactness also has a negative correlation with the window-to-wall ratio (WWR), as a smaller surface limits window openings, reducing heat transmission, solar gains, and ventilation. When employing a lower WWR, glazing qualities must be tuned to maximize heat gain and daylight. Compactness also influences the possibility for energy generation from the façade.

2.5.33 Ventilation

Ventilation systems have the goal to provide heat, cooling, and fresh air to buildings. this way occupants are healthy and comfortable. They assist in controlling indoor temperature and humidity while also eliminating unwanted odors that could hinder concentration and could contribute to sick building syndrome (SBS) (Gonçalves, 2015).

Mechanical Ventilation
Before air conditioning was developed in 1950, passive design principles were the primary approach in high-rise building construction, using orientation, geometry, lighting, and natural ventilation to control inside climate. The introduction of air conditioning facilitated the development of 'glass-box' buildings with larger glazing ratios. These fully air-conditioned high-rises, featuring curtain wall facades and innovative architectural designs, became possible because mechanical climate control allowed buildings to be designed independently of environmental conditions (Gonçalves, 2015).

PV panels on facade **Figure 2.53**

Centralized systems control air temperature from a single unit within the building, whereas decentralized systems have individual units regulating air temperature in different areas. Centralized HVAC systems, in high-rise building especially can require entire floors to handle the massive quantities of air that must be filtered. They are also less efficient due to the lengthier ductwork and the possibility of duct leaks. High-rise buildings, on the other hand, benefit more from decentralized systems that are integrated into the building envelope.

Research suggests that users who have greater control over their ventilation experience higher satisfaction with temperature variations (Wood & Salib, 2013). In this regard, natural ventilation helps balance energy efficiency and thermal comfort.

In high-rise buildings, double-skin facades are sometimes implemented to reduce wind speeds and preheat incoming air before it reaches the interior. However, the effectiveness of natural ventilation depends on wind pressure against the facade. Additionally, the size of ventilation openings is influenced by the building's height.

2.5.34 Electric Load

A typical Dutch apartment's approximate electricity use, excluding lighting, is 2 W/m². This value is simplified and rounded based on reported usage levels. The electrical load is balanced by not using occupancy schedules and was adjusted to match a baseline situation for typical energy-efficient apartments in the Netherlands that rely solely on electric installations, without gas appliances. This electricity load, along with heat released from occupants and lighting, plays a crucial role in the overall heat balance.

2.5.35 Lighting Load

A typical Dutch apartment's approximate electricity use for lighting is 3 W/m². This value is simplified and rounded based on reported usage levels. The electrical load is balanced by not using occupancy schedules and was adjusted to match a baseline situation for typical energy-efficient apartments in the Netherlands that rely solely on electric installations, without gas appliances. This electricity load, along with heat released from occupants and appliances, plays a crucial role in the overall heat balance.

2.5.36 People Load

A residential mid to high-rise structure has an average occupancy density of 0.02 people/m². This number was discovered in an article about a comparable study by Méndez et al. (2022). Where 0,028 people/m² was utilized, but with an attendance schedule. A lower figure was chosen to represent average, rather than maximum, occupancy for a mid- to high-rise apartment in the Netherlands. This modification attempts to simulate daily use without the schedule scheduled peak situations. The amount of people is important because their release of heat influences the heat balance.

2.5.37 HVAC Inputs

For energy performance modeling, a typical Dutch apartment is used as the basis. The operational carbon result will vary if HVAC systems or input values are changed. However, since this research is foccuessed on the impact of façade design and its parameters, dynamic analyses are conducted primarily on them. Still, HVAC inputs play a significant role in operational carbon emissions, and thus they are also an essential area to focus on in the overall energy assessment.

Heating Setpoint (21°C)
The heating setpoint of 21°C is the indoor temperature at which the heating system is engaged. Méndez et al. (2022) offer a slightly higher figure of 21.7°C for heating in residence, which was rounded down to 21°C to match conventional comfort criteria and energy calculations for Dutch residential buildings. This figure is usually considered as a baseline for thermal comfort during the colder months.

Heating Supply Temperature (35°C)
When using an radiant floor heating system, the surface temperature is typically 25°C from the heating supply. This was not possible for use in grasshopper, but a similar system was created with the normal "ideal air" component. This figure reflects the use of low-temperature heating systems, which are common in modern residential buildings in the Netherlands due to their energy efficiency and compatibility with renewable energy sources.

Heating Limit (75 W/m²)
The heating limit of 75 W/m² indicates the maximum output of the heating system. This parameter was chosen to imitate the performance of a radiant floor heating system, which has been slightly simplified for the purposes of this study. This score represents the ability of such systems to maintain comfortable indoor temperatures even in the coldest weather conditions common in the Netherlands.

Cooling Setpoint (25°C)
The cooling setpoint of 25°C is the inside temperature when the cooling system starts. While Méndez et al. (2022) suggest for a lower setpoint of 24.4°C, the higher value of 25°C was chosen to maximize energy efficiency and reflect a more passive cooling technique suitable for moderate locations such as the Netherlands. In addition, the maximum temperature exceedance hours are estimated for temperatures above 25 degrees. This strategy tries to decrease cooling energy use while ensuring adequate thermal comfort.

Cooling Supply Temperature (15°C)
The cooling supply temperature of 21°C represents the temperature of air or water delivered by the cooling system. This value is typical for cooling systems such as chilled beams or air conditioning units in energy-efficient residential applications. It ensures that the system can deliver adequate cooling performance under peak conditions.

Cooling Limit (60 W/m²)
The cooling limit of 60 W/m² is the maximum cooling system output per square meter. This value was selected to represent the typical capacity of HVAC systems used in Dutch residential high-rises, ensuring that the cooling system can meet the demands of warmer weather while operating efficiently.

Sensible Heat Recovery (0.5)
A sensible heat recovery efficiency of 0.5 indicates that 50% of the heat from exhaust air is transferred to incoming air through the ventilation system. This value reflects the performance of standard heat recovery ventilators commonly used in residential buildings to reduce heating and cooling loads. It provides a realistic efficiency benchmark for the simulation.

Cooling Coefficient of Performance (COP = 3)
A cooling COP of 3 reflects the efficiency of the cooling system, meaning it provides three units of cooling for every unit of electricity consumed. This value represents a baseline for air-source cooling systems that are commonly used in Dutch residential buildings. Cooling has a lower COP than heating.

Heating Coefficient of Performance (COP = 4)
The heating COP of 4 represents the efficiency of the heating system, such as a heat pump. This value reflects the performance of air-source or ground-source heat pumps under Dutch climate conditions, where renewable energy sources and efficient heating systems are more and more used in residential applications. Heating COP is more efficient than cooling.

Economizer (Differential Dry-Bulb)
The differential dry-bulb economizer is an energy-saving strategy that uses cooler outdoor air to provide free cooling when conditions are favorable. This is a standard setting in Grasshopper simulations and was retained for this analysis as it aligns with efficient cooling practices in climates like the Netherlands. It reduces mechanical cooling demand and energy use.

2.5.40 Conclusions

The research question this chapter tried to answer is: “How do dynamic variables influence the embodied and operational carbon of mid- to high-rise buildings?” This chapter investigated the impact of dynamic façade variables by examining their effects on building performance through a detailed analysis of three interrelated categories. First, the different variable where subdivided in three types of variables, façade-related factors, environmental-related factor and building-related factors.

façade-related factors were discussed in terms of how thermal properties, glazing, and window-to-wall ratios affect heat transmission, insulation, and ultimately energy consumption. Next, envi-ronmental-related factors were explored by considering how the building’s orientation, surround-ing urban context, and climatic influences alter solar exposure and ventilation, thereby impacting both heat gains and losses. Lastly, building-related factors were analysed by assessing aspects such as floor plan layouts, compactness, and ventilation strategies that dictate the overall geom-etry and energy distribution within a structure. All these variables together create the embodied and operational carbon. This highlights the importance of an integrated design approach. By con-sidering how material properties, environmental conditions, and architectural layouts interact, designers can develop more energy-efficient and sustainable buildings.

Moving forward, specific parameters are selected within each category to build the dynamic fa-çade element in the computational model. For façade-related factors, changes will be made to the window-to-wall ratio (WWR), the U-value of windows (u-window), the R-value of closed façade parts (RC-closed parts), and the g-value of windows (G-window). These changes aim to optimize the balance between thermal insulation, and solar heat gain and the embodied carbon of the used materials. This way the consequences can be observed in both the embodied and operational carbon.
In the environmental category, the building’s orientation will be adjusted to observe the influence of solar exposure and improve solar gains while minimizing overheating. Finally, within the building-related factors, the compactness of the model room will be modified to reduce the external surface area relative to the building volume, thereby lowering energy losses and enhanc-ing overall energy efficiency.

In addition, the computational design chapter provides a clear overview of both the dynamic and fixed variables discussed here. It explains how each variable is presented and measured, and it shows the number of different types and combinations created in the model.
This straightforward breakdown helps us understand the full range of dynamic façade performance. By combining these different variables in the analysis, the study carefully evaluates how each one affects both embodied and operational carbon.

3.

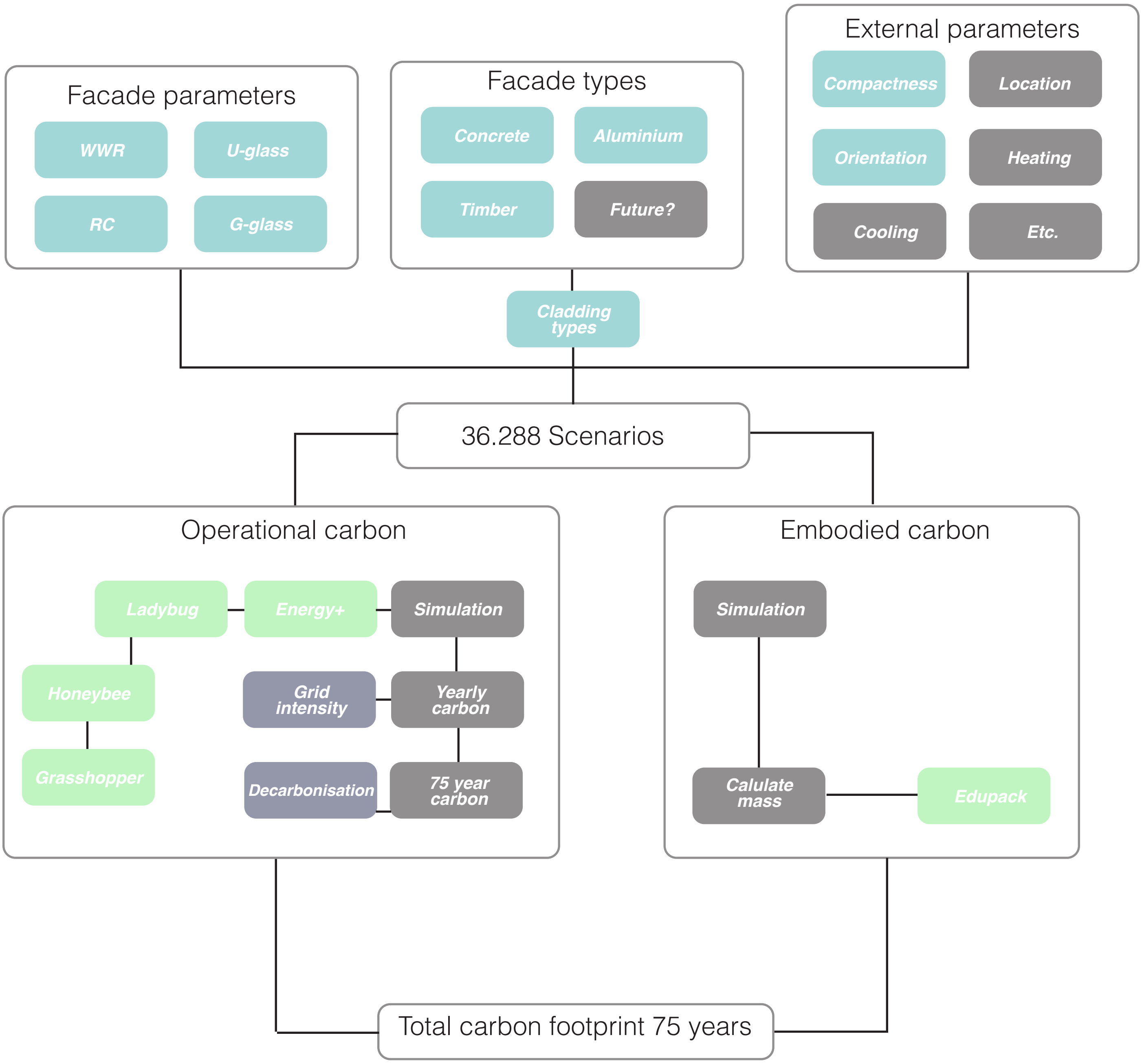
Computational Design

3.1 Computational workflow

This chapter introduces the computational framework developed for this study, which integrates various software and plugins to optimize façade design for energy efficiency and occupant comfort. The framework leverages parametric modeling, environmental simulation, and data analysis tools to enable a dynamic and responsive approach to sustainable design.

The computational framework relies on Rhino and Grasshopper as core modeling platforms, enhanced by specialized plugins including Ladybug, Honeybee, EnergyPlus, and OpenStudio. These tools enable iterative design analysis, allowing precise evaluation of energy performance, thermal comfort, and daylighting within the design workflow.

3.1.1 Overview of The Framework



3.1.5 Overview Of The Inputs

Dynamic variables	
Window wall ratio	0.2 0.3 0.4 0.5 0.6 0.7 0.8
	7
Facade orientation	North South West East
	4
Wall assembly	Concrete HSB ALU
	3
U-glas	1 1.5 2 2.5
	4
G-value	0.8 0.65 0.5
	3
Rc-closed	4.5 6
	2
Compactness	1 1.5 2
	3
Facade claddings	Concrete 100 Brick 100 wood 40 Aluminium 7 Keramiek 40 brick strips 30
	6
Total variations	36288

Fixed variables			
Weatherfile	Amsterdam	Amsterdam	
Program			
	Elecric load	2	W/m2
	Lighting load	3	W/m2
	People load	0.02	People/m2
	Infiltration	0.000241	m3/s/m2
HVAC inputs			
	Heating setpoint	21	C
	Heating suply temp	35	C
	Heating limit	75	W/m2
	Cooling setpoint	25	C
	Cooling suply temp	15	C
	Cooling Limit	60	W/m2
	Heat recovery	0.5	
	Cooling COP	3	
	Heating COP	4	
	Economizer	DifferentialDryBulb	
	Carbon intensity	268.5	g/kWh

In this study, dynamic variables are those that can be adjusted or modified to analyze their impact on both embodied and operational carbon. These variables are flexible and play a significant role in optimizing building performance through computational modeling. On the other hand, fixed variables remain constant throughout the analysis to provide a controlled environment for evaluating the effects of dynamic variables without introducing unnecessary variability.

Why Some Variables Are Dynamic

Dynamic variables are selected based on their ability to significantly influence energy performance and carbon emissions. These include:

Façade-Related Factors

Window-to-Wall Ratio (WWR): Adjusting WWR impacts daylight penetration, solar heat gains, and insulation.
U-value of Windows (U-window): This determines the thermal performance of glazing, affecting heat retention and losses.
R-value of Closed Façade Parts (RC-closed parts): Changing this impacts insulation properties and overall heat transfer.
G-value of Windows (G-window): Modifications influence how much solar radiation enters the building, affecting cooling loads.

Environmental-Related Factors

Building Orientation: This is a key factor in determining solar exposure, heat gain, and natural ventilation potential. Adjusting the orientation helps balance solar gains and overheating risks.

Building-Related Factors

Compactness of the Building Form: Changes to the building's shape and external surface area affect heat loss and energy efficiency. A more compact design reduces energy consumption by minimizing exposed surfaces.

Why Some Variables Are Fixed
Fixed variables remain unchanged to maintain consistency in the analysis and isolate the impact of façade-related modifications. While these variables significantly influence operational carbon, they are kept constant to prevent excessive complexity in the study. Examples include:

HVAC Inputs: Heating, ventilation, and air conditioning (HVAC) systems greatly affect energy consumption, but they are fixed to focus on façade-driven changes.
Occupant Load: The number of people in the building influences energy use, but it remains constant to eliminate behavioral variations.
Electric Load: Equipment and appliance energy use is fixed to avoid additional layers of complexity.Lighting Load: While lighting plays a role in operational energy demand, its impact is not varied in this study.

These factors undeniably contribute to operational carbon, but the focus of this research is on different façade configurations. With over 30,000 simulations already conducted, introducing additional variables such as HVAC and internal loads would require an entirely separate thesis. By keeping these factors fixed, the study remains focused on how dynamic façade elements influence both embodied and operational carbon in mid- to high-rise buildings.

3.1.2 Software and Plugins

Grasshopper
Grasshopper was chosen because of its easy interface with Rhino 7 and ability to enable complicated parametric modeling and iterative design methods. Its visual programming interface allowed for dynamic, programmable algorithms that were simple to understand for students with little to no programming knowledge, making it an ideal base for connecting multiple simulation tools. The program is freely available to TU Delft students, making it suitable for academic use. Also, its application in other similar theses and PhD studies enabled the validation of simulation-generated data. These works also included practical examples and tutorials, which helped to overcome the learning curve and ensure the correctness of simulations.

Ladybug
Ladybug's ability to simulate and visualize environmental factors such as sun radiation, wind, and temperature makes it valuable for assessing climatic implications on building performance. Furthermore, by including Amsterdam's 2018 weather data, it provided site-specific insights for optimizing design parameters like as orientation and solar gains. Its use in other academic research validated its trustworthiness, and reference studies provided advice on how to use its instruments effectively for this thesis.

Ladybug's underlying knowledge was acquired during a Building Technology course, which provided an overview of its capabilities and prospective uses. Ladybug, as a free tool, was also very accessible, making it an ideal choice for academic use at TU Delft.

Honeybee
Honeybee was chosen for its ability to perform advanced energy and daylighting analysis, which extends Ladybug's usefulness. Its connection with EnergyPlus and Radiance allowed for thorough simulations of heating, cooling, shading, and natural ventilation methods.

just like honeybee and grasshopper Honeybee's bedrock knowledge was also acquired during a Building Technology course, which covered the fundamentals of its functionality and potential applications. Honeybee was easily accessible as a free tool, making it a practical and cost-effective solution for academic use at TU Delft.

EnergyPlus
EnergyPlus is the thermal and energy simulation engine, which allows users to calculate heating and cooling loads. It takes

into account contextual geometry, wind speed, and temperature differences based on height, making it easier to analyze natural ventilation, shading systems, and thermal comfort. The program is free to use, and there are numerous free tutorials available, making it easy to integrate into the project.

EnergyPlus integrates effortlessly with Ladybug and Honeybee, and it may also be used directly within Grasshopper, making it a versatile and valuable tool in the computational framework.

Openstudio
OpenStudio acts as an interface for Honeybee's EnergyPlus and Radiance simulations. By combining lighting, ventilation, and energy data, it provides an overview of the building's energy performance, allowing for quicker sustainable design decisions. The application is free to use, and tutorials are easily accessible on platforms like as YouTube, making it simple to learn and incorporate into the framework.

OpenStudio is designed to work with Ladybug, Honeybee, and Grasshopper. These properties make it a valuable tool for creating a cohesive and successful computational approach in sustainable design.

Edupack
Edupack supported the framework by offering a e material database with metrics like embodied carbon and other material proberties like thermal performanse and density.
As a free resource for TU Delft students, Edupack is a cost-effective tool for academic research. Additionally, Edupack was taught at TU Delft during the "SAMS" (Sustainable Architecture and Materials Science) course, which provided foundational knowledge and practical guidance on using the database. This academic exposure helped integrate Edupack into the research and design process.

3.1.3 Vulnerability

Using these software tools in this thesis provided the stated benefits, but they also presented obstacles. One restriction was a lack of understanding of the programming behind these systems. Although Grasshopper, Ladybug, and Honeybee offer user-friendly interfaces, errors or misinterpretations may occur due to complex settings that are not fully understood.

Another risk is that the software could contain bugs or errors. Regardless of how reliable it is, no software is immune to flaws that can affect the results. Although I relied on established workflows, they may not always be directly applicable to my specific situation.

Furthermore, if alternative programs were used, the results may have changed Various tools have different assumptions and approaches, which may lead to different insights into building performance.

3.1.4 Validation

Validation was performed against both manual calculation and comparison simulation to verify the computational model's reliability. Three random hand calculations were made to verify the embodied carbon data retrieved from EduPack. The calculations focused on the key materials utilized in the façade construction, comparing their embodied carbon values to those found in literature sources. The validity of the model's material analysis was determined by comparing the findings to known datasets.

To validate the energy performance, DesignBuilder was used as an independent simulation tool to cross-check the EnergyPlus data received from Honeybee. DesignBuilder employs similar energy modeling but has a distinct interface and methodology, allowing for a different approach to the thermal performance of the façade. The simulations focused on heating and cooling loads, and the outputs from the two software packages were used to compare the results. Any disparities were addressed to determine potential causes of variation, such as variations in default assumptions or model inputs.

This combined method of manual calculation and software validation improved the computational model's validity. By maintaining connection between multiple methods, the validity of energy performance and embodied carbon analysis was increased, which supported the design optimization process.

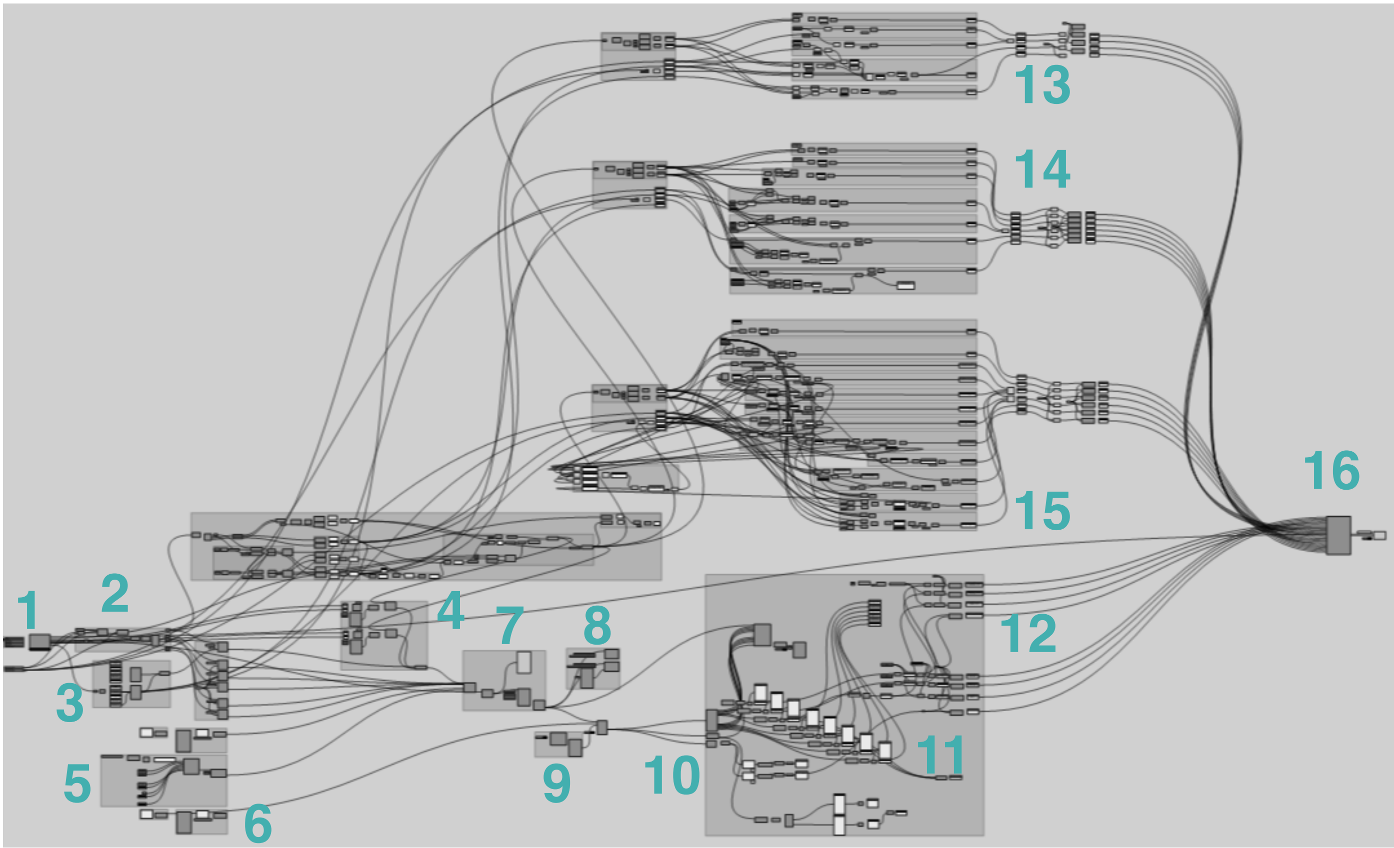
3.1.5 Building The Model

This section outlines the step-by-step process of constructing the computational model within the framework. The model uses parametric tools and simulation engines to evaluate and enhance façade performance. Geometric creation begins in Grasshopper, incorporating environmental data from Ladybug and Honeybee to simulate climatic effects. EnergyPlus and OpenStudio refine thermal and energy simulations, while Edupack supports material selection based on sustainability and thermal properties. This integrated approach ensures the model effectively assesses energy efficiency and thermal comfort, providing a comprehensive foundation for design optimization.

The Grasshopper file follows a sequential structure to create, simulate, and analyse the building model. Below is an outline of all the steps in the workflow:

1. Colibri Inputs:
All parameters, including window options, façade scenarios, compactness ratio, and building orientation, are applied here. The Colibri command generates an Excel/CSV file capturing the variations in parameters, which guides the subsequent computational framework.

2. Basic Geometry of the Residence:
The width and height of the façade element are defined, and a box is created to represent the building geometry. The compactness ratio determines the box's depth, and orientation sets its angular position. Using the Brep



Total grasshopper model (Vedder, 2025)

Figure 3.01

command, the geometry is split into faces, edges, and vertices, isolating the façade face while making other faces adiabatic to prevent energy losses.

3. Material Properties:
Façade scenarios are linked through a Python script that assigns specific material properties for each case. These properties are used to create the Honeybee "opaque construction," which calculates energy losses due to transmission.

4. Window Definition and Options:
The façade face is scaled using the window-to-wall ratio (WWR) parameter. The window frame thickness and material properties (e.g., wood) are added. A Python script determines the appropriate window assembly based on the selected material properties.

5. Room Program Definition:
Key operational inputs, including people load, ventilation, infiltration, lighting, and electricity usage, are defined to simulate the room's energy performance.

6. Structure Type and Climate:
The structure type and climatic conditions are incorporated to reflect the building's location and contextual influences.

7. Creating the Honeybee Room and HVAC System:
The façade element is converted into a Honeybee room, and the HVAC system is added to simulate heating, cooling, and ventilation requirements.
8. Model Validation:

The computational model is validated to ensure all inputs, geometry, and systems are functioning correctly.

9. Energy Simulation:
The Honeybee model is loaded into EnergyPlus and OpenStudio to perform detailed energy simulations.

10. Analyzing Results:
Simulation results are validated through energy balance calculations and visualized using graphs.

11. Data Processing:
Raw energy simulation outputs are converted into yearly energy usage data (kWh).

12. Operational arbon Output Conversion:
Yearly kWh data is transformed into carbon output to quantify the building's operational carbon footprint.

13. Embodied Carbon Analysis for Wooden Timber Frame Façade (HSB):
This step calculates embodied carbon for a timber frame façade made of wood (HSB) by incorporating all materials from the analyzed details. It uses the data the from façade scenarios, glazing choice and the material properties of the timber frame system to calculate the carbon emissions due to material extraction and manufacturing.

14. Embodied Carbon Analysis for the prefab Concrete Façade:
In part of the algoritm, embodied carbon for prefab concrete façade is computed by summing up all the materials of details considered. The analysis integrates the data of the façade scenarios, glazing choice and the material properties particular to the timber frame system to provide an estimate of the carbon emissions from material production and extraction.

15. Embodied Carbon Calculation for Aluminium Element Façade
This phase approximates embodied carbon of an aluminium element façade via the addition of all included materials in the considered details. It considers data from the façade scenarios, glazing choice and actual material properties of the timber frame system to estimate material extraction and production associated carbon emissions.

16. Data Export:
The processed data, including operational and embodied carbon outputs, is collected and exported as a comprehensive CSV file for further analysis.

Colibri Inputs:
Key parameters, including window options, façade scenarios, compactness ratios, and the orientation of the residence, are established. These inputs form the basis for the parametric variations within the simulation.

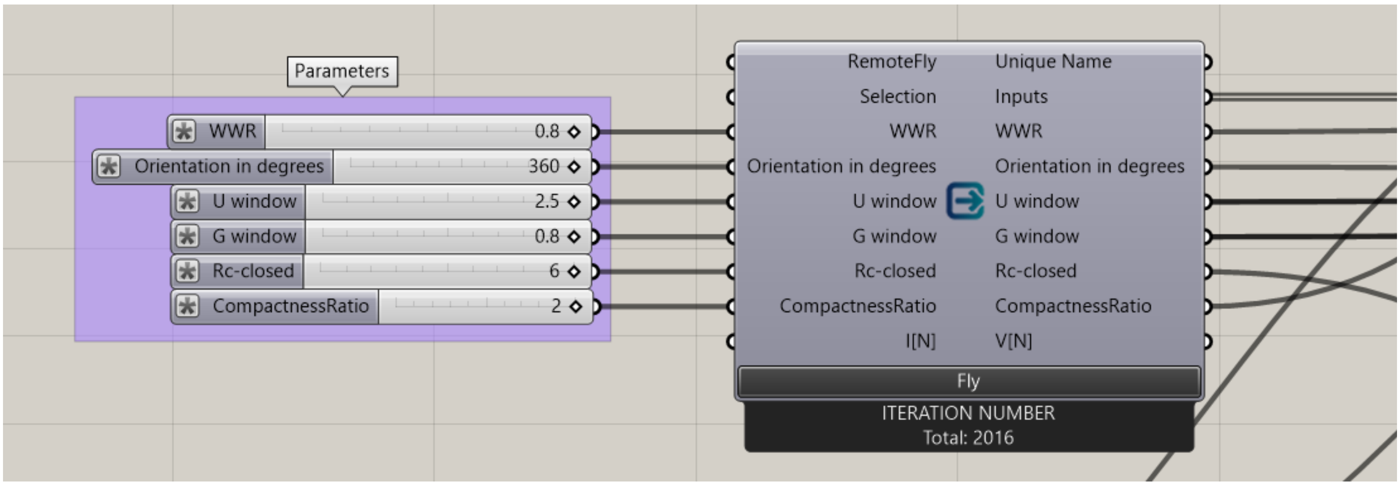


Figure 3.02

Grasshopper explanation

Basic Geometry of the Residence:
The geometric modeling begins by defining the width and height of the façade element. A volumetric box is created, with the compactness ratio dictating its depth and orientation specifying its angular placement. The Brep command is used to separate the box into faces, edges, and vertices.

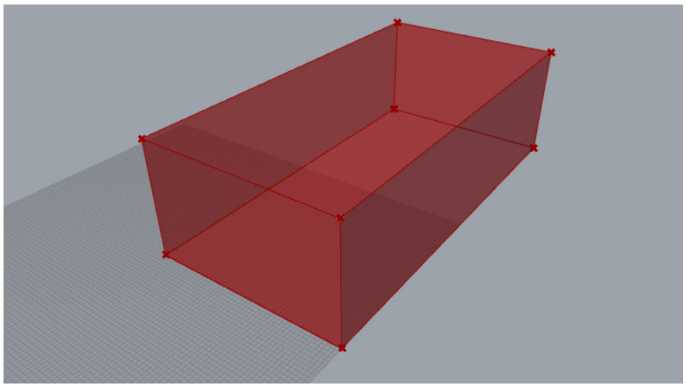


Figure 3.02

Grasshopper explanation

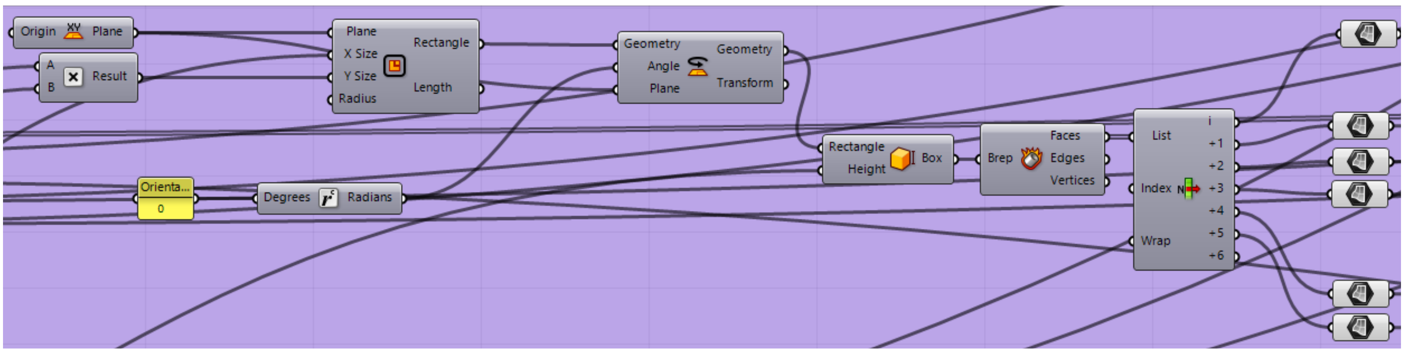
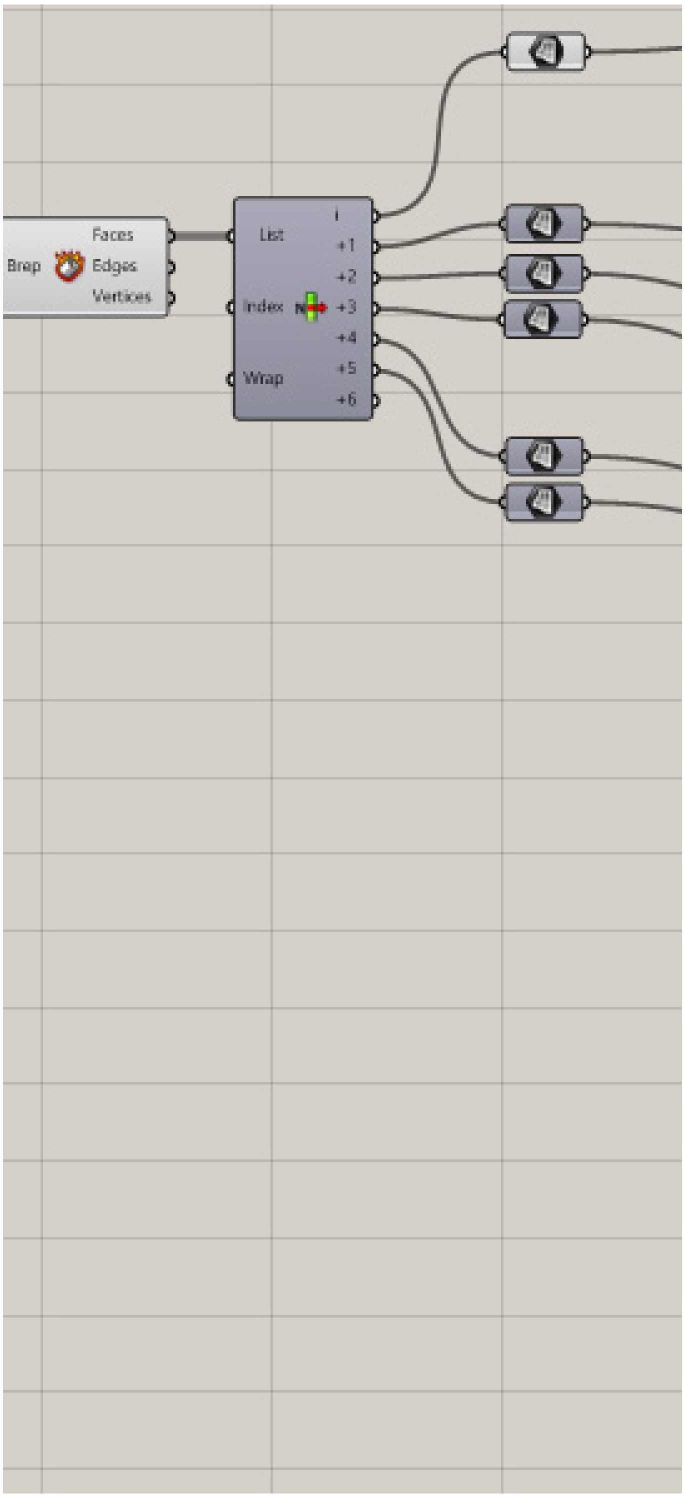


Figure 3.03

Grasshopper explanation



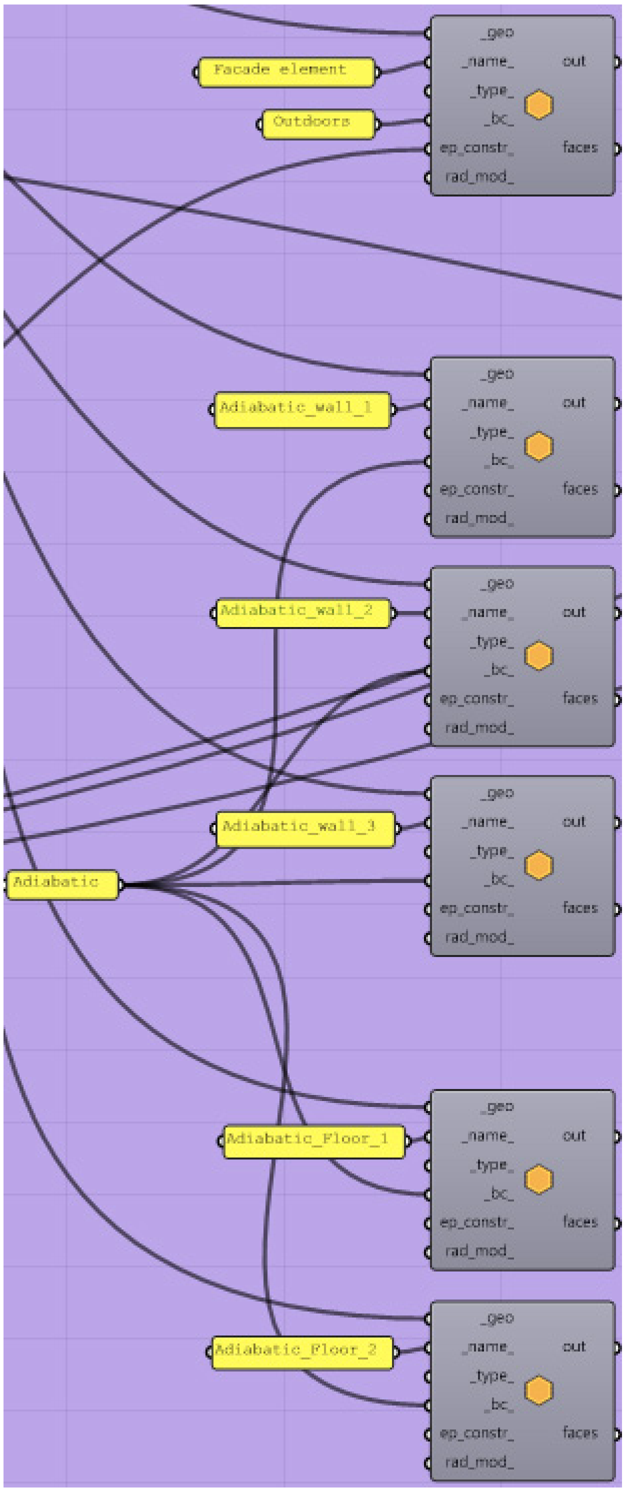
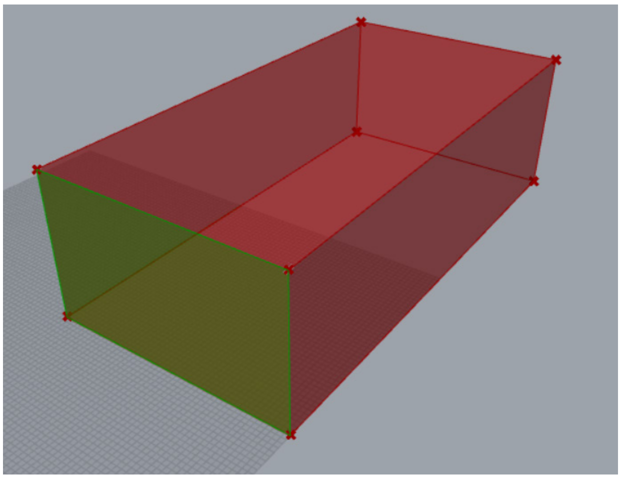


Figure 3.04

Grasshopper explanation



The façade face is isolated, while all other surfaces are made adiabatic to eliminate energy losses. The isolated façade face is subsequently connected to the façade scenarios, material properties, and window options.

Façade Scenarios and Material Properties: Façade scenarios from Colibri inputs are processed using a Python script that assigns the appropriate façade type and associated material properties for each scenario.

These properties are then utilized to create Honeybee "opaque constructions," enabling the calculation of energy losses due to transmission. The construction is linked to the façade face for integration into the simulation.

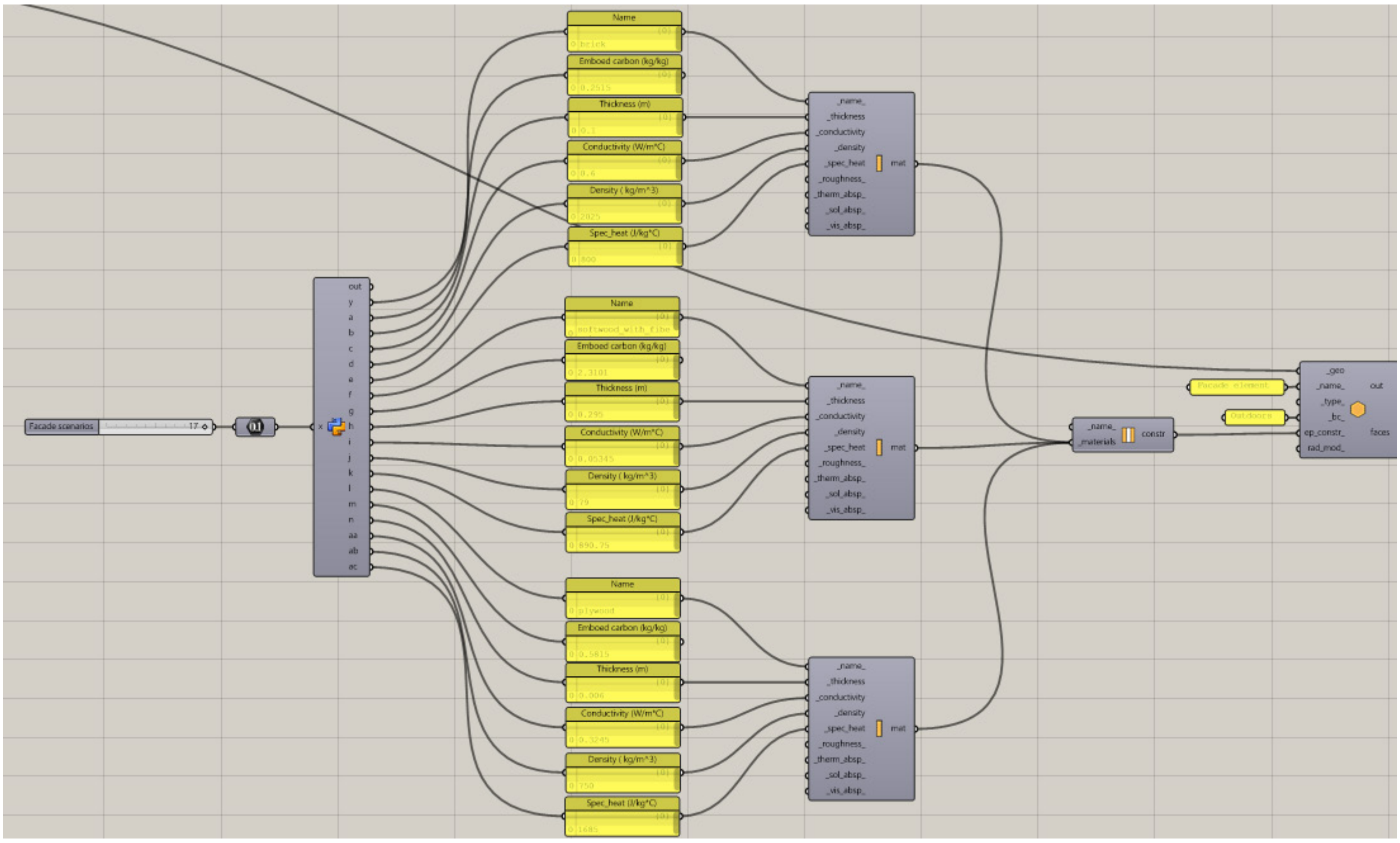


Figure 3.05

Grasshopper explanation

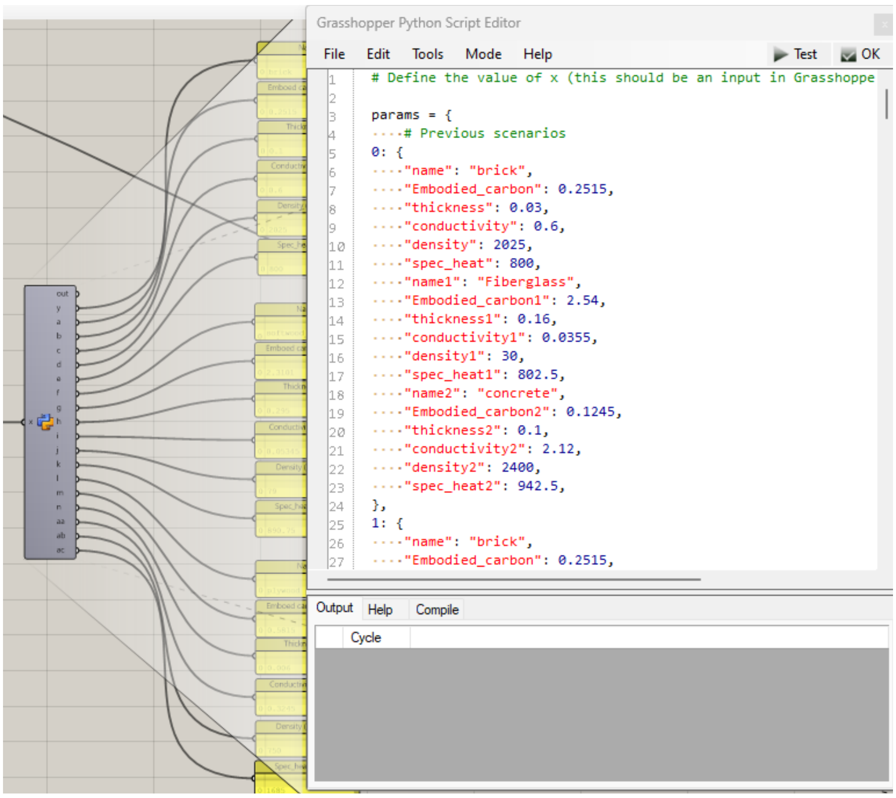


Figure 3.06

Grasshopper explanation

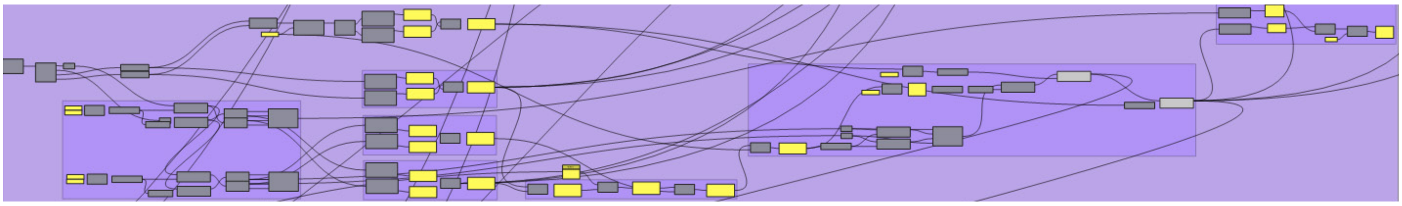


Figure 3.07

Grasshopper explanation

Creating the Windows:
The modeled surface is split into two windows to allow for multiple elements in the case of aluminium. An adjustable distance from the floor is also set. Next, the length and width are calculated based on the WWR, and the final values are fed into the Ladybug window element for further calculations.

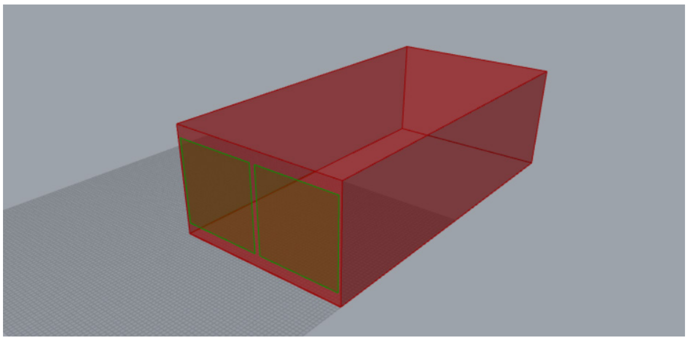


Figure 3.08

Grasshopper explanation

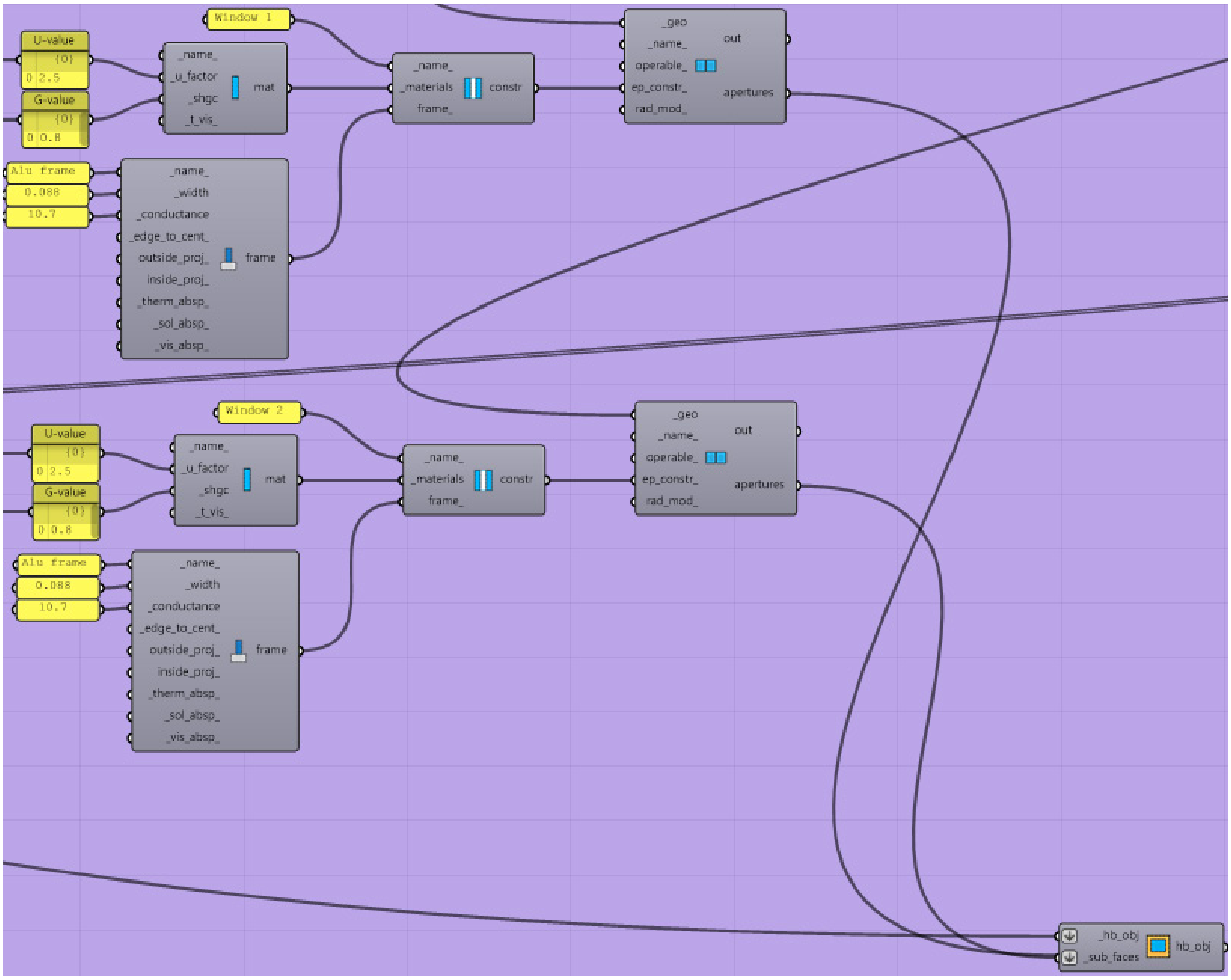


Figure 3.09

Grasshopper explanation

Defining the Program:
Operational inputs critical for energy simulations, such as occupant loads, ventilation rates, infiltration rates, lighting, and electricity usage, are specified. These inputs help simulate realistic building performance.

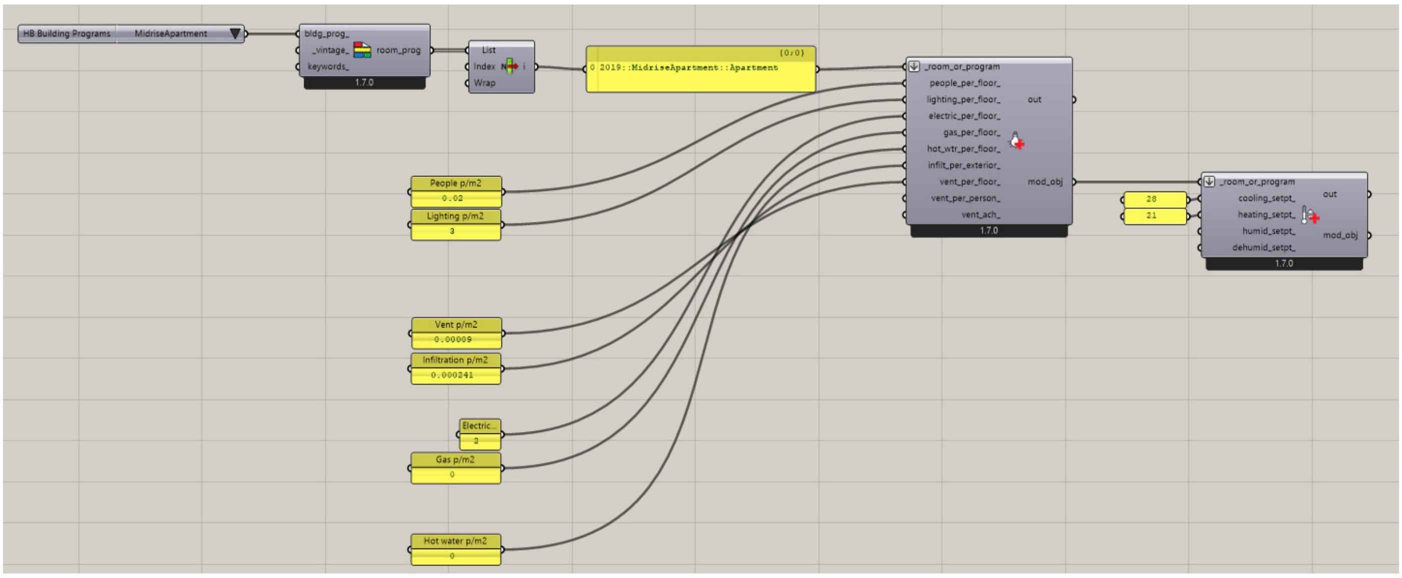


Figure 3.10

Grasshopper explanation

Structure Type and Climate:
Each Honeybee room is assigned a construction type and linked to a climate file. These inputs are essential for simulating energy performance under specific environmental conditions.

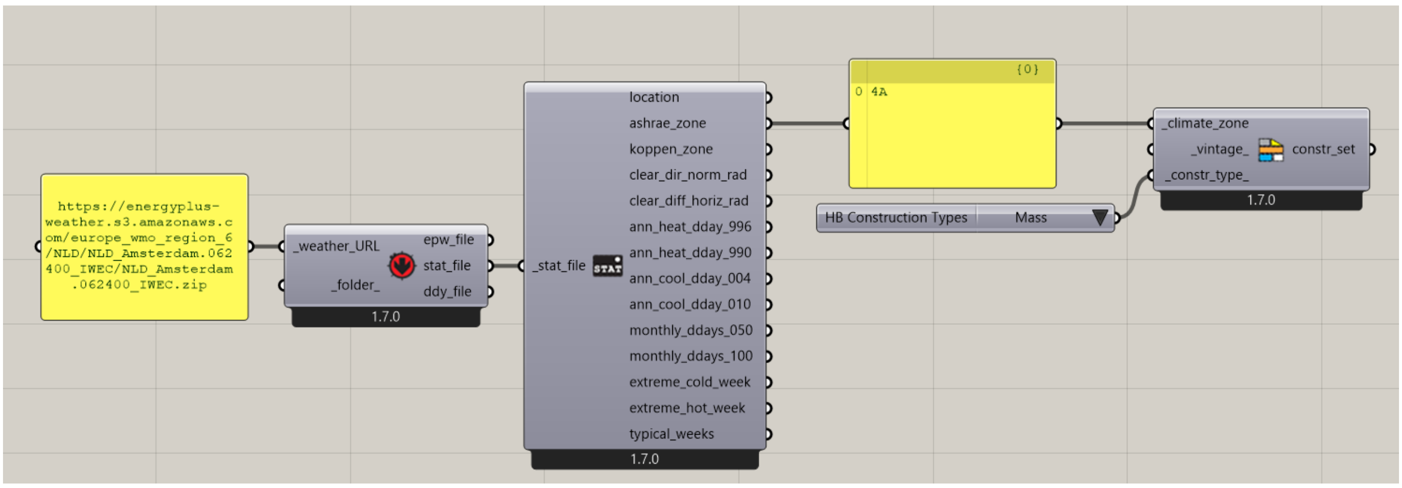


Figure 3.11

Grasshopper explanation

Creating the Honeybee Room and Adding HVAC Systems:

The Honeybee room is created by combining all previously defined inputs, including geometry, façade configurations, and material properties. The HVAC system is added to simulate heating, cooling, and ventilation, using fixed inputs for thermal performance.

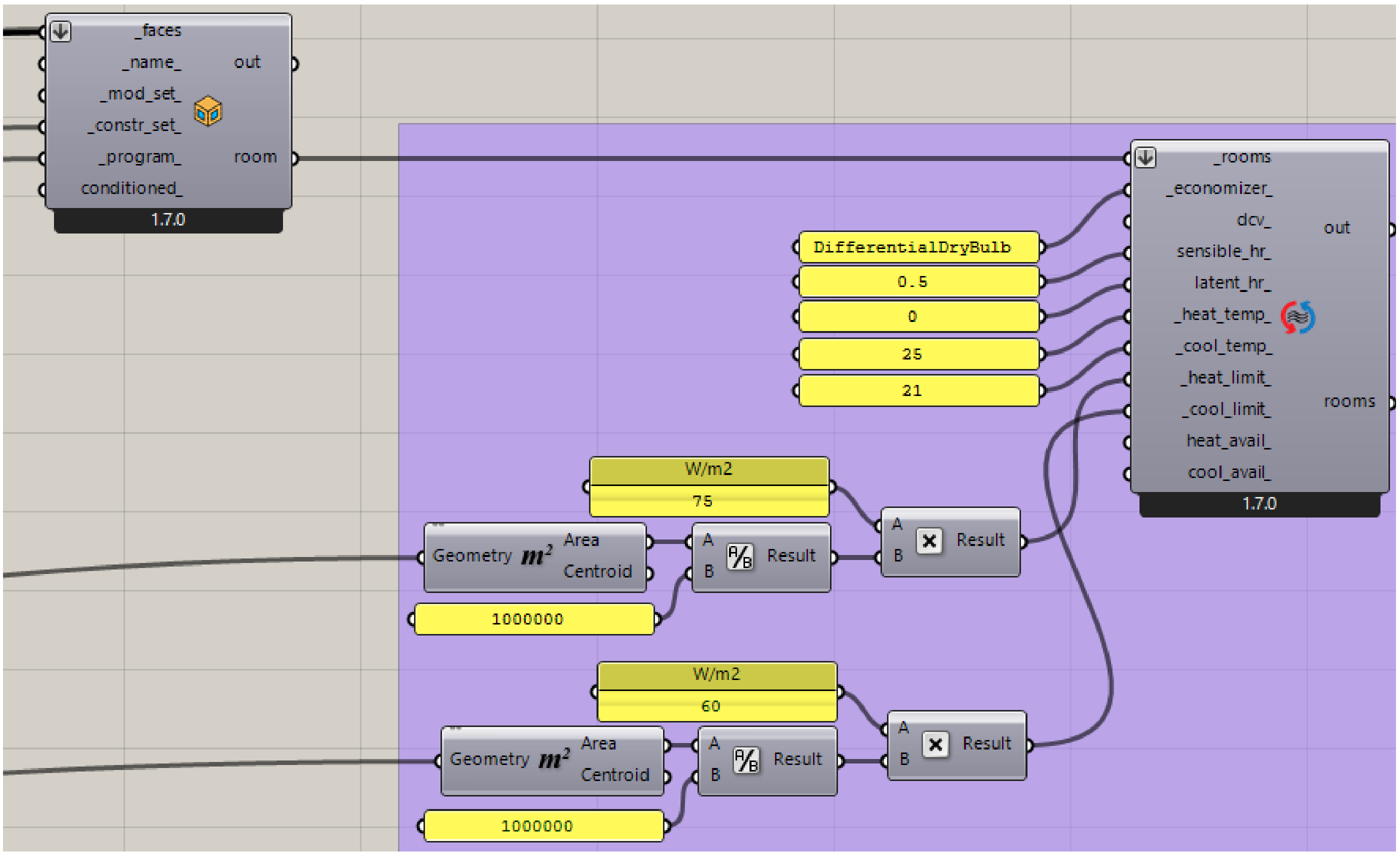
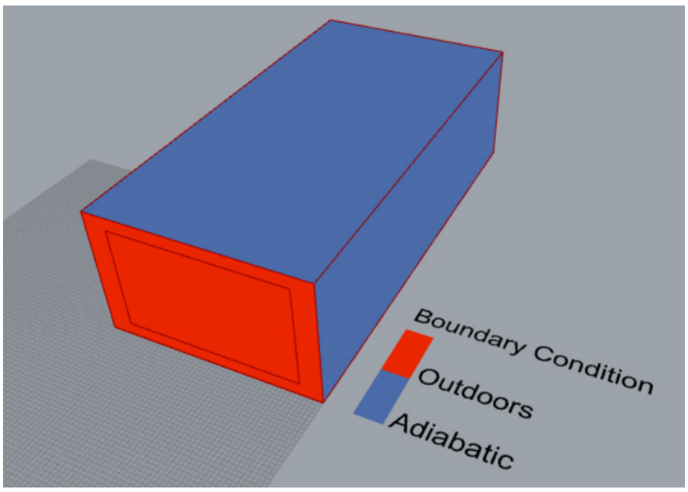


Figure 3.12

Grasshopper explanation

Model Validation:

Validation commands are used to ensure that all inputs have been accurately incorporated into the Honeybee model. This step verifies the integrity of the computational setup before proceeding.



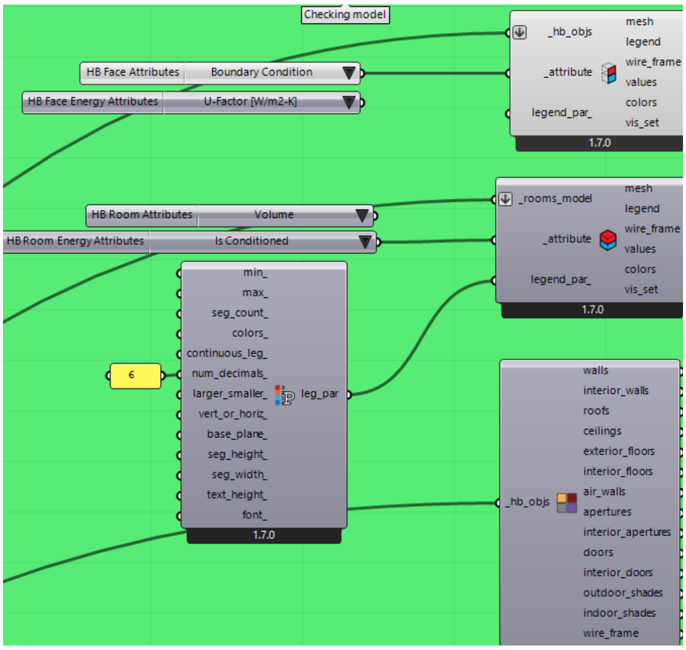


Figure 3.13

Grasshopper explanation

Energy Simulation:
The validated Honeybee model is connected to OpenStudio and EnergyPlus for operational energy simulations. This step generates detailed energy performance data.

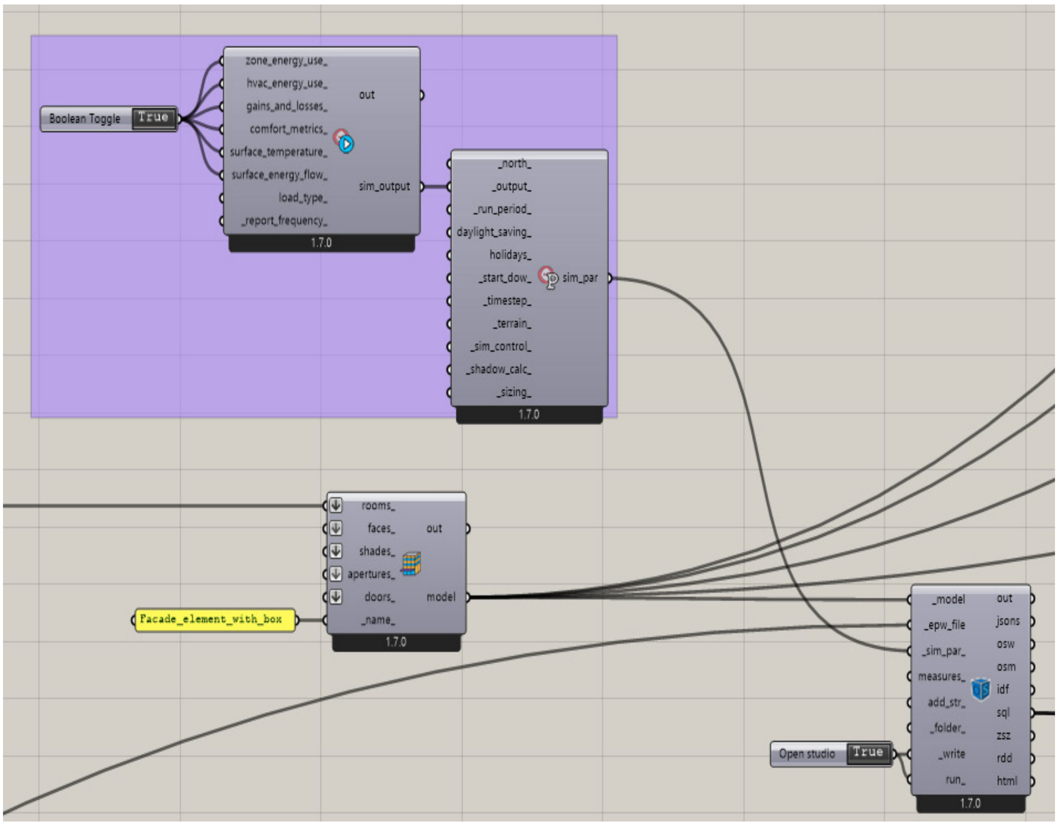


Figure 3.14

Grasshopper explanation

Result Validation and Energy Balance Analysis:
The simulation results are analysed through energy balance calculations and visualized using graphs. This allows for initial validation and enables conclusions, such as identifying higher heating demands during winter due to transmission losses.

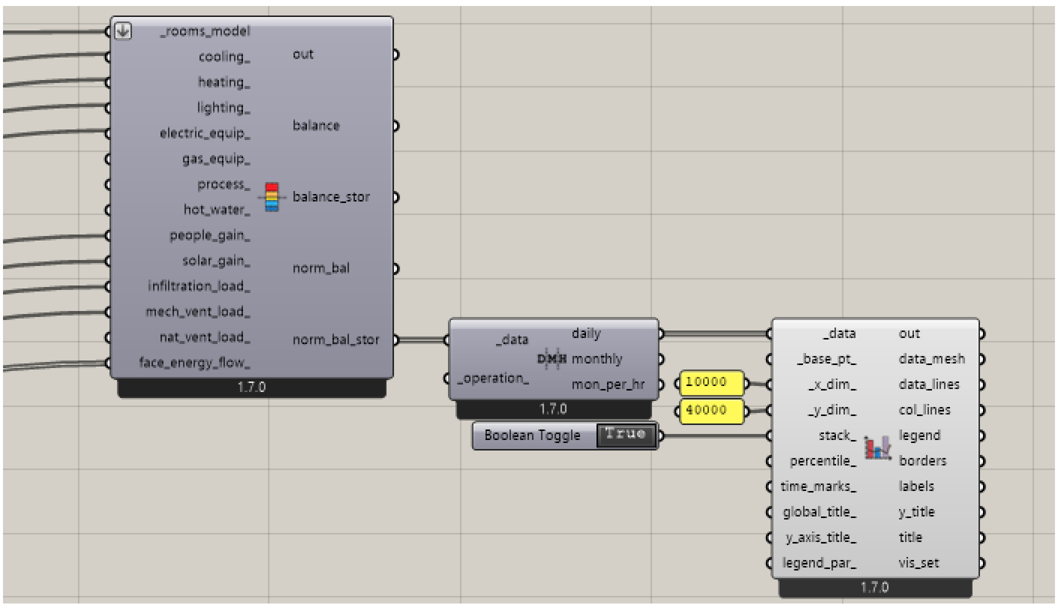


Figure 3.15

Grasshopper explanation

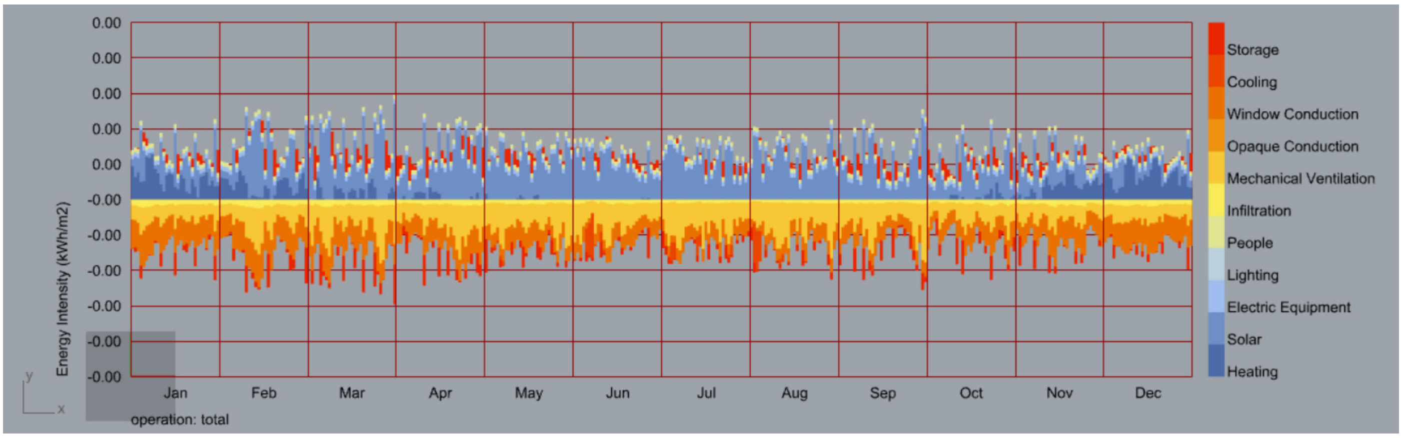


Figure 3.16

Transforming Raw Data to Yearly Energy Data:
Raw simulation outputs are processed to generate yearly energy consumption data in kilowatt-hours (kWh).

Grasshopper explanation

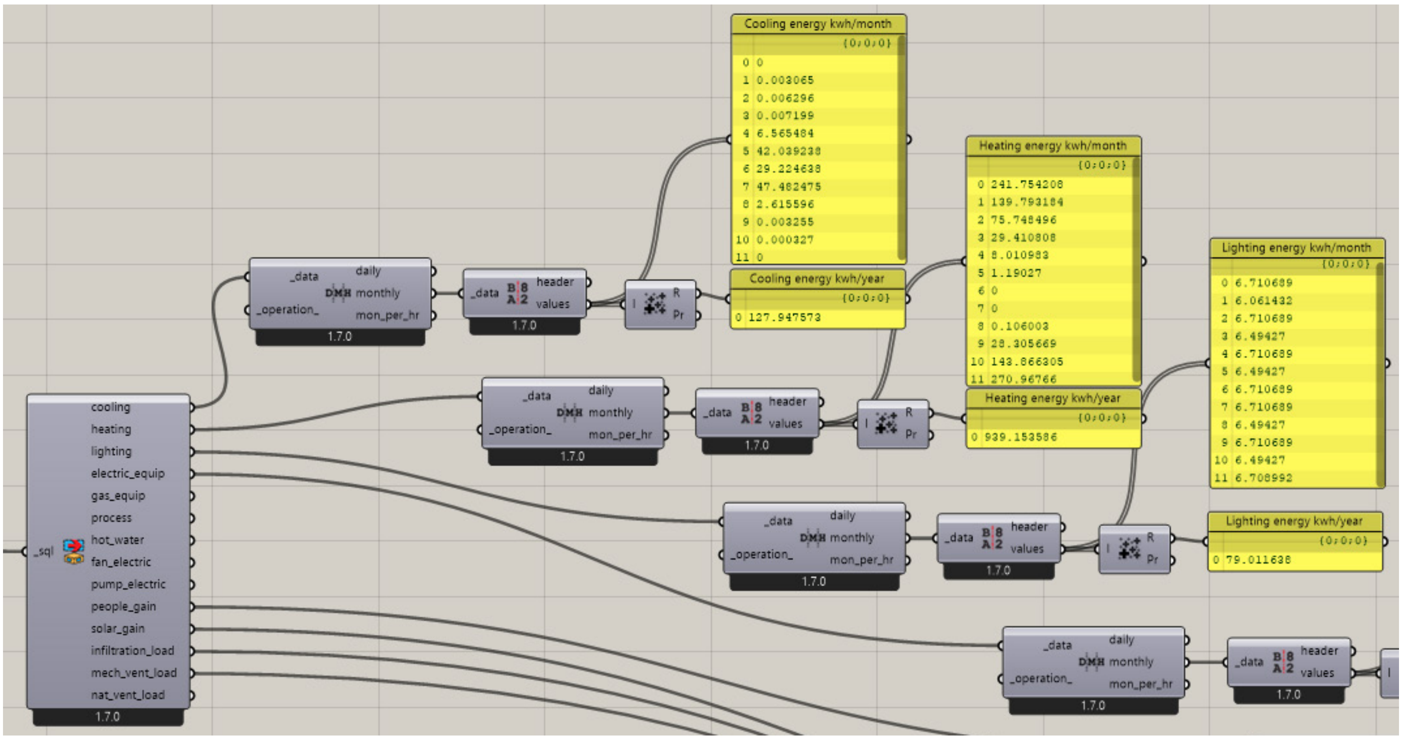


Figure 3.17

Additionally, data on hours where indoor temperatures exceed 25°C is collected for thermal comfort analysis.

Grasshopper explanation

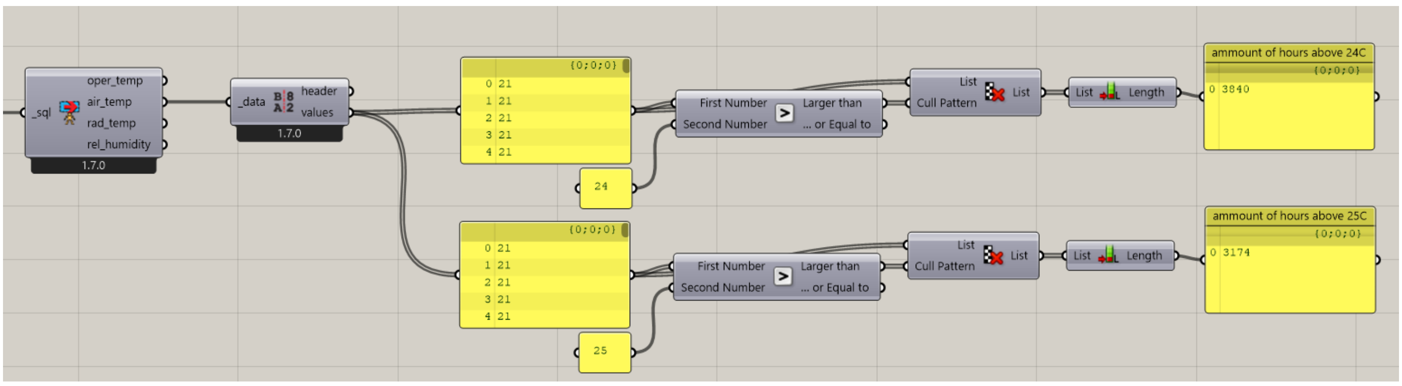


Figure 3.18

Grasshopper explanation

Converting Yearly Energy Data to Carbon Output:

Yearly energy data is converted into carbon emissions (kg CO) by applying the carbon intensity of the energy grid. This calculation also accounts for projected carbon reductions over time.

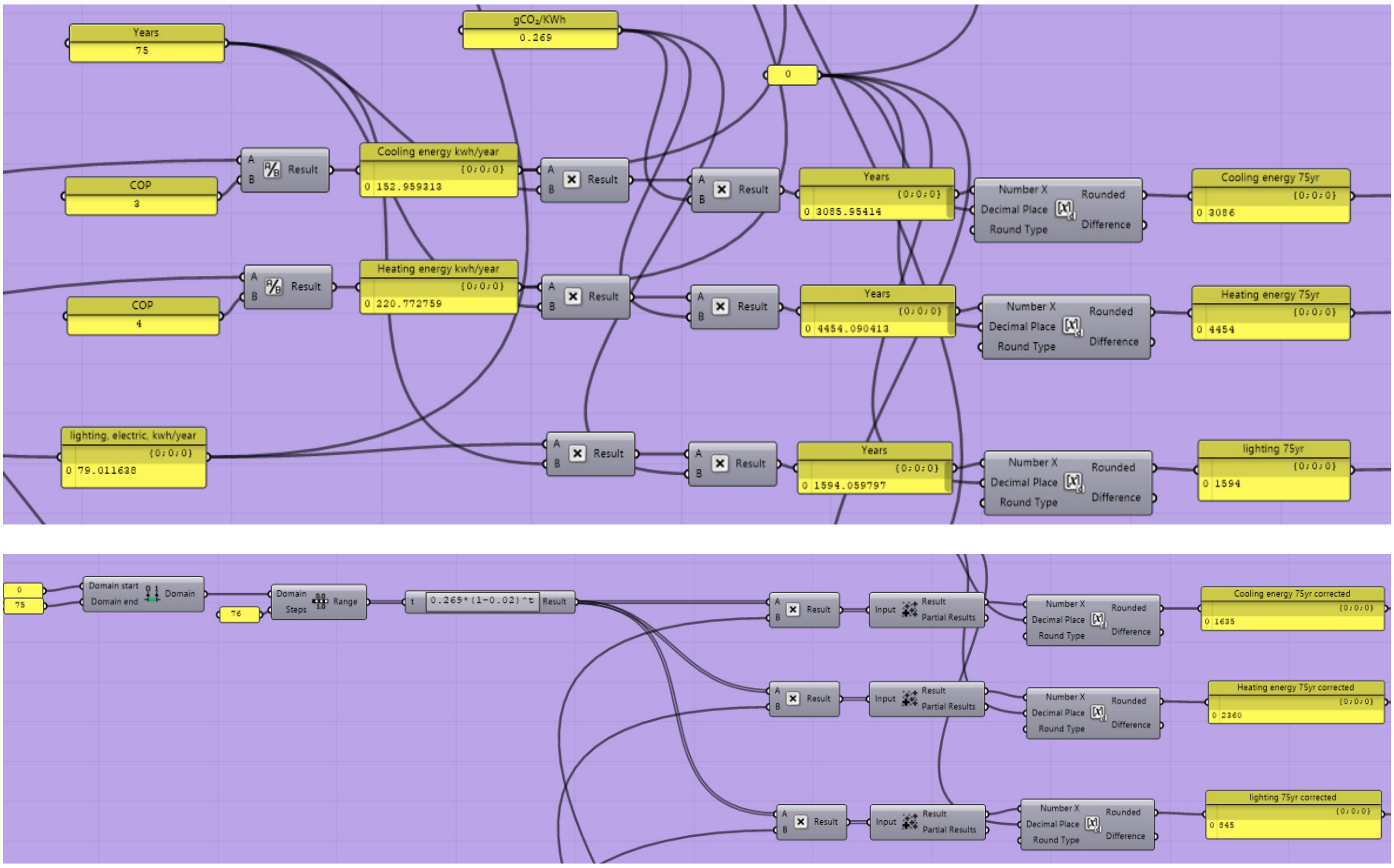


Figure 3.19

Grasshopper explanation

Embodied Carbon Analysis for Façade Scenarios:

Material properties and thicknesses for each façade scenario are used to calculate mass and embodied carbon (kg CO/kg). Data from sources such as Edupack informs this calculation, ensuring accuracy in assessing embodied impacts.

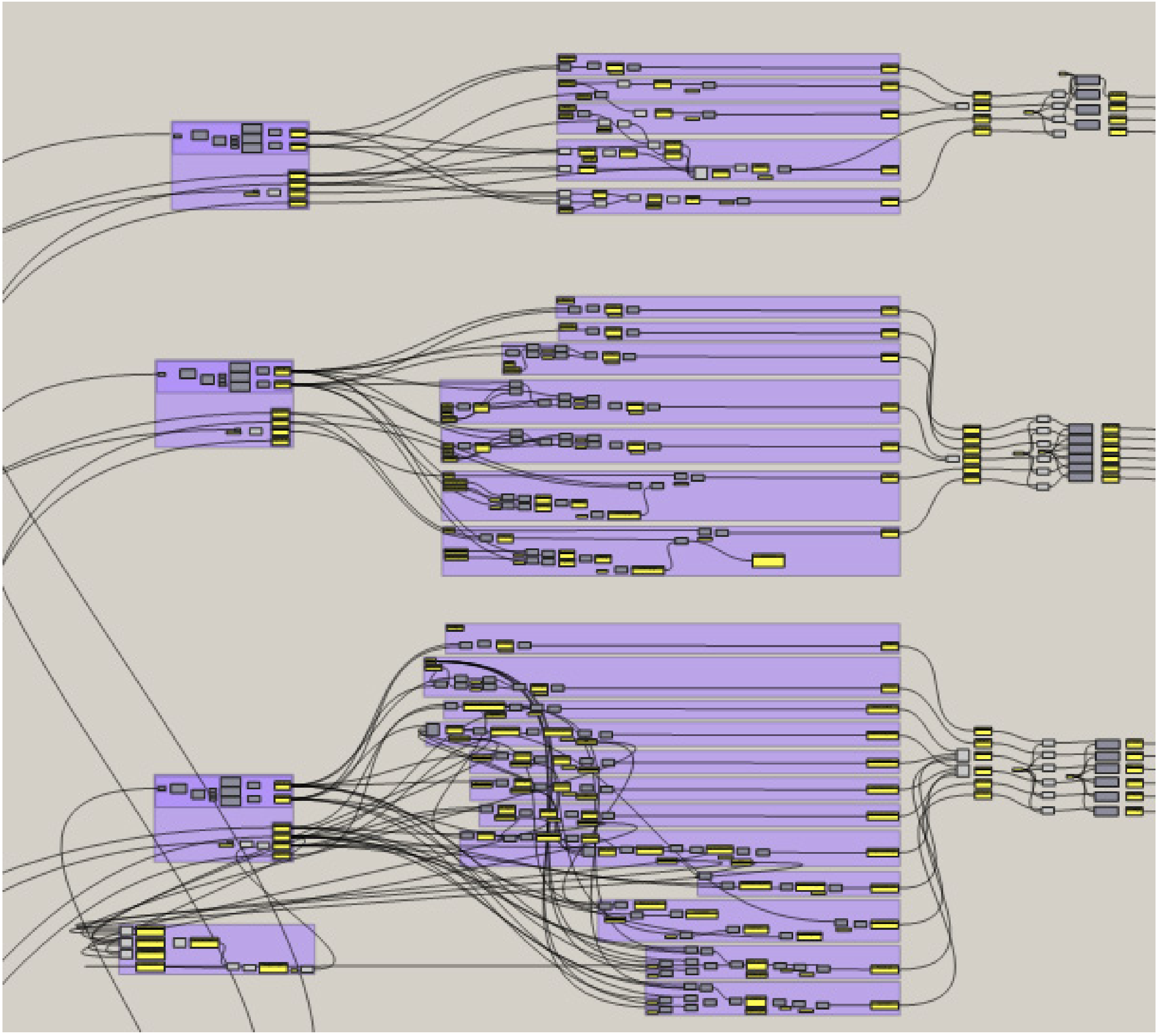


Figure 3.20

Grasshopper explanation

Data Collection and Export to CSV:
The final step involves aggregating all data points, including operational and embodied carbon outputs, and exporting them to an Excel/CSV file. This structured dataset is prepared for further analysis and visualization.

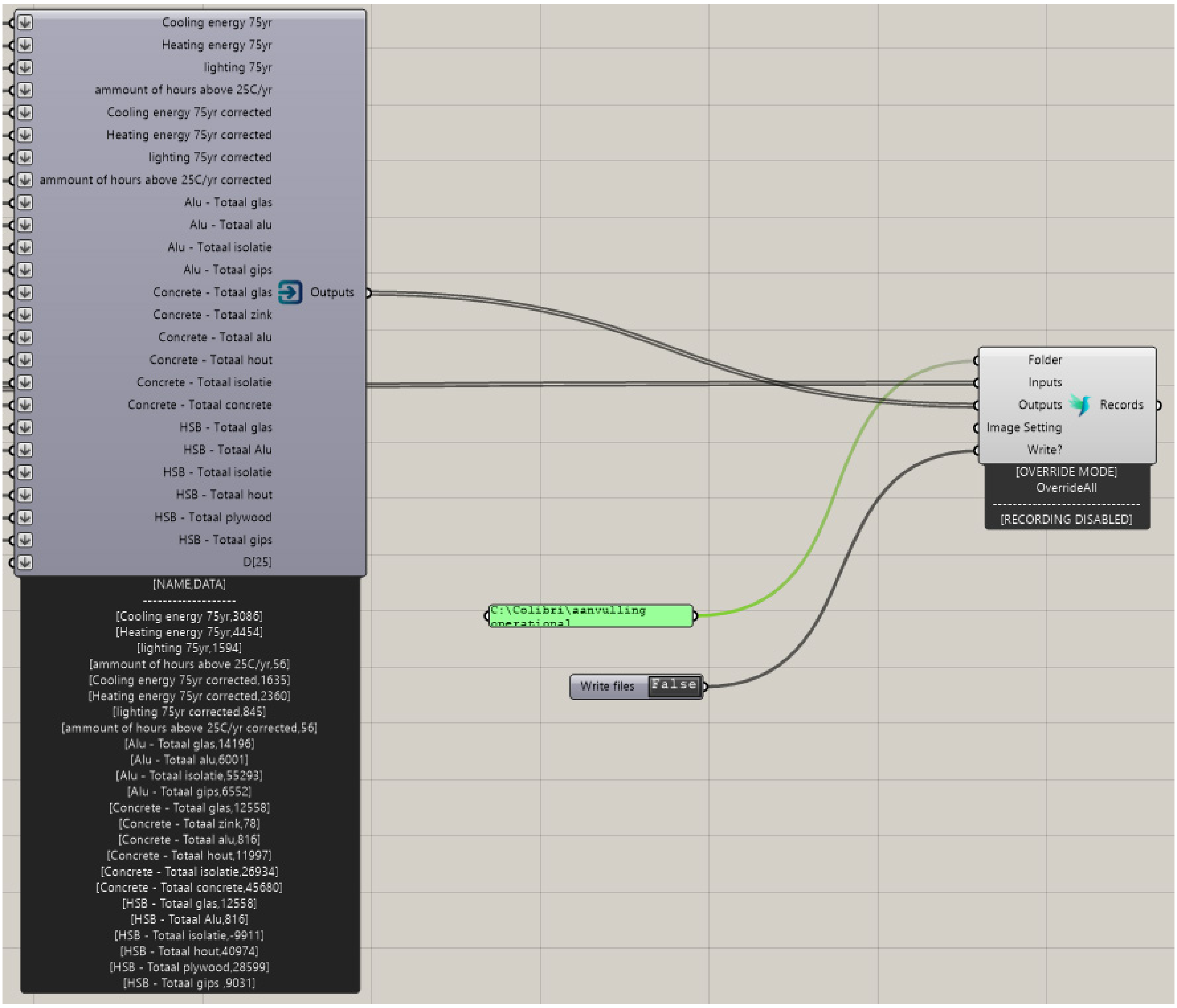


Figure 3.21

Grasshopper explanation

3.2 Validation

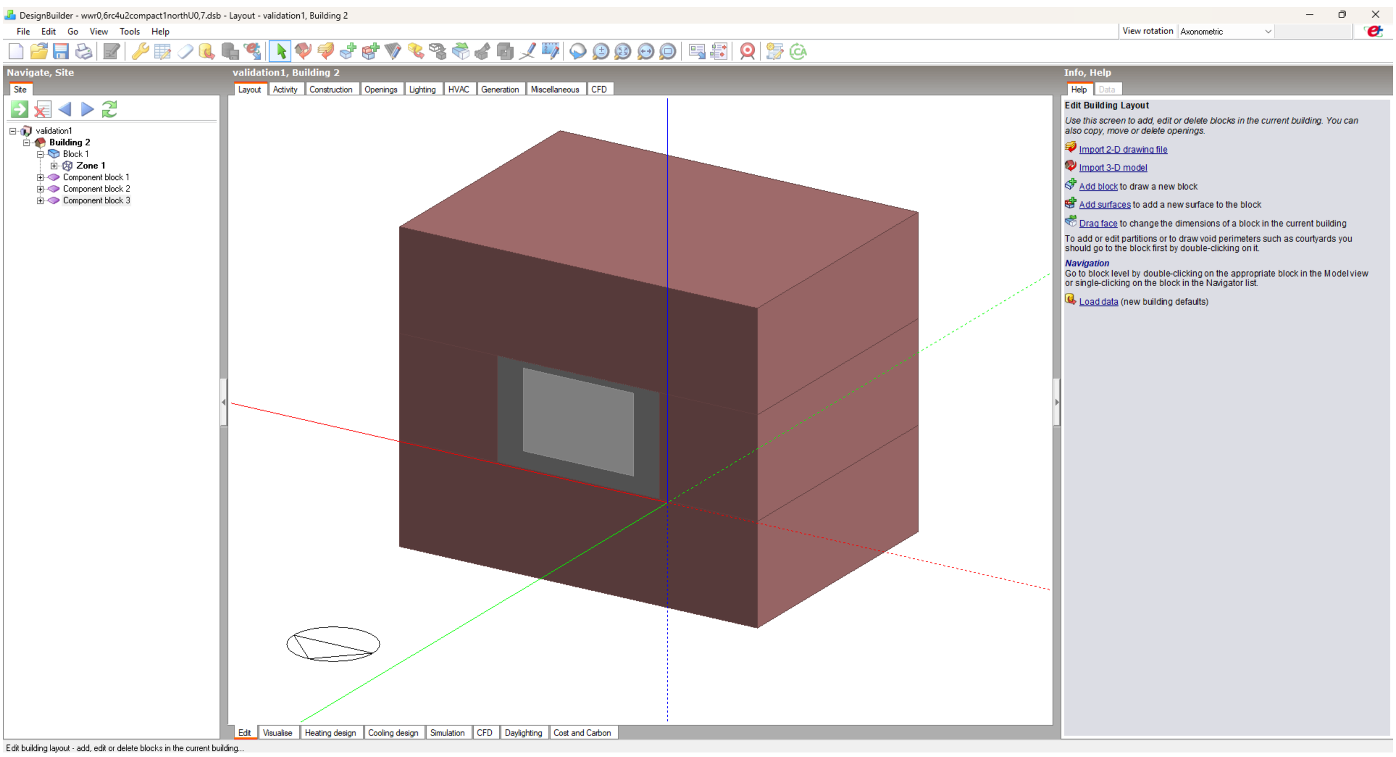
A comparative analysis is performed to determine the accuracy of the parametric framework by simulating nine different model versions. This identifies any potential errors and determines whether the chosen tools (Rhino, Grasshopper, Ladybug, Honeybee, EnergyPlus, and OpenStudio) produce consistent and correct results.

By comparing important performance measures like as energy consumption, thermal comfort, and solar gains across multiple façade configurations, validation assures that the model appropriately depicts real-world behavior. If considerable disparities develop, adjustments can be made to improve the alignment between the computational framework and the DesignBuilder output. This stage increases the study's credibility and demonstrates that the façade optimization process is based on a reliable and verified simulation approach.

3.2.1 Building The Model

The modeling process starts with creating the room, where I define the orientation and compactness. The gray block represents the apartment, while the red blocks indicate adiabatic walls, where no heat loss occurs.

Next, I set the activity parameters, which include defining the number of occupants and the heating and cooling setpoints. These values are aligned with my Grasshopper model.

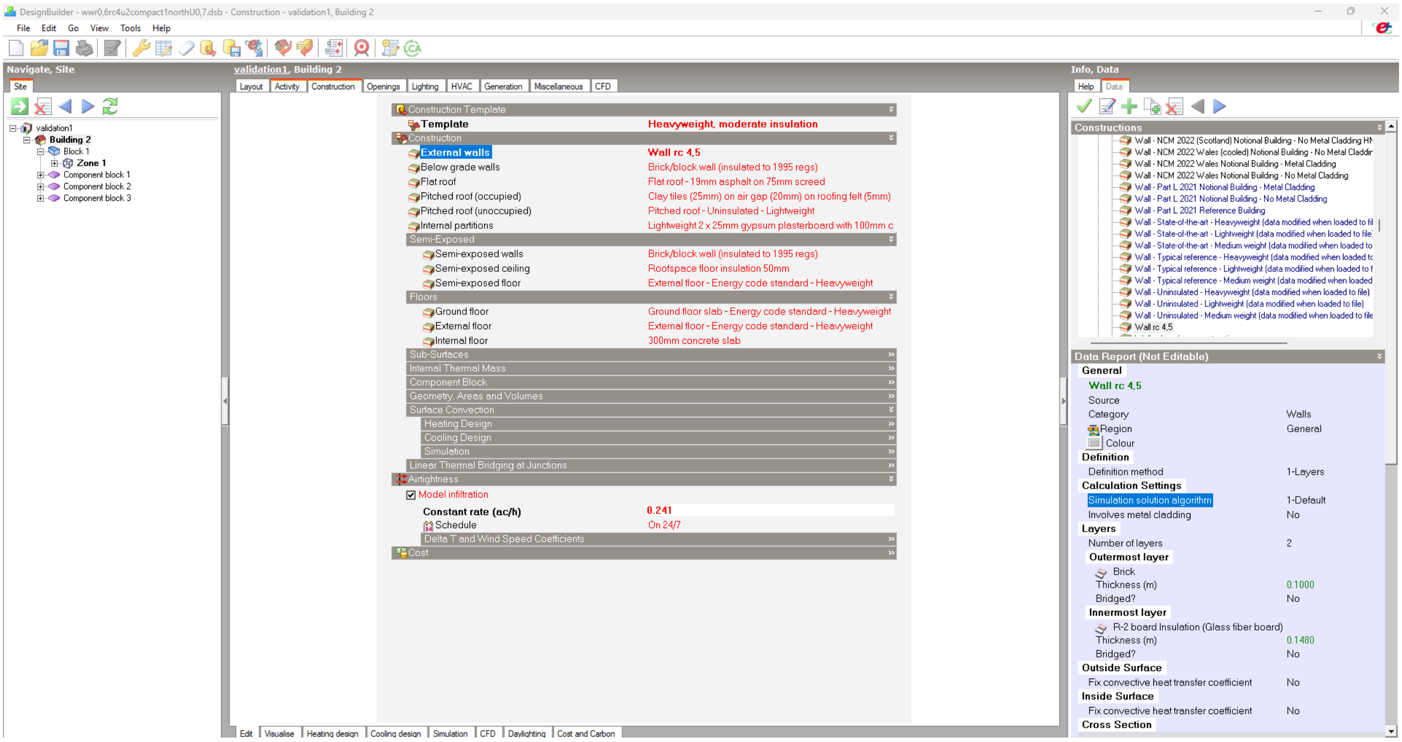


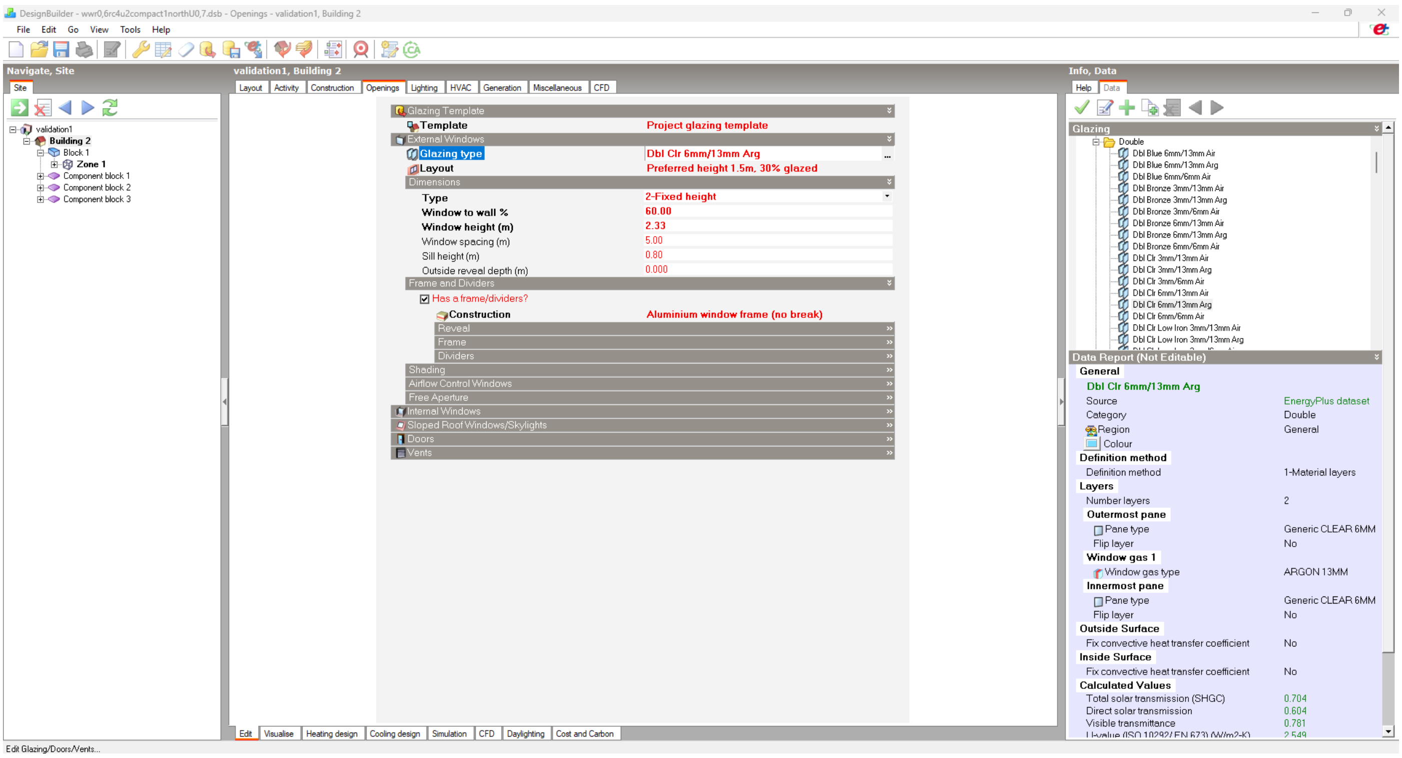
In the construction tab, the material properties of the façades are specified, including the RC value and airtightness. These settings are also matched to my Grasshopper model.

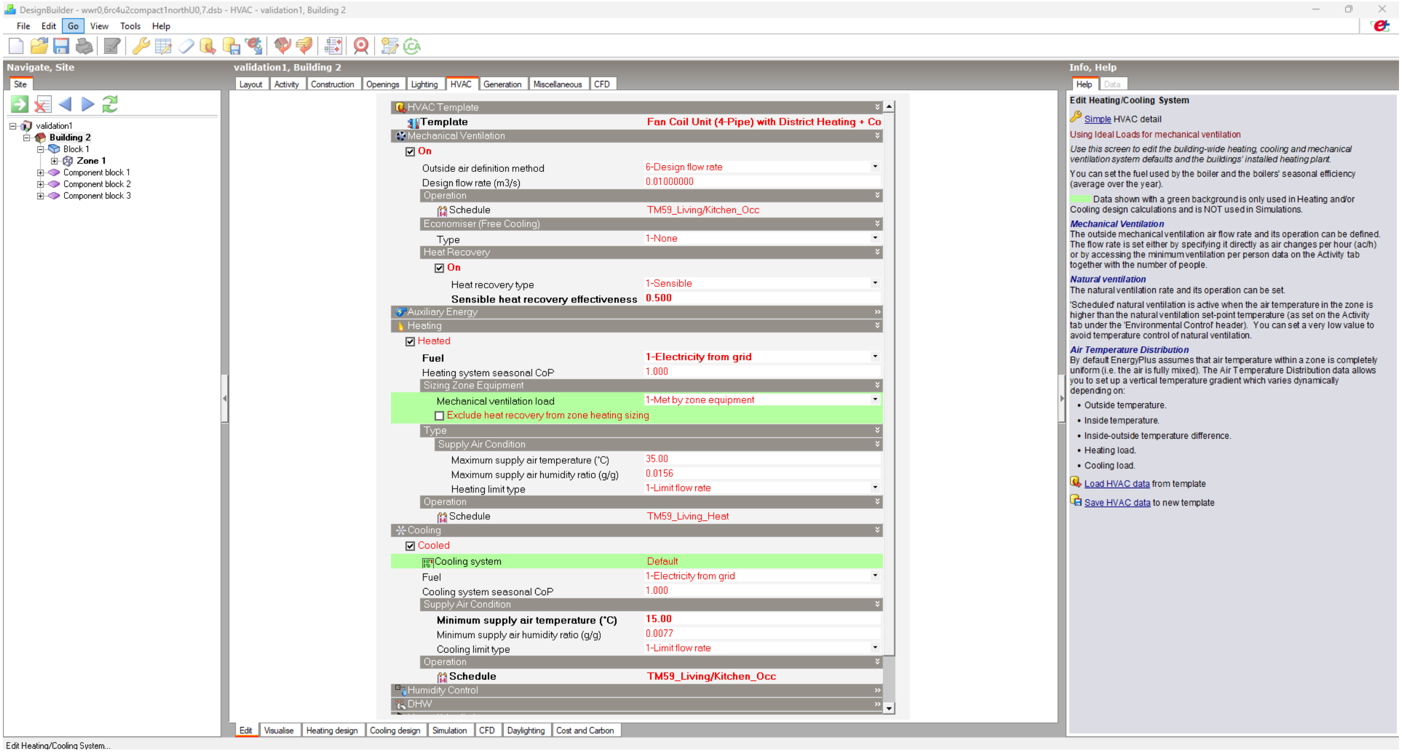
Under the openings tab, I select the type of glass and define the window-to-wall ratio (WWR). The software provides predefined glass combinations, which I eventually implemented in my Grasshopper model to ensure consistent material properties.

Under the HVAC tab, I select the HVAC system. Here, I encountered some challenges, as the Ideal Air component from Grasshopper is not available in DesignBuilder. To address this, I selected a template that closely matches the results obtained from Grasshopper. I calibrated this based on the first simulation, using the following parameters:

0.3 | 4.5 | 2.5 | 0.7 | 1 | north







Ultimately, this resulted in the following simulations:

						Grasshopper			Designbuilder			Deviation		
WWR						heating	Cooling	lighting	heating	Cooling	lighting	heating	Cooling	lighting
0.3	4.5	2.5	0.7	1	north	1186	36	39.5	735.27	36.28	41.4	-38.00%	0.78%	4.81%
0.5	4.5	2.5	0.7	1	north	1442	68	39.5	893	111	41.4	-38.07%	63.24%	4.81%
0.7	4.5	2.5	0.7	1	north	1707	99	39.5	1042	187.22	41.4	-38.96%	89.11%	4.81%
						Grasshopper			Designbuilder			Deviation		
WWR						heating	Cooling	lighting	heating	Cooling	lighting	heating	Cooling	lighting
0.3	4.5	1.62	0.68	1	South	518	133	39.5	464	319	41.4	-10.42%	139.85%	4.81%
0.5	4.5	1.62	0.68	1	South	537	239	39.5	497	676	41.4	-7.45%	182.85%	4.81%
0.7	4.5	1.62	0.68	1	South	592	338	39.5	541	1029	41.4	-8.61%	204.44%	4.81%
						Grasshopper			Designbuilder			Deviation		
WWR						heating	Cooling	lighting	heating	Cooling	lighting	heating	Cooling	lighting
0.3	4.5	1.62	0.68	1	West	780	96	39.5	474	177	41.4	-39.23%	84.38%	4.81%
0.5	4.5	1.62	0.68	1	West	850	160	39.5	508	601	41.4	-40.24%	275.63%	4.81%
0.7	4.5	1.62	0.68	1	West	943	221	39.5	551	920	41.4	-41.57%	316.29%	4.81%

There is a consistent deviation in heating, where the values in the Grasshopper model are almost always higher. However, the overall trend remains the same when comparing different WWRs. Cooling, on the other hand, deviates significantly, requiring much more energy in DesignBuilder.

After running additional simulations, I discovered that this discrepancy is due to the cooling system or the specified air exchange rate in the HVAC tab. However, I am unable to match these exactly because of the differences in HVAC systems between the models.

4.

Simulation Results

4.1 Embodied Carbon

This chapter provides the findings from an examination of the embodied carbon of several façade systems and construction processes. The focus is on three types of façades: aluminum unitized, prefabricated concrete, and prefabricated timber. These systems were chosen based on the analysis presented in previous chapters and represented as parametric systems. The characteristics that allow these façades to be dynamically modified were developed in previous chapters.

The analysis investigates the impact of various parameters on the environmental performance of the façades, such as embodied carbon, including the window-to-wall ratio (WWR), the U-value of glass (U-glass), the solar heat gain coefficient of glass (g-glass), and the thermal resistance of the façade (Rc-value). The emphasis is on the composition of the façade elements themselves, ignoring the façade panels and outside cladding, which are studied independently.

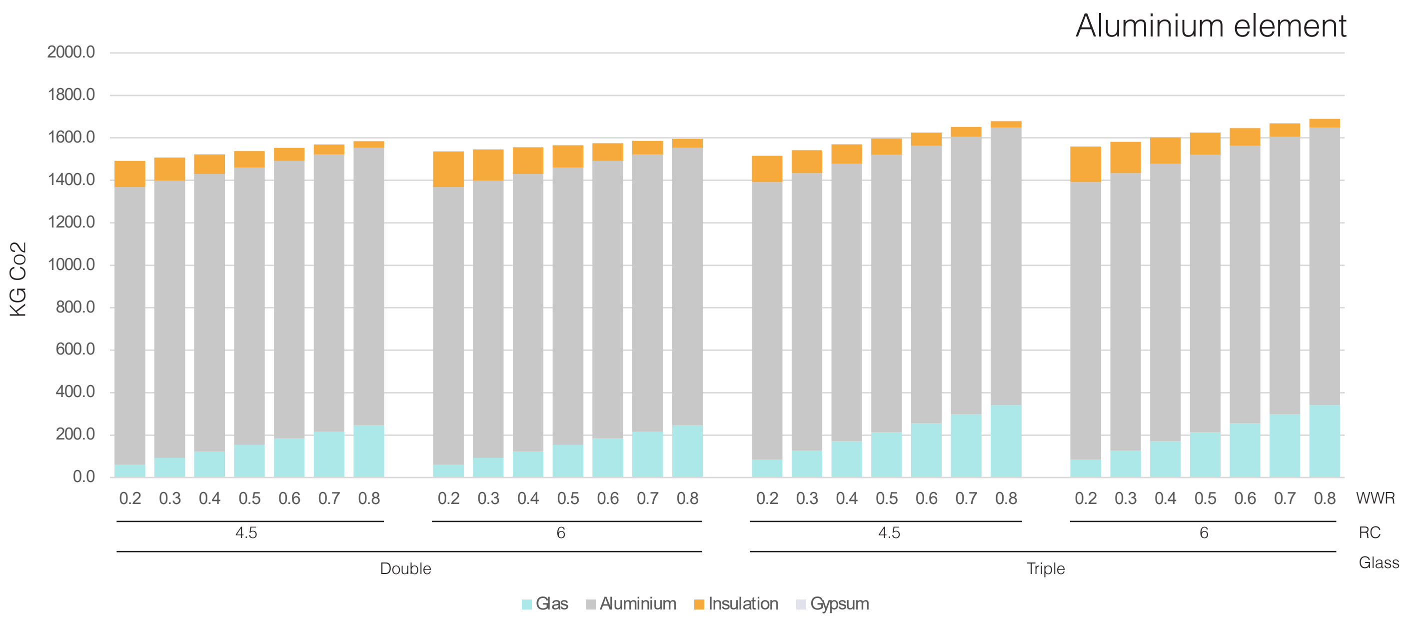
This research explores the environmental impact of various construction processes and façade compositions, which tries to provide a greater understanding of how to reduce CO emissions from building envelopes.

4.1.1 Aluminium Element Facade

The analysis shows that the embodied carbon of the aluminum unitized façade is significantly higher than that of the other façade systems examined. Compared to the prefabricated timber and concrete façades, the aluminum façade has the highest environmental impact.

One of the main factors contributing to this high value is the use of aluminum itself, as it has the highest embodied carbon of the materials used. Aluminum profiles extend across the full length and width of the façade, resulting in a substantial amount of material. In this simulation, the number of panels was not reduced, keeping the amount of aluminum consistently high.

Additionally, the embodied carbon increases as the window area becomes larger. Glass has a higher environmental impact than insulation material, meaning that an increase in the window-to-wall ratio (WWR) leads to a further



rise in total embodied carbon. This effect is clearly visible in the simulation.

The results indicate that the embodied carbon of the aluminum unitized façade is, on average, four times higher than that of the prefabricated timber façade. In comparison with the prefabricated concrete façade, the value is approximately twice as high.

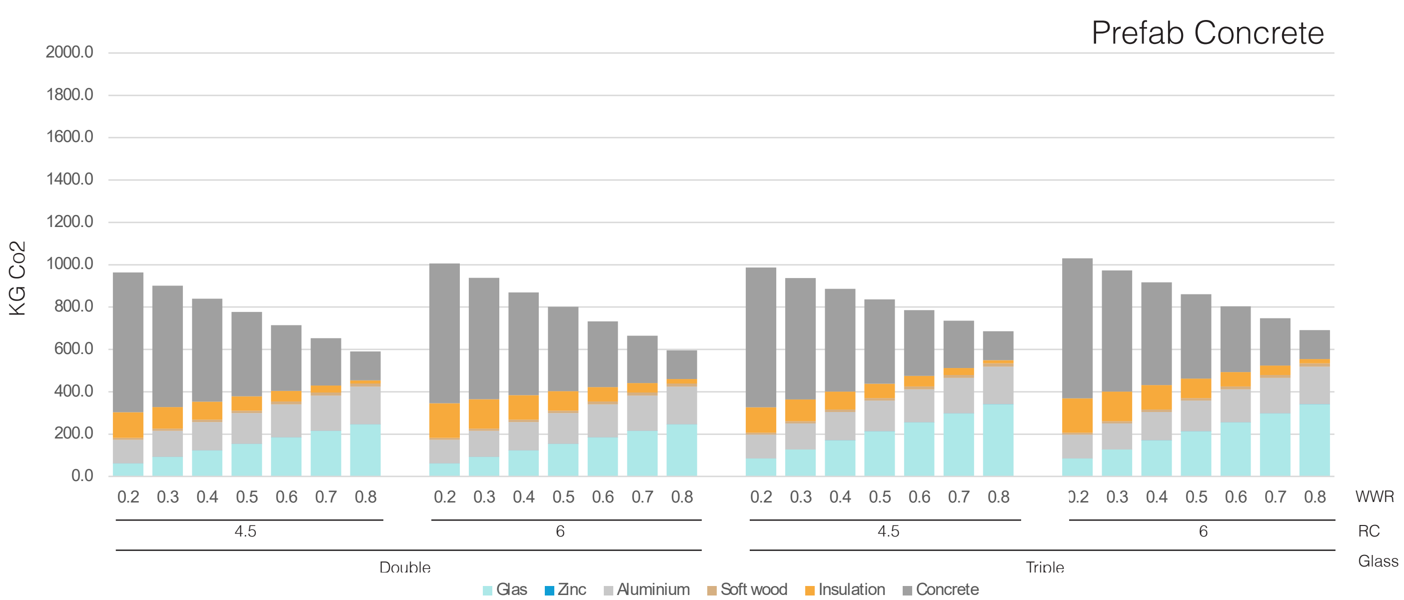
Finally, the analysis shows that as the WWR increases, the embodied carbon also rises, due to the higher use of both aluminum and glass. This confirms the impact of material choice and façade design on the environmental performance of the façade.

4.1.2 Prefab Concrete Facade

The prefabricated concrete façade falls in between the aluminum and timber façades in terms of embodied carbon. While concrete has a relatively low emission per kilogram, it is an extremely heavy material, making it one of the largest contributors to the overall environmental impact of this façade element.

One notable finding is that embodied carbon decreases as the window-to-wall ratio (WWR) increases. This occurs because the relative percentage of concrete in the element is reduced in favor of glass. In the simulation, a reduction of approximately 40% was observed when increasing the WWR from 20% to 80%.

This is an interesting result, as a higher WWR is typically associated with higher operational carbon emissions due to increased energy consumption for heating and cooling. The opposite trend in embodied carbon suggests intriguing trade-offs and insights when optimizing the overall CO emissions of a building.



4.1.3 Prefab Wood Facade

The prefabricated timber façade performs the best in terms of embodied carbon, having the lowest emissions of the three façade types analyzed. Timber has the lowest carbon footprint per kilogram among the materials used, making it the most environmentally favorable option.

A key observation is that as the window-to-wall ratio (WWR) increases, the embodied carbon also rises. This is because the relative amount of timber in the façade decreases, while materials with a higher environmental impact, such as glass for the windows and aluminum for the frames, replace it. In the simulation, an increase of approximately 50% in embodied carbon was observed when the WWR increased significantly.

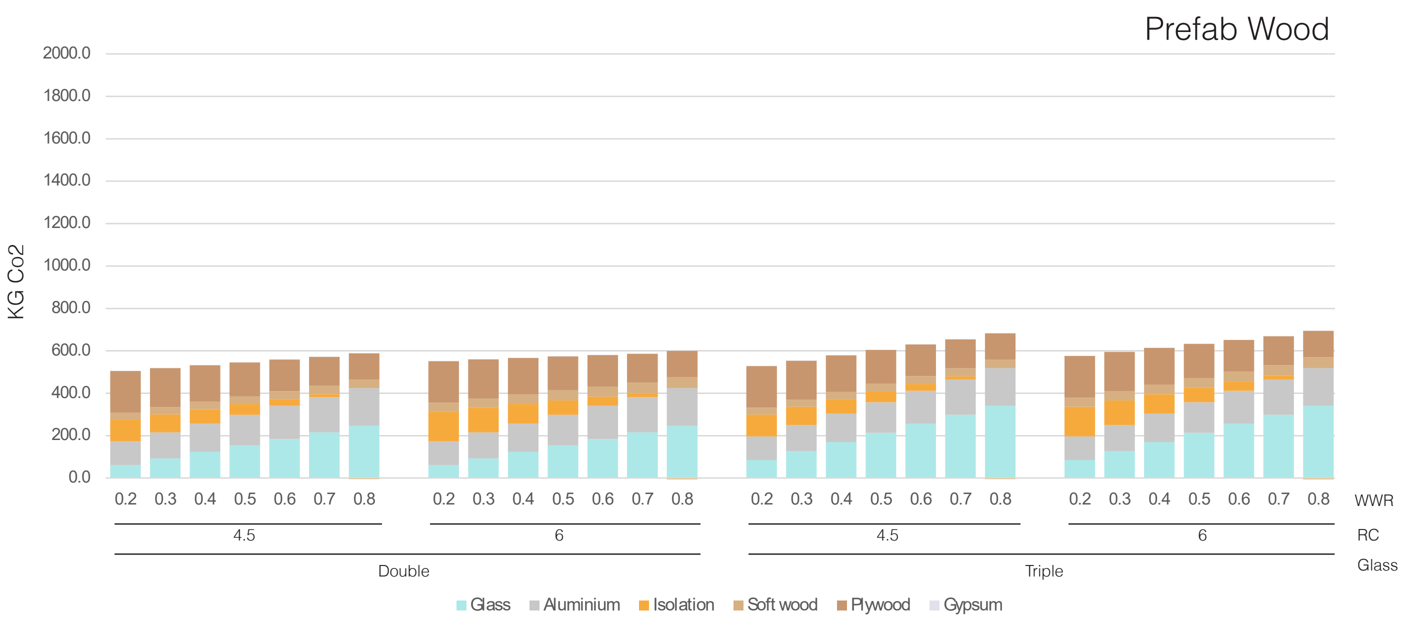
Additionally, the carbon sequestration potential of timber is an important factor to consider. Unlike concrete and aluminum, timber can temporarily store carbon during its lifecycle, further reducing its net environmental impact.

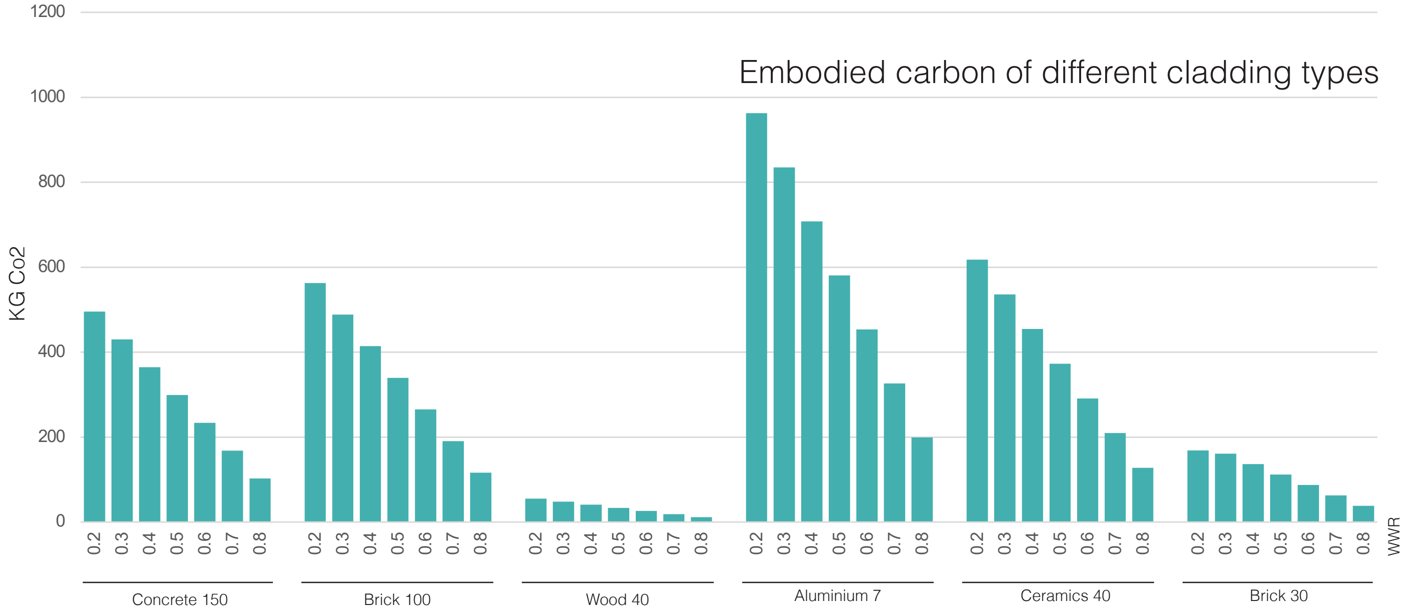
This analysis highlights the trade-offs between material choice and façade design. While the timber façade initially has the lowest embodied carbon, increasing the WWR shifts the balance toward materials with a higher impact. This emphasizes the need an approach that considers both embodied and operational carbon when optimizing façade performance.

4.1.4 Different Facade Elements With Cladding Types

As a final step in calcualting the embodied energy, the exterior cladding was analyzed separately for different WWR values ranging from 0.2 to 0.8. The materials considered in this analysis include 150mm concrete, 100mm brick, 40mm wood, 7mm aluminum, 40mm ceramics, and 30mm brick veneer. A bar chart illustrates the embodied carbon impact of these materials, revealing that aluminum has by far the highest emissions, especially at a WWR of 0.2, where its embodied carbon is ten times greater than that of wood, the most sustainable option. Additionally, the data shows that using thin brick veneer (brick slips) reduces embodied carbon by a factor of three compared to traditional brick.

To put all of this data into context, the total embodied carbon of the façade, containing both the structural element and its exterior cladding, was displayed using a scatter plot, in which the mass of the element is plotted against its total embodied carbon. This analysis attempts to illustrate an important point: a heavier façade feature has an impact on

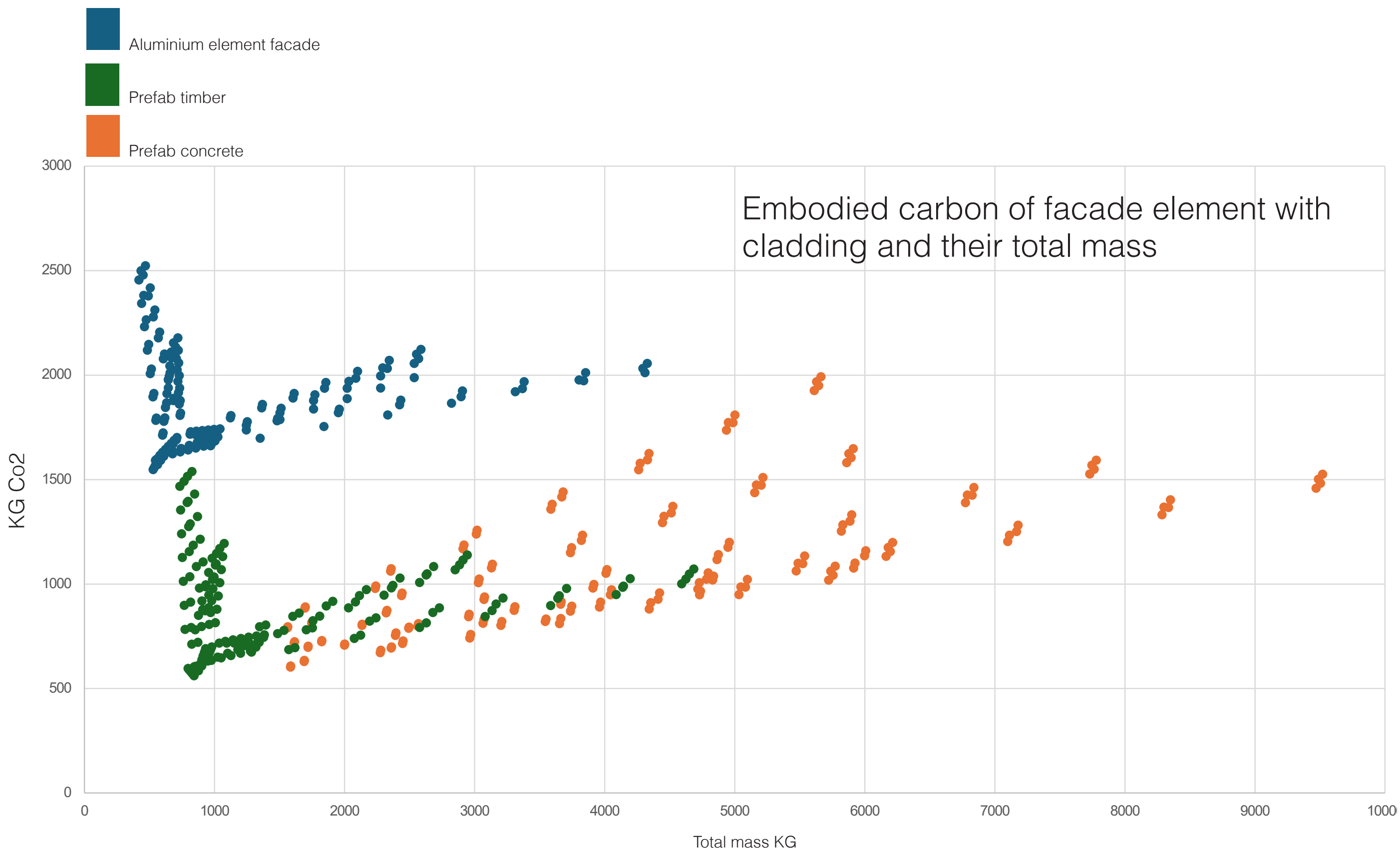




the building’s structural system, resulting in increased carbon emissions due to structural support requirements.

This figure reveals several trends. Aluminum is the lightest material, but it also has the most embodied carbon, beginning with timber and in their carbon offset. Even when timber is combined with aluminium cladding. Timber façades are still the most sustainable alternative, while concrete has the broadest variety of embodied carbon values, both for the structural element of the façade and the cladding, depending on the material selections.

Additionally, the relationship between WWR and embodied carbon varies significantly across materials. While increasing WWR reduces embodied carbon for concrete façades, it leads to an increase in embodied carbon for timber façades, highlighting the importance of balancing material selection and façade design to optimize environmental performance.



4.2 Operational Carbon

While the previous chapter looked at embodied carbon, this chapter examines the operational carbon of different façade systems. Operational carbon is CO emissions generated over the life of a building due to energy consumption for heating, cooling, ventilation, and lighting, taken over 75 years. The impact of façade design on these energy needs is significant, and therefore it is an important factor in the overall environmental performance of a building.

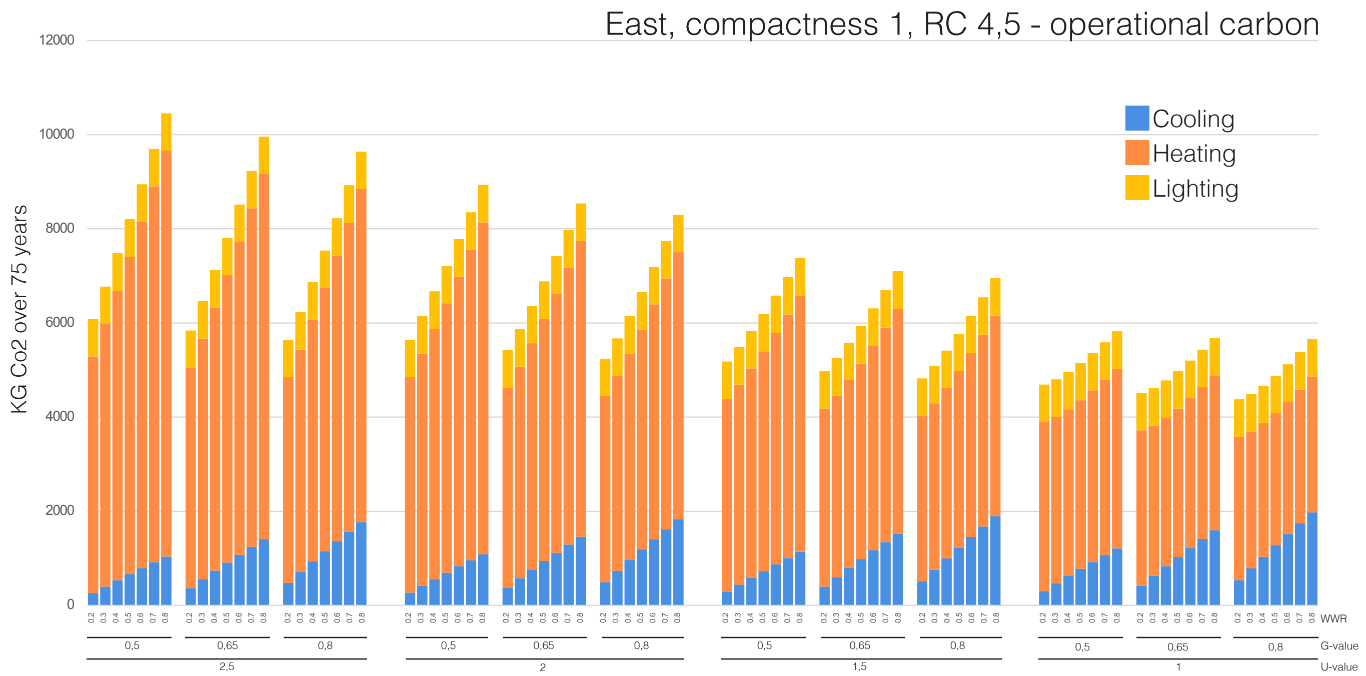
This research evaluates the effect of factors such as window-to-wall ratio (WWR), glass U-value (U-glass), solar heat gain coefficient (g-glass), façade insulation (Rc-value), and building compactness on operational carbon emissions. The study also considers the efficiency of energy production and the carbon intensity of the electricity grid, examining how cleaner sources of energy influence overall emissions.

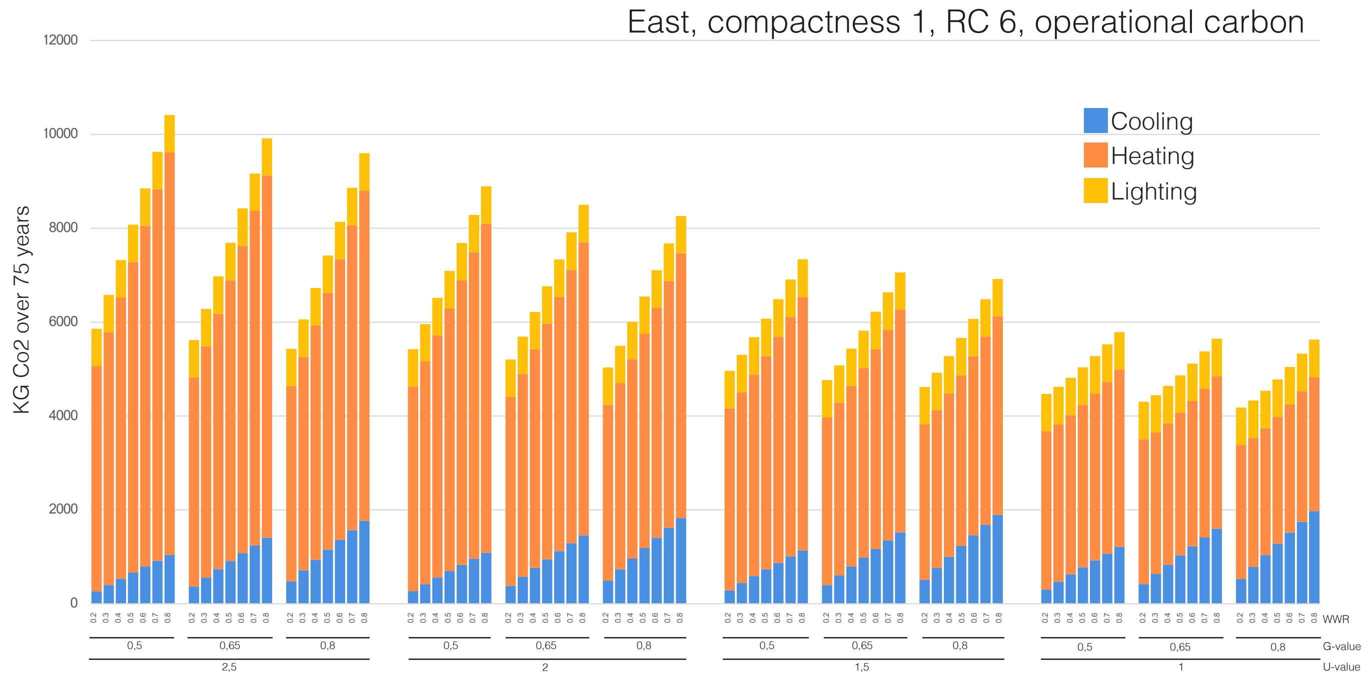
Building orientation effect is also examined, with east, north, and south-facing facades being emphasized. East-facing facades were used as this orientation is the most avarage of the four. North facades will have more operation carbon because they have less solar gain, and the south facades get more sun and thus less heating demand. The other orientations and additional variations can be seen in appendix.

Through understanding these relationships, this chapter aims to set out strategies for minimizing lifecycle CO emissions, reconciling both embodied and operational impacts through maximized façade and energy system design.

4.2.1 East

When analyzing the results for the east-facing façade, it becomes evident that lowering the U-value of the glass (U-glass) significantly reduces operational carbon emissions. In a scenario with a compactness of 1, an Rc-value of 4.5, and a g-value of 0.5, a decrease in U-glass from 2.5 to 1 results in a reduction of 4,634 kg of CO, representing a 44.3% decrease. This suggests that improving the insulating performance of glazing has a major impact, particularly in cases where heat loss

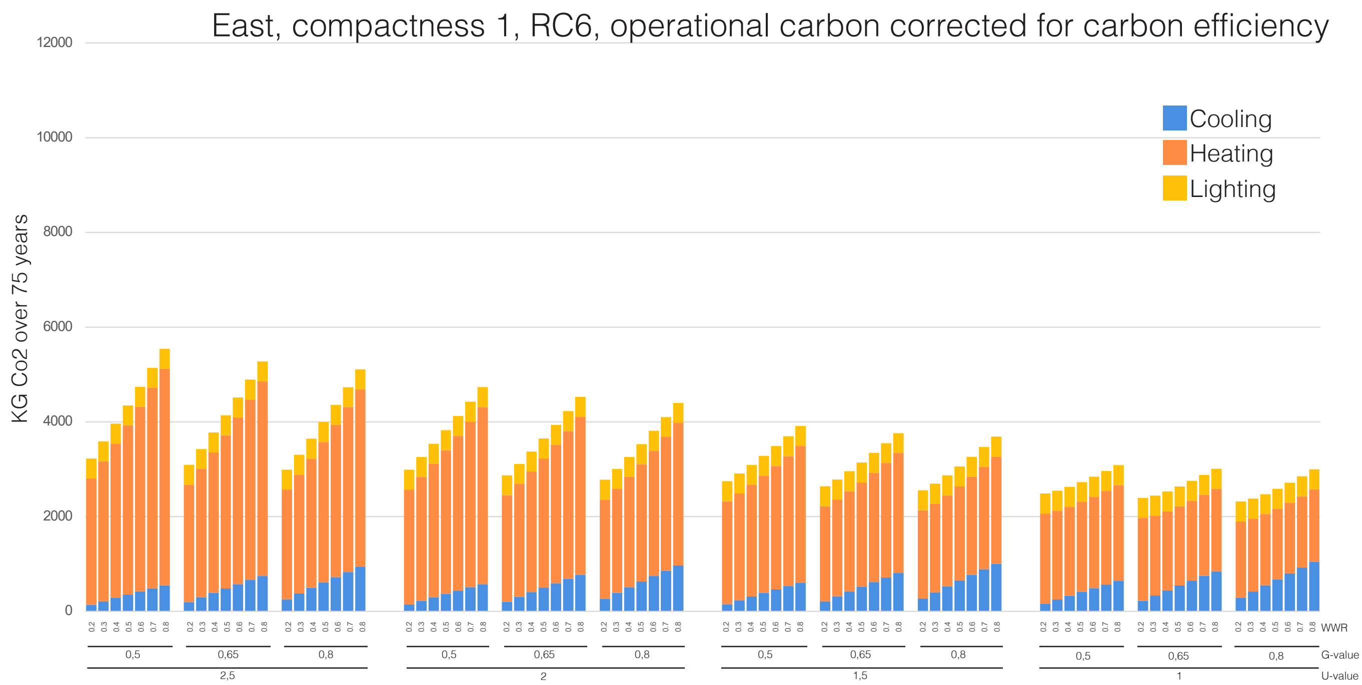




through windows is substantial. Additionally, as U-glass improves, the differences in operational carbon emissions between different WWR configurations become less pronounced. This indicates that optimizing glazing performance offers the greatest potential for reducing emissions in this configuration.

In contrast, increasing the Rc-value has a much smaller effect on operational carbon, especially when window-to-wall ratios are high. For instance, when increasing the Rc-value from 4.5 to 6 in a façade with a WWR of 7, a U-glass value of 0.2, and a g-value of 0.8, the reduction in operational carbon is only 62 kg CO, or 0.8%. In another case, under similar conditions, the reduction amounts to 174 kg CO, or 3.1%. These findings suggest that at higher WWRs, the impact of additional insulation is marginal, as heat transfer through glazing plays a more dominant role in the overall energy balance.

Looking at long-term projections, an assumed 2% annual improvement in energy efficiency leads to a substantial decrease in the the total operational carbon over a 75-year period, close to 50%. This highlights the significant role of decarbonization in energy generation and efficiency improvements in reducing lifetime emissions.



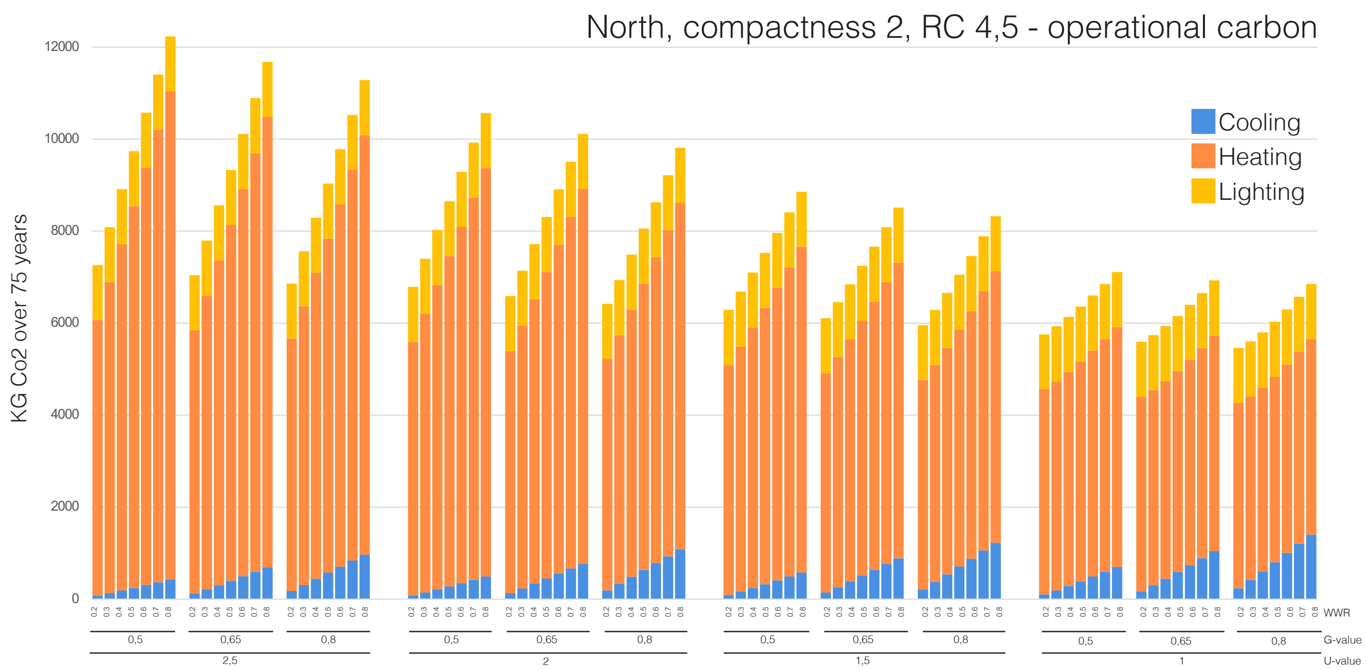
4.2.2 North

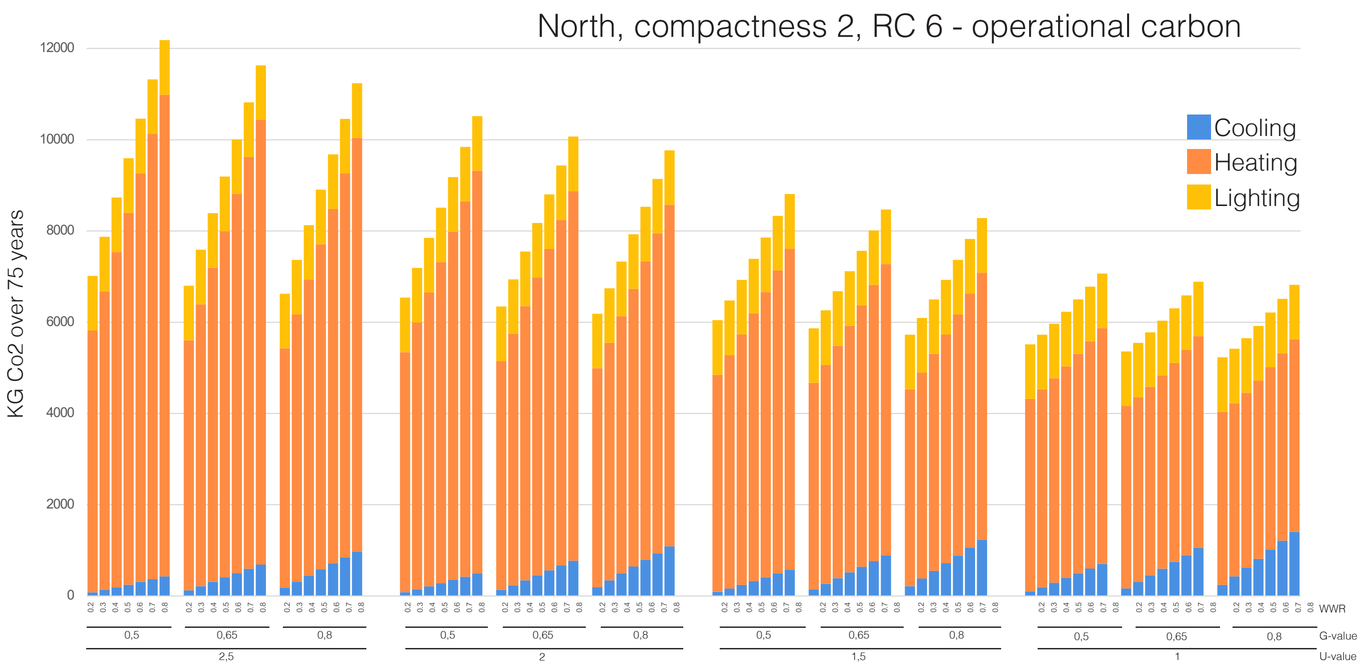
For the north-facing façade, heating energy demand is significantly higher, while cooling demand is lower. This is due to the reduced solar exposure, which limits passive solar gains. As a result, operational carbon emissions are generally higher compared to other orientations.

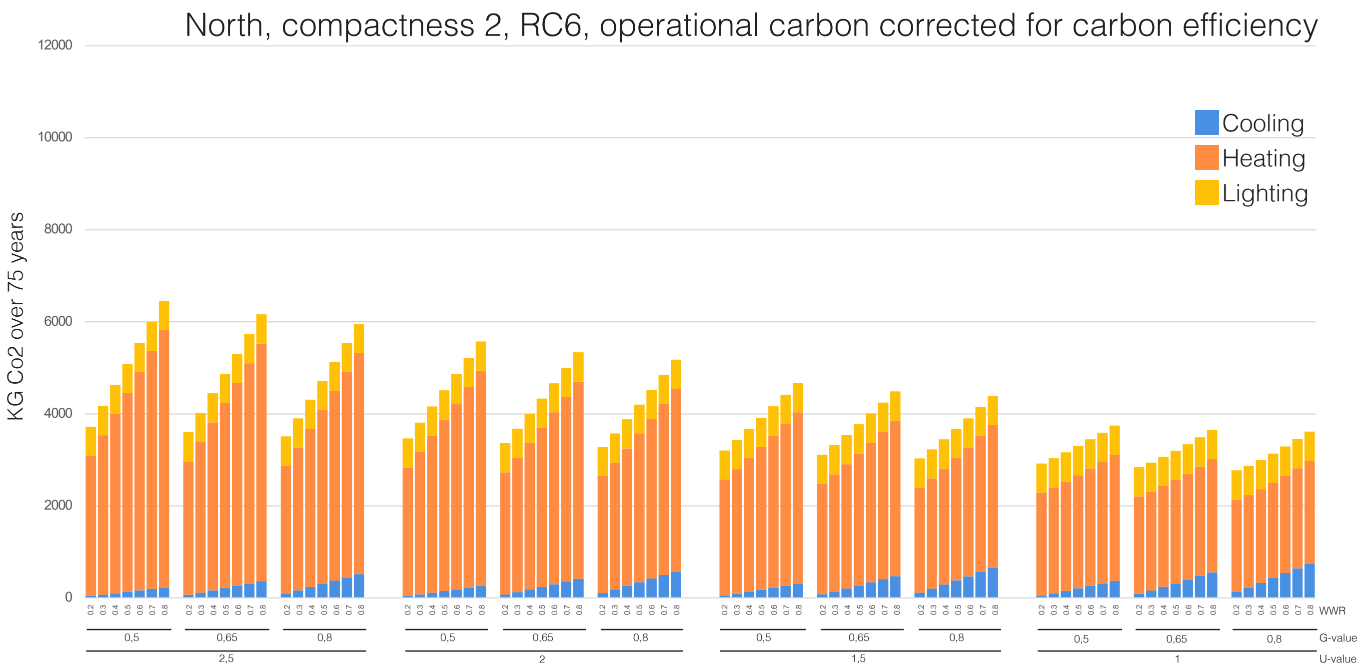
The differences between configurations are even more pronounced, particularly when U-glass performance is poor. When the U-glass value is 2.5, the total operational carbon emissions can range from 12,100 kg to approximately 7000 kg, representing a 42.1% reduction. As seen in previous cases, improving U-glass performance also reduces the variation in operational carbon between different WWR configurations, making the impact of window size less significant.

Additionally, lowering the g-value consistently leads to an increase in operational carbon emissions. This is because a lower g-value reduces solar heat gain, increasing heating demand, which is particularly relevant in this orientation.

Long-term projections again highlight the enourmous effect of efficiency improvements and grid decarbonization. With an assumed 2% annual improvement in carbon intensity, operational emissions are expected to decrease by approximately 50% over a 75-year period, reinforcing the importance of energy-efficient design and cleaner energy sources in reducing total emissions.




North, compactness 2, RC 6 - operational carbon
KG Co2 over 75 years
12000
10000
8000
6000
4000
2000
0
Cooling
Heating
Lighting
WWR
G-value
U-value
0,5
0,65
0,8
2,5
2
1,5
1


North, compactness 2, RC6, operational carbon corrected for carbon efficiency
KG Co2 over 75 years
12000
10000
8000
6000
4000
2000
0
Cooling
Heating
Lighting
WWR
G-value
U-value
0,5
0,65
0,8
2,5
2
1,5
1

4.2.2 South

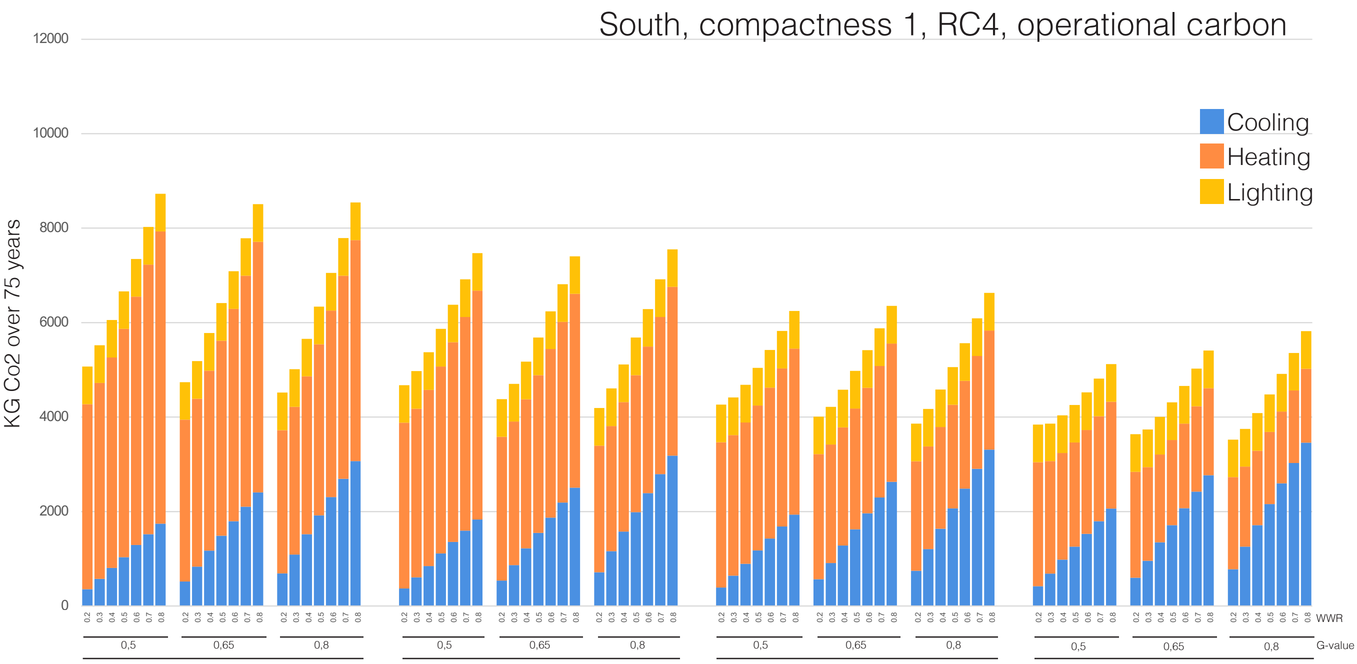
For the south-facing façade, operational carbon emissions are the lowest among all orientations due to high solar exposure, which provides significant passive heating during colder months. As a result, heating demand is considerably lower, while cooling demand increases. However, since heating energy typically has a higher carbon intensity than cooling, the overall impact remains favorable. In the best-performing façade configurations, cooling demand even surpasses heating demand—an effect observed exclusively in south-facing façades.

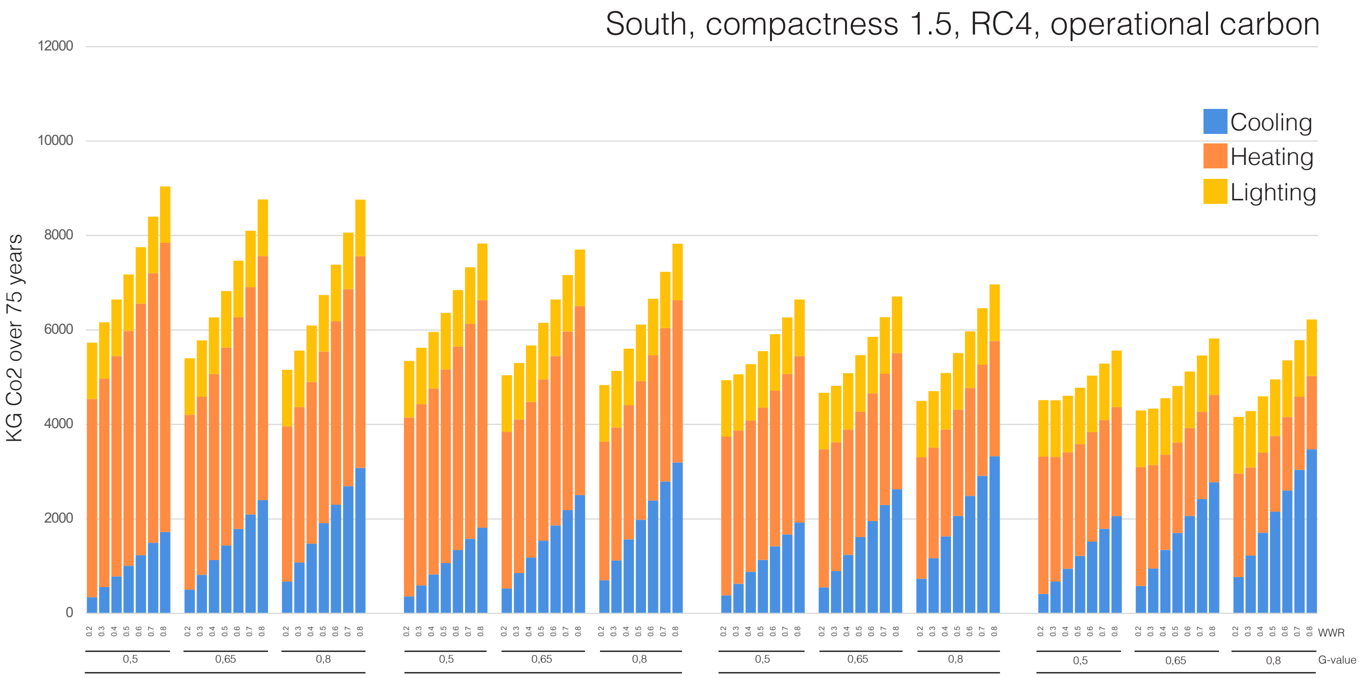
The influence of U-glass performance follows the same trend as in other orientations, with better insulation reducing operational emissions and minimizing the differences between WWR configurations. However, in this case, the effect is less pronounced compared to the north-facing façade, as solar gains compensate for heat loss more effectively.

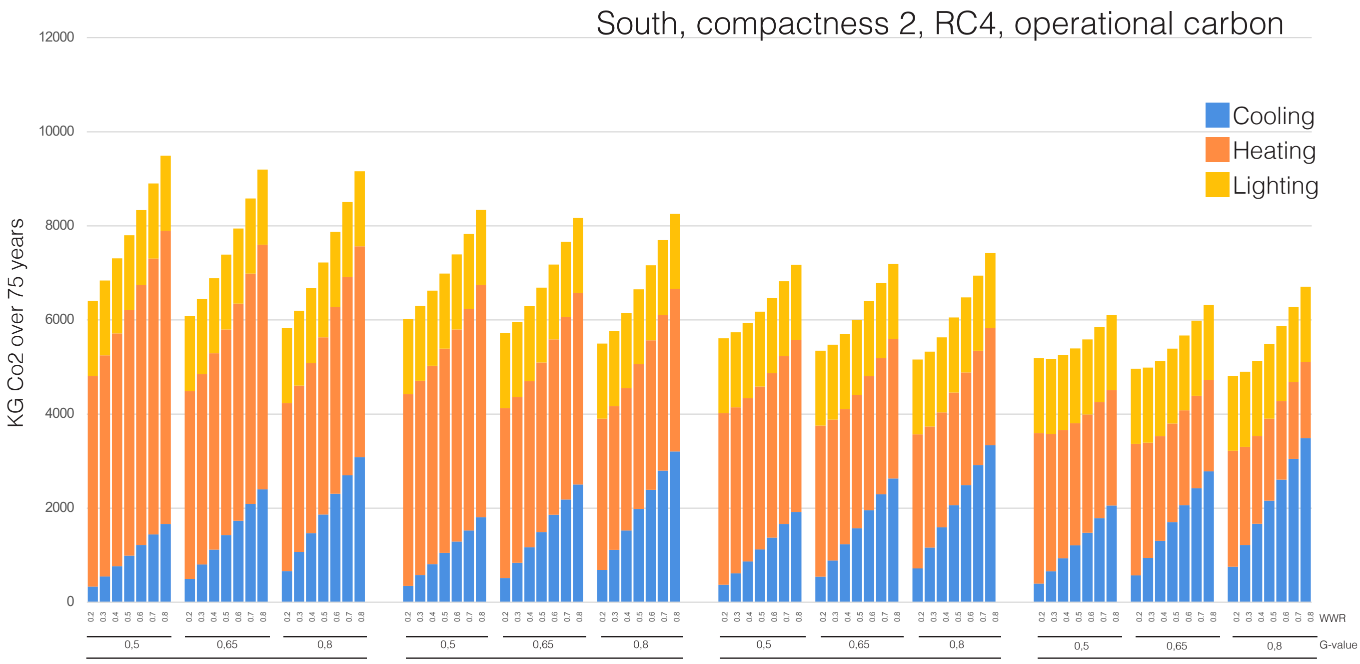
Unlike in the north-facing orientation, lowering the g-value has a more complex effect. While it reduces cooling demand by limiting solar heat gain, it also increases heating demand in winter. Depending on the balance between heating and cooling needs, the impact of g-value adjustments varies.

Over the long term, improvements in energy efficiency and grid decarbonization again lead to a substantial reduction in emissions. With an assumed 2% annual improvement, total operational carbon emissions are projected to decrease by approximately 50% over 75 years, further emphasizing the importance of material selection, glazing performance, and energy efficiency in façade design.

Additionally, these results highlight the impact of building compactness. The more interior space situated behind the façade, the higher the total emissions, as greater volumes require more energy for heating and cooling. This effect is clearly visible across the different configurations, reinforcing the role of building form in overall energy performance.




South, compactness 1.5, RC4, operational carbon
KG Co2 over 75 years
12000
10000
8000
6000
4000
2000
0
Cooling
Heating
Lighting
WWR
G-value
0,5
0,65
0,8

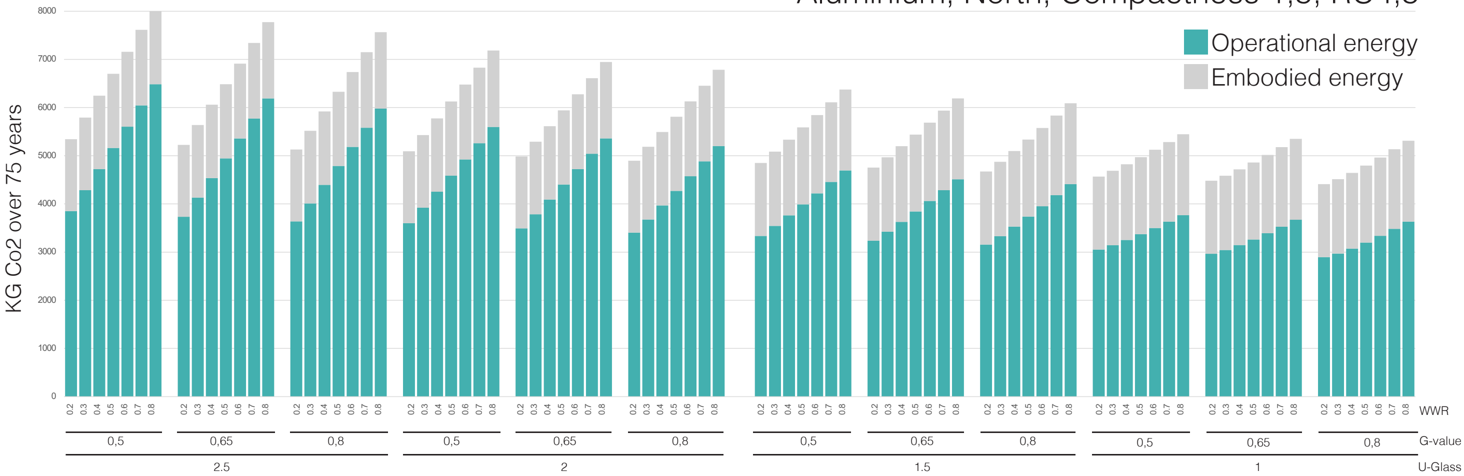

South, compactness 2, RC4, operational carbon
KG Co2 over 75 years
12000
10000
8000
6000
4000
2000
0
Cooling
Heating
Lighting
WWR
G-value
0,5
0,65
0,8

4.3 Operational & Embodied Carbon

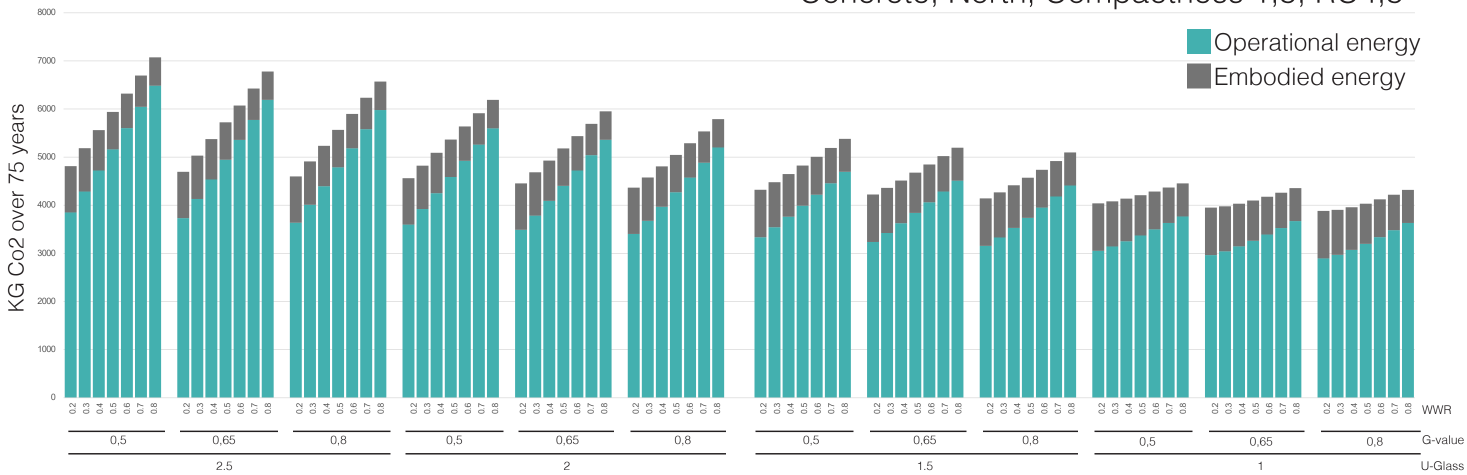
In the next step, operational carbon was added to the embodied carbon of the different façade elements, with adjustments made to account for the projected decrease in carbon intensity over time.

This analysis was conducted for both the north- and south-facing orientations, representing the most extreme cases, while the other variations can be found in the appendix. The combined results provide insight into whether increasing the Rc-value is effective when both operational and embodied carbon are considered together. Additionally, it becomes evident that

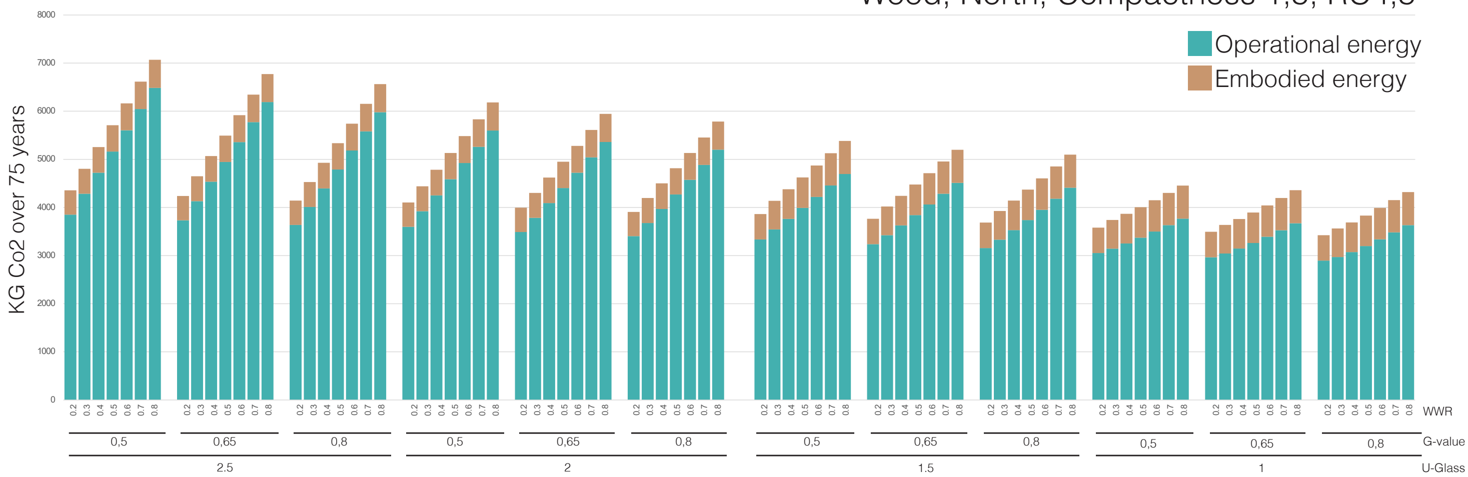
Aluminium, North, Compactness 1,5, RC4,5



Concrete, North, Compactness 1,5, RC4,5



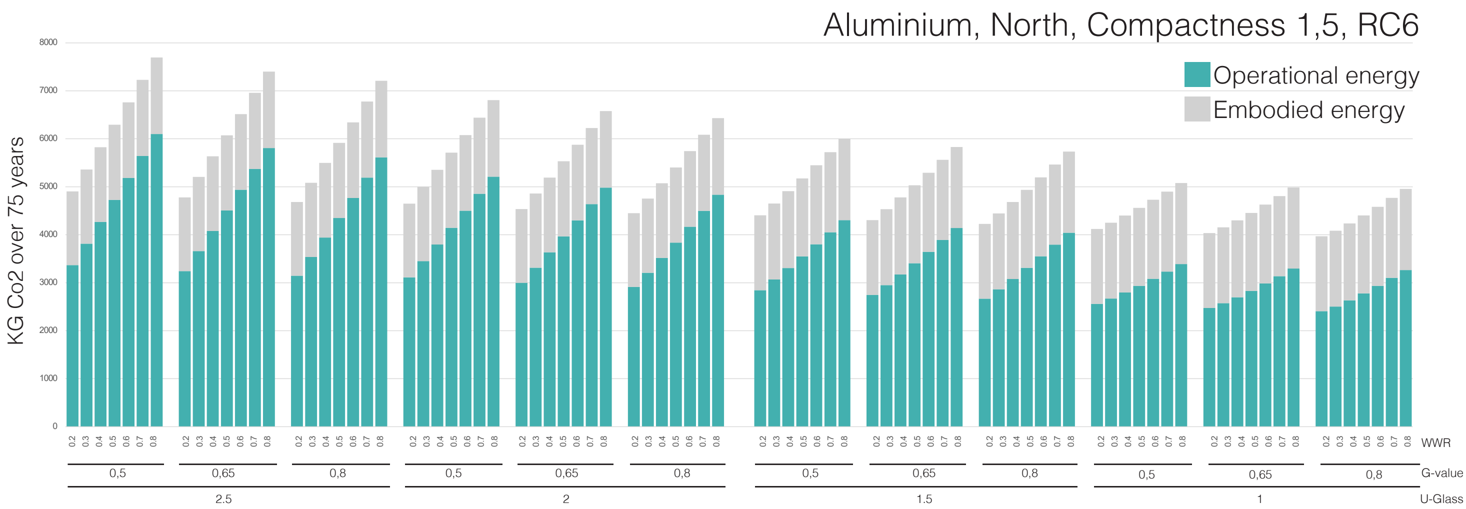
Wood, North, Compactness 1,5, RC4,5

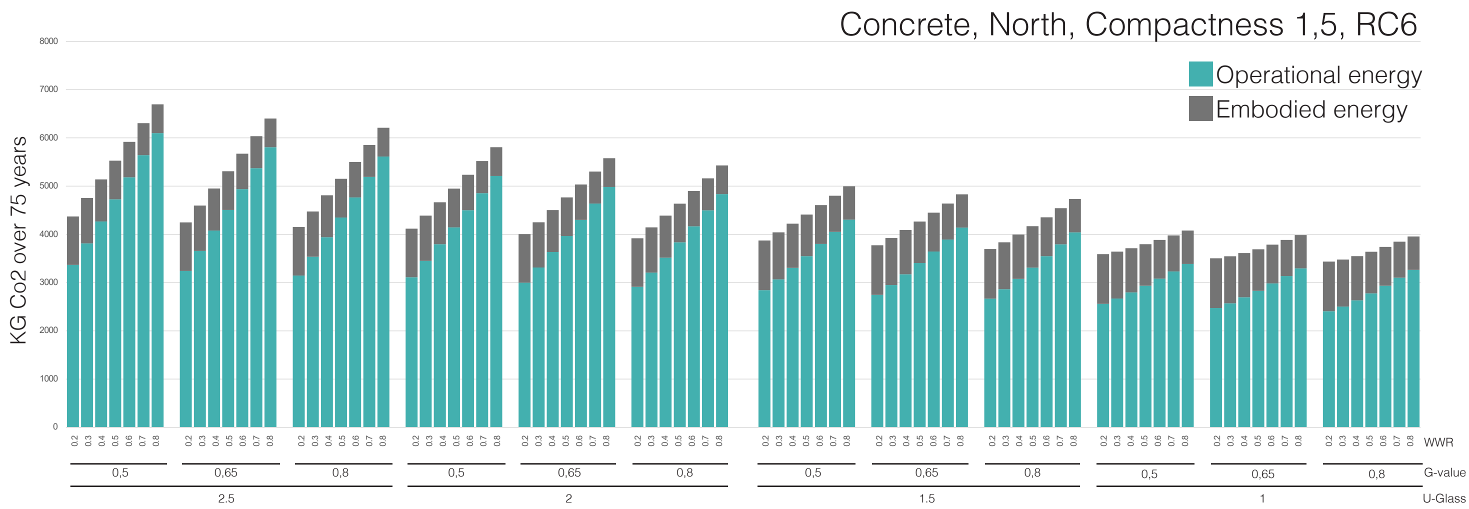


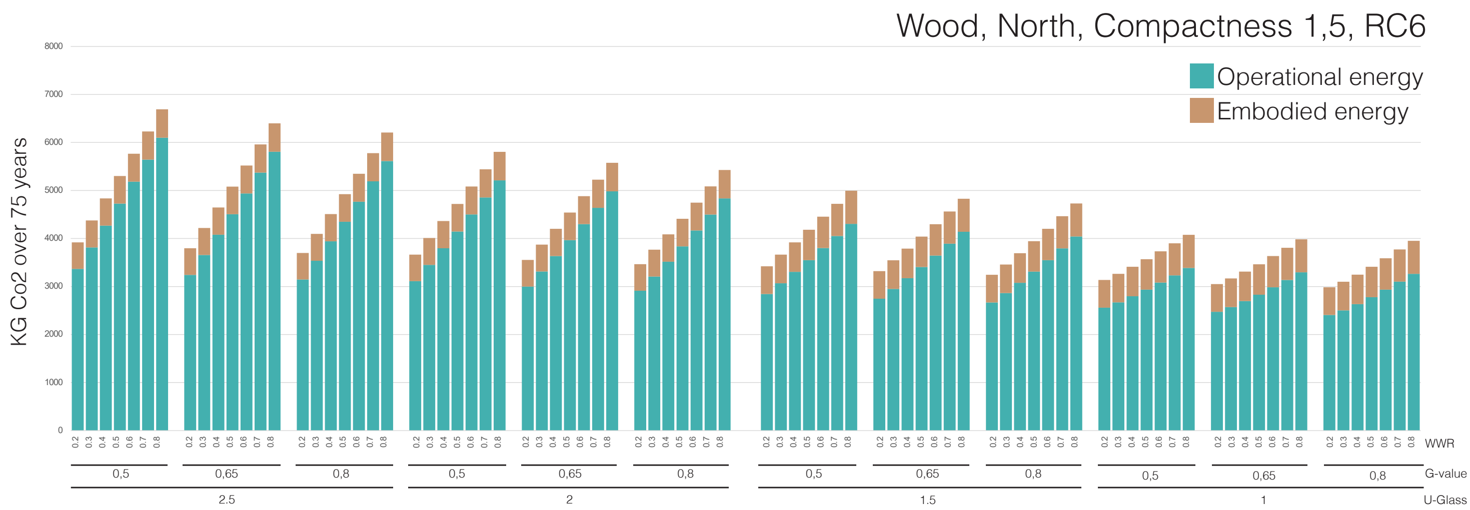
when U-glass is improved beyond a value of 1.5, embodied carbon begins to rise due to the introduction of triple glazing.

For both concrete and timber façades, a lower U-glass value and a high WWR result in a reduction in total emissions when the Rc-value is increased. However, as WWR decreases, the opposite effect occurs, and an Rc-value of 4.5 proves to be the more sustainable option in terms of total emissions.

An important observation is how, as the façade becomes more efficient in reducing operational energy demand, embodied carbon accounts for a larger share of the total emissions. In aluminum façades, embodied carbon makes up approximately 30% of the total impact, whereas for timber, it remains consistently low, below 10% in all cases. This further highlights the importance of balancing operational efficiency with material selection when

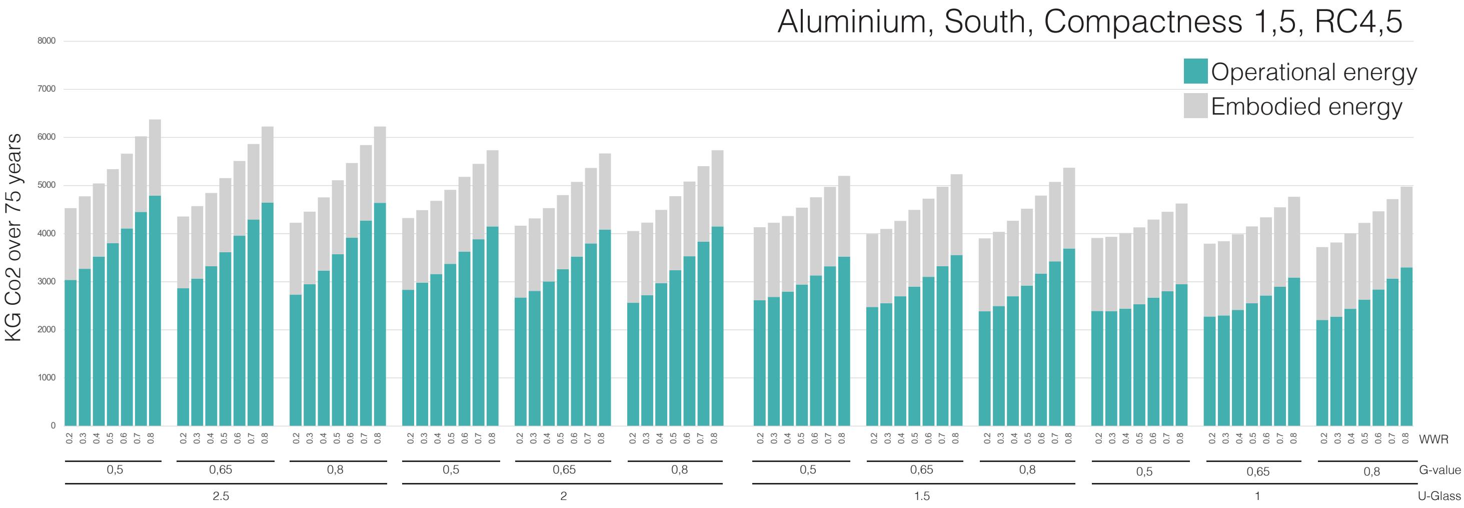


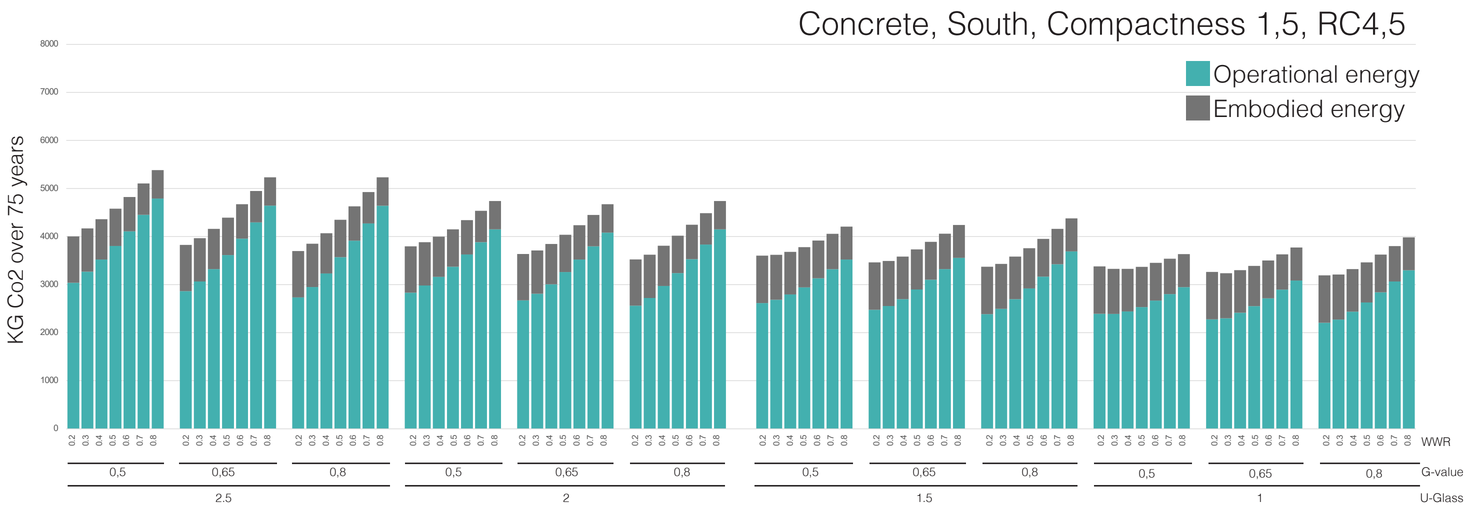


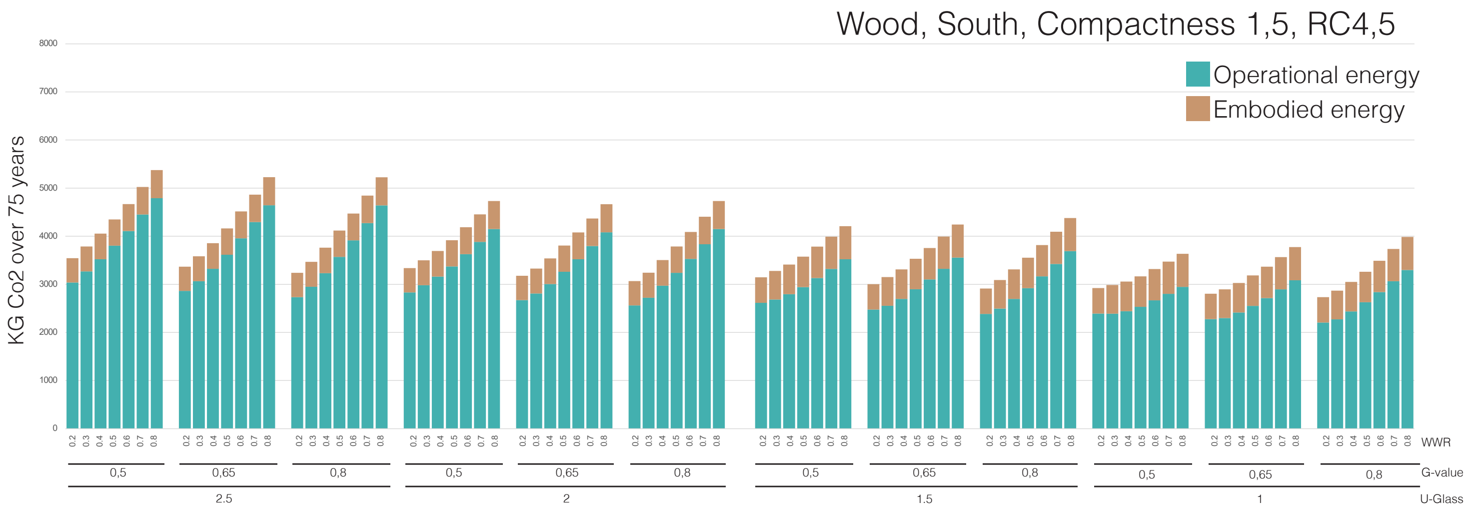


designing low-carbon building envelopes.

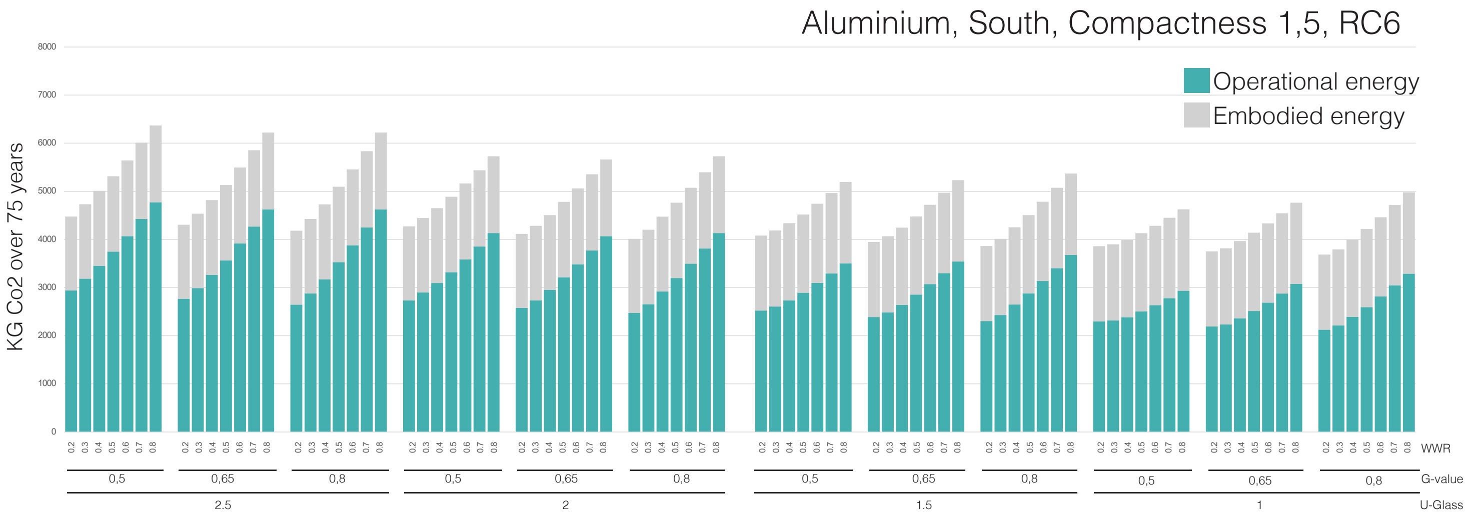
For the south-facing façade, the embodied carbon of aluminum façades accounts for nearly half of the total emissions in the best-performing configurations. This highlights the growing significance of embodied emissions as operational efficiency improves. Additionally, the results show that, regardless of façade type, a lower WWR generally leads to lower total emissions when insulation values remain constant, except in the case of concrete. Here, a unique trend emerges where a lower WWR actually increases emissions, likely due to the

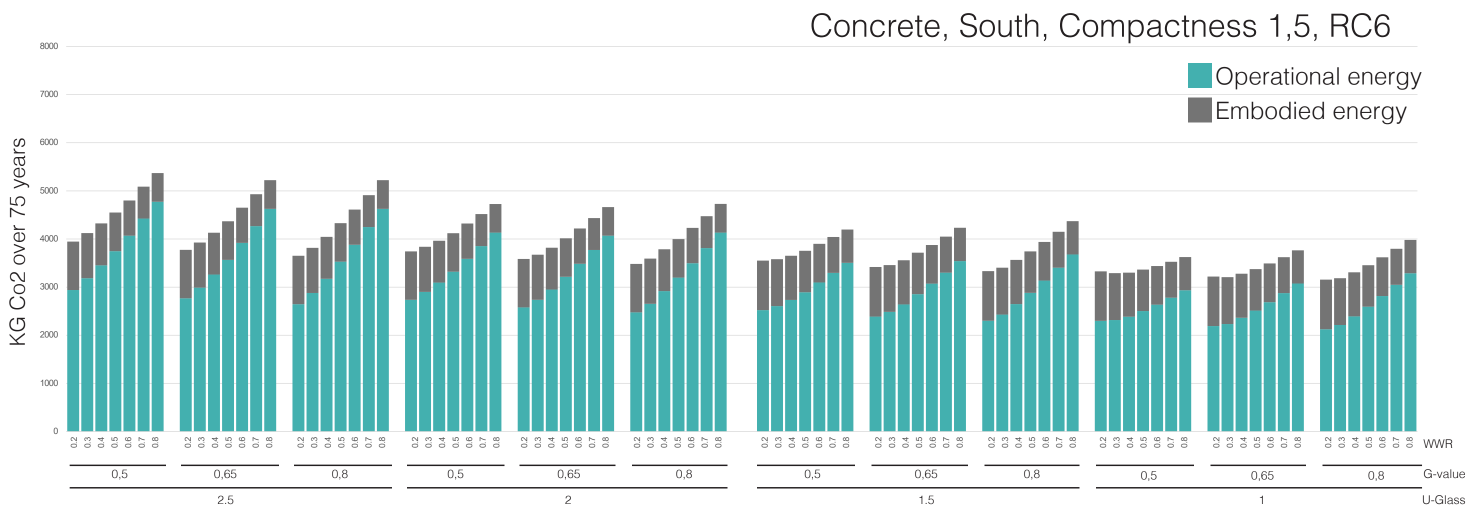


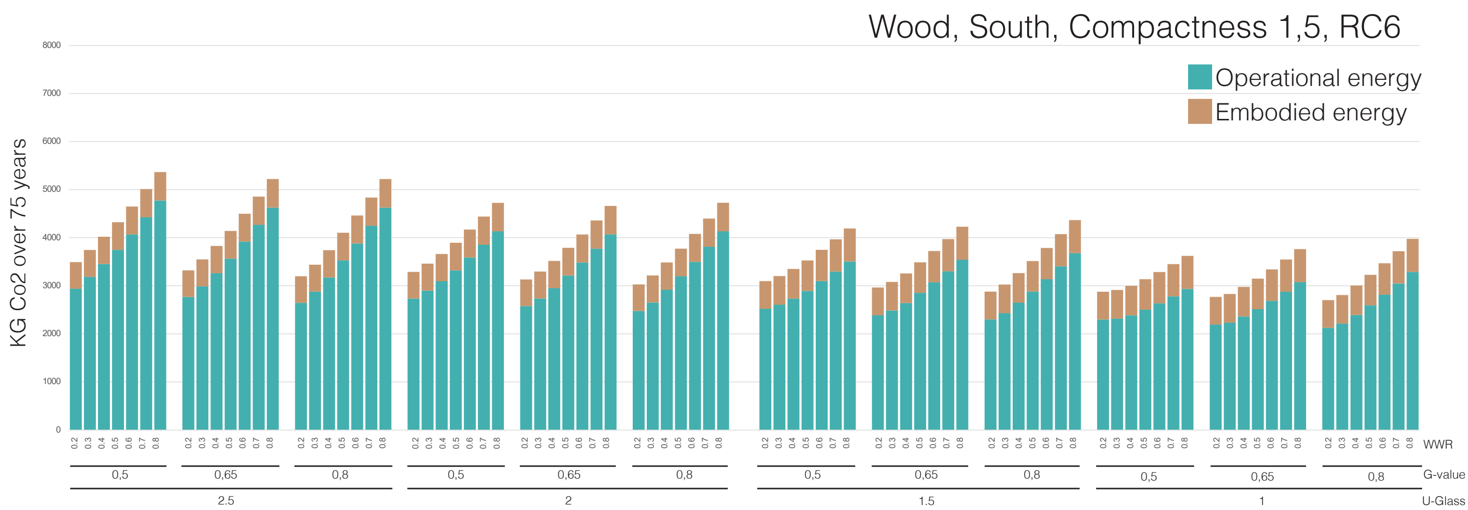




high embodied carbon of concrete relative to glazing.







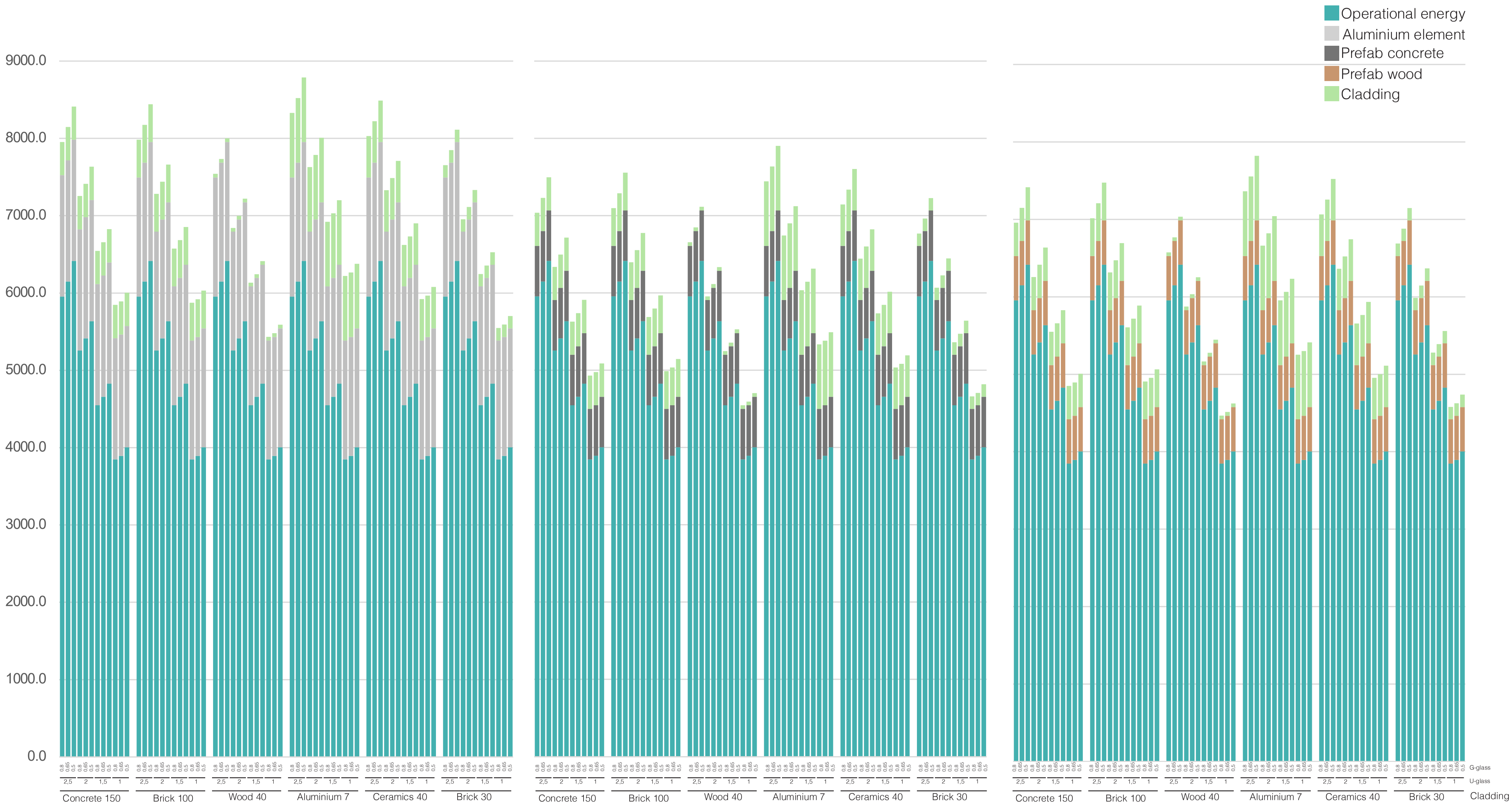
After assessing both operational and embodied carbon, an extra layer was added to the bar charts to include the embodied carbon of several material options. In principle, all conceivable variations across different parameters may be shown, resulting in over 10,000 combinations. To keep the results comprehensible, specific selections were chosen based on a single WWR, compactness level, orientation, and Rc value. This provides for a clear comparison of how material selection alone affects emissions. The other charts are found in the apendix section.

In the first graph, which depicts a north-facing façade with WWR 70, compactness 2, and Rc 4.5, the total emissions range from roughly 4,300 kg in the lowest-emission façade to approximately 8,700 kg in the highest-emission façade, a 4,400 kg difference. This difference is solely attributable to improvements in construction processes and the use of materials with higher U-glass values, illustrating the potential for emission reductions.

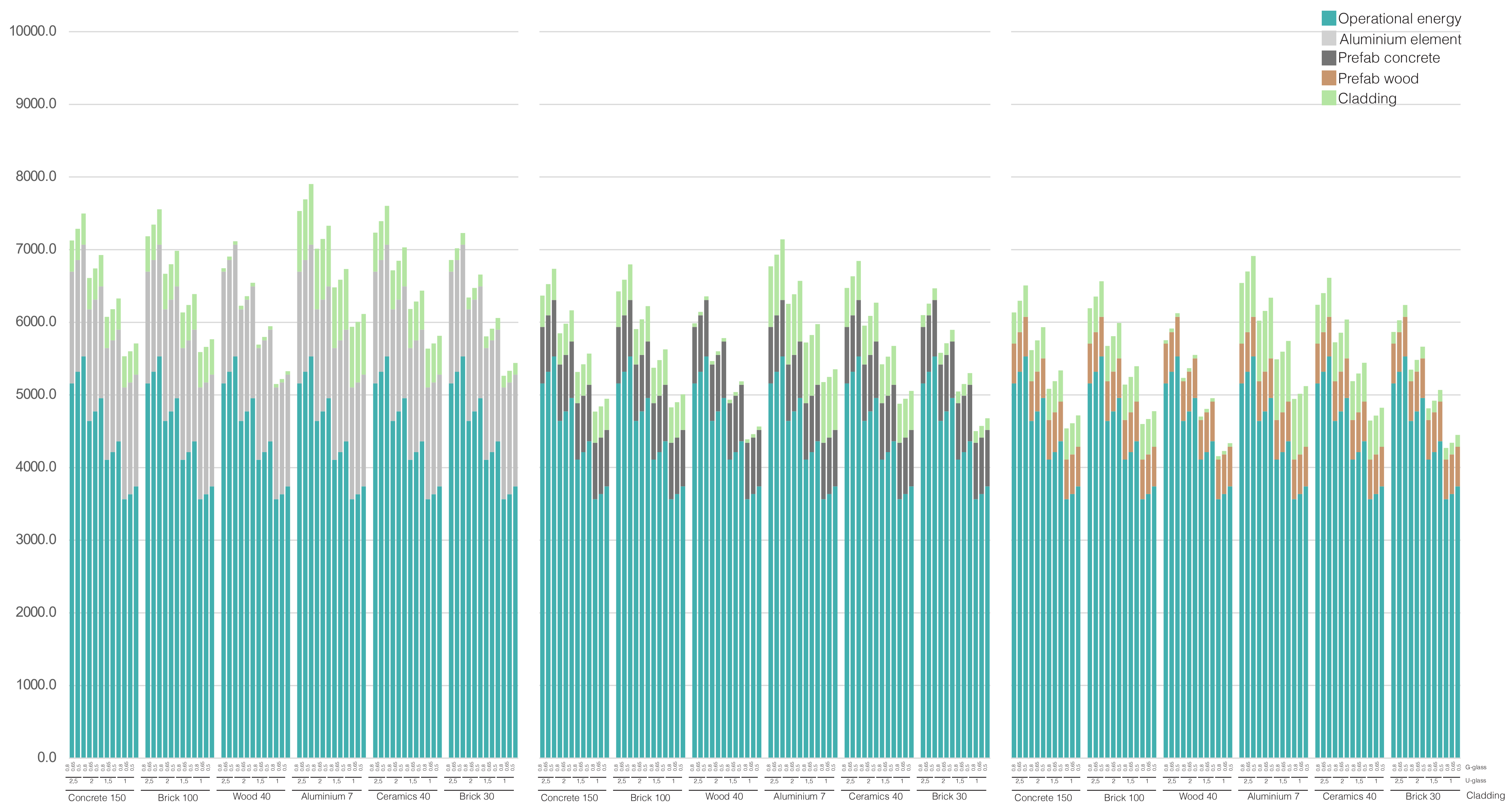
When examining the impact of reducing WWR, the results show that in a timber-frame (HSB) façade with wooden cladding (North, WWR 30, Compactness 2, Rc 4.5), the total emissions drop to 4,000 kg, which is 300 kg less than the 4,300 kg in the previous configuration. While the difference is slight, it is considerably more noticeable in other construction methods, where reducing WWR results in significant emission reductions.

urthermore, the results show that material selection becomes increasingly important as operating efficiency improves. In high-performing façades with minimal heating and cooling demand, materials' embedded carbon becomes a major driver of overall emissions. This underscores the importance of balancing material sustainability and energy performance when developing low-carbon buildings.

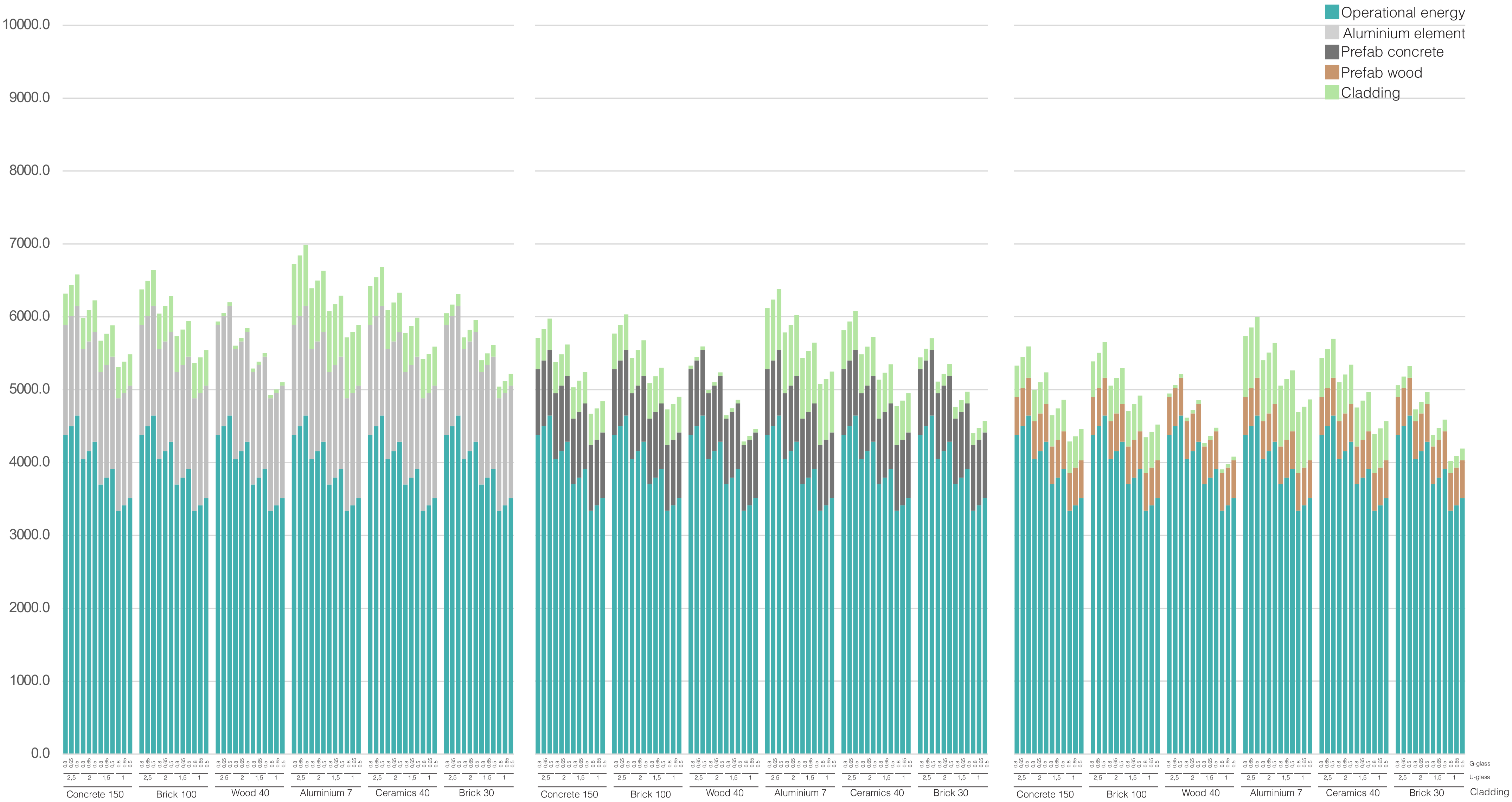
North, WWR 70, Compactness 2, RC4,5



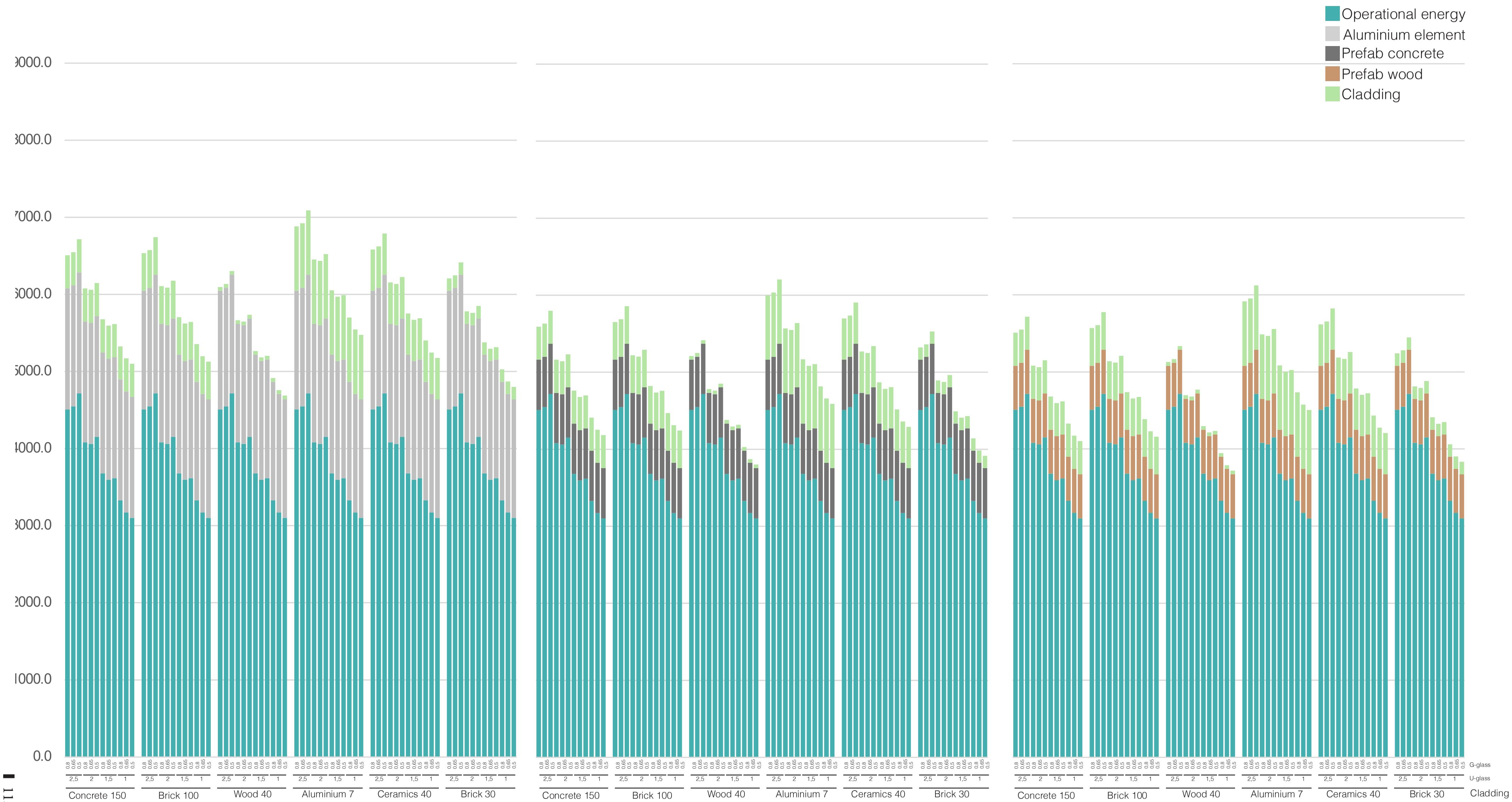
North, WWR 50, Compactness 2, RC4,5



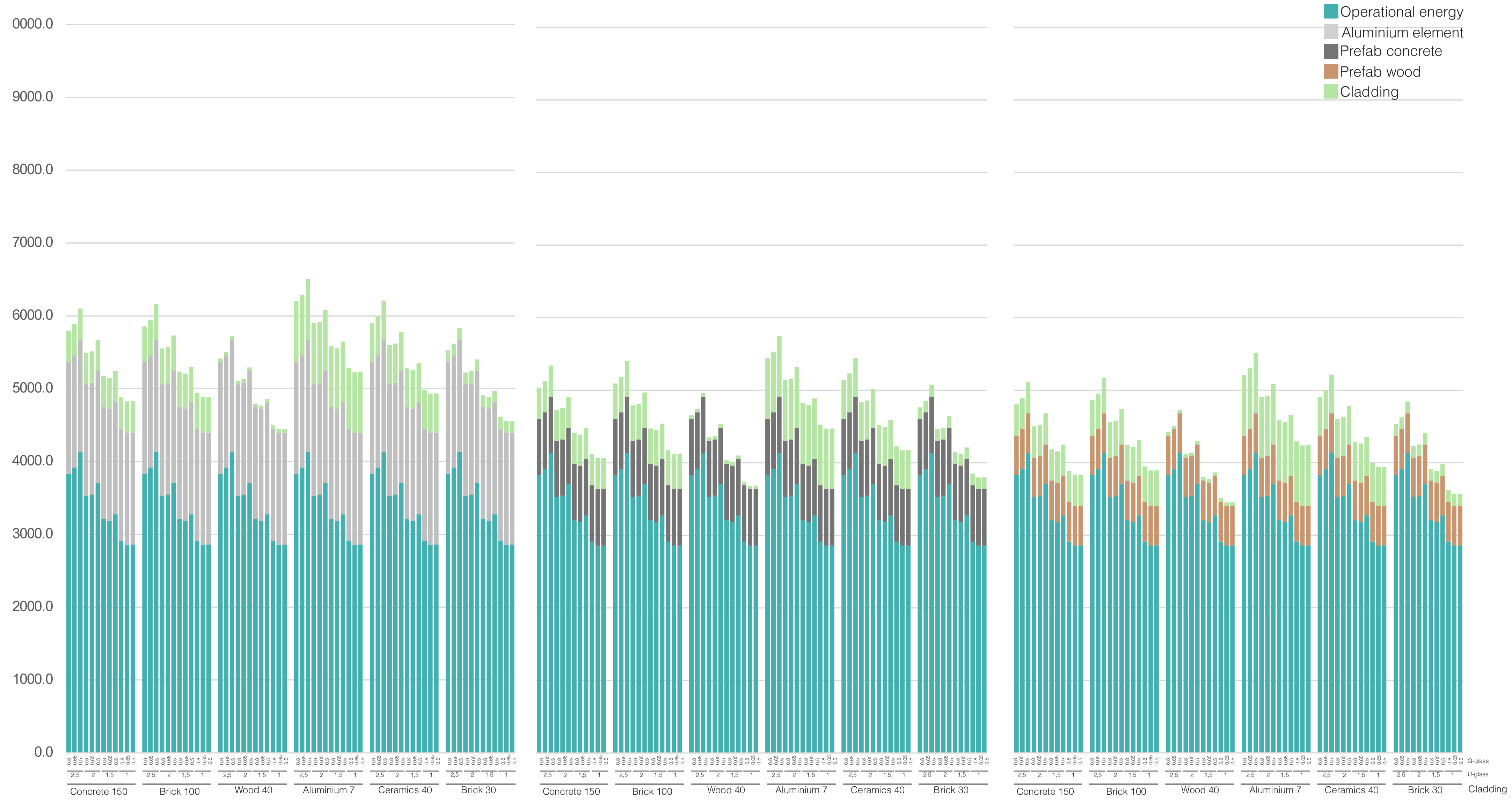
North, WWR 30, Compactness 2, RC4,5



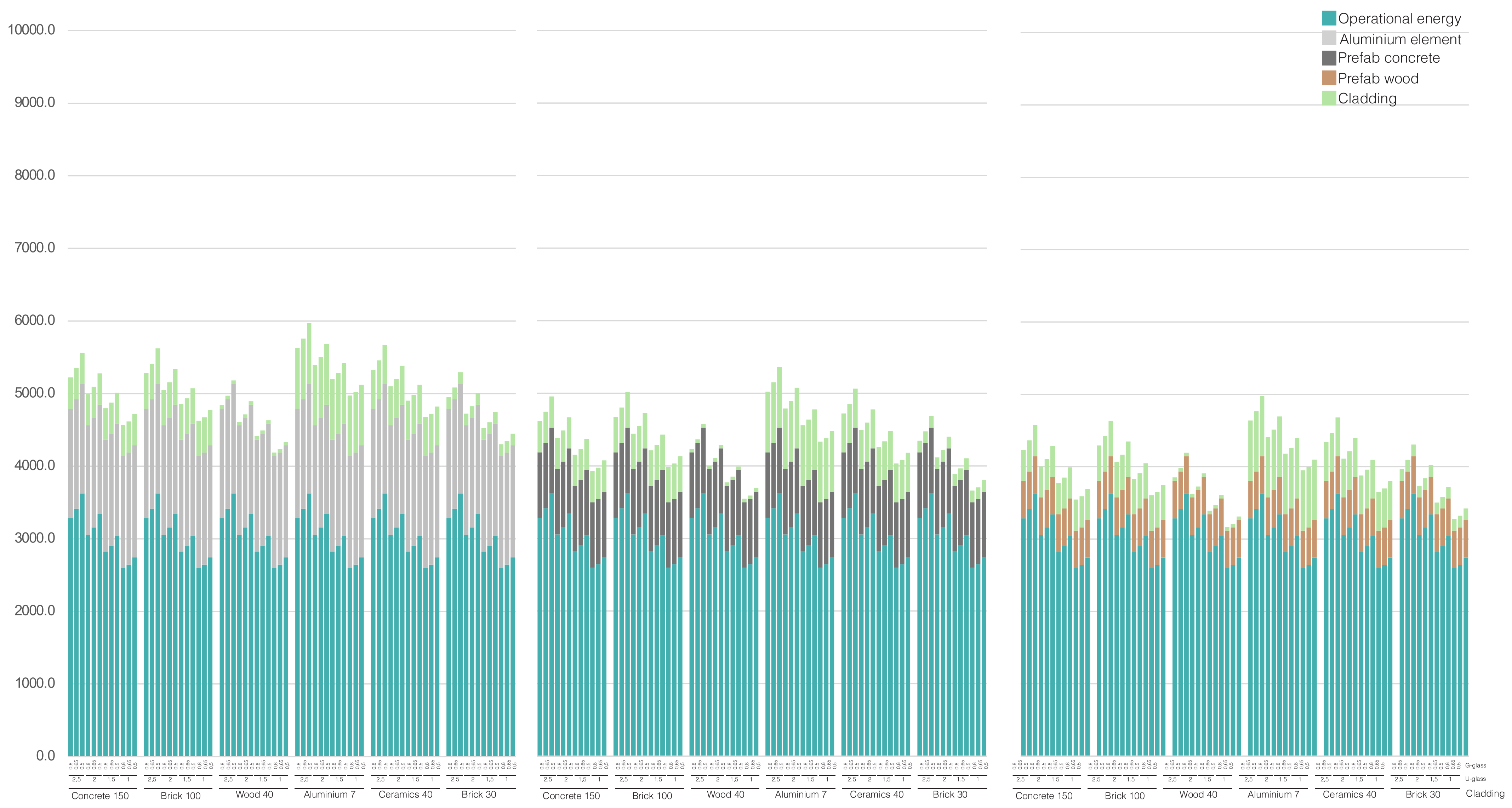
South, WWR 70, Compactness 2, RC4,5



South, WWR 50, Compactness 2, RC4,5



South, WWR 30, Compactness 2, RC4,5



In the final tables, it becomes clear that the large number of results generated by the simulation makes it difficult to present the data in a clear and comprehensible manner. To facilitate the comparison of design choices, an attempt was made to visualize this in a more structured table.

This was achieved by compiling all data from the various parameters into an Excel file, allowing users to select specific parameters through drop-down menus. This results in two side-by-side bar charts displaying the values for operational carbon and embodied carbon. In this way, for instance, a façade consultant can easily provide design advice based on the visualized data.

The visualization tool that was developed is especially useful for multidisciplinary design teams. It helps users quickly understand the carbon impact of different design options, making it easier to make well-informed choices early in the design process. For instance, a façade consultant can use the tool to give advice on material or design decisions that match both the architect's vision and sustainability goals. This makes the tool not only helpful for analysis but also useful for communication between team members.

Besides its current features, the tool also has potential for further development. It could be made more automated by linking it directly to simulation software or the Excel file. This way, when new simulations are run, the results can be automatically added to the tool. That would make it easier to use during ongoing design changes and speed up the carbon assessment process.

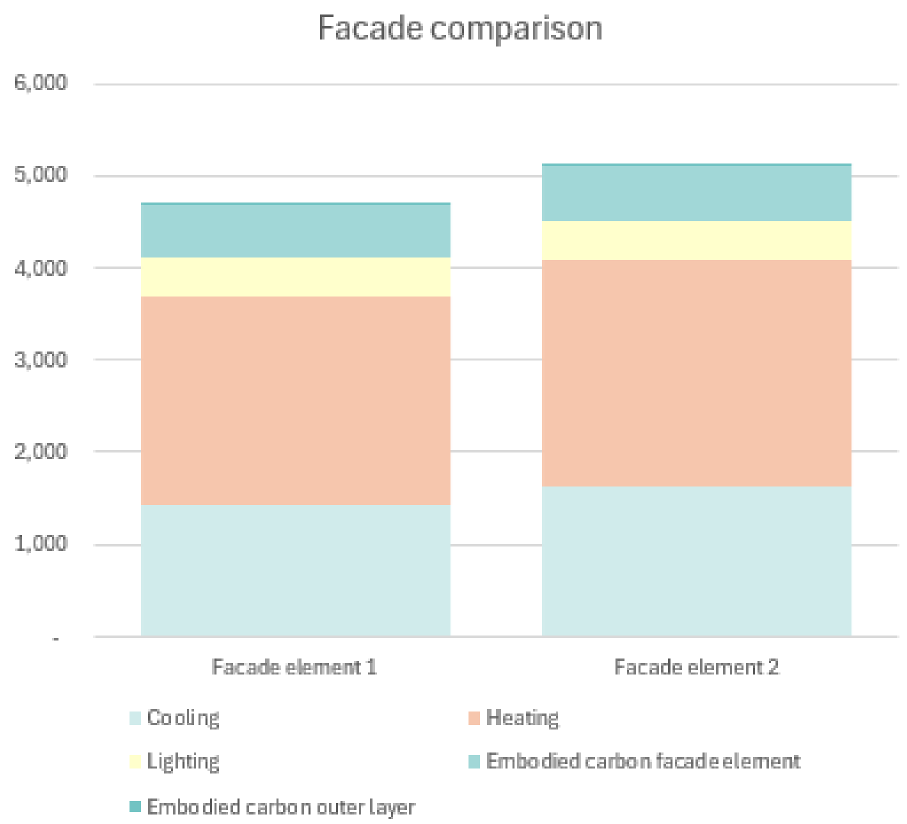
There are, however, a few limitations to keep in mind. The quality of the results depends on how accurate and consistent the input data is. The parameters must be clearly defined and entered in the same format, otherwise the results might be misleading. Also, the current Excel file only includes a limited amount of data. It is possible to add more data if needed, for example embodied carbon data from other databases.

Inputs facade element 1		
Building parameters	Orientation	360
	Compactness	1
Facade parameters	WWR	0.7
	G-value window	0.8
	U-value window	2.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	wood 40

Outputs facade element 1		
Total Operational carbon	4,102	kg
Cooling	1,427	kg
Heating	2,253	kg
Lighting	422	kg
Embodied carbon facade element	587	kg
Embodied carbon outer layer	19	kg
Total of 75 years	4,708	kg

Inputs facade element 2		
Building parameters	Orientation	360
	Compactness	1
Facade parameters	WWR	0.8
	G-value window	0.8
	U-value window	2.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	wood 40

Outputs facade element 2		
Total Operational carbon	4,511	kg
Cooling	1,627	kg
Heating	2,462	kg
Lighting	422	kg
Embodied carbon facade element	593	kg
Embodied carbon outer layer	11	kg
Total of 75 years	5,115	kg



5.

Scenario´s

To better demonstrate the practical value of the developed comparison tool, this chapter tries to present three real-life scenarios in which the tool could be applied during the design process. These scenarios reflect typical moments in architectural and engineering projects where decisions around sustainability and material choices must be made. By replicating these situations, the goal is to show how the tool can support professionals in making more informed and balanced choices regarding operational and embodied carbon.

Each scenario focuses on a specific role or challenge within a project team. for example, selecting between different façade materials, optimizing insulation levels, or comparing structural systems. The tool is used to quickly visualize the carbon impact of each design option, helping stakeholders to evaluate the trade-offs clearly and efficiently. These examples are not only meant to highlight the functionality of the tool, but also to illustrate how it can improve communication and collaboration between disciplines.

By placing the tool in a realistic context, this chapter bridges the gap between simulation results and real-world application, and emphasizes the tool's potential to contribute to more sustainable decision-making throughout the design process.

Senario 1

Situation
The case concerns an apartment located on the south façade with a compactness ratio of 1.5. In the preliminary design (VO), the architect designed a window-to-wall ratio (WWR) of 50%, using glazing with a g-value of 0.65 and a U-value of 1.5. The façade is designed as an aluminum unitized system with aluminum cladding.

The architect wishes to reduce carbon emissions without changing the aesthetic aspects of the design.

Embodied carbon
As an advising party, my first step is to reduce the embodied carbon by changing the construction method to a timber frame element (HSB) with aluminum cladding. Since the timber structure is not visible, and the aluminum appearance remains unchanged, the visual design is preserved.

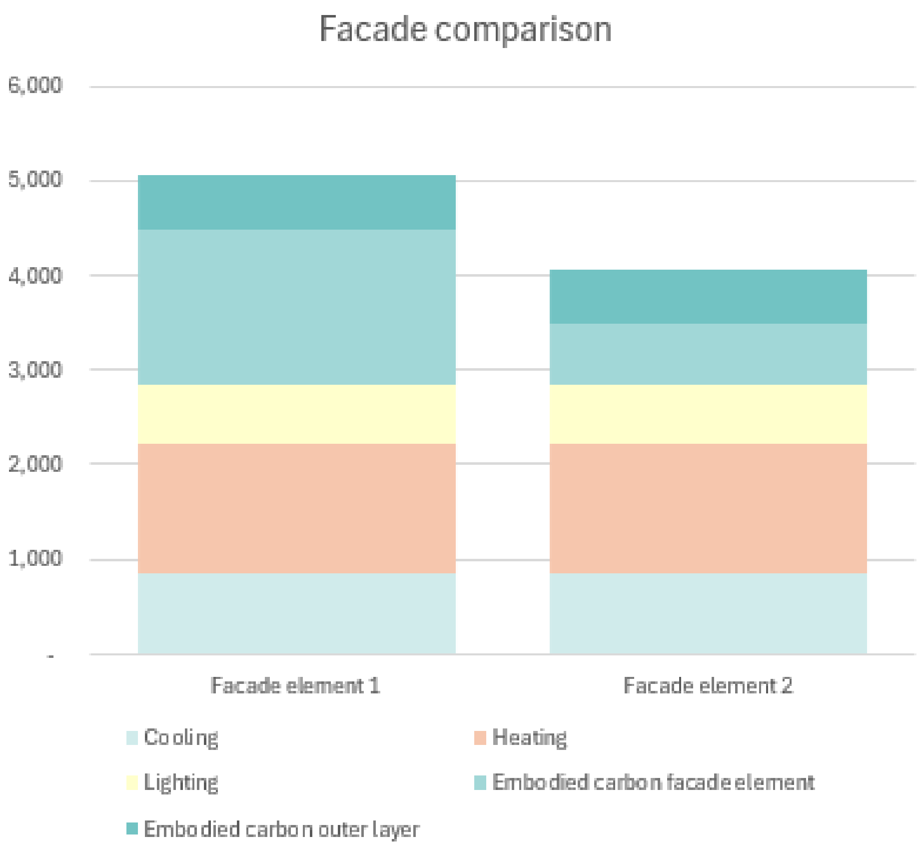
In the graph is a reduction found of 1000kg embodied carbon

Inputs facade element 1		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	Aluminium Element
	Outer layer	Aluminium 7

Outputs facade element 1		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	1,625	kg
Embodied carbon outer layer	581	kg
Total of 75 years	5,060	kg

Inputs facade element 2		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 2		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	4,068	kg



To take it one step further the an attemd is made to lower the operational carbon. The thermal performance of the window is increased by lowering the U-value from 1.5 to 1.0.

In te results it´s found that the cooling demand is increased from 857 to 905 but the heating demands are decreased from 1363 to 975kg Carbon.

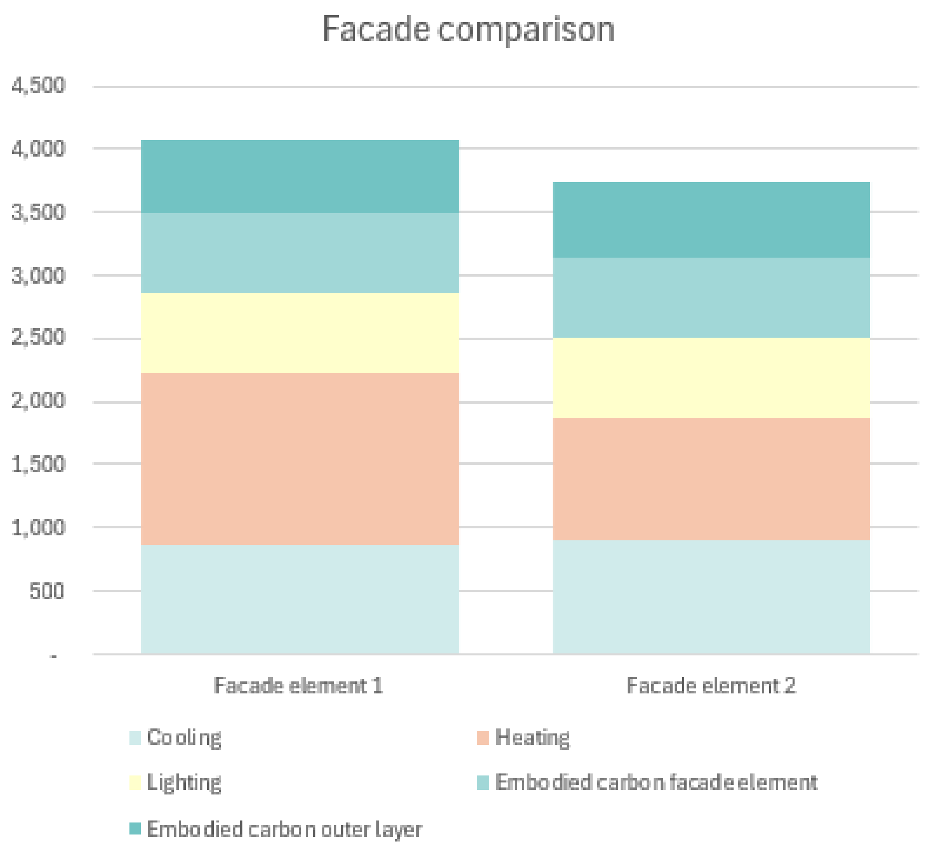
In the end, the total carbon emissions were reduced from 5,060 kg to 3,728 kg, which represents a reduction of approximately 26.3%. The next step would be to consult with the contractor to assess how these changes affect costs and construction time

Inputs facade element 1		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1.5
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 1		
Total Operational carbon	2,854	kg
Cooling	857	kg
Heating	1,363	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	4,068	kg

Inputs facade element 2		
Building parameters	Orientation	360
	Compactness	1.5
Facade parameters	WWR	0.5
	G-value window	0.65
	U-value window	1
	RC-value closed	6
Building technique	Facade element	HSB Element
	Outer layer	Aluminium 7

Outputs facade element 2		
Total Operational carbon	2,514	kg
Cooling	905	kg
Heating	975	kg
Lighting	634	kg
Embodied carbon facade element	634	kg
Embodied carbon outer layer	581	kg
Total of 75 years	3,728	kg



Senario 2

Situation
This scenario involves the renovation of an existing office building into residential units. The entire façade will be stripped and replaced with a new one. The municipality has made it a strict requirement that the façade be rebuilt to match its original appearance, using brick with a window-to-wall ratio (WWR) of 60%.

The façade in question is on the North side of the building, with a compactness ratio of 2 based on the preliminary design (VO).

According to the existing drawings, the g-value is 0.8, the U-value of the windows is 2.0, and the RC-value of the opaque parts is 4.5.

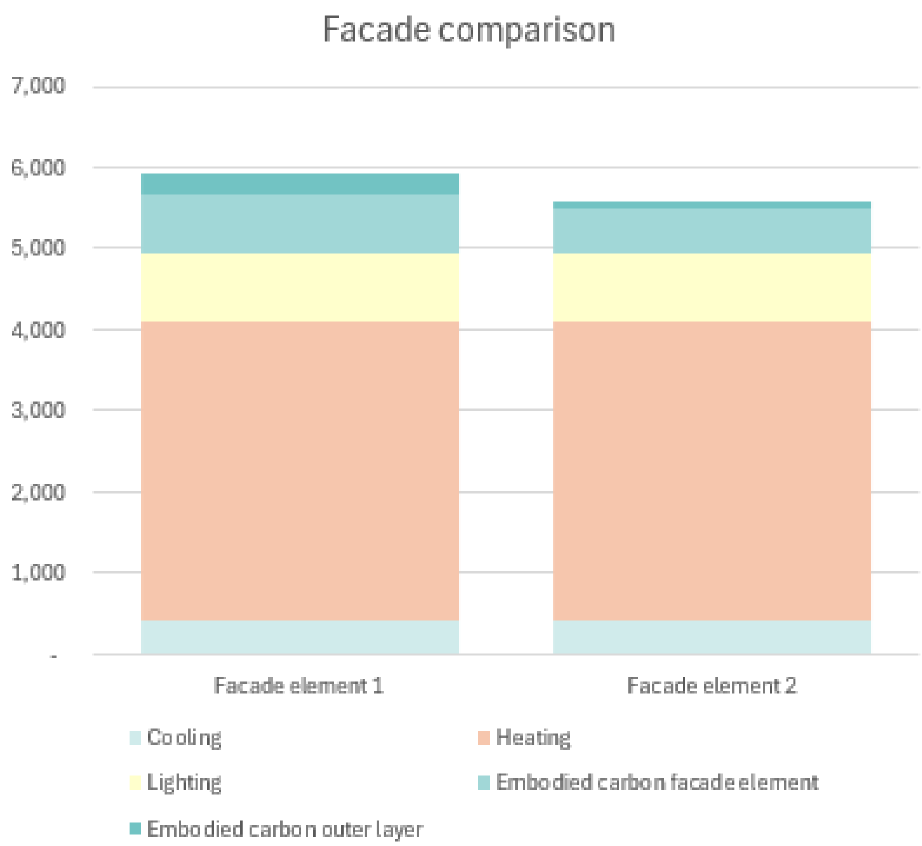
In the current redesign, a prefab concrete façade with brick cladding is proposed. However, the architect is interested in exploring what the carbon savings would be if a timber frame (HSB) element with brick slips were used instead. If the difference in carbon emissions is significant, there may be an opportunity to persuade the municipality to allow for a lighter façade system that still maintains the same visual appearance.

Inputs facade element 1		
Building parameters	Orientation	180
	Compactness	2
Facade parameters	WWR	0.6
	G-value window	0.8
	U-value window	2
	RC-value closed	4.5
Building technique	Facade element	Concrete Element
	Outer layer	brick 100

Outputs facade element 1		
Total Operational carbon	4,945	kg
Cooling	417	kg
Heating	3,683	kg
Lighting	845	kg
Embodied carbon facade element	715	kg
Embodied carbon outer layer	265	kg
Total of 75 years	5,925	kg

Inputs facade element 2		
Building parameters	Orientation	180
	Compactness	2
Facade parameters	WWR	0.6
	G-value window	0.8
	U-value window	2
	RC-value closed	4.5
Building technique	Facade element	HSB Element
	Outer layer	brick strips 30

Outputs facade element 2		
Total Operational carbon	4,945	kg
Cooling	417	kg
Heating	3,683	kg
Lighting	845	kg
Embodied carbon facade element	559	kg
Embodied carbon outer layer	87	kg
Total of 75 years	5,591	kg



By adjusting the façade design, it is clearly evident that the embodied carbon, including both the inner and outer layers, has decreased from 715 + 265 = 980 kg to 559 + 87 = 646 kg, which represents a reduction of 34.1%.

It is also noticeable that the total reduction across the entire façade is relatively small, from 5,925 kg to 5,591 kg, a reduction of 5.6%. This is because the façade is located on the north side, and the operational phase accounts for the majority of energy consumption. As an additional step, I would also improve the efficiency of the operational phase by adjusting the window specifications.

By lowering the U-value of the window from 2.0 to 1.0, we can reduce the operational phase from 4,945 kg to 3,699 kg, which represents a 25.1% decrease.

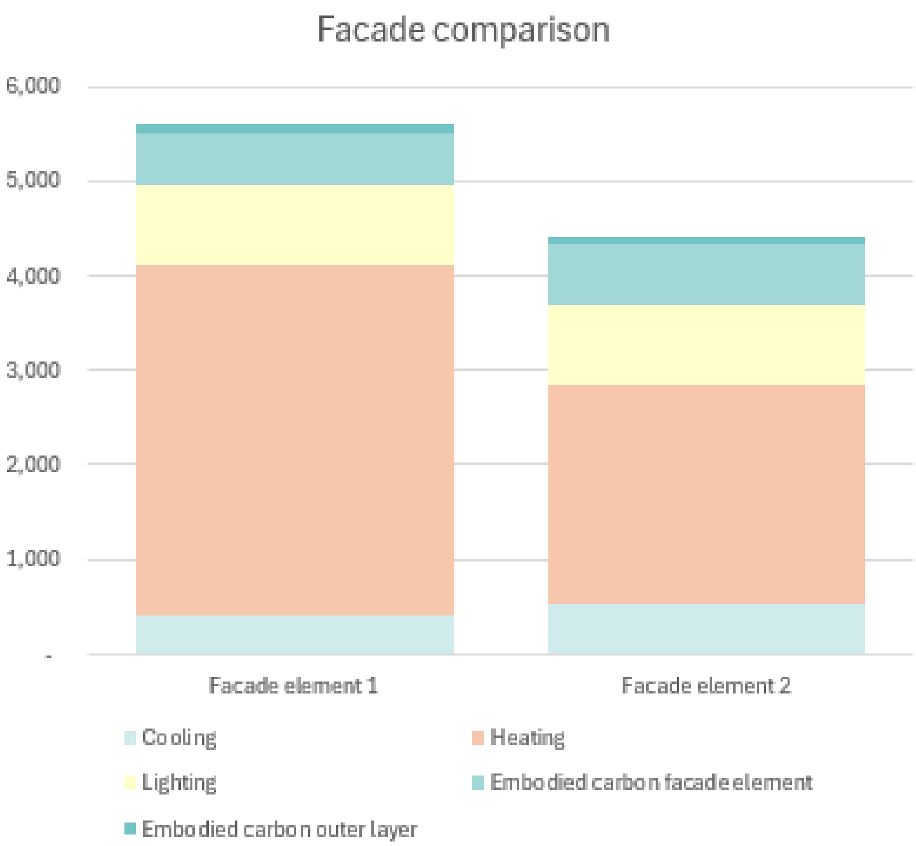
However, the embodied carbon slightly increases because triple glazing is used instead of double glazing. In total, a reduction is still achieved, from 5,925 kg to 4,416 kg, which represents a 25.5% decrease.

Inputs facade element 1		
Building parameters	Orientation	180
	Compactness	2
Facade parameters	WWR	0.6
	G-value window	0.8
	U-value window	2
	RC-value closed	4.5
Building technique	Facade element	HSB Element
	Outer layer	brick strips 30

Outputs facade element 1		
Total Operational carbon	4,945	kg
Cooling	417	kg
Heating	3,683	kg
Lighting	845	kg
Embodied carbon facade element	559	kg
Embodied carbon outer layer	87	kg
Total of 75 years	5,591	kg

Inputs facade element 2		
Building parameters	Orientation	180
	Compactness	2
Facade parameters	WWR	0.6
	G-value window	0.8
	U-value window	1
	RC-value closed	4.5
Building technique	Facade element	HSB Element
	Outer layer	brick strips 30

Outputs facade element 2		
Total Operational carbon	3,699	kg
Cooling	529	kg
Heating	2,325	kg
Lighting	845	kg
Embodied carbon facade element	630	kg
Embodied carbon outer layer	87	kg
Total of 75 years	4,416	kg



6.

Conclusion

The primary objective of this study was to analyse the environmental impact of different façade systems by assessing their embodied and operational carbon emissions. Specifically, the research examined how material selection, window-to-wall ratio (WWR), and glazing performance influence the total carbon footprint of a building's façade.

This way the study tried to answer the question: "How do dynamic façade variables influence the embodied and operational carbon of mid to high-rise residences during the early design phase, and what are the optimal combinations of these variables that minimize environmental impact while meeting regulatory standards?"

In the literature study was found that façade systems offer diverse design possibilities, enabling various aesthetic and performance goals. This study focuses on three widely used systems in the Netherlands: element façades with concrete inner walls, element façades with timber frames, and aluminium curtain walls. These prefabricated systems enhance construction efficiency, quality, sustainability, and scalability while allowing customization and cost reduction.

These façade typologies were modelled into a computational framework to assess their embodied carbon trough finding the different materials and their emissions. after that operational carbon was calculated through an annual energy balance, which calculates energy flows related to heat transfer, ventilation, and solar heat gain. By integrating building physics and climate data, the operational carbon footprint can be estimated over the lifespan of the façade, considering the regional electricity grid's carbon intensity and potential future decarbonization trends.

Existing legislation establishes a minimum Rc-value of 4.5 and a minimum window-to-wall ratio (WWR) of 10% of the usable floor area. Additionally, calculations are typically based on a 75-year lifespan.

Furthermore, the most influential factors highlight that façade-related aspects, such as thermal properties, glazing, and window-to-wall ratio, play a crucial role in heat transmission and insulation, affecting both energy consumption and embodied carbon. Environmental factors, including orientation, urban context, and climate, regulate solar exposure and ventilation, impacting heat gains and losses. Meanwhile, building-related factors, such as floor plan layout and compactness, shape energy efficiency by influencing heat distribution and the external surface area.

To integrate these findings into a computational model, specific parameters such as WWR, U-values, R-values, and g-values, are adjusted to optimize the balance between thermal insulation, solar heat gain, and material impact. Additionally, changes in orientation and compactness find operational energy demand while minimizing embodied carbon.

Concluding, the findings of this study underscore the significant impact of material selection, façade design, and energy efficiency on the total carbon footprint of mid- to high-rise buildings.

Among the façade types analysed, aluminium unitized façades were shown to have the highest embodied carbon emissions, largely due to the carbon-intensive production of. The prefabricated timber façade, on the other hand, has the lowest embodied emissions, benefiting from its lower carbon footprint and carbon sequestration potential. Concrete façades fall in between, with their heavy weight contributing to higher total embodied carbon despite lower emissions per kilogram. The relationship between window-to-wall ratio (WWR) and embodied carbon varies by material, as a higher WWR leads to increased emissions for aluminium and timber façades, whereas for concrete façades, a higher WWR reduces embodied carbon since glass replaces carbon-intensive concrete elements.

Operational carbon emissions are strongly influenced by façade orientation, with north-facing façades experiencing the highest heating demand due to limited solar exposure, while south-facing façades benefit from passive heating but face higher cooling loads. Reducing the U-value of glazing proves to be the most effective strategy in lowering operational carbon, particularly in colder orientations, whereas increasing the Rc-value of insulation has only a marginal effect when WWR is high, as heat transfer through windows dominates. Additionally, an assumed 2% annual improvement in energy efficiency and grid decarbonization over a 75-year lifespan is projected to halve operational carbon emissions, making embodied carbon an increasingly dominant factor in total environmental impact.

When considering both embodied and operational emissions, timber façades remain the most sustainable option, especially when paired with optimized glazing and insulation values. In contrast, aluminium façades have the highest total carbon footprint, with embodied emissions accounting for nearly half of the total impact in the most efficient configurations.

Concrete façades present a unique trend where reducing WWR can sometimes increase total emissions due to the high embodied carbon of concrete relative to glazing.

These findings emphasize the importance of an integrated approach to façade design, where material selection, insulation levels, glazing performance, and orientation can be balanced to achieve the lowest total carbon footprint.

7. Discussion

This chapter evaluates the validity and reliability of the study, ensuring that findings are robust and comparable to existing research. It then interprets key results, highlighting insights on operational and embodied carbon. Limitations are discussed, outlining constraints and assumptions. Finally, the chapter explores practical implications and suggests directions for future research.

Validity
The validity and reliability of this study were taken into account using representative sampling, and comparison with other studies.

The study's internal validity is established by the use of simulation models that have been shown useful in other academic works, in assessing the effects of building orientation, materials, and window-to-wall ratio (WWR) on operational and embodied carbon. The 75-year time horizon was chosen to provide meaningful insights into long-term implications, as guided by literature on energy transition and other national legislation.

The studies' external validity is limited because they focus on specific building types, materials and climate circumstances. However, the overall trends may be applicable to similar projects in regions with comparable climate conditions and decarbonization aims. The study could be done again with different climate conditions since the model is explained in the research.

Efforts were taken to assure reliability by using proven software and procedures, and input parameters were tested against existing literature. The embodied carbon estimates were cross-checked using separate Excel calculations, providing an aiding point of reference. While manual calculations of the energy consumption was not reasonable because of its complexity, an effort was made to match the results with data from comparable simulation software. The results were compared to check if the generated data has any value.

Interpreting Results
The outcomes of this study try to provide valuable insights into the shifting balance of operational and embodied carbon in façade designs.

The findings are consistent with predictions, particularly in verifying the projected dominance of embodied carbon in future scenarios typified by a highly decarbonized energy grid, which is why the study was initiated.

Also, increasing the window-to-wall ratio (WWR) has a major impact on thermal performance, resulting in higher heating demands, particularly on the northern facade. In some circumstances, cooling loads are increased, particularly for southern orientations. Furthermore, materials such as concrete and aluminum have high embodied carbon levels. these are things that are already well known.

The study also revealed some new findings. The complexities of these calculations are essentially endless, and this study is simply an introduction into the subject. It became clear that optimization might be reviewed for each orientation, as alternative configurations may produce best outcomes depending on the orientation's individual characteristics.

Certain variables, such as raising the thermal resistance (Rc value), appeared to have a smaller impact than expected. Furthermore, the interaction of WWR, solar heat gain coefficient (g-value), and thermal transmittance (U-value) is significantly greater than originally assumed. Adjusting one parameter frequently results in totally different new ideal values for each orientation. The graphs show that there are sweet spots for every parameter.

Lastly, The use of biobased materials for interior walls does not necessarily result in a significant reduction in the overall carbon since the operational carbon still makes up most of the impact. However, the data used to evaluate these materials has only a partial impact on the outcome, signaling that larger datasets are required to identify their full potential.

Limitations
his study, like many others, has limitations that affect how the findings are interpreted.

The first big limitation is the dependence on scenarios for future energy grid decarbonization, which inevitably include uncertainty about policy and technology advances.

Furthermore, the study only employed one simulation program; a more thorough validation would include comparisons of various simulation tools, or even real-world testing, to identify significant differences.

The number of material possibilities and facade scenarios evaluated was limited. While representative materials were chosen, the scope does not cover the entire range of accessible building materials, such as alternate structural materials, cladding possibilities, and insulation kinds. Simplifications in façade details were also required; smaller components such as adhesives, fasteners, spacers, and rubber parts were excluded from the analysis.

Material longevity, and material replacement over time were not taken into account. This analysis also eliminated the carbon costs related with element manufacture and transportation.

The model also excludes many other potential important facade parameters, such as shading effects, the energy generation potential of building-integrated photovoltaics, more realistic or different HVAC systems and the structure's heat accumulation. Furthermore, the façade mass, which effects the overall carbon footprint of the structure, was not investigated beyond the façade components themselves.

Finally, the embodied carbon calculations were based only on the EduPack database. Future study could benefit from using different databases or combining data from many sources to improve reliability.

These limitations suggest possibilities for development, such as the use of dynamic climate models, a fuller investigation of material options, and the incorporation of occupant behavior simulations in future studies.

Implications
The results of this study have theoretical, practical, and economic implications and value.

From a theoretical standpoint, the study emphasizes the need to incorporate embodied carbon into sustainability policies and regulations. This is consistent with the growing acknowledgment of embodied carbon as an essential factor influencing the overall environmental performance of buildings.

On a practical level, architects and policymakers can apply these findings to create orientation-based design solutions that reduce both operational and embodied carbon. This includes, for example, recommending the use of glass with low G-values (solar heat gain coefficient) for southern façades while prioritizing materials with higher u-values for northern façade insulation. Alternatively, consider employing a similar framework to find the best design options in optimizing for carbon offset.

Policy-wise, the findings argue for including building-, function-, and orientation-specific embodied carbon criteria into certification systems like as BENG and BREEAM. The study aims to demonstrate how orientation, function, and HVAC systems affect ideal material values and window-to-wall ratios (WWR). Incorporating focused simulation studies into frameworks such as BENG or BREEAM could improve design accuracy and ensure certifications are suited to project-specific requirements. This could lead to systematic reductions in lifecycle carbon footprints and link industry practices with global decarbonization targets.

The findings also help to produce climate-specific design suggestions by demonstrating how different design alternatives, such as window-to-wall ratios and material selections, are affected by climate conditions and energy grid decarbonization scenarios.

By addressing the relationship between operational and embodied carbon, this work indirectly contributes to climate change mitigation by lowering overall carbon emissions from buildings. It emphasizes the importance of material efficiency in construction by employing a resource-efficient design strategy that reduces waste.

Last but not least, it will improve cost-benefit analysis by including carbon pricing into financial decisions about building materials and designs. This will provide a clear financial justification for implementing low-carbon solutions, taking into account the economic or environmental benefits of specific window-to-wall ratios or glazing materials.

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Suggestions for Future Research

From the results and limitation of this study, some suggestions for future studies could be done as follows:

The simulations could add adaptive behavior in order to understand the occupants better in adjusting to environmental factors; thus, more precise assessments of thermal comfort and energy use.

Also, adding passive shading or active shading devices, other HVAC systems, thermal mass effects, and/or integration of renewable energy sources that develop an informed understanding of the influencing operational and embodied carbon.

Extending the range of options to for materials and details or extending these studies to a greater range of construction methods, with the intention of finding new ways in which embodied carbon could be mitigated and building performance can be improved.

Increasing the comprehensiveness of the Embodied Carbon Database to enable robust, detailed, and accurate information about material impacts across projects and scenarios.

Finally, modifying weather files and investigating additional places may provide more insight into how changing climates and decarbonization scenarios affect both operational and embodied carbon.

8.

Reflection

The approach has been effective in allowing me to explore the impact of façade typologies on the embodied carbon and energy of mid- to high-rise buildings. The combination of computational design and sustainability-focused research provided useful insights, and I was able to identify some of the trends I had hoped to uncover. Through this process, I gained a deeper understanding of the "how and why" behind the optimization of façade designs using dynamic modelling and energy simulations, and I recognized the importance of material choices and the facade parameters trying to minimize environmental impact.

The feedback from my mentors was very valuable, especially regarding the integration of regulatory standards and more precise modelling techniques. They advised me to simplify the number of parameters used in my simulations, as fewer parameters would make it easier to spot trends and reduce the time required for complex simulations. They also suggested that I conduct an exploratory simulation first and then focus on optimization afterward, to ensure clarity and better focus in the results.

Additionally, my mentors emphasized the importance of keeping the approach simple and clear. They encouraged me to develop a strong narrative around my research, highlighting its relevance and the potential societal and academic benefits. I was advised to clearly explain the reasoning behind each choice I made during the process, for example in the fixed inputs, discussing why and how I made those decisions and acknowledging any limitations or shortcomings attached to them.

I translated this feedback into my work by refining my computational framework to better align with industry standards, while also simplifying my modelling process. This allowed me to maintain focus on the goals of the thesis and enhance the overall clarity and relevance of my research.

Through the process, I learned to balance technical constraints with sustainable design goals, and the iterative nature of my work allowed me to continually improve my methods and outcomes. I also gained valuable skills, such as learning how to use Grasshopper and how to code in python, which significantly enhanced my computational design skills. These skills not only helped in my approach but also enabled me to create more efficient and effective simulations. Reflecting on this experience, I believe that if I were to conduct this research again, I would be able to complete it in a shorter span of time, given the knowledge and skills I've learned along the process. The learning process has been valuable, making my understanding better of how to approach complex architectural problems trough computational and sustainable solutions. Overall, this project has enhanced my ability to integrate innovative design strategies into real-world building challenges.

The graduation project has a direct connection to the Master of Science in Architecture, Urbanism, and Building Sciences (AUBS), specifically the incorporation of sustainability, energy efficiency, and computational design. My study on improving façade typologies for mid- to high-rise buildings is directly related to the intersection of architecture and building technologies (BT), which is the master track I am now following.

The thesis's goals have a direct relation to my track's focus on sustainable architecture and building performance, since they address crucial concerns related to lowering buildings' embodied and operational carbon emissions through innovative façade design. Furthermore, parametric modelling via computational design has gotten an important role in the Building Technology program. As a result, my graduation thesis is a practical application of the information and methodology acquired during the master's curriculum, notably in the context of sustainable building practices and the use of computational tools.

My research did not include a direct design component, but rather served as an advisory function that attempted to supplement the design process. My research findings can be understood as design guidelines for façade features, providing insights into optimizing energy efficiency and reducing embodied carbon. However, the findings also show that the impact of façade typologies is very context-dependent, highlighting the importance of doing similar simulations for specific situations to truly understand optimalisation. In this regard, my research offers a framework for educated decision-making rather than a one-size-fits-all design solution.

The approach I chose for this study, which combined computer simulations, lifecycle analysis, and dynamic modelling, was successful in meeting the research objectives. The inclusion of parametric design tools enabled quick optimization of façade variables. This methodology not only provided a foundation for understanding the environmental implications of façade design, but it also enabled a thorough comparison of various design alternatives.

This technique, in my opinion, is both academically and practically beneficial. Academically, it adds to the expanding body of knowledge about employing computational simulations for sustainable design methods, which can help reduce the building industry's carbon footprint. Practically, it provides designers with a framework for making data-driven decisions that lower carbon footprints while also combating climate change.

The study was done with ethics in mind. All data and methodology were presented in a transparent manner, with source attribution. My research focuses on analysing façade typologies to reduce energy consumption and embodied carbon, with the goal of promoting sustainability and environmental responsibility while also addressing the larger societal issue of climate change. I maintained academic honesty by trying to avoid plagiarism. Furthermore, the methodologies and recommendations focused on practical solutions for increasing building performance, guaranteeing that the research positively contributes to both the discipline of architecture and society's efforts to achieve a more sustainable future.

Finally, I was asked to answer two reflection questions that I created myself. They are:

What would I do differently?
I would begin with a more specific plan and aim in order to ensure a more focused approach. To produce a more in-depth analysis, I would explore more materials, lifetime alternatives, and constructing processes. Finishing the literature review early would free up more time for the research itself. I would also devote extra time to the conclusion, discussion, and reflection to ensure full analysis and critical thinking. In addition, I would seek additional feedback during the process, possibly by emailing my work rather than just waiting for meetings.

Am I satisfied with the work I have completed?
I am content with the work I have done. While it may not be as groundbreaking as I hoped, I did discover several interesting and new perspectives. The process has been a valuable learning experience for me, and I believe I have improved my writing and structure skills for academic projects. Most importantly, I've learnt how to approach a project with academic mindset.

9.

References

Aish, R., & Woodbury, R. (2005). Multi-level interaction in parametric design. In A. Butz, B. Fisher, A. Krüger, & P. Olivier (Eds.), Smart graphics (pp. 151–162). Springer Berlin Heidelberg. https://doi.org/10.1007/11536482_13

Aldrete, G. S. (2004). Daily life in the Roman city: Rome, Pompeii and Ostia. Bloomsbury Academic.

Ali, M. M., & Al-Khodmany, K. (2012). Tall buildings and urban habitat of the 21st century: A global perspective. Buildings, 2 (4), 384-423. https://doi.org/10.3390/buildings2040384

Ambrose, G., Harris, P., & Stone, S. (2008). The visual dictionary of architecture. Switzerland: AVA Publishing SA.

Arcadis. (2019). The Future Of The European Built Environment: A forward looking

Augenbroe, G., 2002. Trends in building simulation. Build. Environ. 37, 891–902.

Behrens-Abouseif, D. (1992). Islamic architecture in Cairo. Brill Publishers.

Bentley, 2014. MicroStation V8i.

Bouwbesluit 2012. (2023, 07 september). Overheid.nl. Visited on 23 oktober 2024, found on https://rijksoverheid.bouwbesluit.com/Inhoud/docs/wet/bb2012

Brown, Z., & Cole, R. J. (2009). Influence of occupants' knowledge on comfort expectations and behaviour. Building Research & Information, 37(3), 227–245. https://doi.org/10.1080/09613210902794135

Cabeza, L. F., Rincon, L., Vilarino, V., Perez, G., & Castell, A. (2014). Lifecycle assessment (LCA) and lifecycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews, 29, 394–416. https: // doi.org/10.1016/j.rser.2013.08.037

Caldas, L., Norford, L., 2001. Architectural Constraints in a Generative Design System: interpreting energy consumption levels. In: Seventh International IBPSA Conference. pp. 13–15.

CarbonCure. (2024, February 2). What is embodied carbon? CarbonCure. https://www.carboncure.com/concrete-corner/what-is-embodied-carbon/

Ching, F. D. K. (2014). Building construction illustrated (5th ed.). John Wiley & Sons.

Citherlet, S., Clarke, J. A., & Hand, J. (2001). Integration in building physics simulation. Energy and Buildings, 33(5), 451–461.

Courtney L. Fromberg, Situ, Y., Issaa, R., 2015. Explorations, Challenges, + Possible Future Solutions. In: Computational Design Progression, and Future Generation.

Crawford, R. (2020). Embodied energy. Your Home. Australian Government. https://www.yourhome.gov.au/materials/embodied-energy

Davis, D., & Peters, B. (2013). Design ecosystems: Customising the architectural design environment with software plug-ins. Architectural Design, 83(6), 124–131.

Davis, D., Villaggi, L., Bailey, C., 2014. Not Everything is Captured by the Fitness Function. Colon 4 2.

Eastman, C.M., Teicholz, P., Sacks, R., Liston, K., 2011. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Architects, Engineers, Contractors, and fabricators. Wiley.

Ekici, B. F., Kazanasmaz, R. F., Turrin, M. F., Tasgetiren, M. F., & Sariyildiz, S. F. (2019). A Methodology for daylight optimization of high-rise buildings in the dense urban district using overhang length and glazing type variables with surrogate modelling. Retrieved from https://www.researchgate.net/publication/335715852`

Ellis, P G., & Torcellini, P. A. (2005). Simulating tall buildings using EnergyPlus. Proceedings of IBPSA International Conference, Montreal,Canada.

Emporis. (2015). "Skyscraper, Emporis standards". Emporis.com. Archived from the original on 11 May 2015. Retrieved 31 May 2024.

Engineering ToolBox. (2003). U.S. Standard Atmosphere. Retrieved from https://www.engineeringtoolbox.com/

EPA, 1991. Indoor Air Facts No. 4 Sick building syndrome, Air and Radiation

European Commission (2010). DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 May 2010 on the energy performance of buildings. Retrieved May 15, 2024 from http://data.europa.eu/eli/dir/2010/31/ojgebouwen/wetten-en-regels/nieuwbouw/energieprestatiebeng

European Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009. Off. J. Eur. Union 140, 16–62

Godoy-Shimizu, D., Steadman, P., Hamilton, I., Donn, M., Evans, S., Moreno, G. and Shayesteh, H. (2018). Energy use and height in office buildings. Building Research & Information, 46(8), pp.845-863. Retrieved from https://doi.org/10.1080/09613218.2018.1479927

Godoy-Shimizu, D., Steadman, P., Hamilton, I., Donn, M., Evans, S., Moreno, G. and Shayesteh, H. (2018). Energy use and height in office buildings. Building Research & Information, 46(8), pp.845-863. Retrieved from https://doi.org/10.1080/09613218.2018.1479927

Godoy-Shimizu, D., Steadman, P., Hamilton, I., Donn, M., Evans, S., Moreno, G. & Shayesteh, H. (2018). Energy use and height in buildings, Building Research & Information, 46:8, 845-863. [online] Retrieved May 15, 2024 from https://www.tandfonline.com/doi/full/10.1080/09613218.2018.1479927

Gonçalves, J. C., & Umakoshi, E. M. (2015). The environmental performance of tall buildings. London: Routledge.

Granta EduPack. (2009). CES Eco Selector. Granta Design Limited. https://www.grantadesign.com/download/pdf/CES_Eco_Selector_datasheet.pdf

Handelbouwadvies. (n.d.). EPC NORM. Retrieved September 5, 2024, from https://www.handelbouwadvies.nl/epc-berekening/epc-norm/

Harding, J., Joyce, S., Shepherd, P., & Williams, C. (2012). Thinking topologically at early stage parametric design. In Advances in architectural geometry 2012 (pp. 67–76). Springer Vienna.

Hermund, A., 2009a. Building information modeling in the architectural design phases: And why compulsory BIM can provoke distress among architects. eCAADe 1–8.

Hoffmann, D. (1969). Frank Lloyd Wright and Viollet-le-Duc. Journal of the Society of Architectural Historians, 28(3), 173–183. https://doi.org/10.2307/988556

Hudson, R. (2010). Strategies for parametric design in architecture. University of Bath: Bath, UK.

J. Steinmann, M. Röck, T. Lützkendorf, K. Allacker, X. Le Den, Whole Life Carbon Models for the EU27 to Bring Down Embodied Carbon Emissions from New Buildings. Review of Existing National Legislative Measures Funded, Tech. Rep., Ramboll, 2022, p. 43. Retrieved May 15, 2024URL https://c.ramboll.com/reducing-whole-life-carbon.

James J. Hirsch & Associates, 2013. DOE-2.

Kanters, J., Horvat, M., Dubois, M.C., 2014. Tools and methods used by architects for solar design. Energy Build. 68, 721–731

Kataras, P., 2010. Multi-objective Performance Optimization Of Building Form based on the principle of analytical geomertry. Architecture. University College London.

Konstantinou, T., Ćuković Ignjatović, N., & Zbašnik-Senegačnik, M. (Eds.) (2018). Energy: resources and building performance. (Reviews of Sustainability and Resilience of the Built Environment for Education, Research and Design; Vol. 4). Delft: TU Delft Open. http://resolver. tudelft.nl/uuid:320f4b29-235d-4355-913f-2b07f0d5d44c

Lang, B. (2009, February 23) Energy-saving alternatives to generic low-e glass. Retrieved March 4, 2019 from: https://www.energy-manager.ca/news/energy-saving-alternatives-to-generic-low-e-glass-233

Laustsen, J., Ruyssevelt, P., Staniaszek, D., Zinetti, S., Strong, D., 2011. Europe ' s buildings under the microscope. Buildings Performance Institute Europe.

MacLeamy, P., 2013. Bim-Bam-Boom! The future of the building industry. HOK, YouTube.

Malkawi, A. M. (2004). Developments in environmental performance simulation. Automation in Construction, 13, 437–445. https://doi.org/10.1016/j.autcon.2004.03.002

Meijs, M., Knaack, U., & Klein, T. (2007). Façades: Principles of construction. Birkhäuser Verlag AG.

Méndez Echenagucia, T., Moroseos, T., & Meek, C. (2022). On the trade-offs between embodied and operational carbon in building envelope design: The impact of local climates and energy grids. Energy and Buildings, 112589. https://doi.org/10.1016/j.enbuild.2022.112589

Milne, G., & Reardon, C. (n.d.). Embodied energy. State of California. https://ohp.parks.ca.gov/pages/1054/files/embodied%20energy.pdf

Mora, R., Bédard, C., Rivard, H., 2008. A geometric modelling framework for conceptual structural design from early digital architectural models. Adv. Eng. Informatics 22, 254– 270.

Nationale Milieu Database. (n.d.). Twee sets tegelijk. Retrieved September 5, 2024, from https://milieudatabase.nl/nl/milieudata-lca/milieu-impact-categorieen/weegset-en-schaduwkosten/

Nationale Milieu Database. (n.d.). Van 11 naar 19 milieu-impact categorieën. Retrieved September 5, 2024, from https://milieudatabase.nl/nl/milieudata-lca/milieu-impact-categorieen/weegset-en-schaduwkosten/

Negendahl, K. (2016). Consequence based design (PhD thesis). Department of Civil Engineering, Denmark. https://www.researchgate.net/publication/308695354_Consequence_based_design_An_approach_for_integrating_computational_collaborative_models_Integrated_Dynamic_Models_in_the_building_design_phase

Nieman. (2020). Eisen Luchtdichtbouwen. Retrieved from www.nieman.nl/specialismen/bouwtechniek-en-praktijk/luchtdicht-bouwen/eisen/

Ochoa, C. E., Aries, M. B. C., van Loenen, E. J., & Hensen, J. L. M. (2012). Considerations on design optimizationcriteria for windows providing low energy consumption and high visual comfort. Applied Energy, 95(0), 238-245. doi:http://dx.doi.org/10.1016/j.apenergy.2012.02.042

Paulson Jr., B.C., 1976. Designing to Reduce Construction Costs. J. Constr. Div.

Pedersen, F.Ø., 2006. A method for optimizing the performance of buildings. Technical University of Denmark.

Peterson, C. E. (1950). Ante-bellum skyscraper. Journal of the Society of Architectural Historians, 9(3), 25–28. https://doi.org/10.2307/987464

Peterson, I. (1986). The first skyscraper – new theory that Home Insurance Building was not the first. CBS Interactive. Archived from the original on 8 July 2012. Retrieved 31 May 2024.

Petruzzello, M. (2022). "Skyscraper". Encyclopaedia Britannica. Retrieved 31 May 2024.

Pietrzak, J., & Stefańska, A. (2019, October). The role of structural elements in the design of facade details of tall European buildings. [Journal Name Unknown]. Retrieved from https://www.researchgate.net/publication/336532512

Raji, B., Tenpierik, M. and van den Dobbelsteen, A. (2016). A comparative study: design strategies for energy-efficiency of high-rise office buildings. Journal of Green Building, 11(1), pp.134-158.

Raji, B., Tenpierik, M. and van den Dobbelsteen, A. (2016). A comparative study: design strategies for energy-efficiency of high-rise office buildings. Journal of Green Building, 11, pp.134-158.

Retrieved from RVO.nl: https://www.rvo.nl/onderwerpen/duurzaamondernemen/Rijksdienst van Ondernemend Nederland. (n.d.). Energieprestatie - BENG.

Rijkdienst van Ondernemend Nederland. (2017, Juli 12). Energieprestatie - BENG. RVO. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/beng#ontstaan-beng

Rijkdienst van Ondernemend Nederland. (2017, June 1). MilieuPrestatie Gebouwen - MPG. RVO. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/milieuprestatie-gebouwen-mpg#wat-is-de-mpg%3F

Saint-Gobain, (2017, August 22). How do buildings affect the environment? Retrieved 01 may, 2024 from https://www.saint-gobain.co.uk/how-do-buildings-affect-the-environment

SBI, 2013. Be10.

SBR. (2010, January). SBR-Referentiedetails. ISSO. https://open.isso.nl/

Schittich, C. (2006). In Detail: Building Skins: New Enlarged Edition. Basel: Birkhäuser - Publishers for architecture.

Sherman, M. H., Chan, R. (2004). Building Airtightness: Research and Practice. Retreived from https://www.researchgate.net/publication/238573993_Building_Airtightness_Research_and_Practice/stats

Solar Heating & Cooling Programme, 2010. IEA Task 41 State-of-the-art of digital tools used by architects for solar design, Solar Energy and Architecture.

Steemers, K. (2002, May 24). Energy and the city: Density, buildings and transport. Retrieved March 23, 2019 from https://www.sciencedirect.com/science/article/pii/S0378778802000750

Sutherland, G., Maldonado, E., Wouters, P., *Papaglastra, M., 2013. Implementing the Energy Performance of Buildings Directive (EPBD).*

Tiseo, I. (2024, July 18). Carbon intensity of the power sector in the Netherlands from 2000 to 2023. Statista. Retrieved December 6, 2024, from https://www.statista.com/statistics/1290441/carbon-intensity-power-sector-netherlands/#:~:text=In%20 2023%2C%20the%20carbon%20intensity,553%20 gCO%E2%82%82%2FKWh%20in%202015.

UNEP, 2021 Global status report for buildings and construction: Towards a zero-emission, Effic. Resilient Build. Constr. Sect. (2021) 1–105.

United Nations, (2017, June 21). World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100. Retrieved May 01, 2024 from https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

United Nations, (2018, May 16). 68% of the world population projected to live in urban areas by 2050, says UN. Retrieved 01 may, 2024 from https://www.un.org/development/desa/en/news/population/world-population-prospects-2017.html

van de Griendt, B., & de Vries, J. (2016). Energieprestaties nieuwbouwwoningen deel 1: Een terugblik naar de toekomst. Vastgoedrecht (VGR), 99.

van der Linden, A. C., Boerstra, A. C., Raue, A. K., Kurvers, S. R., & de Dear, R. J. (2006). Adaptive temperature limits: A new guideline in The Netherlands: A new approach for the assessment of building performance with respect to thermal indoor climate. Energy and Buildings, 38(1), 8-17. https://doi.org/10.1016/j.enbuild.2005.02.008

WolframlAlpha. (n.d.). WolframlAlpha: Making the world's knowledge computable. Retrieved September 4, 2024, from https://www.wolframalpha.com

Wood, A., & Salib, R. (2013). Natural ventilation in high-rise office buildings: An output of the CTBUH Sustainability Working Group: CTBUH technical guide. Abingdon, Oxon: Routledge.

Zhai, Z. (2003). Developing an integrated building design tool by coupling building energy simulation and computational fluid dynamics programs . Massachusetts Institute of Technology.

10.
Appendix

This appendix contains supplementary materials that support the main findings of this thesis. It includes additional graphs from the simulations conducted, providing a more detailed visualization of the results. Any extraneous text that was not essential to the main discussion has been excluded to maintain clarity and focus. These materials serve to enhance the understanding of the methodologies and outcomes presented in the core chapter

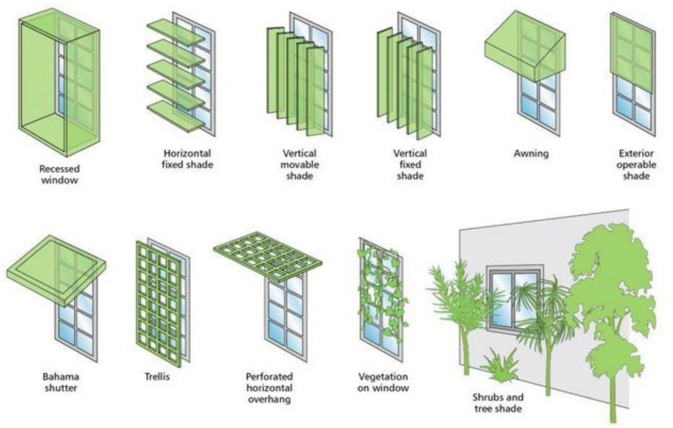
2.xx Shading

Shading can have an important role in controlling solar heat gain, daylight access, and occupant comfort in building design. Well-designed shading devices redvuce cooling loads by preventing to much solar radiation, while still allowing sufficient natural light, which helps reduce the need for artificial lighting and ads to the users comfort. Especially for high-rise buildings, shading can be optimized for different orientations and floor levels to handle thermal and visual comfort more effectively.

External shading systems, like louvers and overhangs can effectively hinder sunlight from entering the building and reduce heat gain for better energy efficiency. These can be either fixed or adjustable to control heat gain and natural light. Louvers and overhangs for example are some of the external shading devices that could allow buildings with larger windows to stay cool during summer while allowing sunlight in winter. The major benefit of external shading is the fact that it can block solar radiation early and, hence, reduce heat transfer during the hot season. One important note for high-rise buildings is that they become more exposed to high wind speeds, raising risks concerning pedestrian safety and possible damages.

The second alternative is an internal shading-blind and curtain-that is protected from wind and requires less maintenance. But this may result in a higher cooling demand due to the greenhouse effect inside the space between the shading and the window. While internally, it is handy in the case of glare control and visual comfort.
Dynamic shading systems, like motorized blinds or smart glass, automatically adjust based on sunlight, optimizing daylight and heat control in real time.

Shading strategy also depends on orientation: south-oriented façades require horizontal shading strategies, east and west orientations can be provided either with vertical or dynamic solutions in view of coping with low-angle sun.



Shading strategies (Al-Yasiri, Qudama & Szabo, Marta. (2021)) **Figure 2.29**

2.xx Structural Properties

Structural considerations determine the façade's load-bearing capacity and influence design decisions related to material selection, support systems, and safety.

Load-Bearing Capacity
The ability of a façade system to support weight varies based on material composition. A concrete inner wall can sustain heavier loads compared to lightweight timber or aluminium frames. Structural glazing and reinforced composite panels enhance load distribution and stability, particularly in high-rise applications where wind and seismic forces are critical factors.

Wind and Impact Resistance
Façade systems must withstand wind loads, particularly in tall buildings exposed to high wind speeds. Reinforced glass, impact-resistant coatings, and engineered support systems mitigate damage risks from windborne debris and extreme weather events. Computational Fluid Dynamics (CFD) analysis is often used to optimize façade designs for wind resistance and pressure distribution.

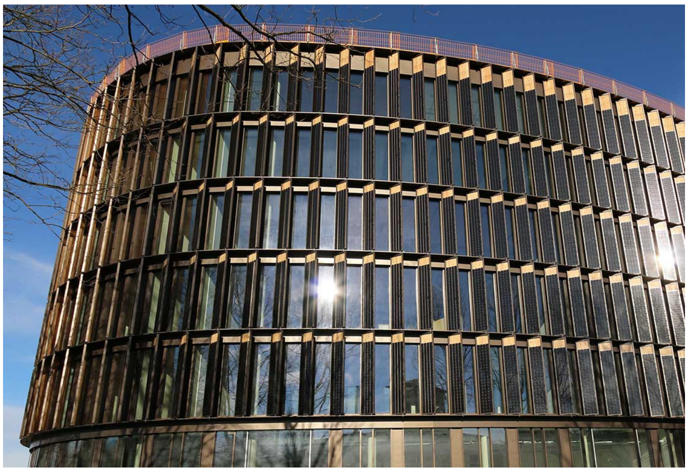
By integrating these principles, façade systems can achieve optimal performance in terms of energy efficiency, durability, adaptability, safety, and occupant comfort. Each design decision contributes to a holistic approach that balances environmental impact, resilience, and long-term functionality.

2.xx Energy Generation

With the introduction of BENG legislation, generating energy through the building's exterior has become increasingly important. Traditionally, energy generation is focused on the roof because this is the most efficient way to use solar panels. However, in high-rise buildings, as the height increases, the available roof space becomes smaller compared to the building's total floor area, which is limiting the energy production potential.
To tackle this, the façade of the building can also be used for energy generation. Some examples include:

- Photovoltaic (PV) panels that convert sunlight into electricity.
- Algae panels, which can generate biomass and heat.
- Wind energy systems that harness wind power.
- In this study, the focus is on the use of PV panels on building façades. Depending on the window to wall ratio PV panels could be used to generate energy.

PV cells come in a variety of varieties, each with a particular level of performance and efficiency. The most prevalent are crystalline silicon cells., which include polycrystalline cells with an efficiency range of 13% to 16%, and monocrystalline cells, which offer a higher efficiency of 15% to 20%, but come at a higher cost (Konstantinou, ukovi Ignjatovi & Zbašnik-Seneganik, 2018).



PV panels on facade **Figure 2.29**

2.xx Material Selection and Lifecycle Impact

The selection of façade materials significantly influences the sustainability, durability, and energy performance of a building. Thoughtful material choices can reduce environmental impact, enhance building efficiency, and improve long-term performance. Key considerations include recyclability, embodied carbon, and durability.

Recyclability
Materials like aluminium, glass, and steel have high recyclability, enabling repurposing after a building's lifecycle and reducing construction waste. Innovations such as bio-based materials, recycled plastics, and reclaimed wood provide eco-friendly alternatives for façade systems. The adoption of closed-loop systems, where materials are continuously recycled back into the production

process. further minimizes waste and resource depletion.

Embodied Carbon
Embodied carbon accounts for emissions from material extraction, manufacturing, transportation, and installation. Aluminium, for example, is energy-intensive to produce but has a significantly lower carbon footprint when recycled. Cross-laminated timber (CLT) acts as a carbon sink, making it a sustainable alternative in façade construction. Conducting lifecycle assessments (LCAs) is essential for selecting materials with minimal embodied carbon, optimizing both environmental impact and energy performance.

Durability and Maintenance
Long-lasting materials, such as treated glass, stone, and coated metals, reduce the need for frequent replacements, thereby minimizing lifecycle impact. Façade systems incorporating self-cleaning properties (e.g., hydrophobic coatings) or corrosion-resistant treatments (e.g., anodized aluminium) enhance durability and reduce maintenance efforts. Materials resistant to weathering, UV degradation, and pollutants are particularly beneficial in harsh climatic conditions.

2.xx Acoustic Performance

particularly in dense urban environments. Reducing external noise infiltration improves indoor environmental quality and enhances user well-being.

Sound Insulation
Effective sound insulation minimizes noise transfer from external sources such as traffic, construction, and mechanical equipment. Materials such as acoustic glass, laminated panels with damping interlayers, and façade insulation systems designed for sound absorption provide superior noise reduction. Noise Reduction Coefficient (NRC) and Sound Transmission Class (STC) ratings are essential for selecting materials with optimal acoustic performance.

Material Damping Properties
Materials with high damping properties, such as viscoelastic layers and composite panels with a damping core, help dissipate vibrational energy and reduce structural noise. The integration of acoustic barriers or dampeners at structural junctions further mitigates sound transmission, ensuring a quieter indoor environment.

2.xx Ventilation

Ventilation systems have the goal to provide heat, cooling, and fresh air to buildings. this way occupants are healthy and comfortable. They assist in controlling indoor temperature and humidity while also eliminating unwanted odors that could hinder concentration and could contribute to sick building syndrome (SBS) (Gonçalves, 2015).

Mechanical Ventilation

Before air conditioning was developed in 1950, passive design principles were the primary approach in high-rise building construction, using orientation, geometry, lighting, and natural ventilation to control inside climate. The introduction of air conditioning facilitated the development of 'glass-box' buildings with larger glazing ratios. These fully air-conditioned high-rises, featuring curtain wall facades and innovative architectural designs, became possible because mechanical climate control allowed buildings to be designed independently of environmental conditions (Gonçalves, 2015).

PV panels on facade ***Figure 2.29***

Today, mechanical ventilation systems are categorized into two main types:

- Centralized ventilatio
- Decentralized ventilation

Centralized systems control air temperature from a single unit within the building, whereas decentralized systems have individual units regulating air temperature in different areas. Centralized HVAC systems, in high-rise building especially can require entire floors to handle the massive quantities of air that must be filtered. They are also less efficient due to the lengthier ductwork and the possibility of duct leaks. High-rise buildings, on the other hand, benefit more from decentralized systems that are integrated into the building envelope.

Decentralized systems may include:

- Horizontal and vertical facade ventilation units
- Underfloor units
- Ceiling units

Facade ventilation units can also incorporate additional functions, such as:

- Filtration of outdoor air
- Heat recovery
- Thermal conditioning
- Natural Ventilation

Research suggests that users who have greater control over their ventilation experience higher satisfaction with temperature variations (Wood & Salib, 2013). In this regard, natural ventilation helps balance energy efficiency and thermal comfort.

In high-rise buildings, double-skin facades are sometimes implemented to reduce wind speeds and preheat incoming air before it reaches the interior. However, the effectiveness of natural ventilation depends on wind pressure against the facade. Additionally, the size of ventilation openings is influenced by the building's height.

Hybrid Ventilation
Hybrid, or mixed-mode, ventilation systems combine mechanical and natural airflow. Natural ventilation may be not feasible in extreme weather conditions, particularly on the upper floors of high-rise buildings, where wind speeds are higher and temperatures lower. Hybrid systems maximize thermal comfort for users while consuming the least amount of energy.

2.xx Adaptability and Modularity

Adaptive and modular façade systems allow for flexible building use, easy upgrades, and sustainable lifecycle management. These systems facilitate adjustments to evolving energy standards and design preferences, enhancing long-term efficiency and reuse potential.

Reconfigurable Panels
Façade panels designed for disassembly and reconfiguration enable future modifications without disrupting the overall structure. Modular systems allow for simple replacement of individual elements, such as upgrading to higher-performance insulation or integrating photovoltaic (PV) panels.

Demountable Systems
Demountable façade systems utilize standardized connections, enabling efficient material reuse and recycling during renovations or dismantling. These systems align with circular economy principles, reducing waste and promoting sustainability. Curtain wall systems with interchangeable panels, for instance, simplify the integration of energy-efficient glazing or adaptive shading technologies.

2.xx Fire Resistance

Fire-resistant façade materials and design strategies enhance building safety, particularly in high-rise structures where evacuation is more complex. Fire-rated panels and fireproof seals are essential to prevent the spread of flames and smoke.

Fire-Rated Panels
Non-combustible materials such as mineral wool insulation, intumescent panels, and fire-retardant-treated wood delay fire spread and maintain structural integrity under high temperatures. High-rise buildings benefit from fire-resistant curtain wall systems incorporating spandrel panels and perimeter fire barriers.

Fireproof Seals
Joints and gaps in the façade must be sealed with fire-resistant materials, such as intumescent sealants and silicone-based fireproof barriers. Compliance with standards such as EN 13501 (European classification) or NFPA 285 (American standard) ensures robust fire safety performance, reducing risks associated with rapid fire propagation.

2.xx Environmental Parameters in High-Rise Buildings

As building height gets larger, microclimate factors such as wind speed, temperature variation, and solar exposure can change the higher the building gets. These factors play an important role in architectural and engineering decisions (Godoy-Shimizu et al., 2018). Taller structures consume more energy because they must respond to changing thermal and visual comfort (Ekici, Kazanasmaz, Tasgetiren, Turrin and Sariyildiz, 2019). Floors higher up in high-rise can experience stronger wind pressure, bigger temperature fluctuations, and more direct sunshine, this results in different lighting, heating, and cooling requirements than levels located in lower parts of a building.

Temperature Variation

As height increases in high-rise buildings, the temperature of the external air decreases. Research shows that there is a 0.7°C to 1.2°C drop in temperature for every 100 meters (National Weather Service, 2019; Engineering Toolbox, 2003). Season, time of day, and location all have an impact on this fluctuation. As a result, building geometry and envelope design must consider this. Upper floors, for example, may need higher insulation R-values to maintain a stable indoor environment, which affects ventilation, heating, and cooling systems (Hamilton et al., 2017).

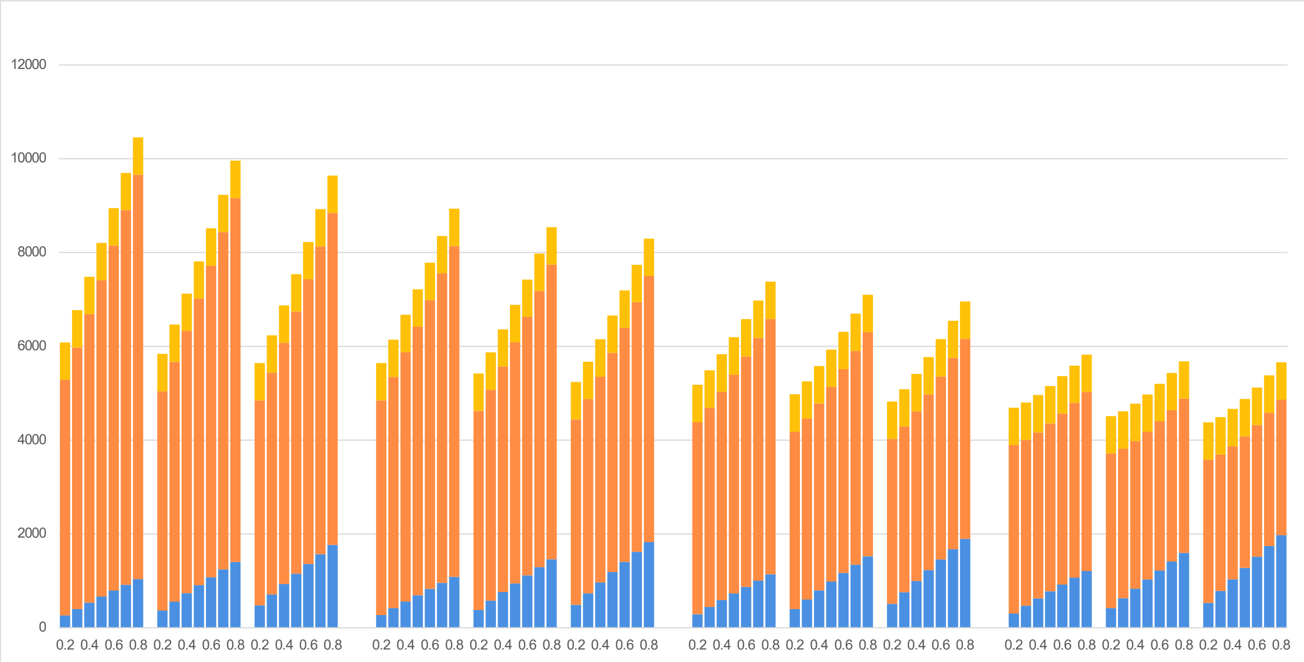
Wind Pressure

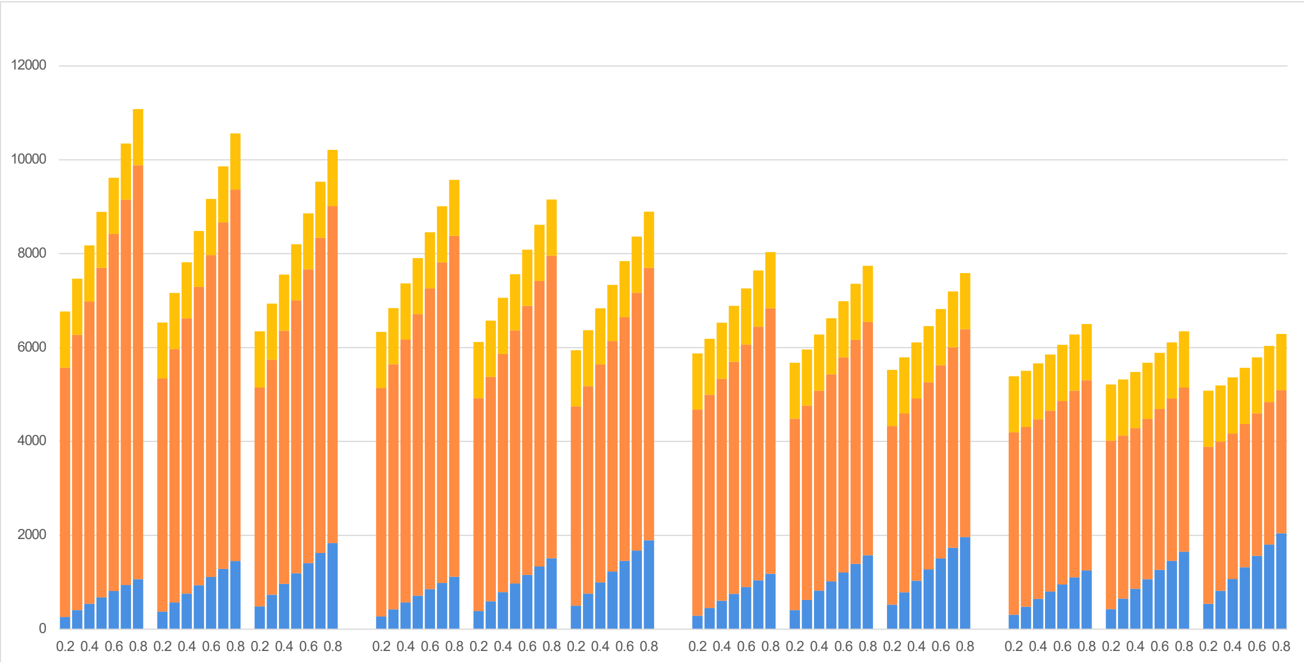
Wind speed increases with height and is impacted by the building's urban surroundings (CIBSE, 2006). Wind flow influences energy consumption since taller structures have higher infiltration rates due to increased wind pressure, which affects gas consumption and heating (Hamilton et al., 2017; Ali & Al-Khodmany, 2012).

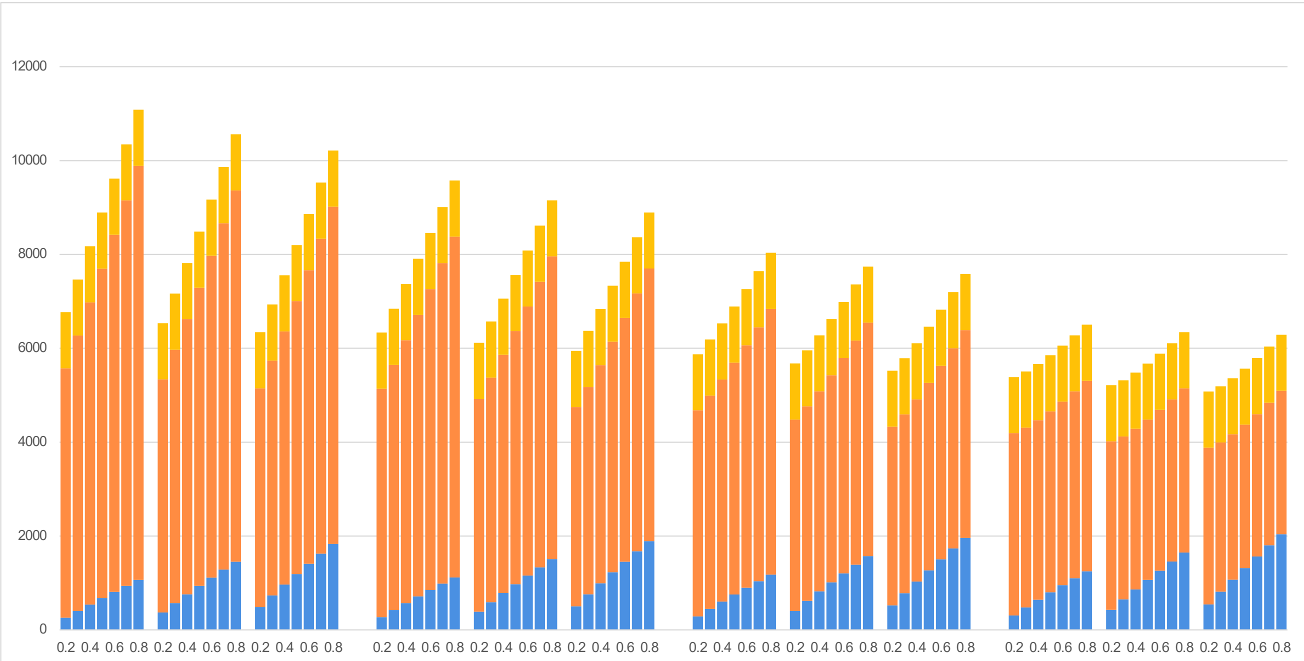
Direct Sun and Daylight

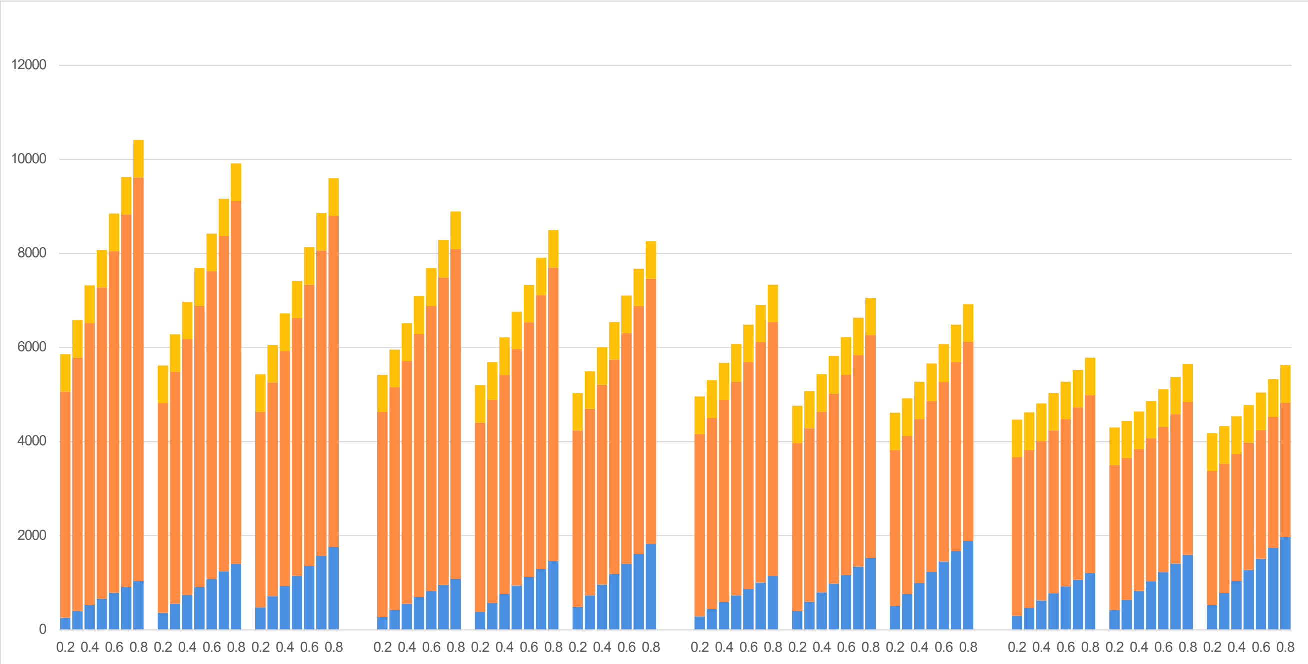
Because of the reduced shadowing, upper floors receive more natural light and solar gain. While this minimizes the requirement for artificial lighting, it also raises cooling demand to avoid overheating (Godoy-Shimizu et al., 2018). The mix of daylight, solar gains, and shading systems must be carefully planned, taking into account urban location, building height, and envelope features (Ekici et al. 2019).

East operational carbon





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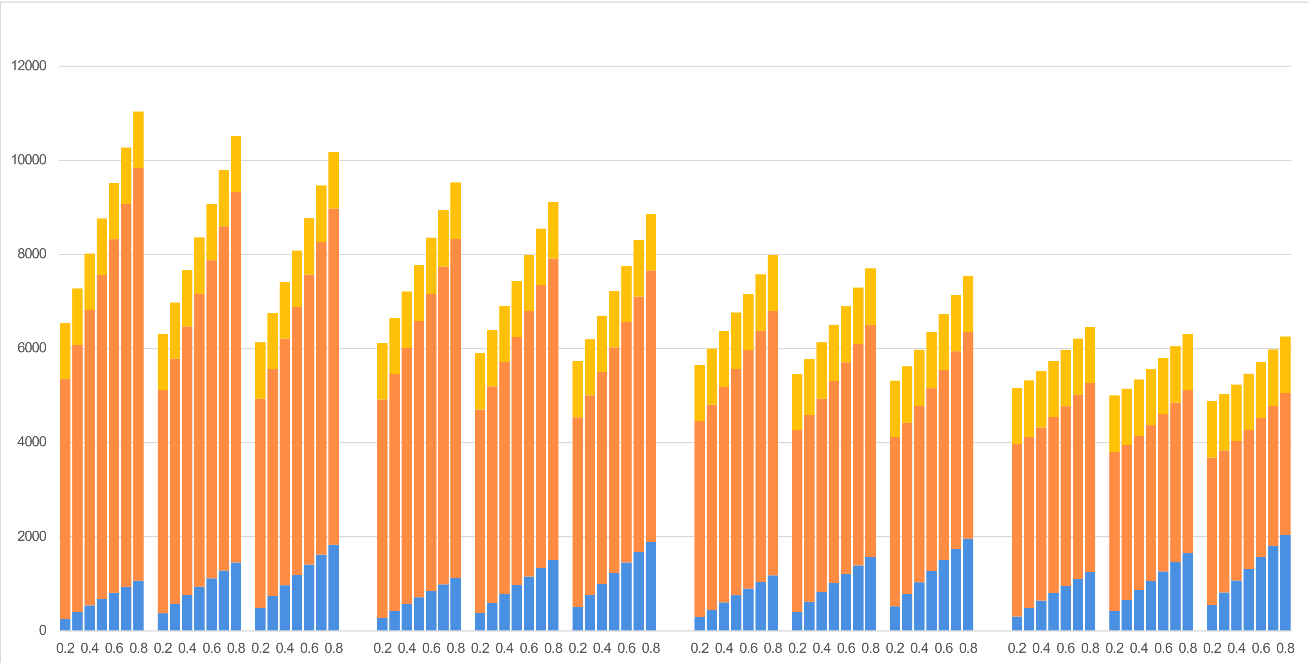
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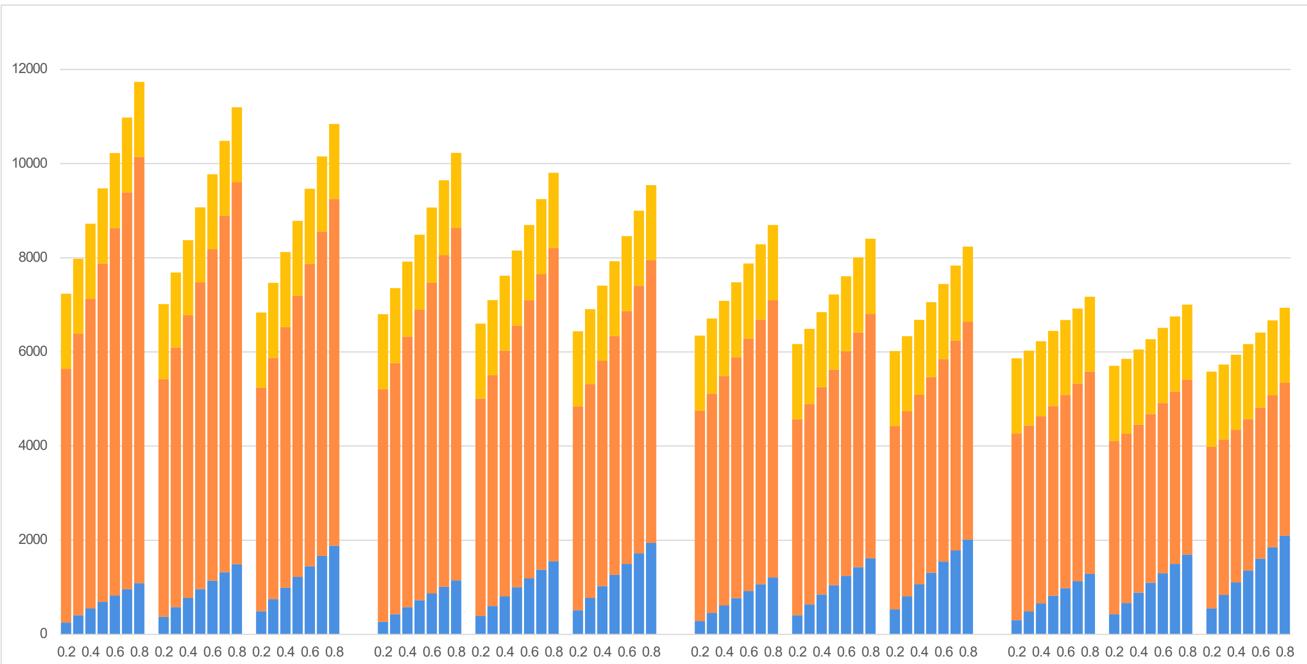
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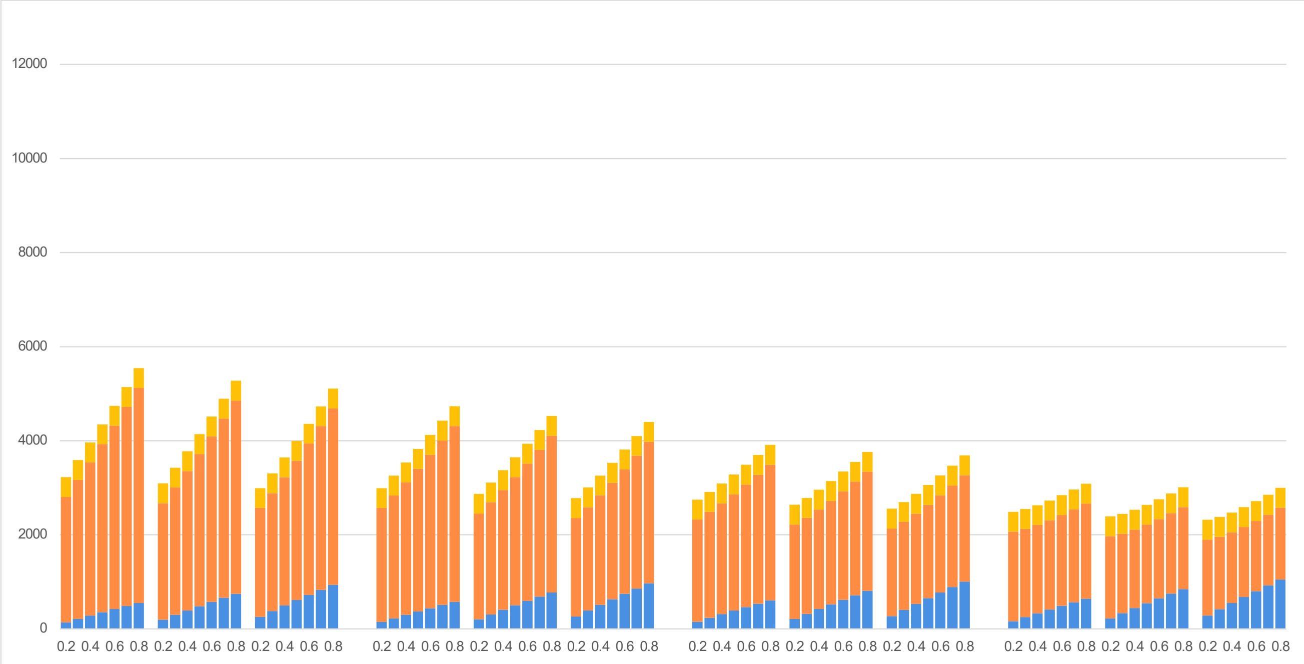

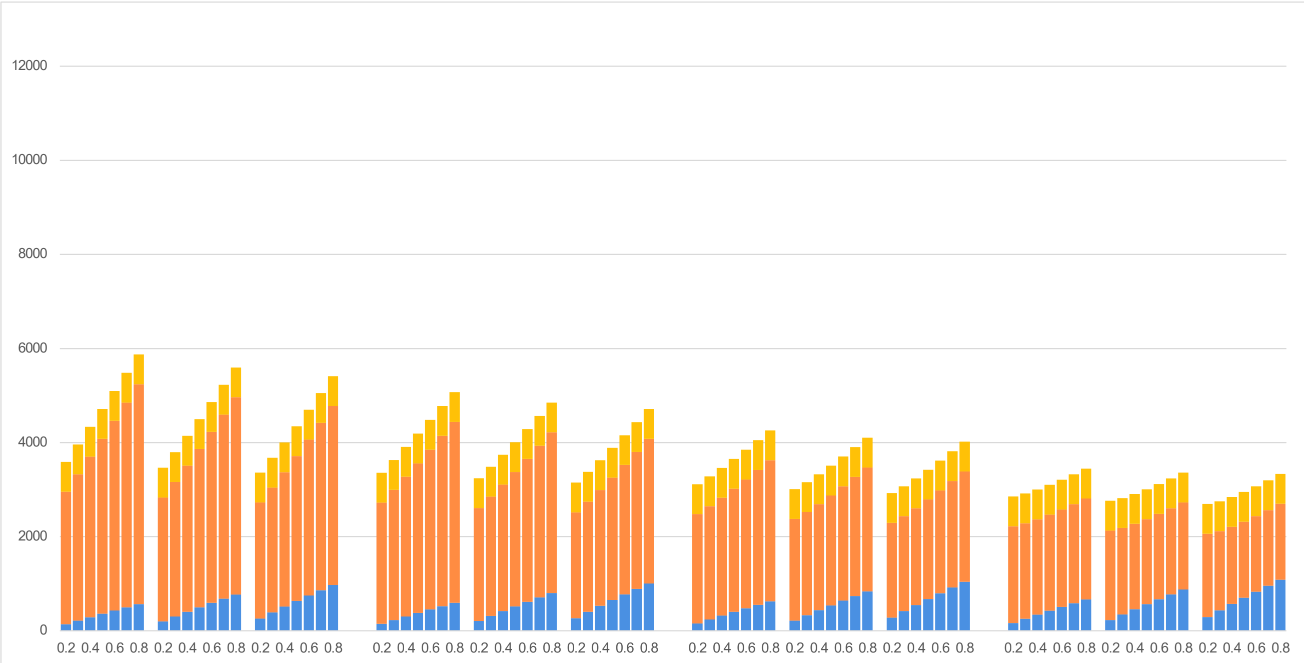

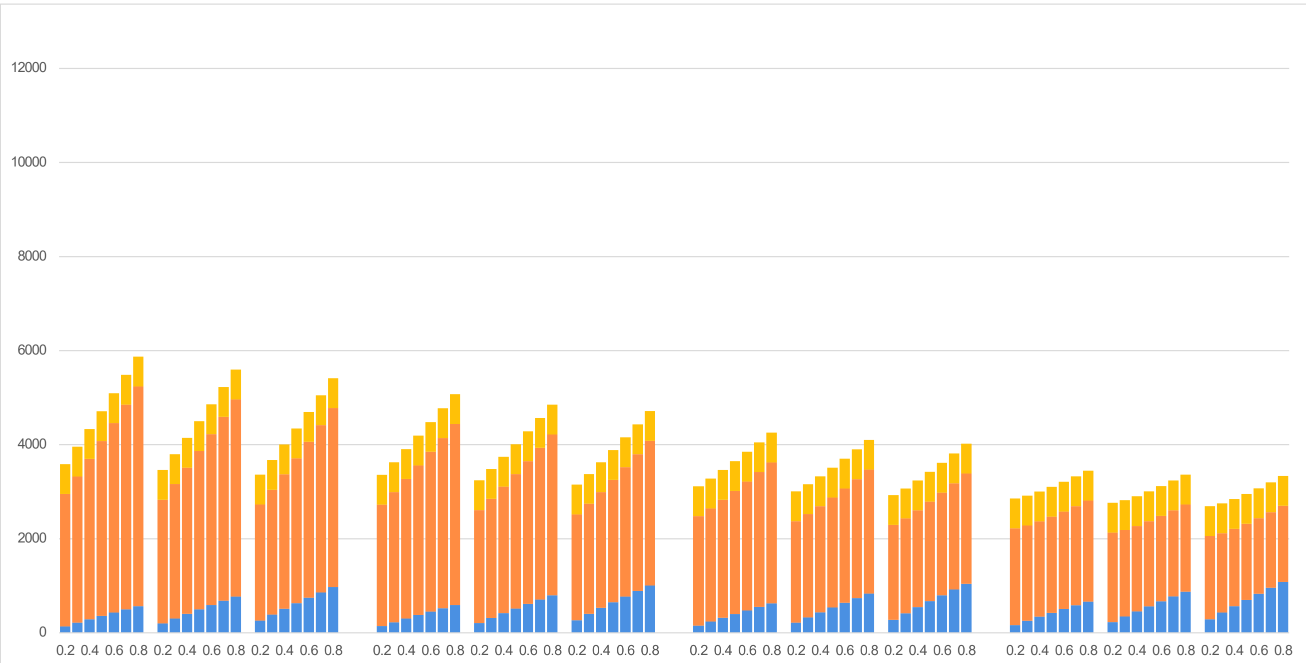

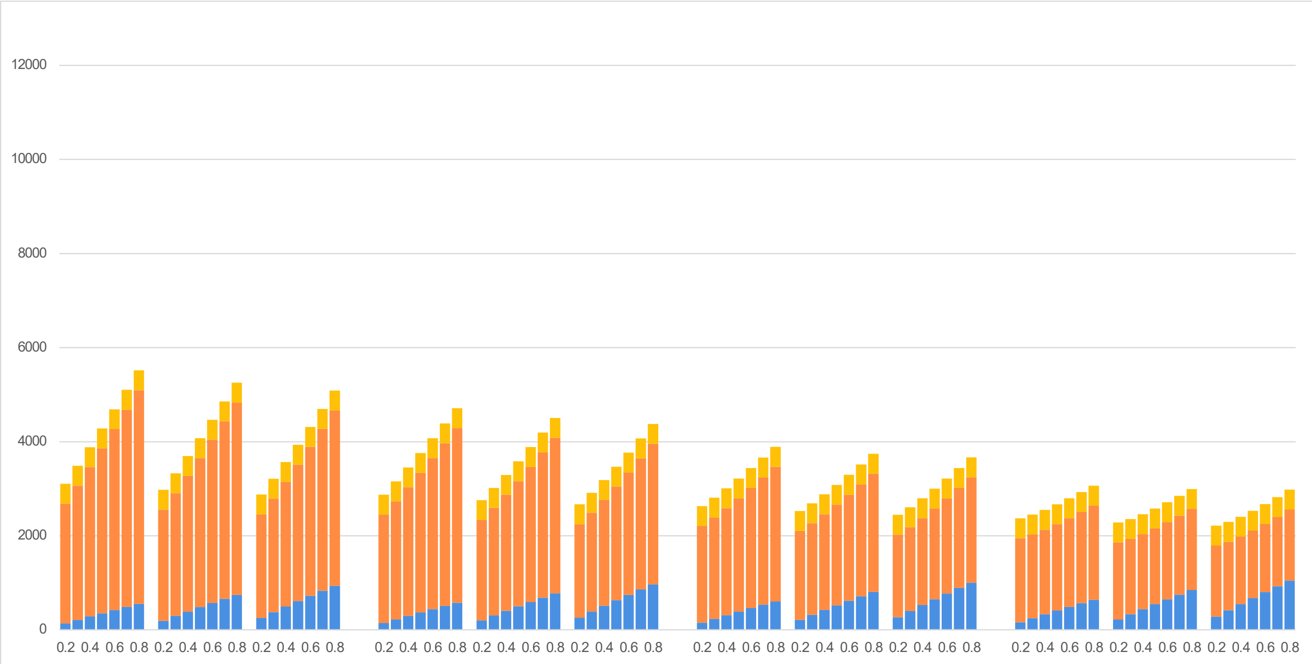
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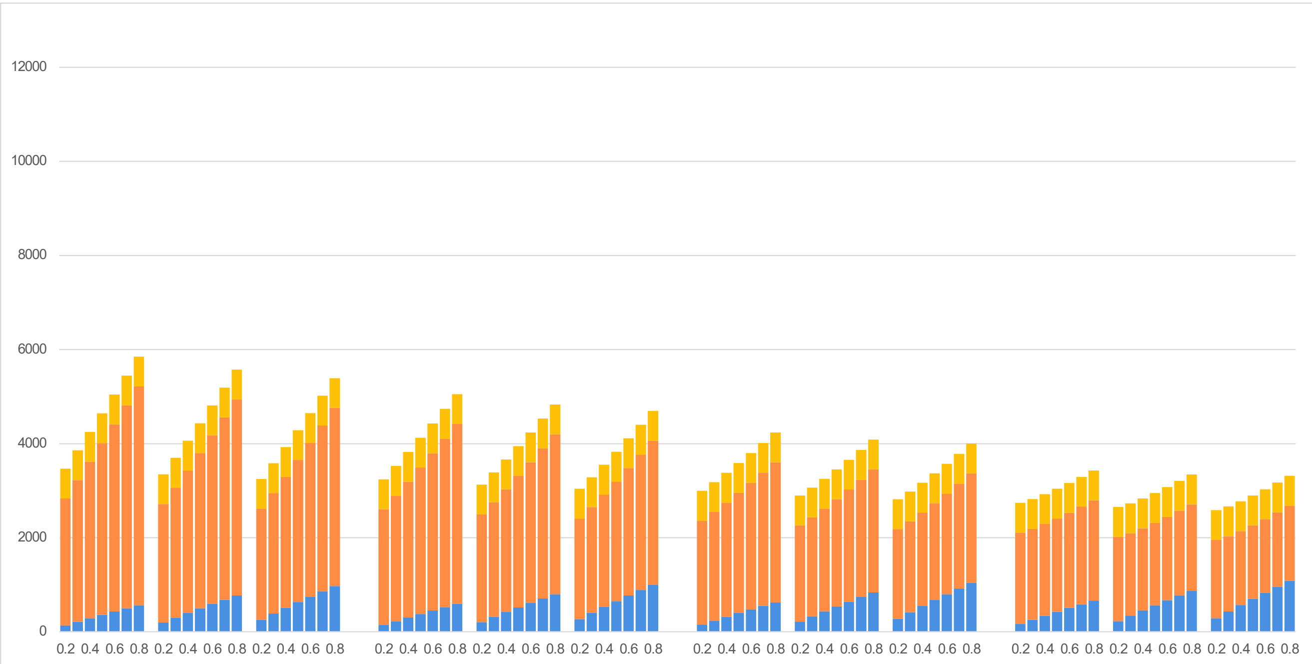
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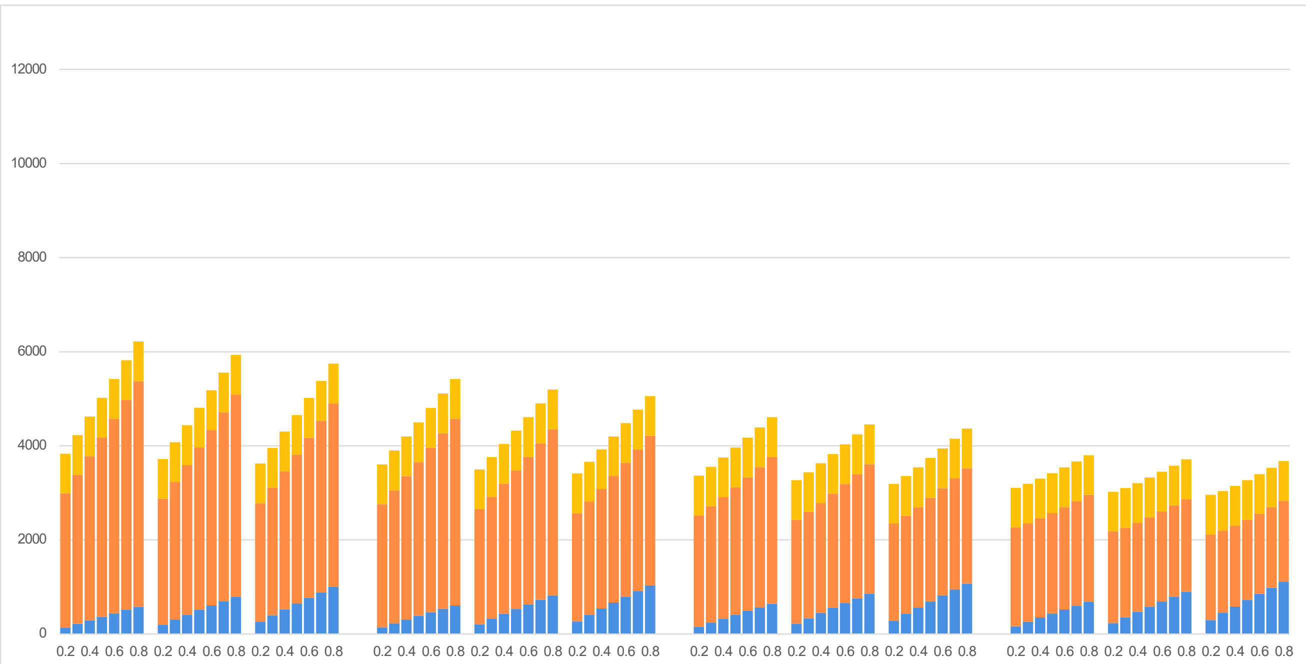
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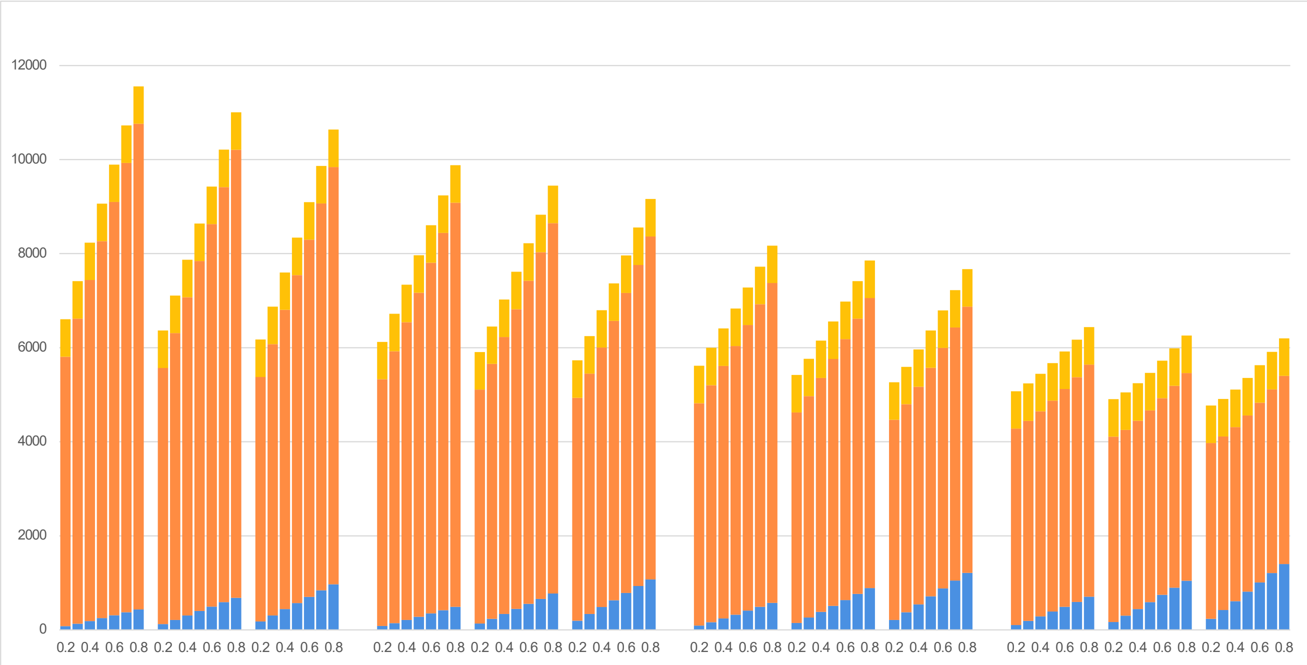
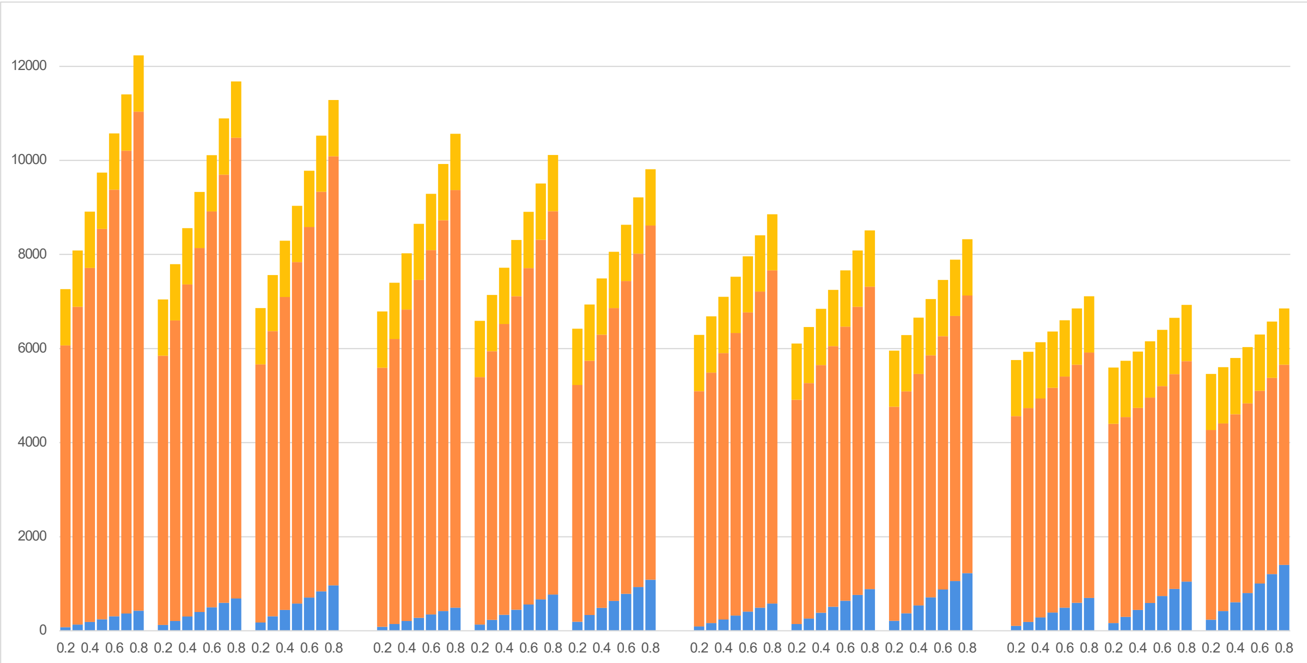
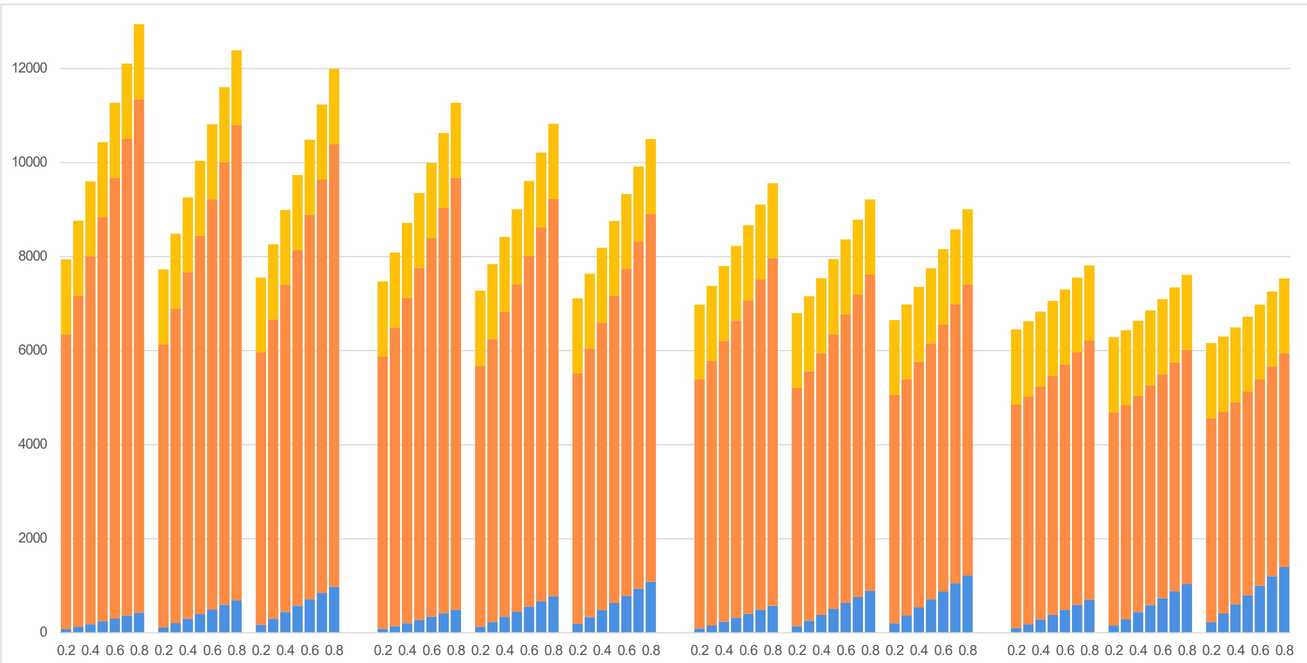
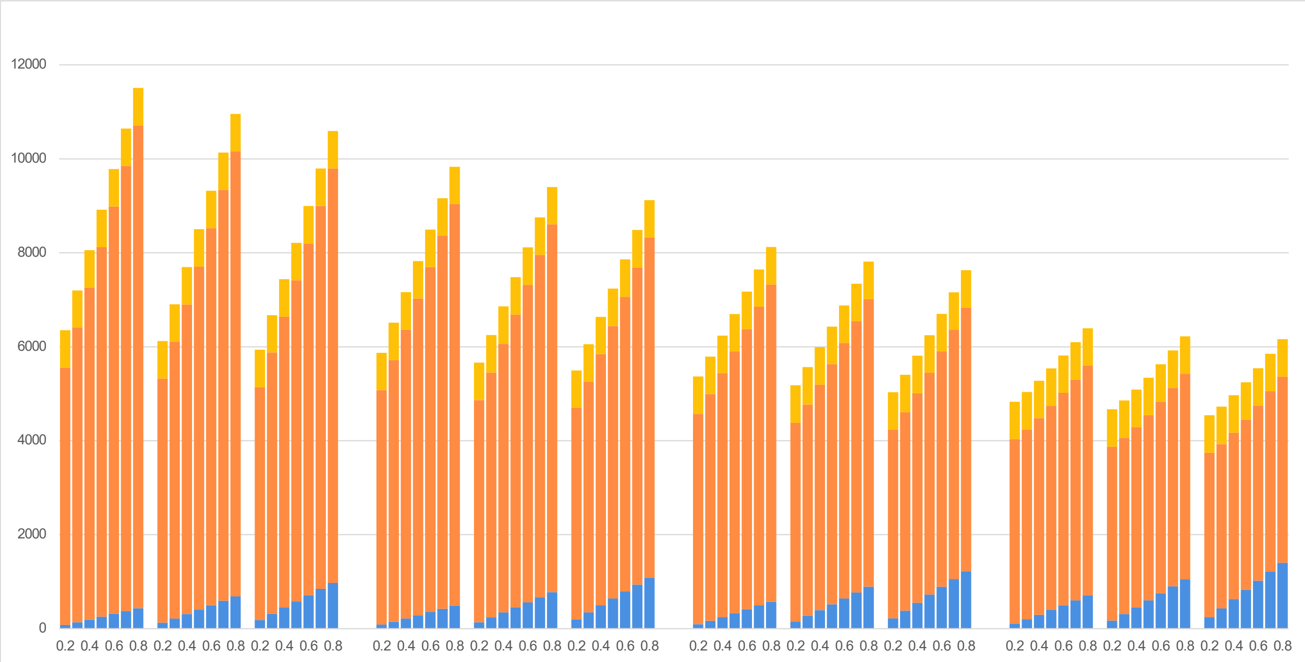
North operational carbon





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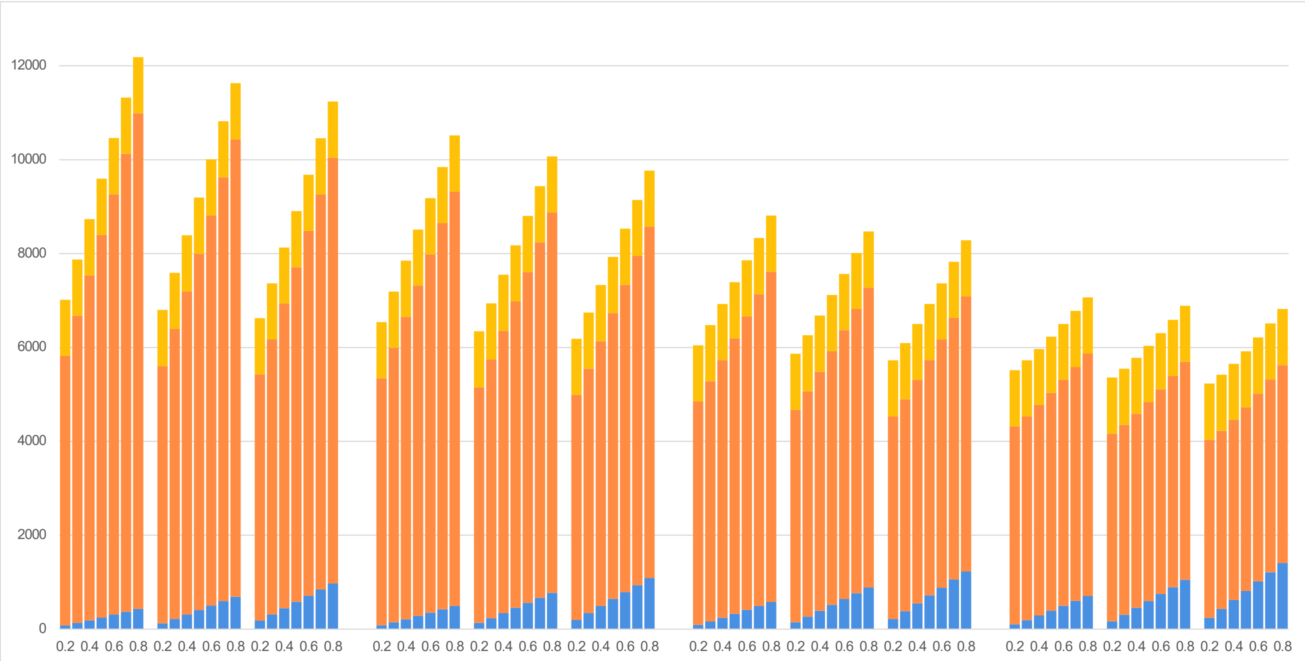
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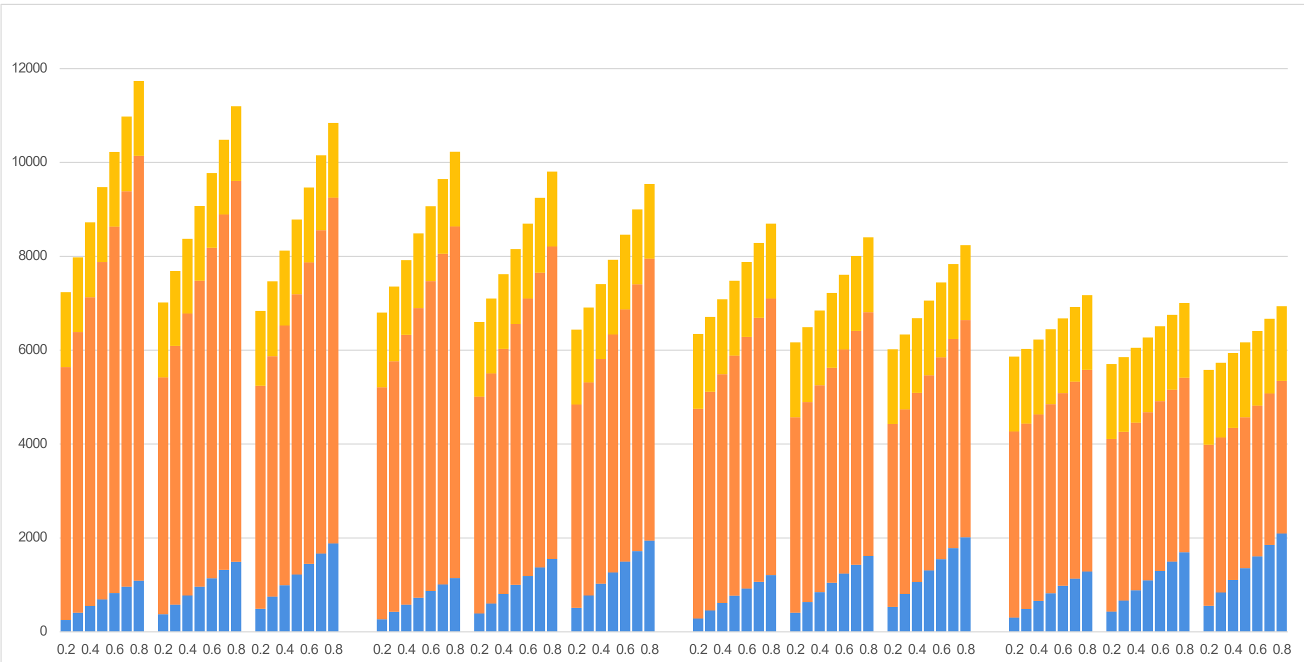
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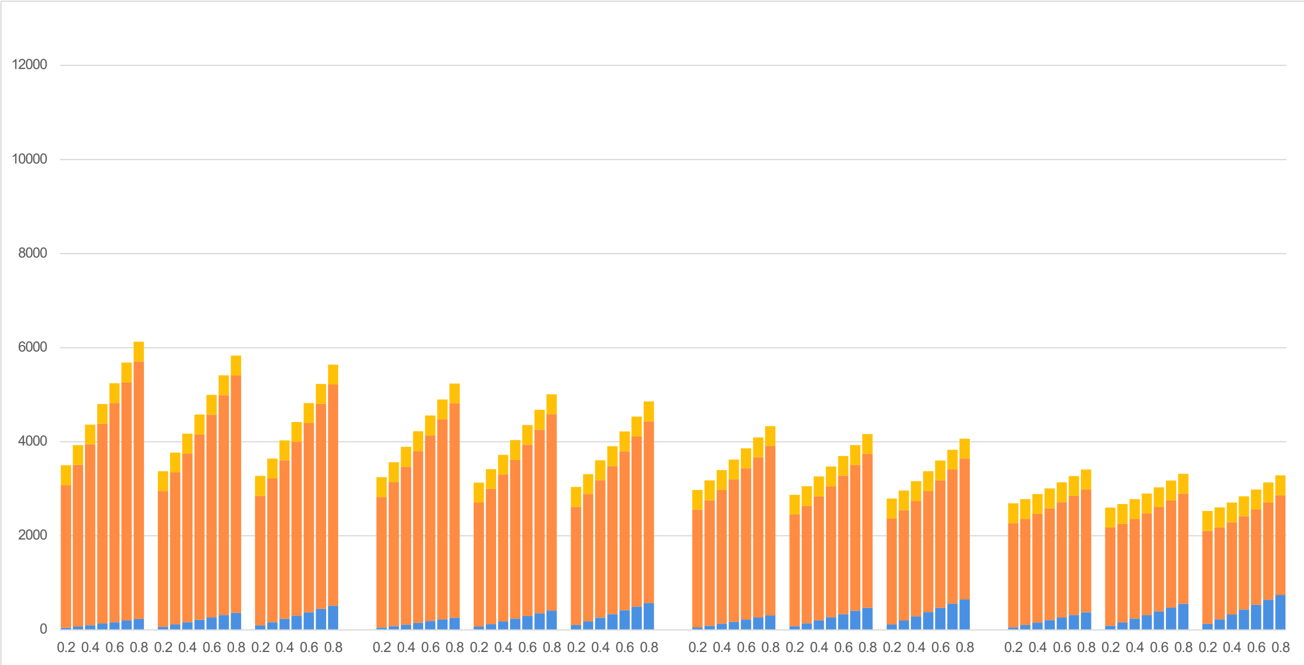
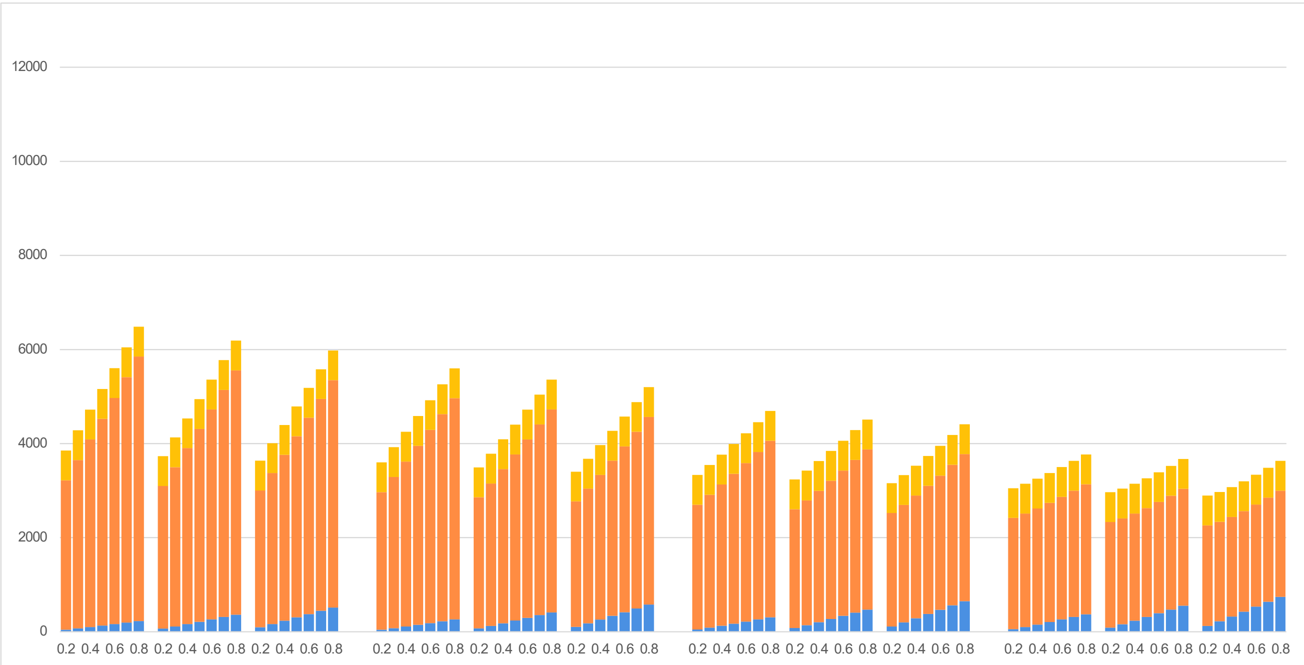
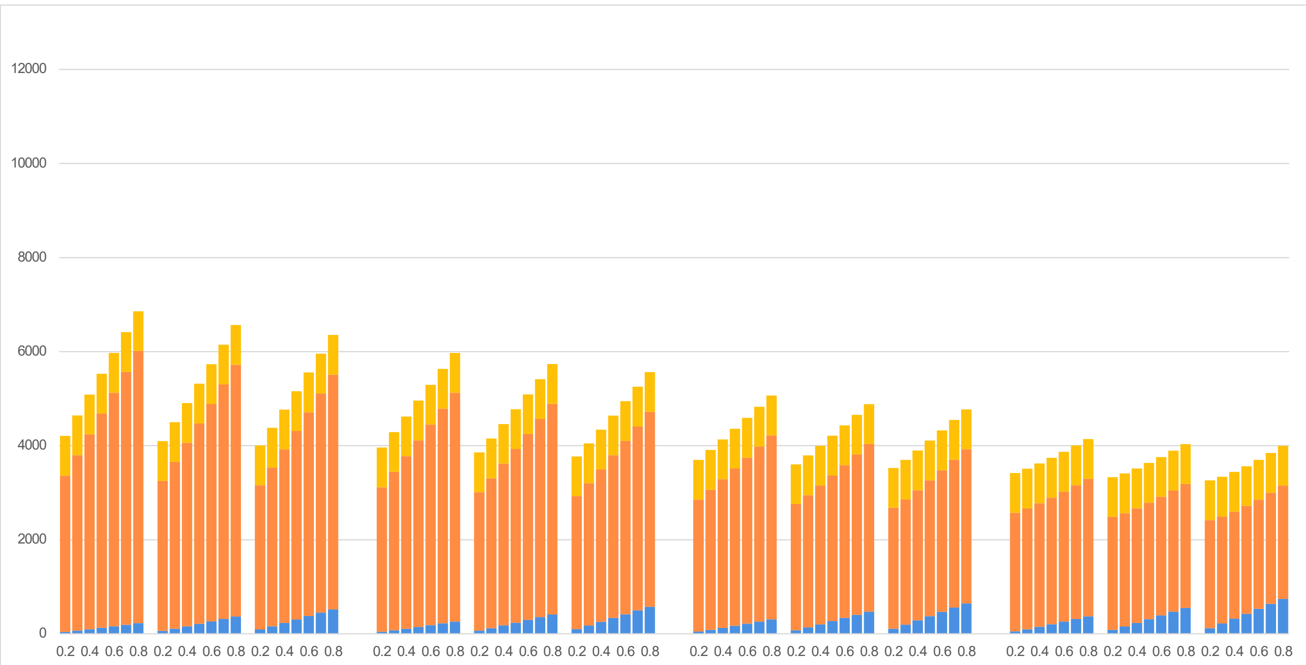
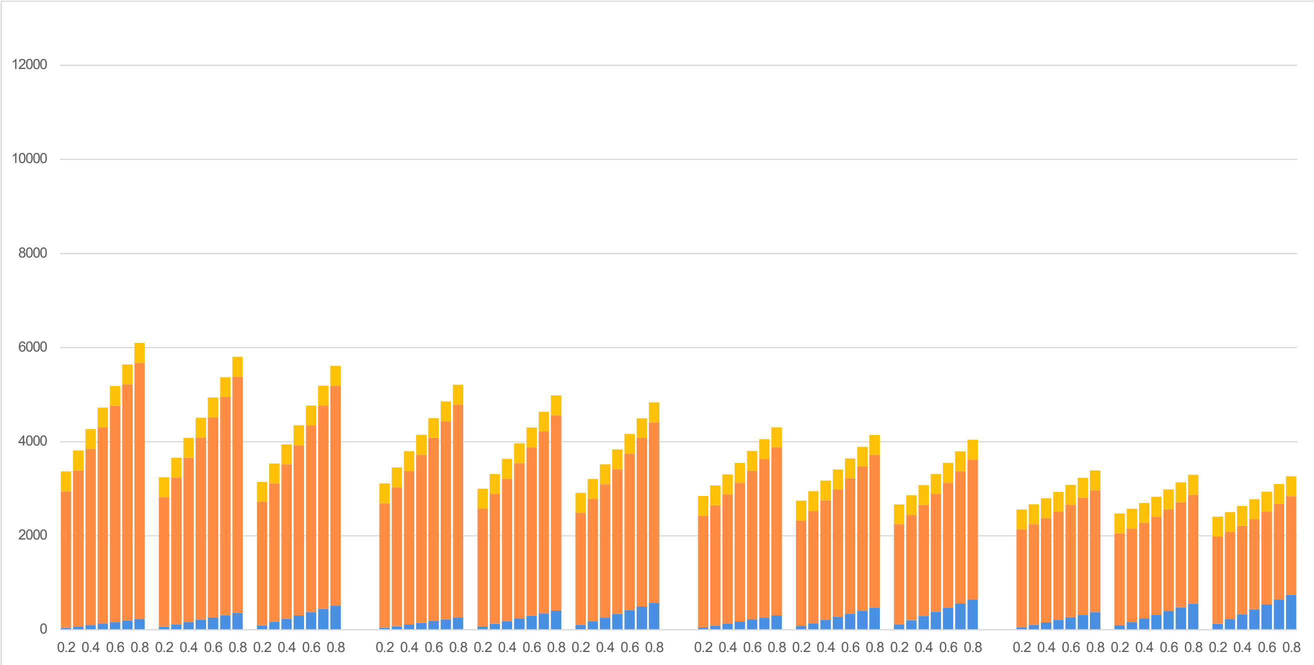
North operational carbon corrected for carbon decrease





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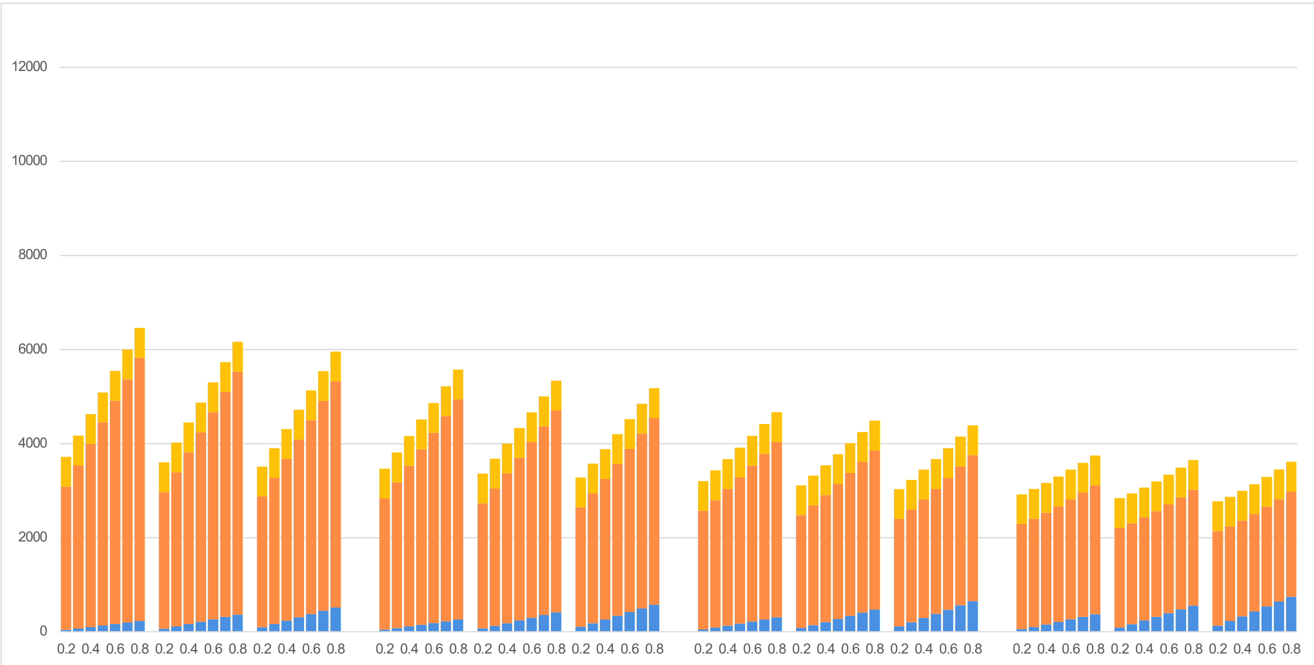
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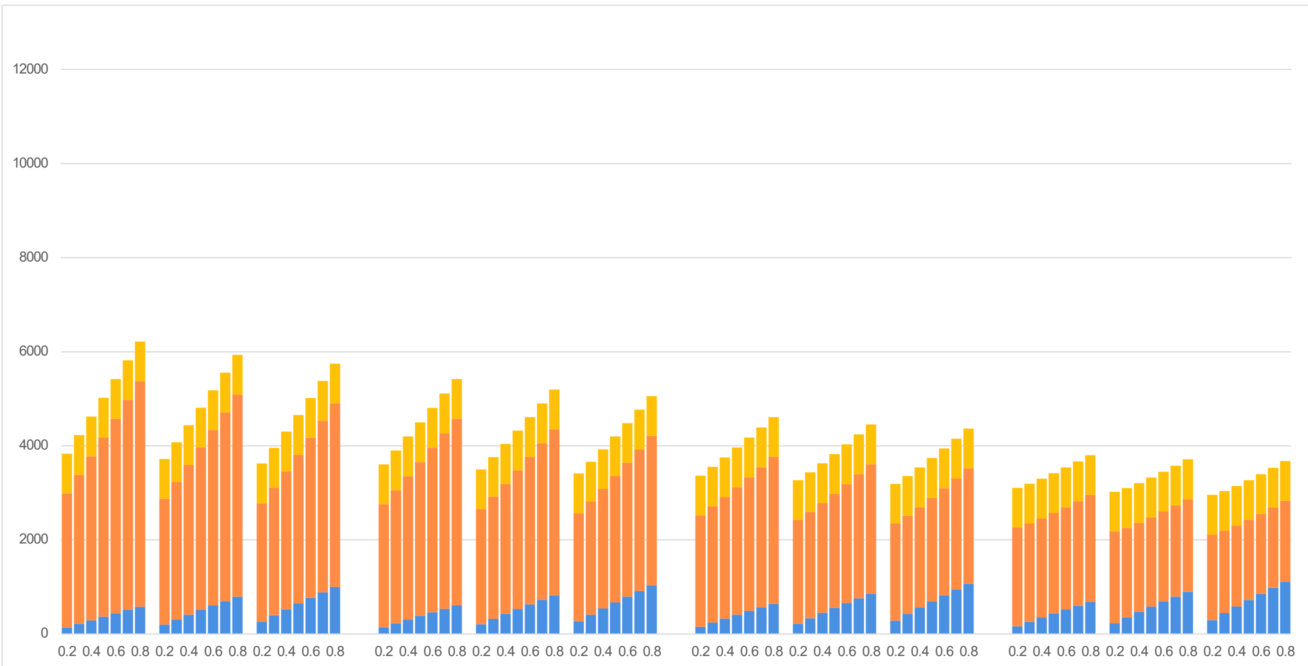
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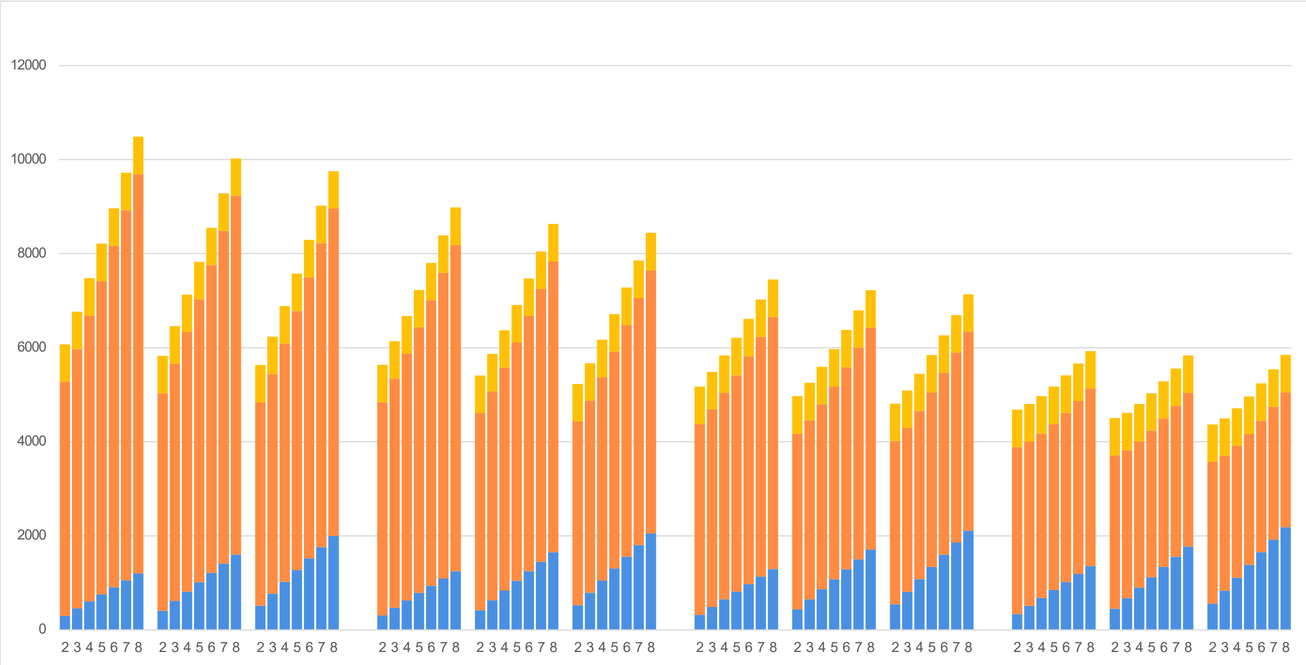
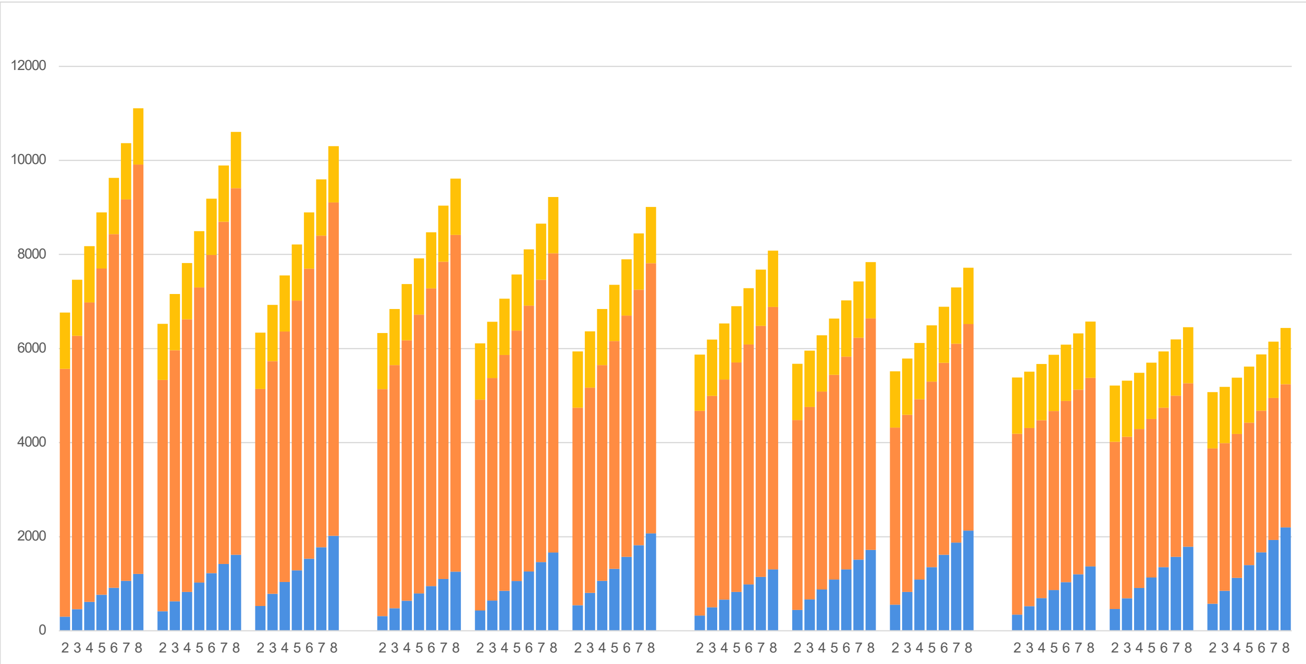
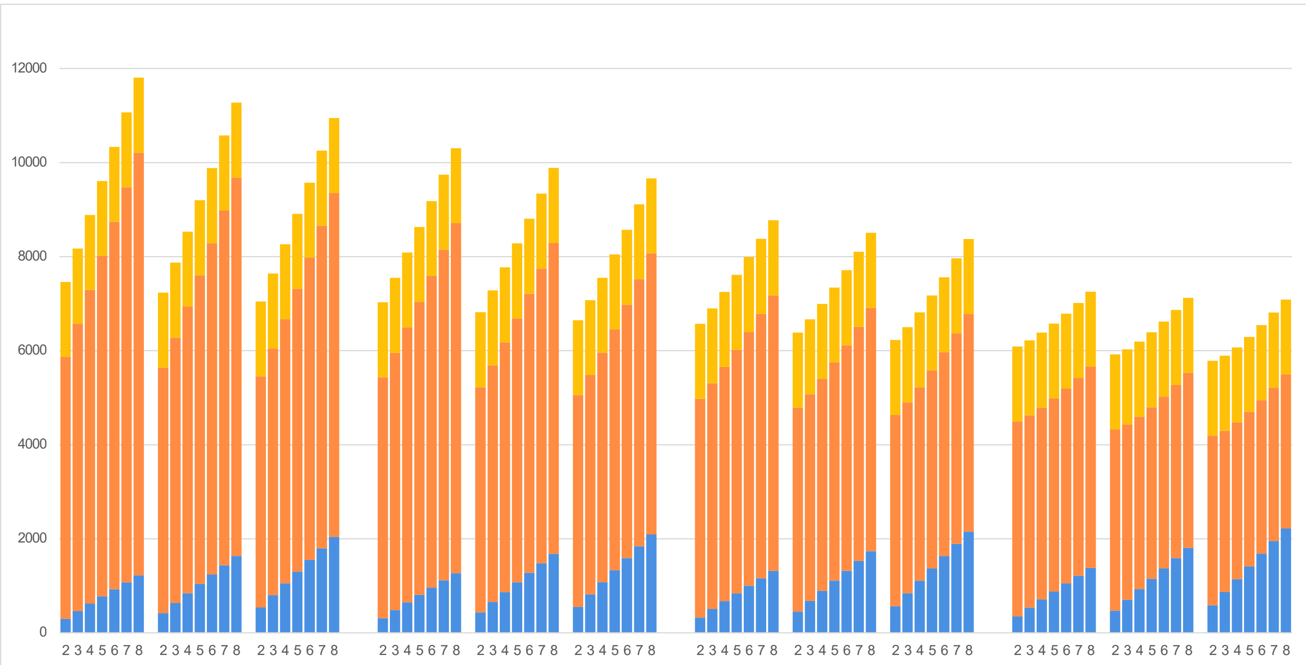
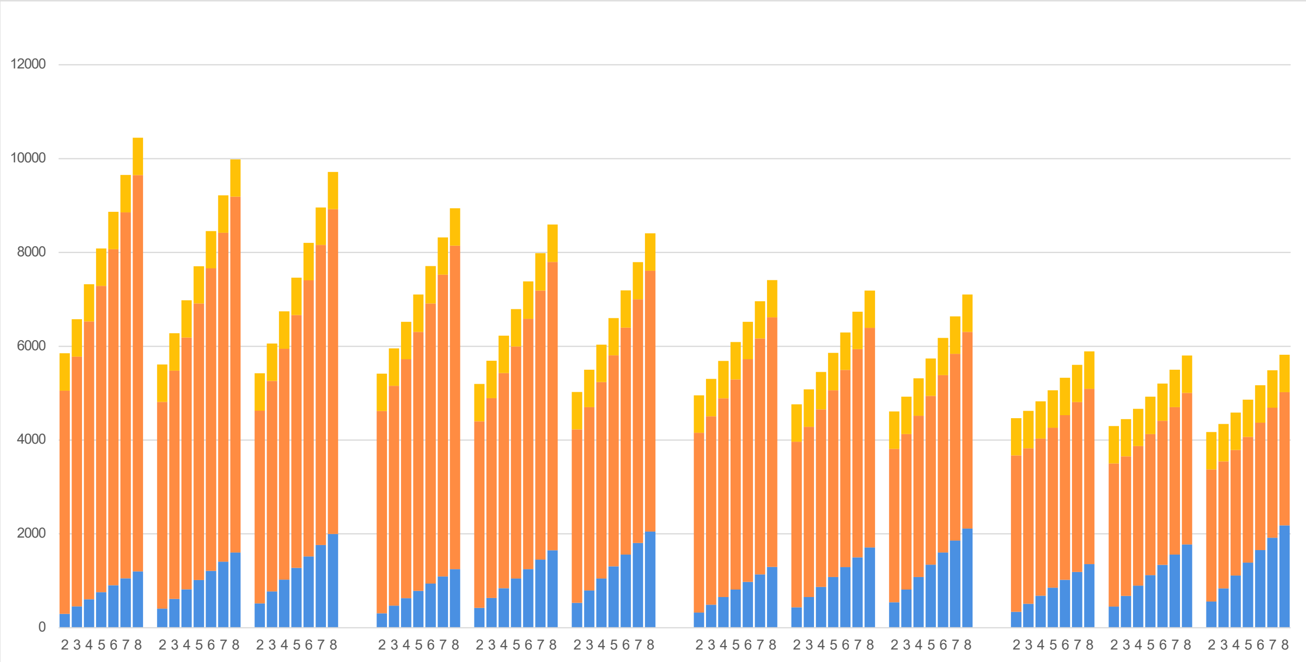
West operational carbon





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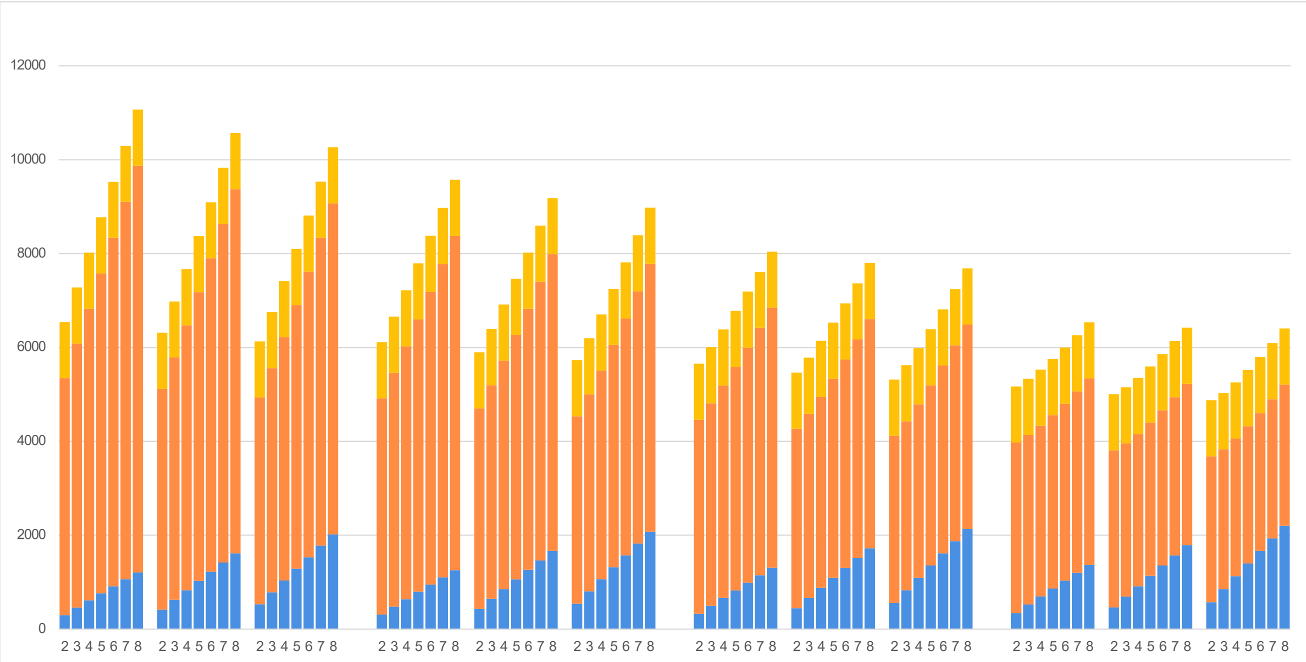
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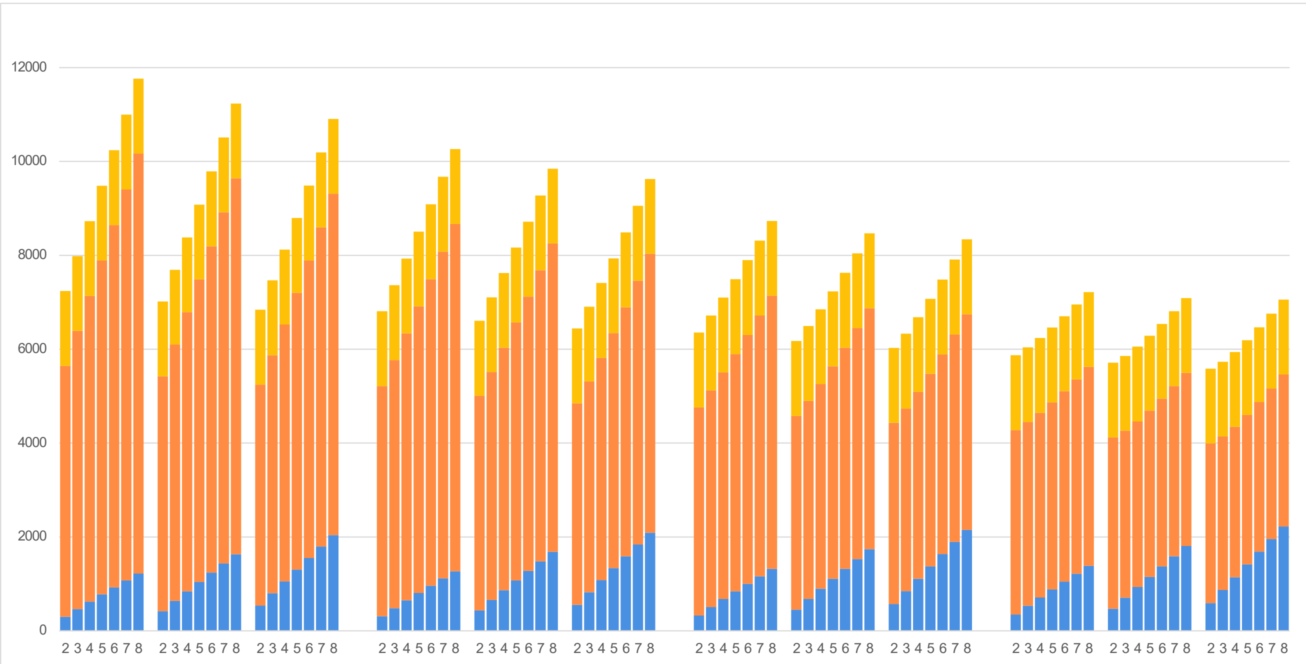
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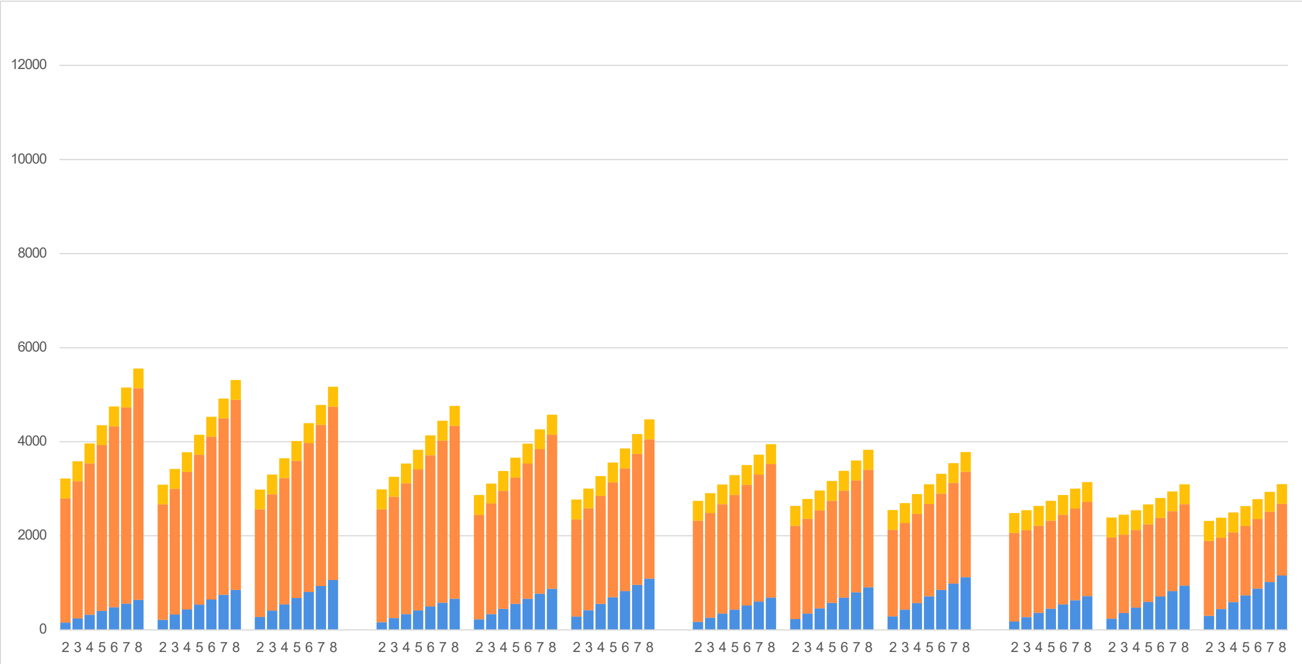
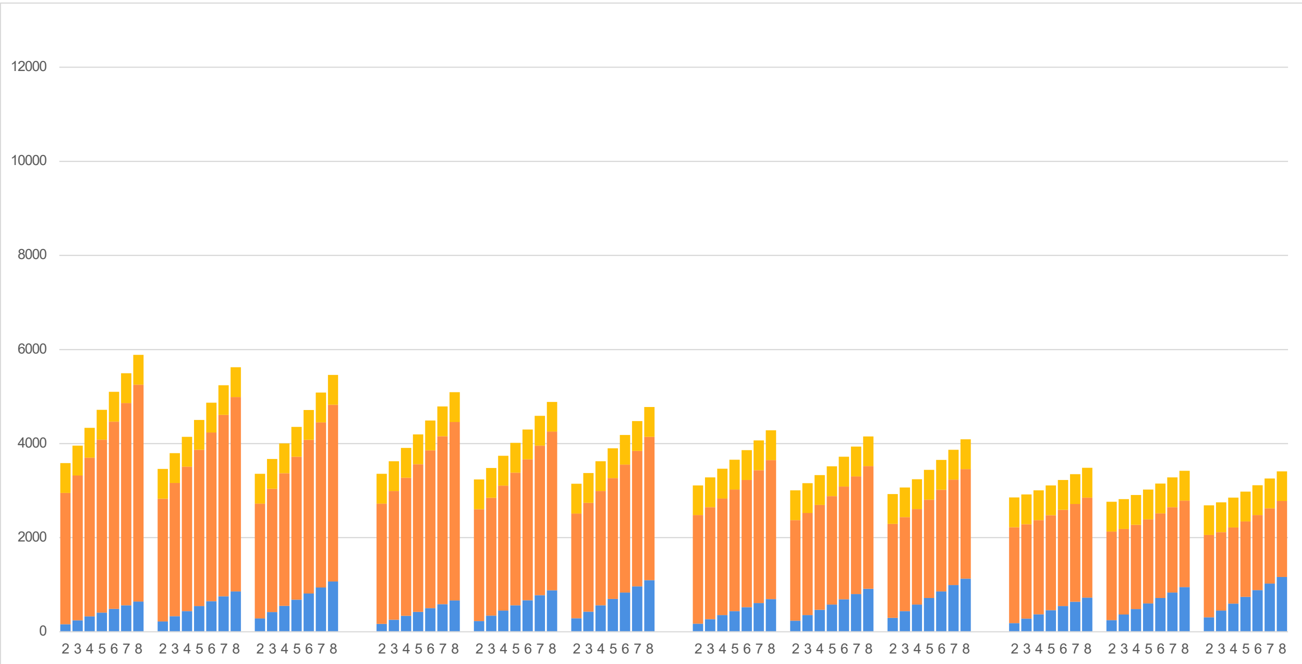
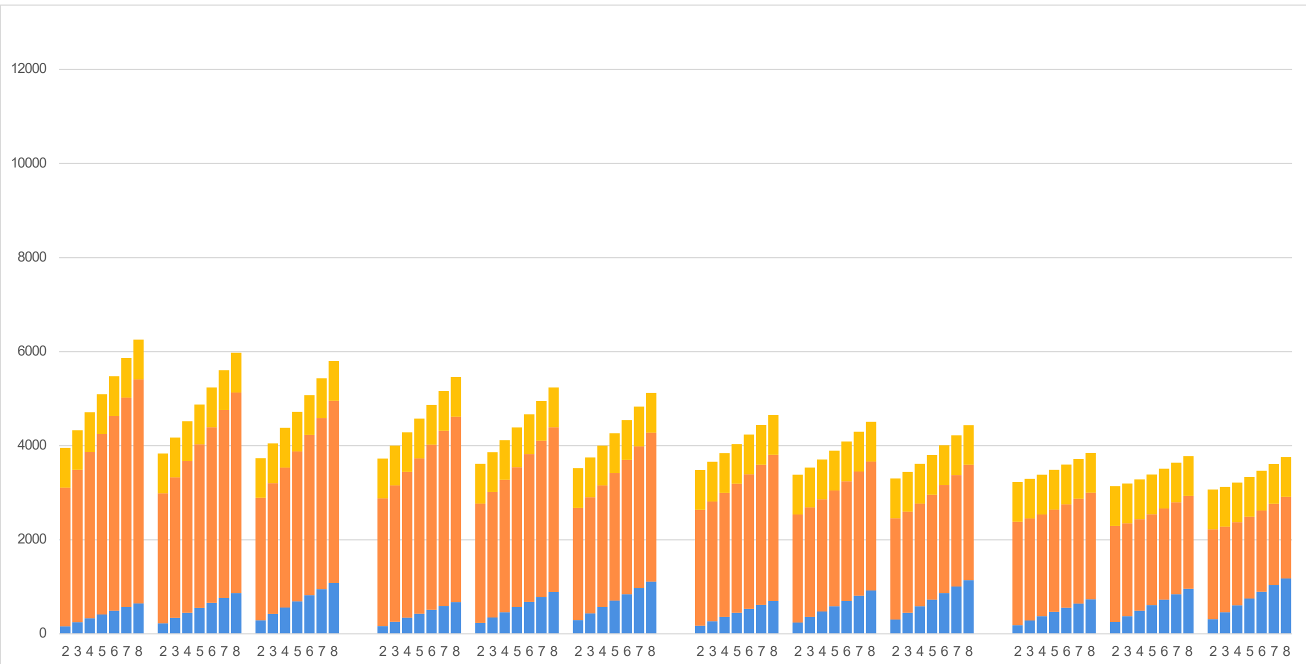
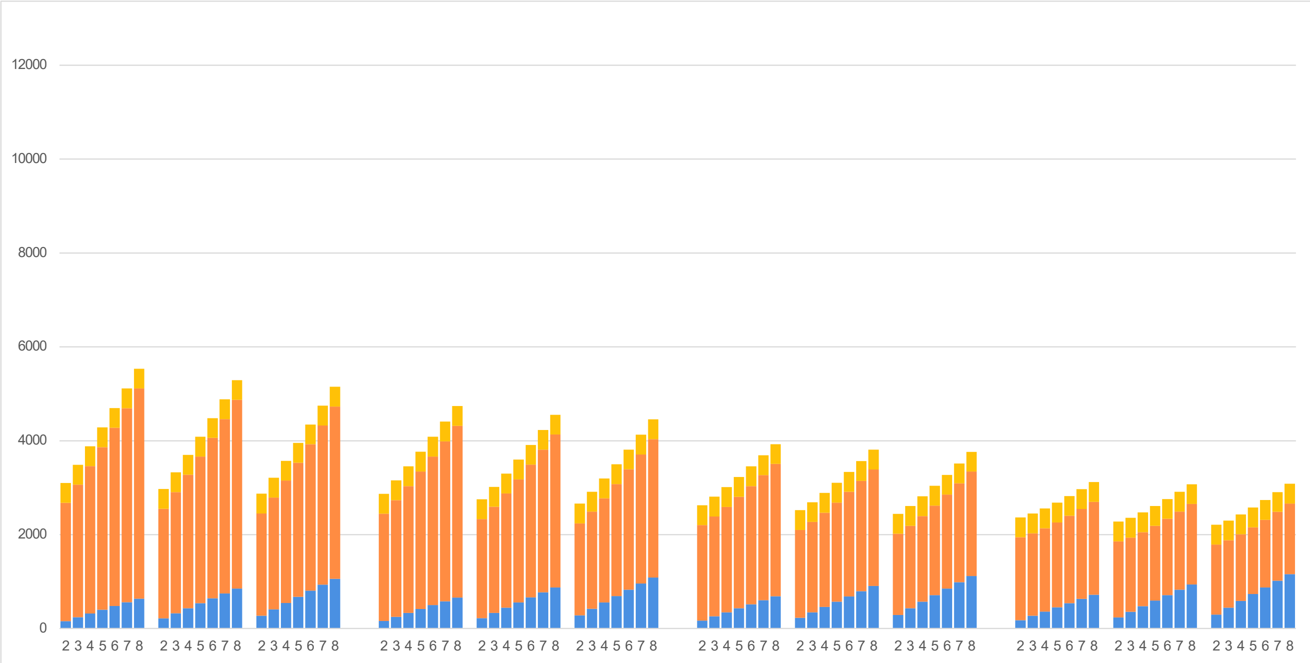
West operational carbon corrected for carbon decrease





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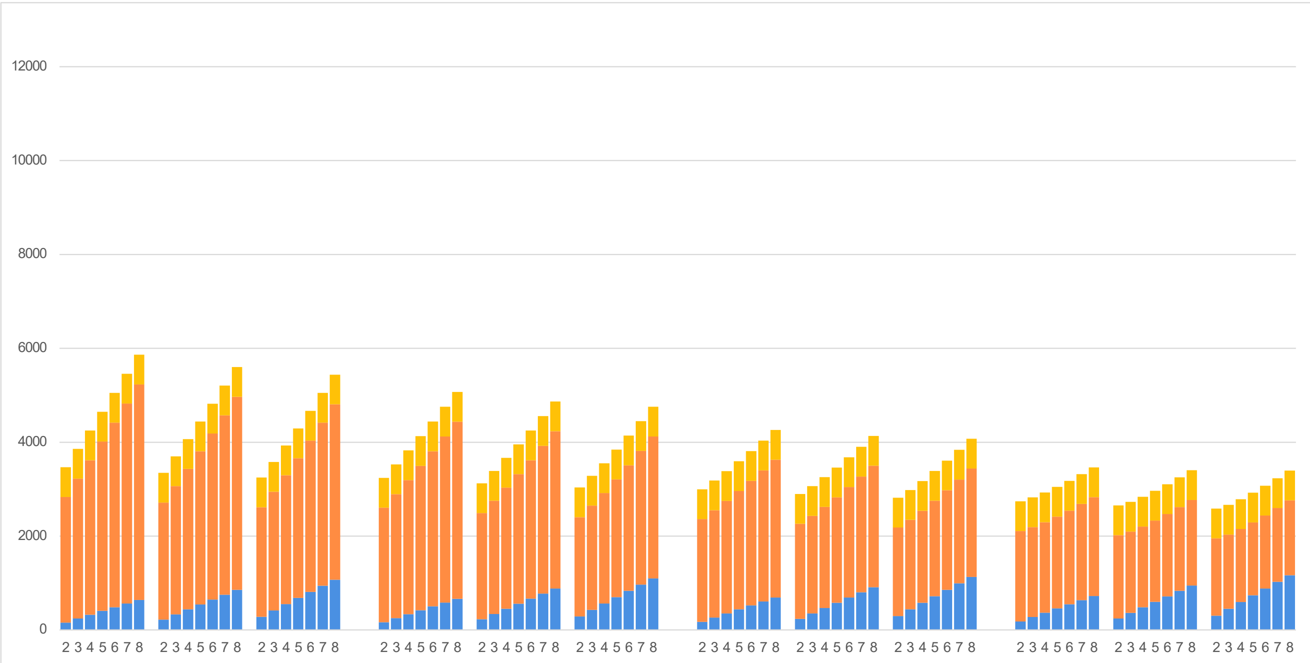
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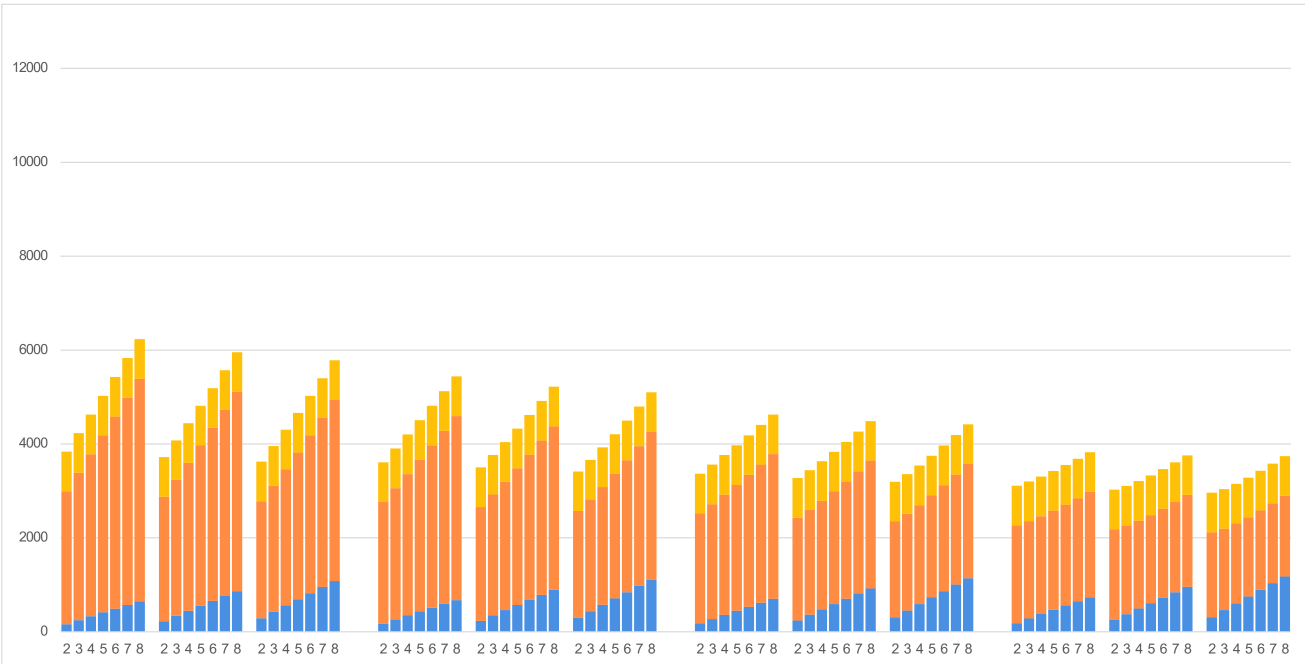
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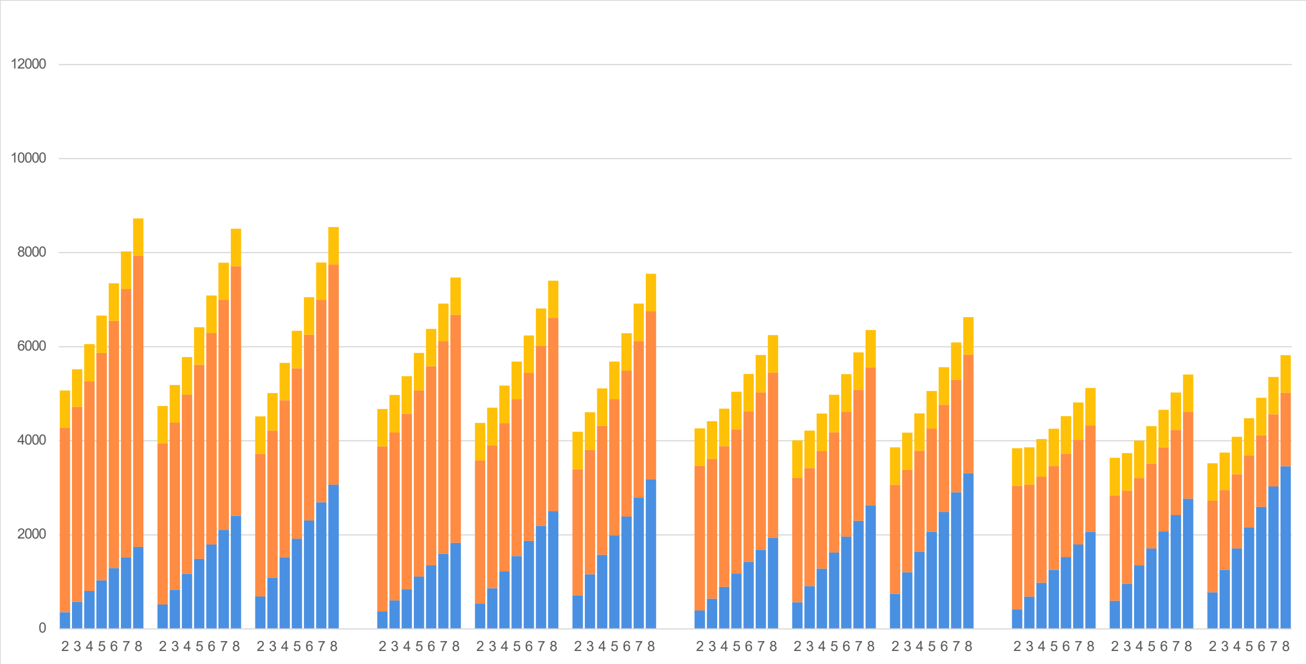
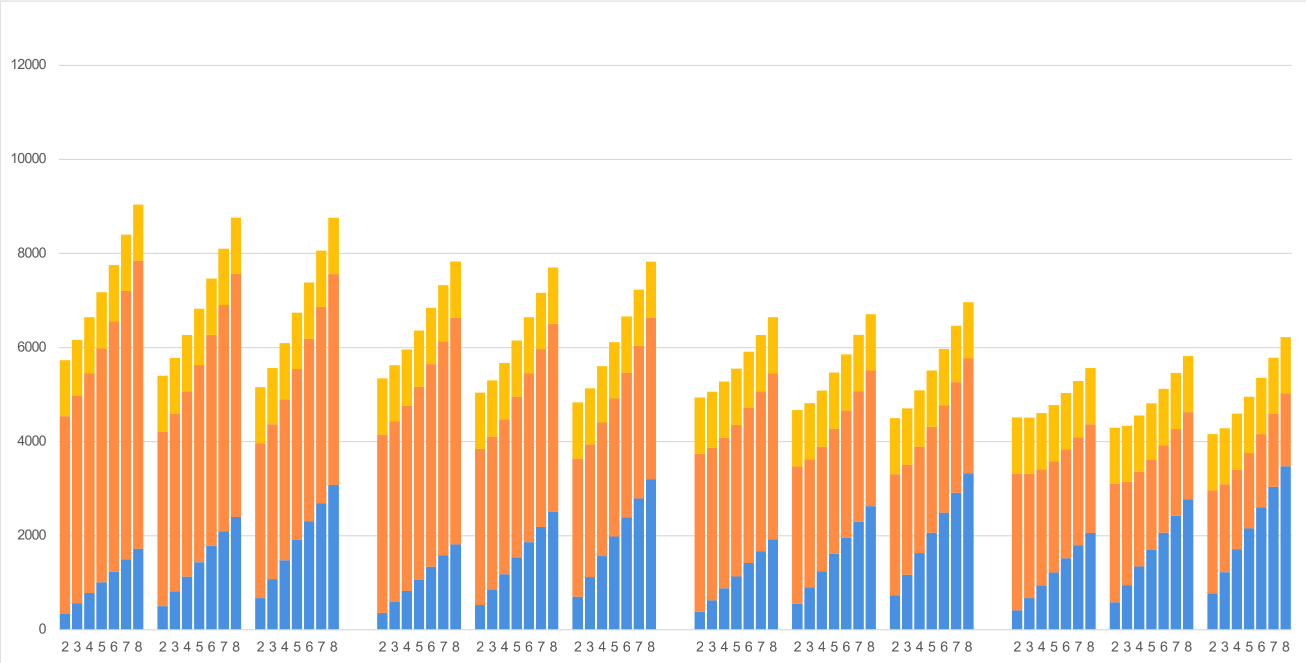
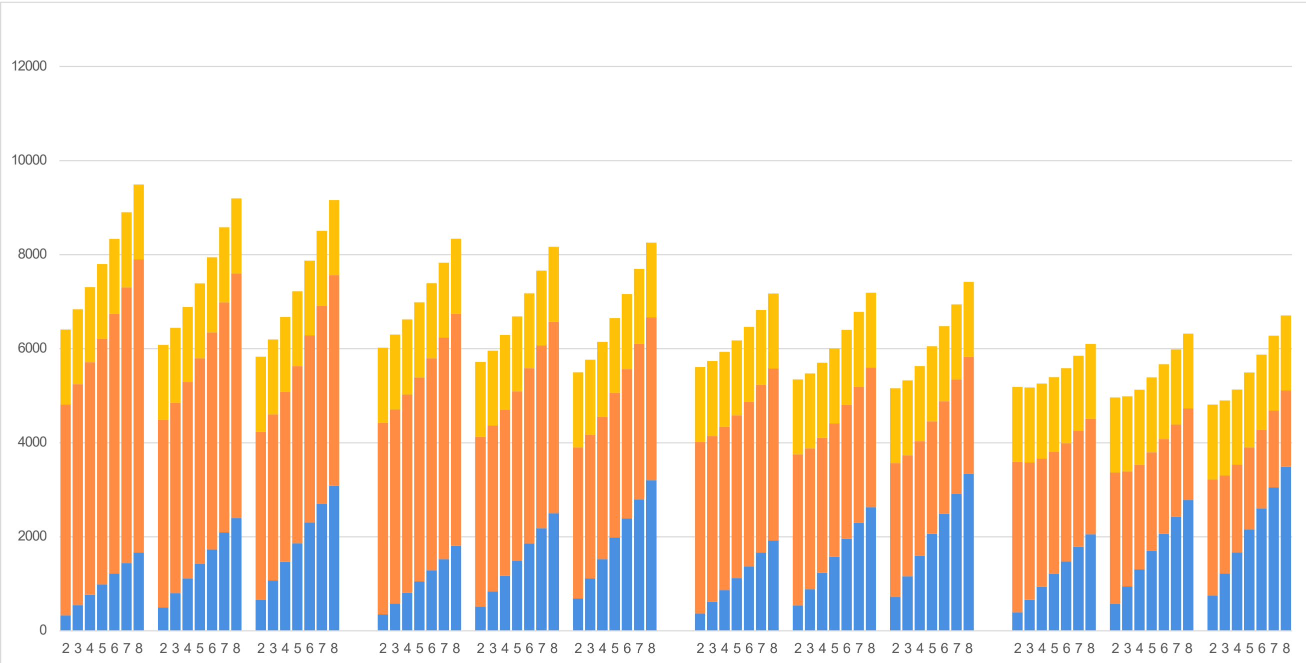
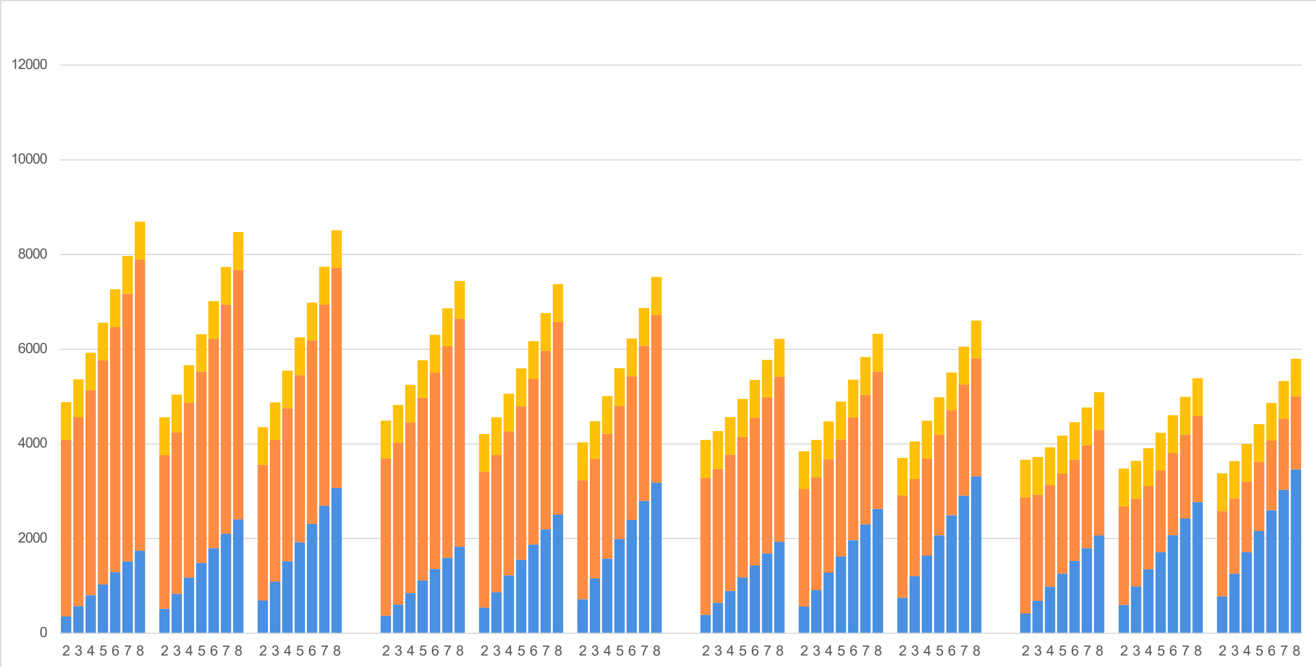
South operational carbon





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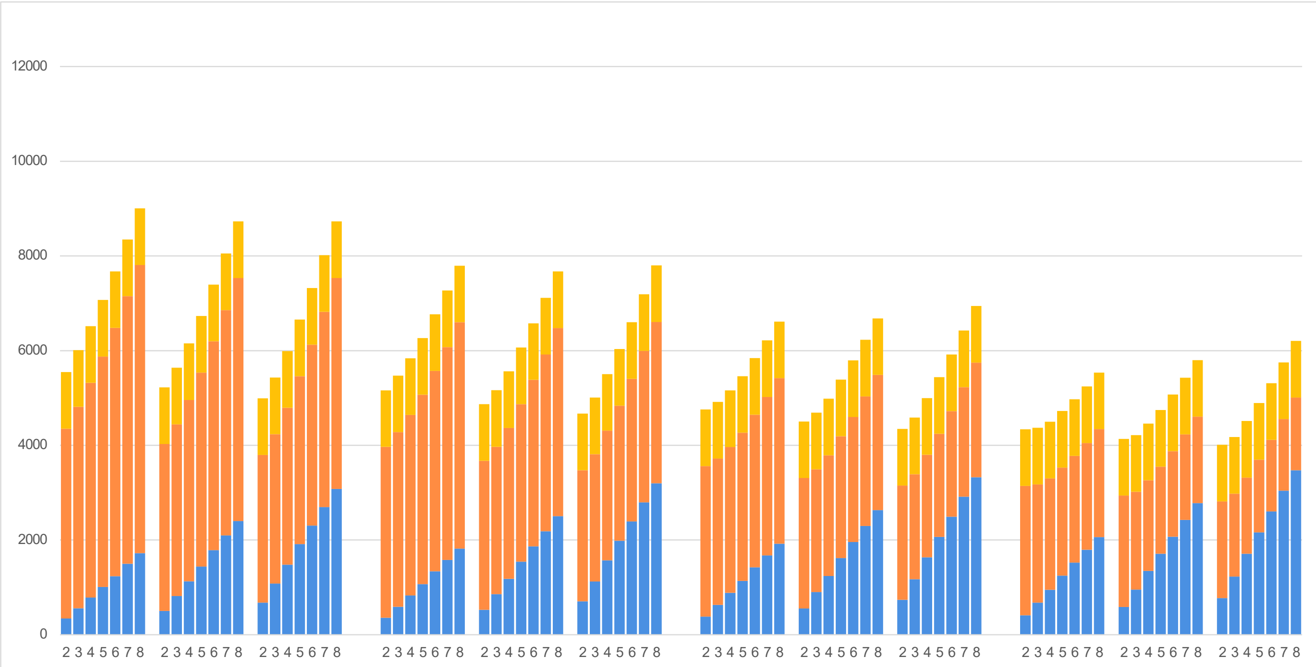
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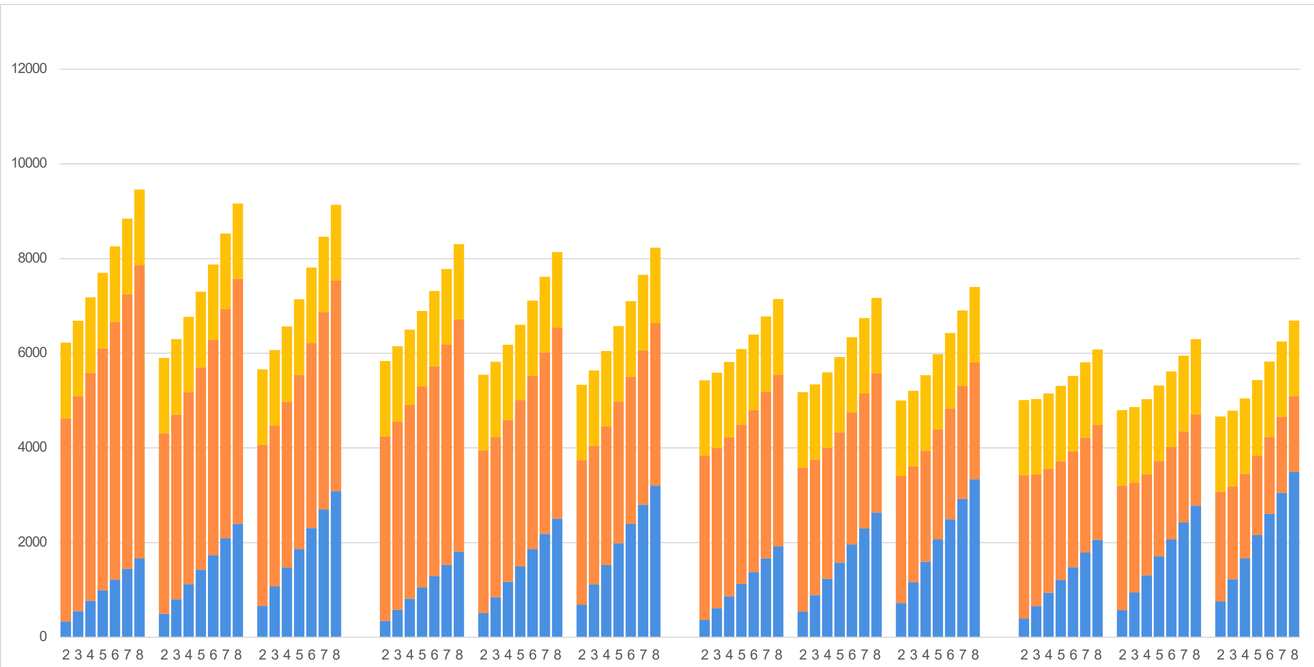
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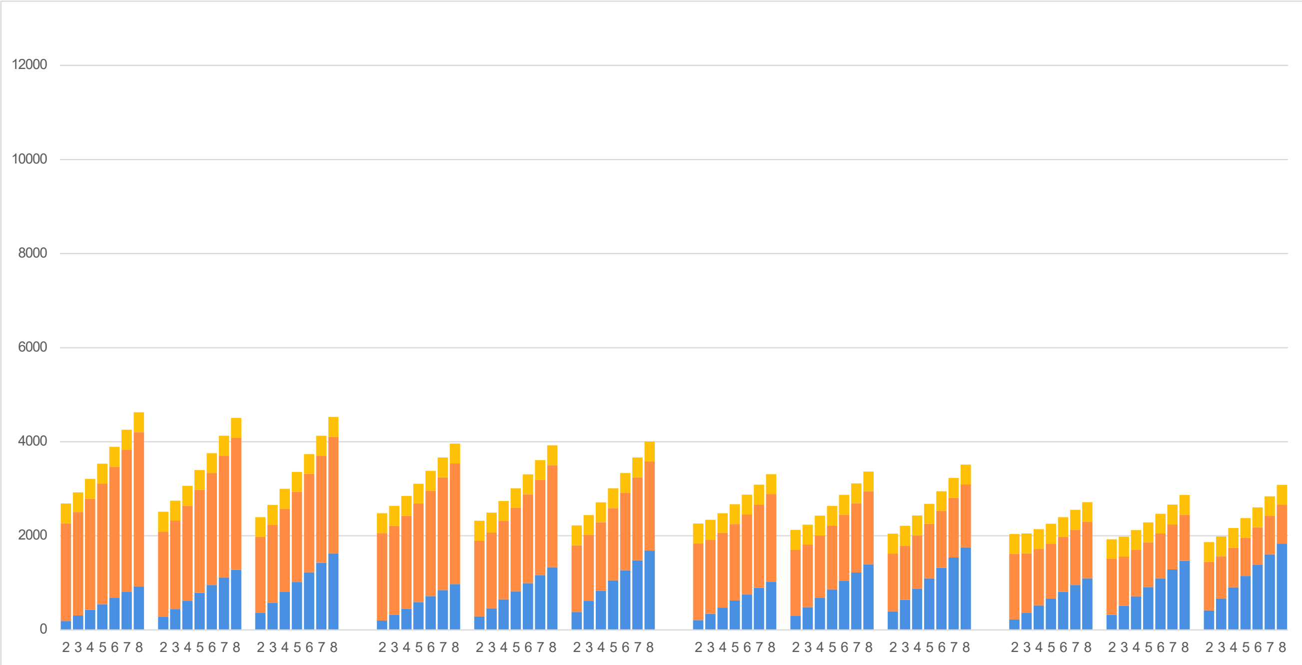
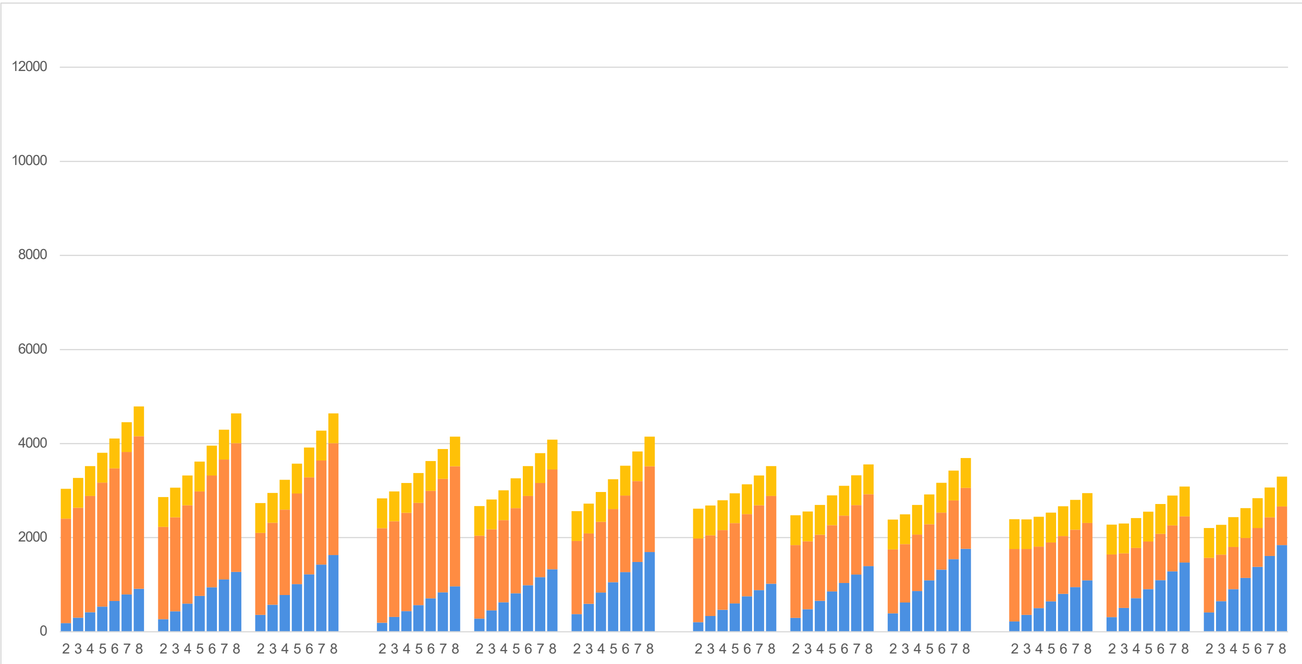
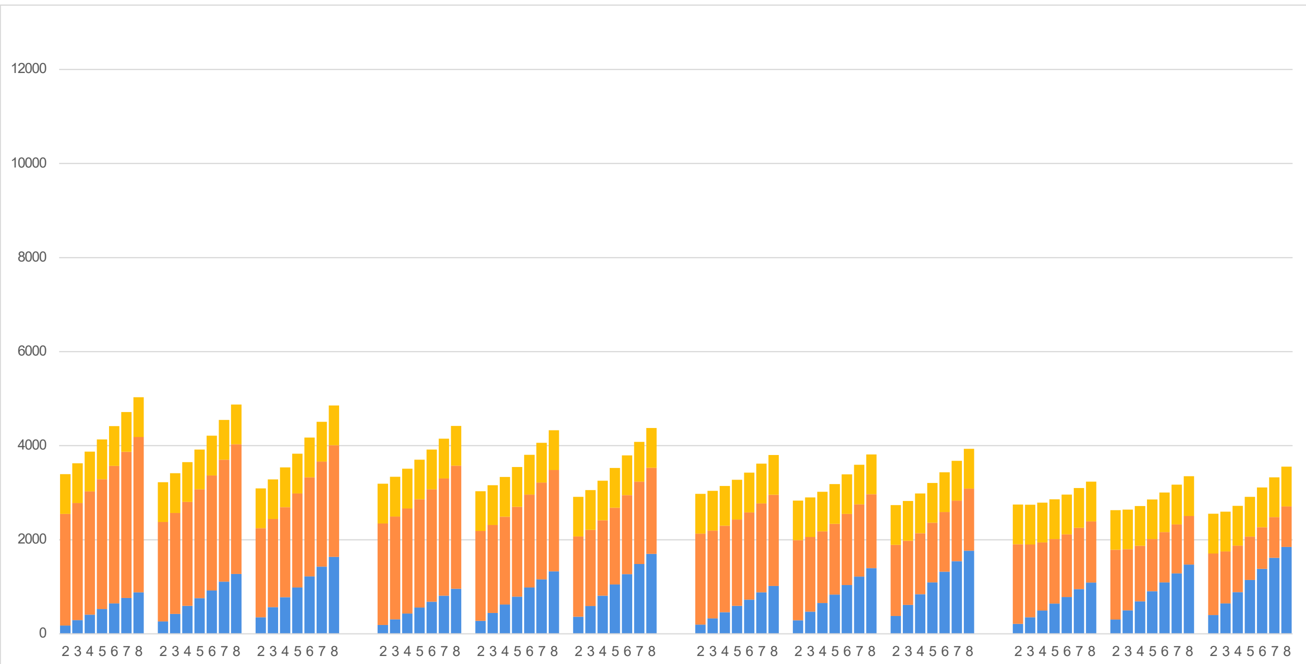
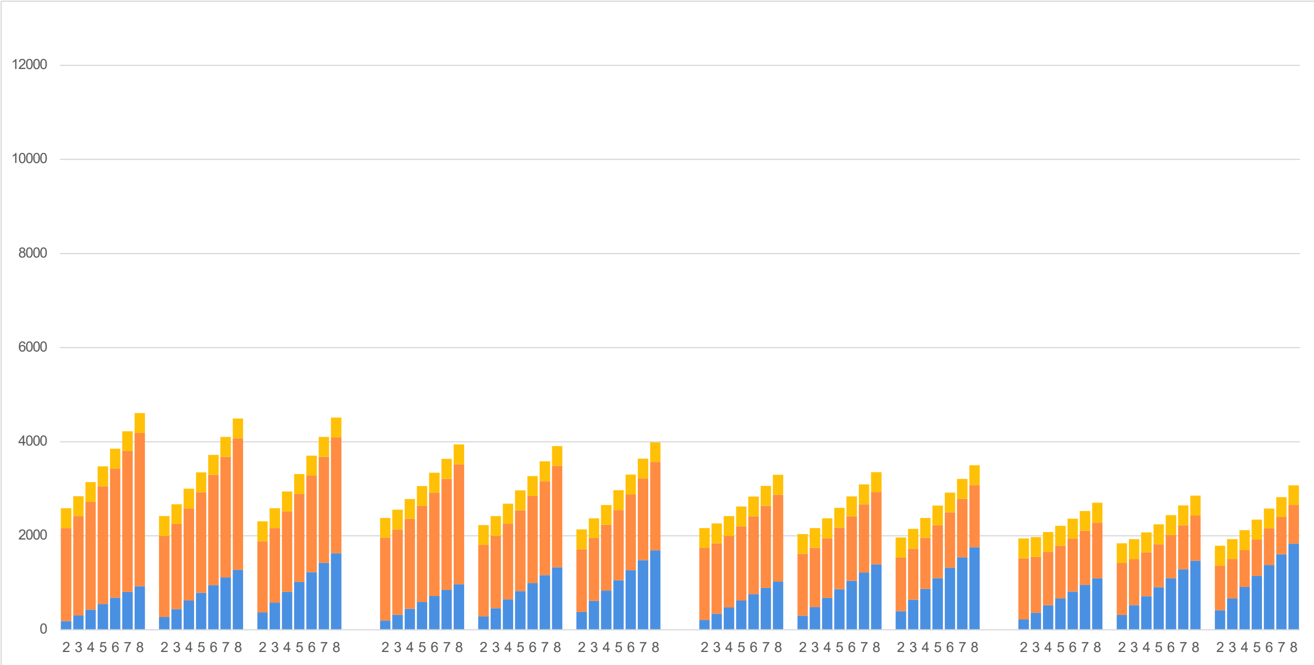
South operational carbon corrected for carbon decrease





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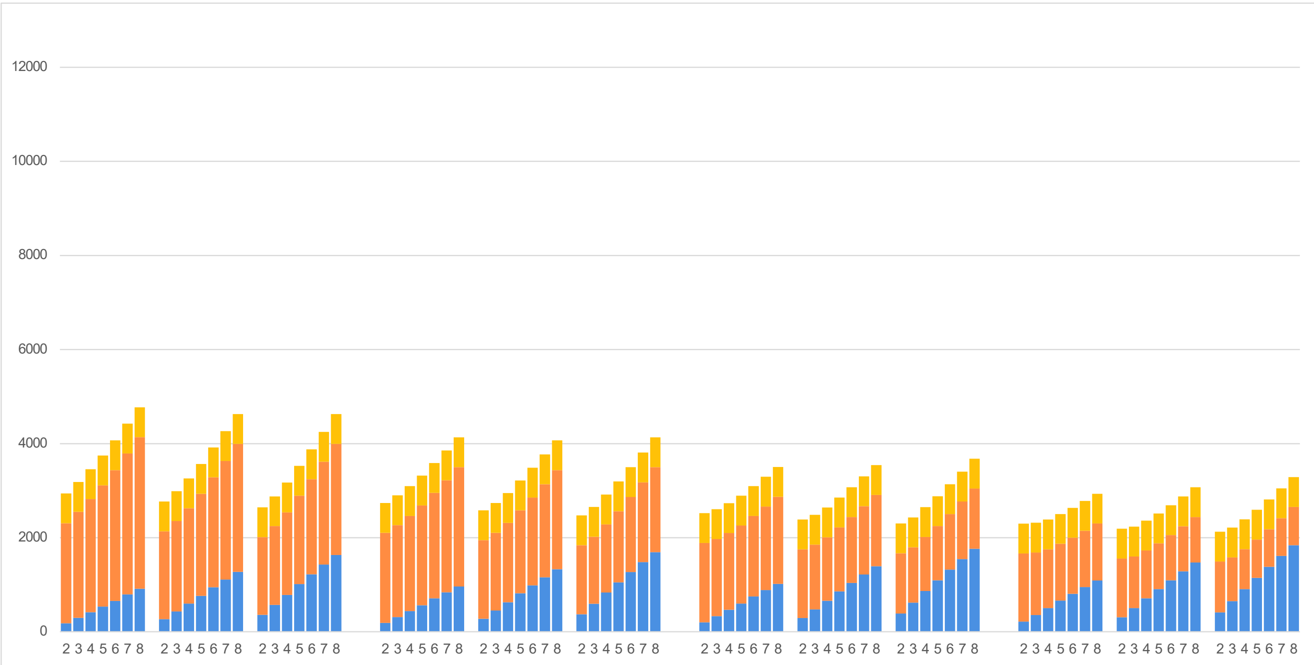
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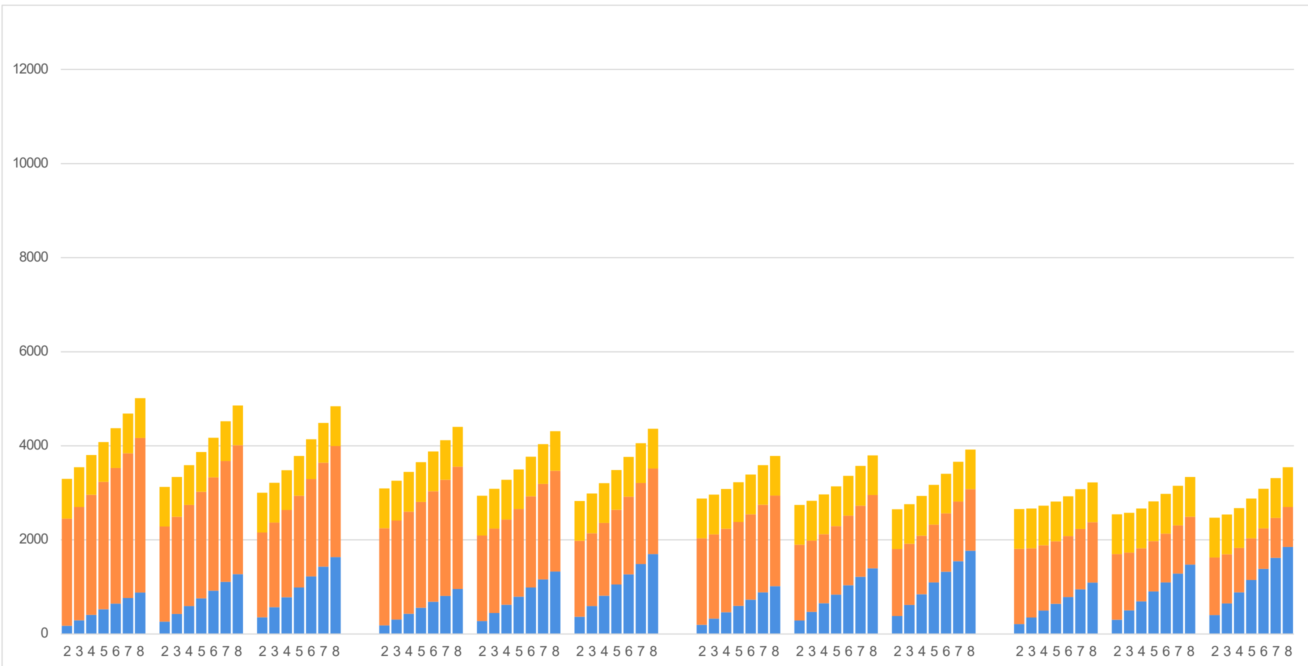
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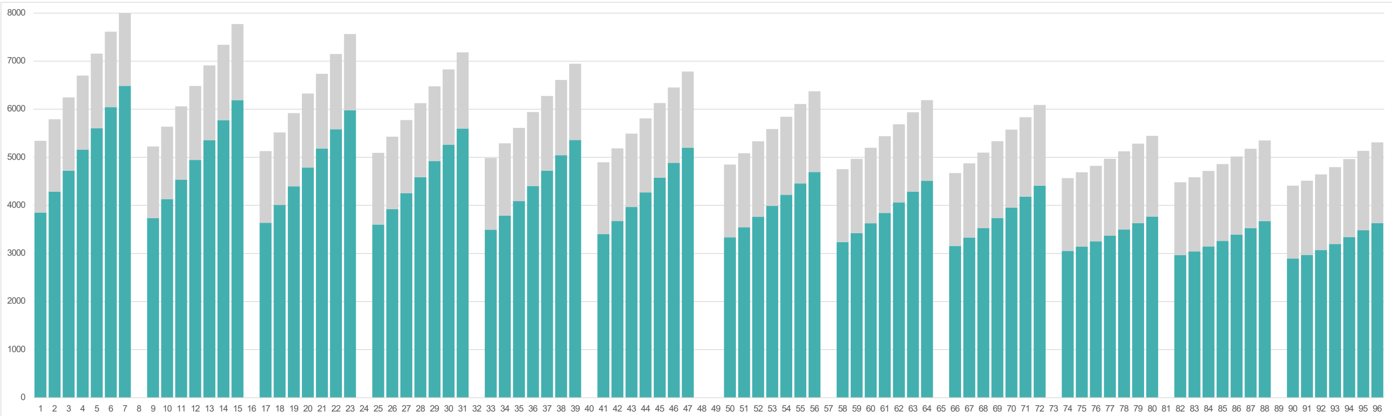
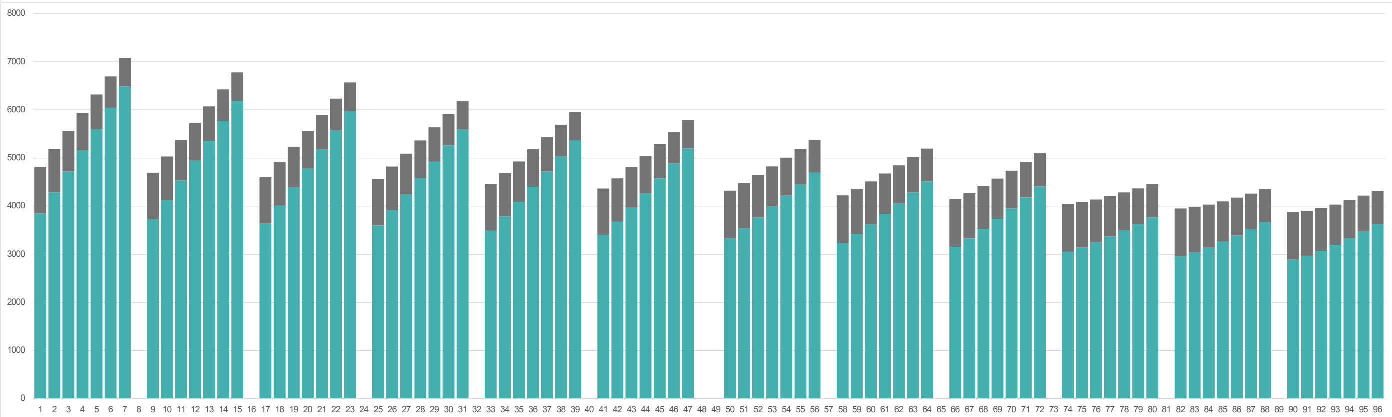
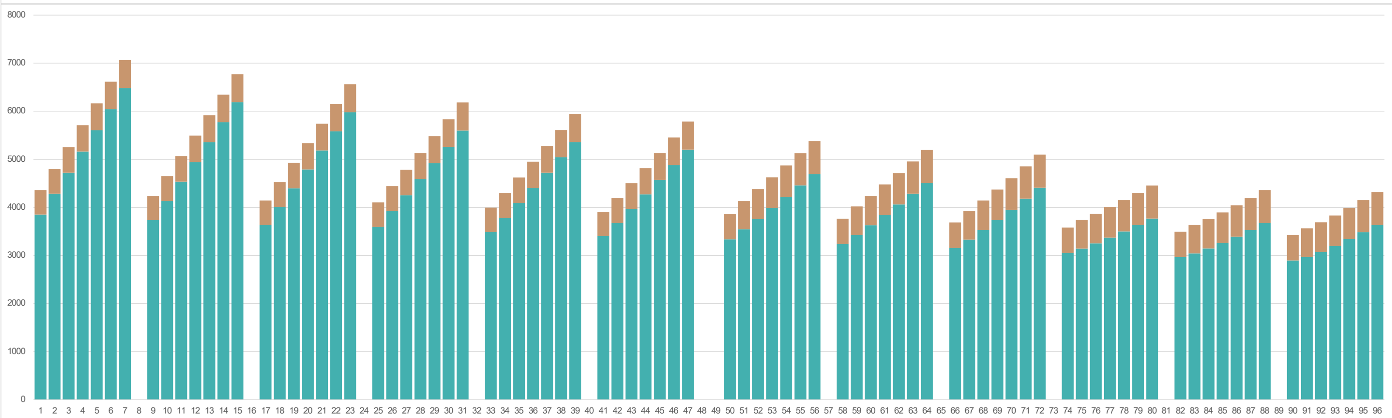
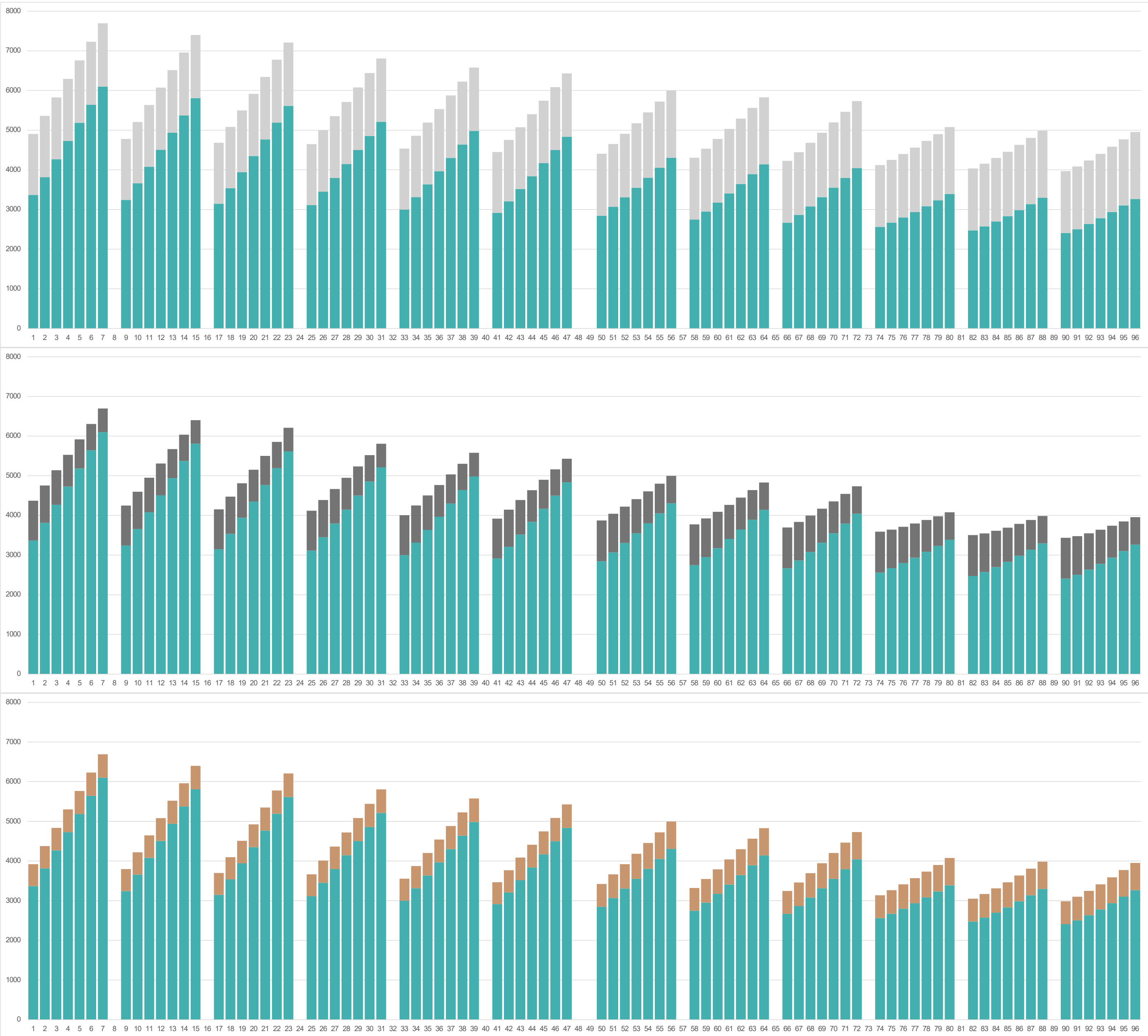
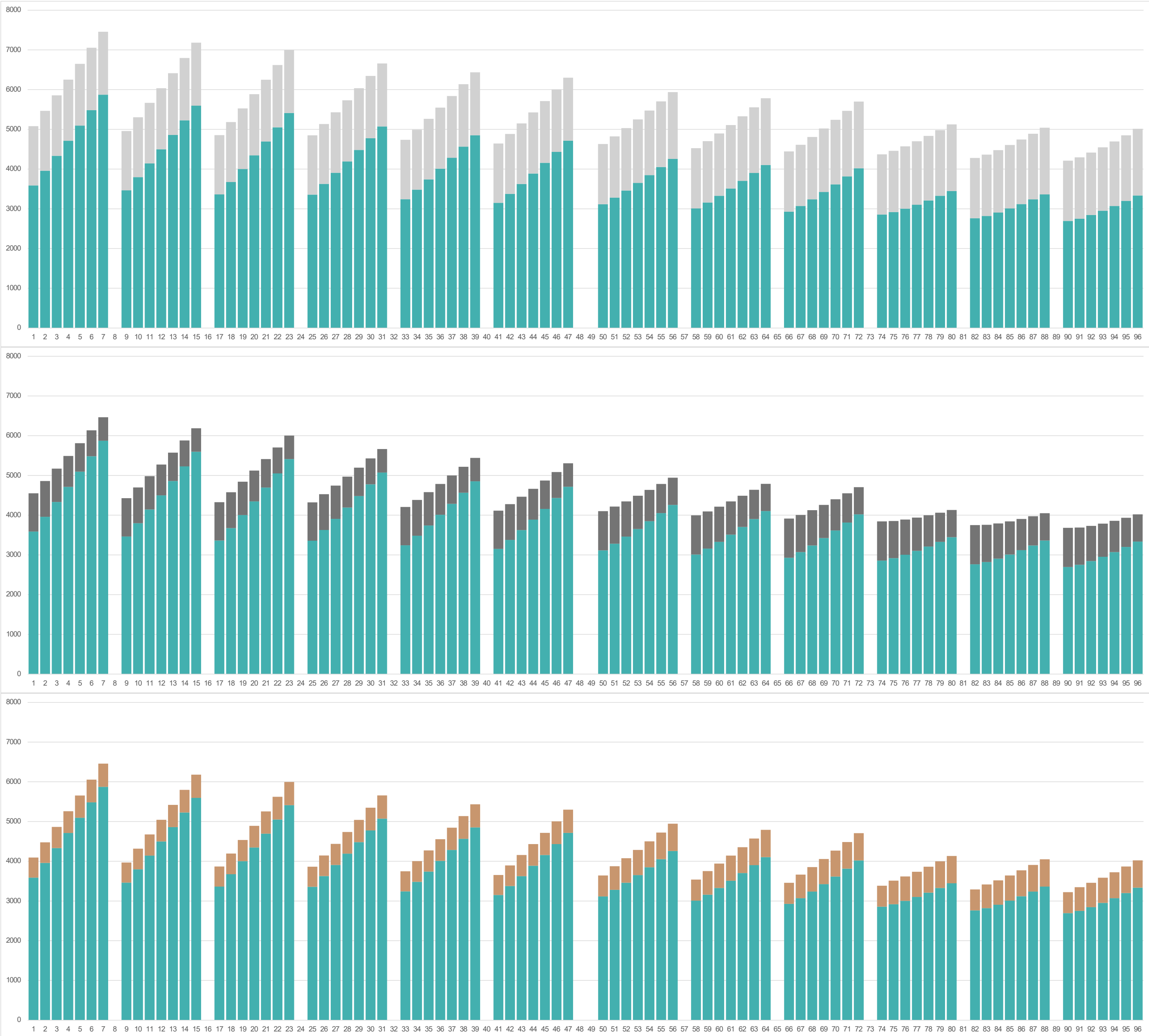
North operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5

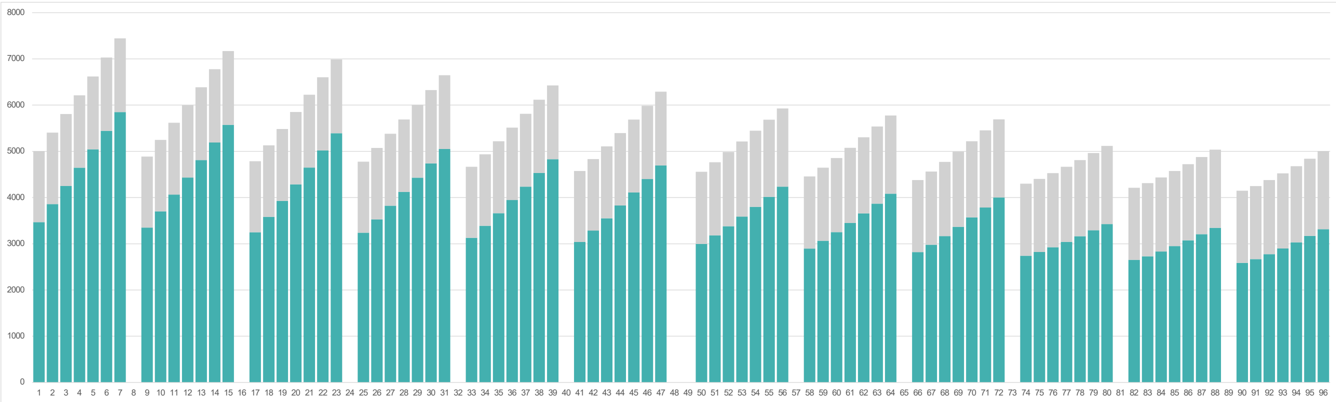
North operational carbon corrected for carbon decrease + embodied carbon facade types rc 6

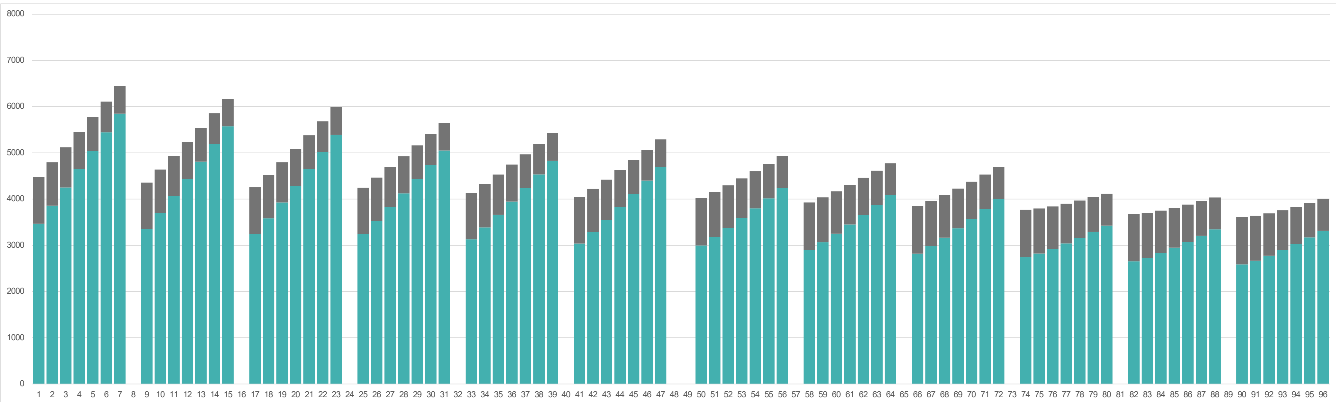


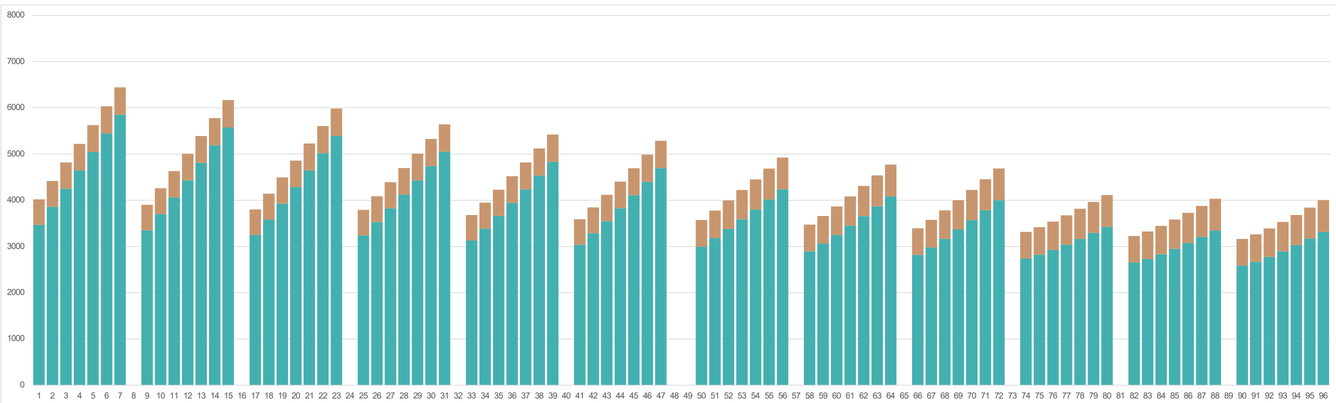
East operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5



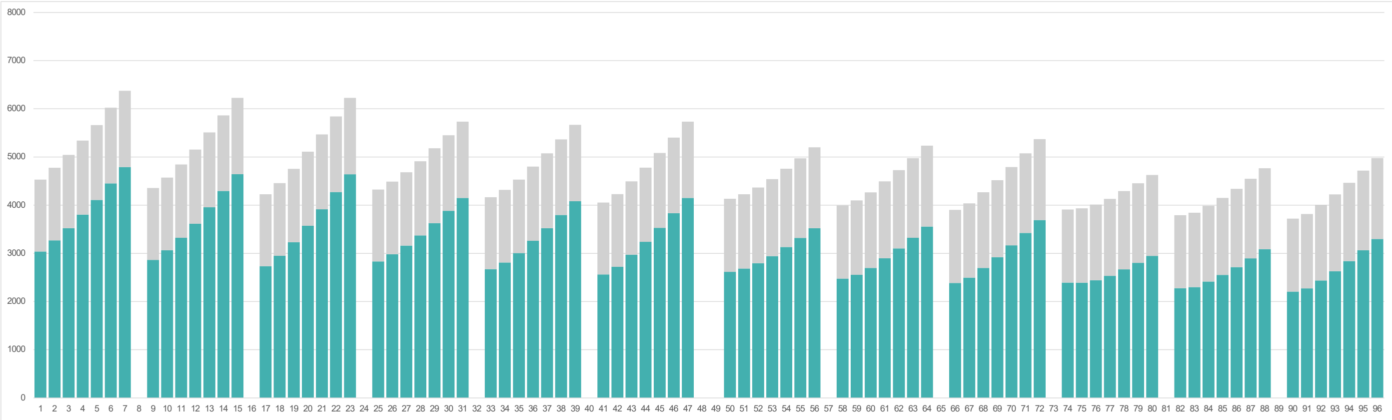
East operational carbon corrected for carbon decrease + embodied carbon facade types rc 6

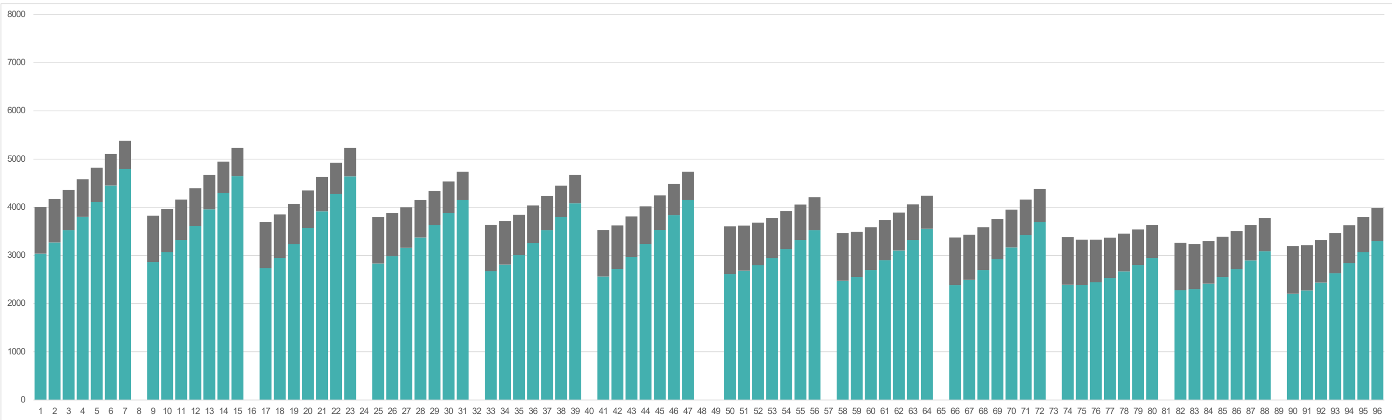


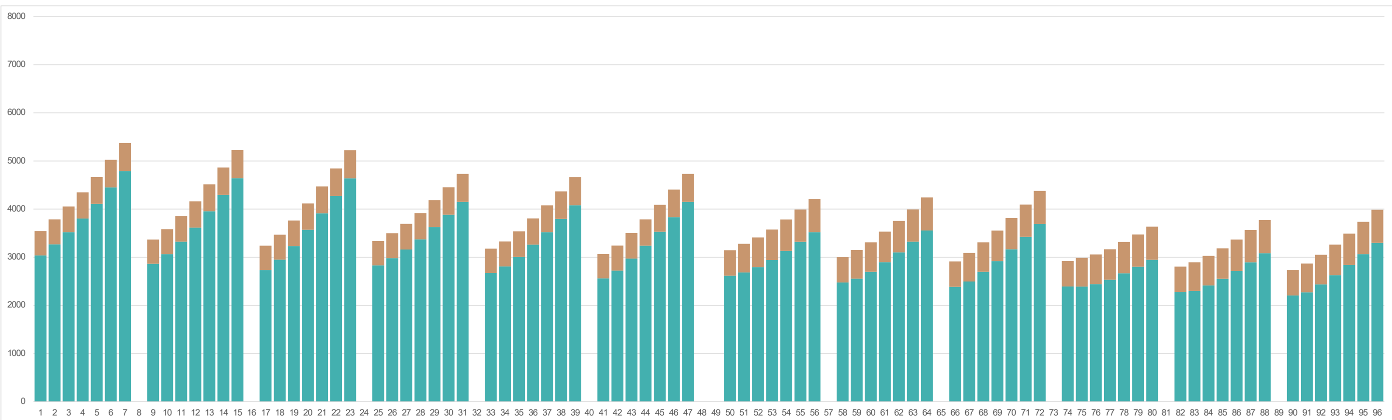




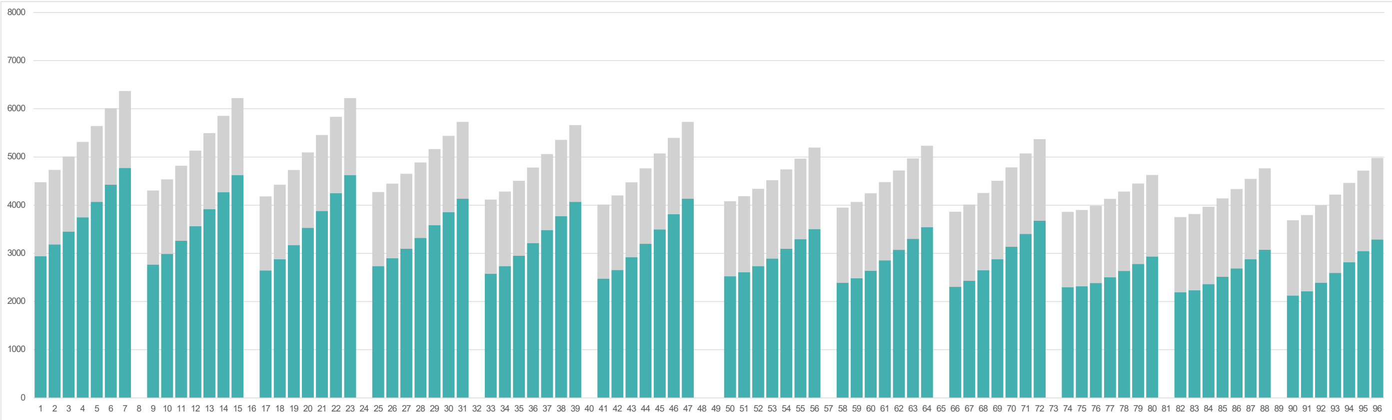
South operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5

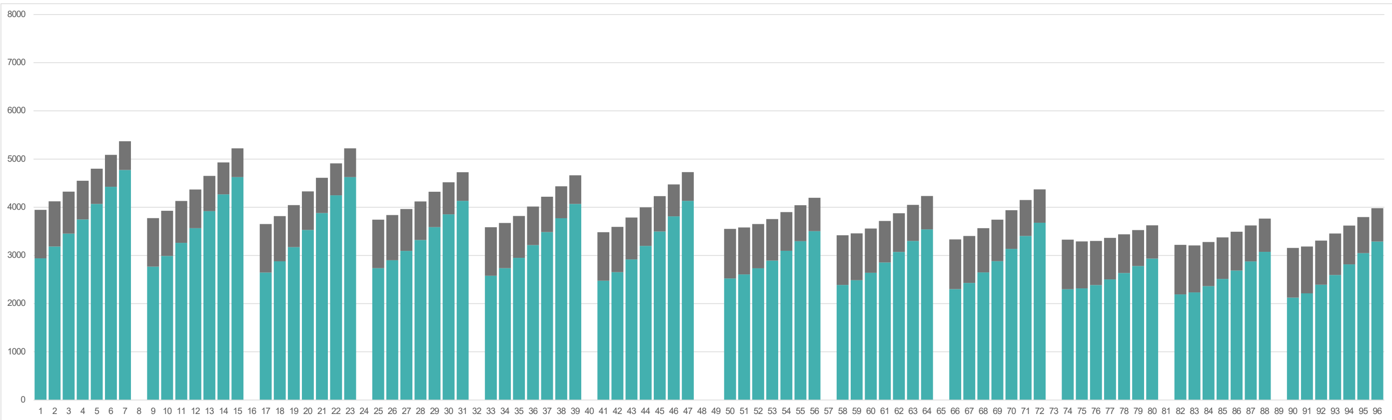


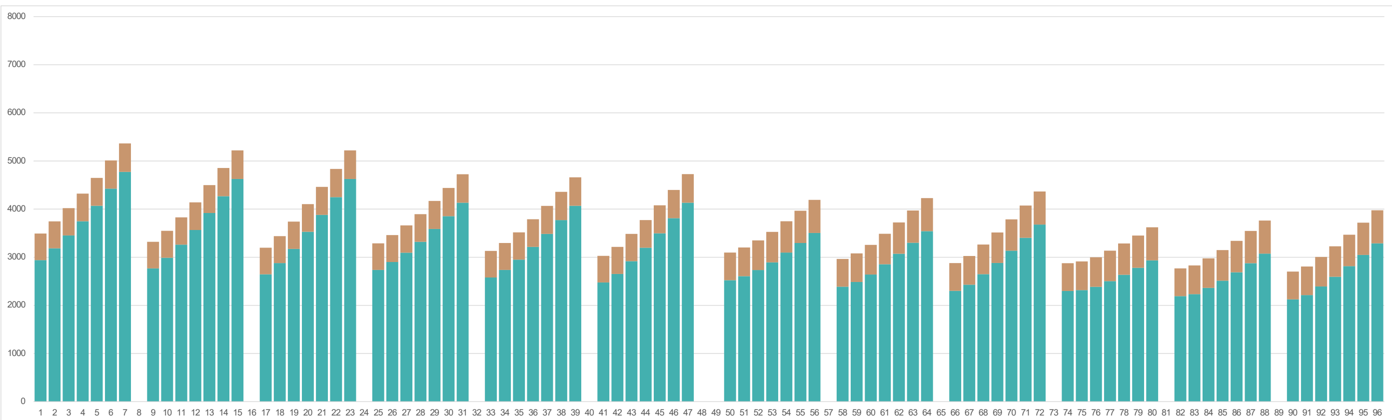


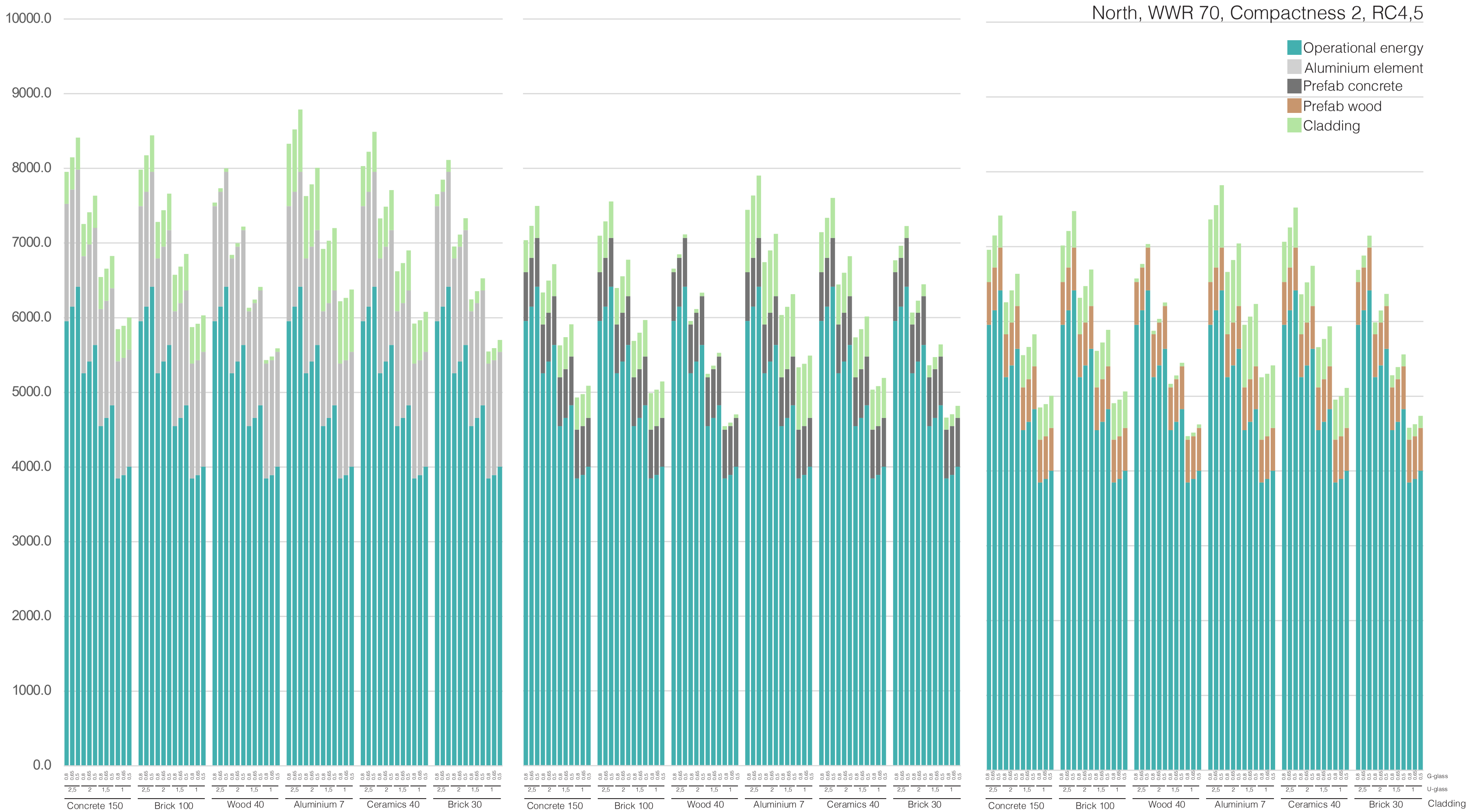


South operational carbon corrected for carbon decrease + embodied carbon facade types rc 6

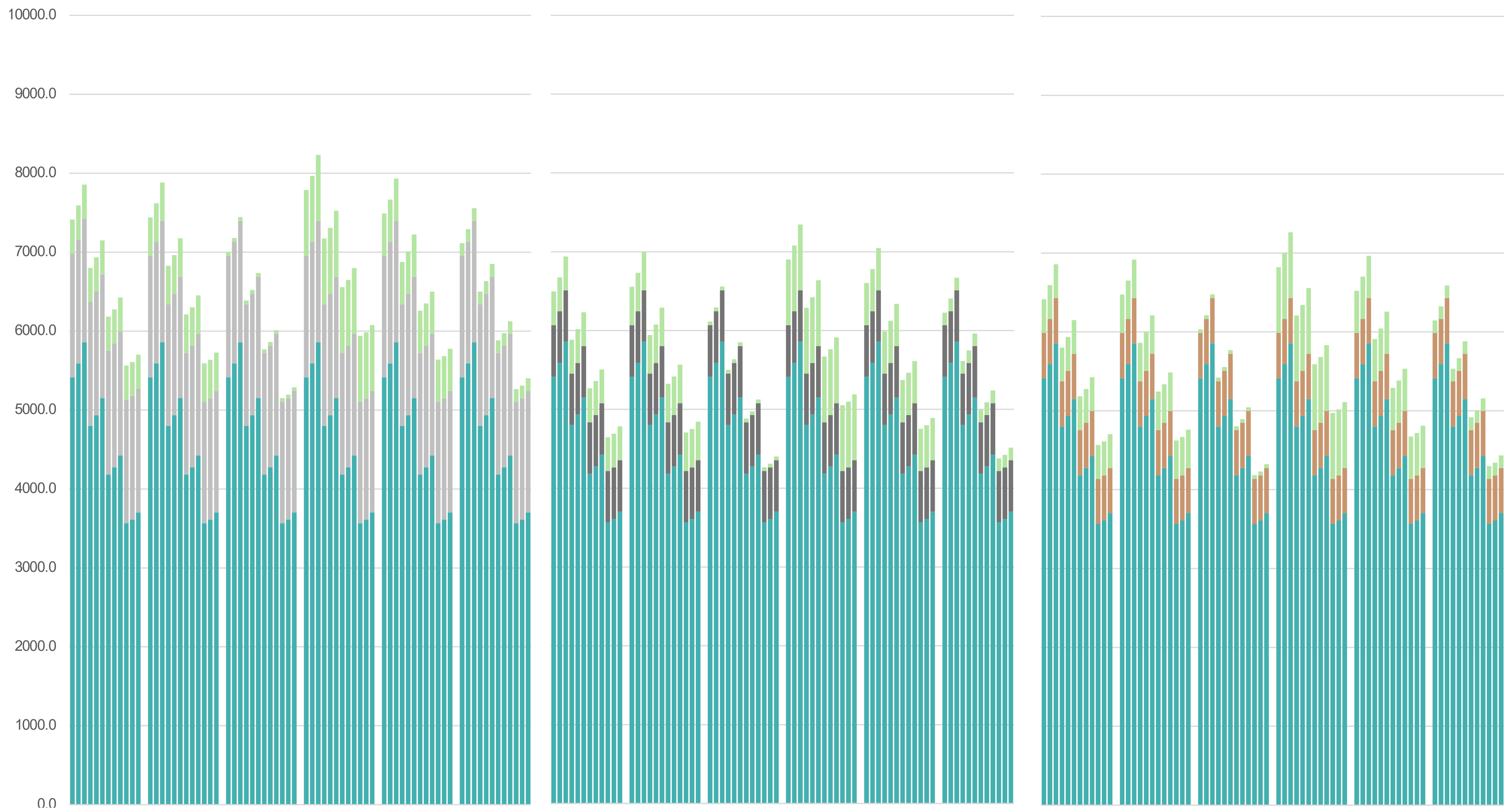




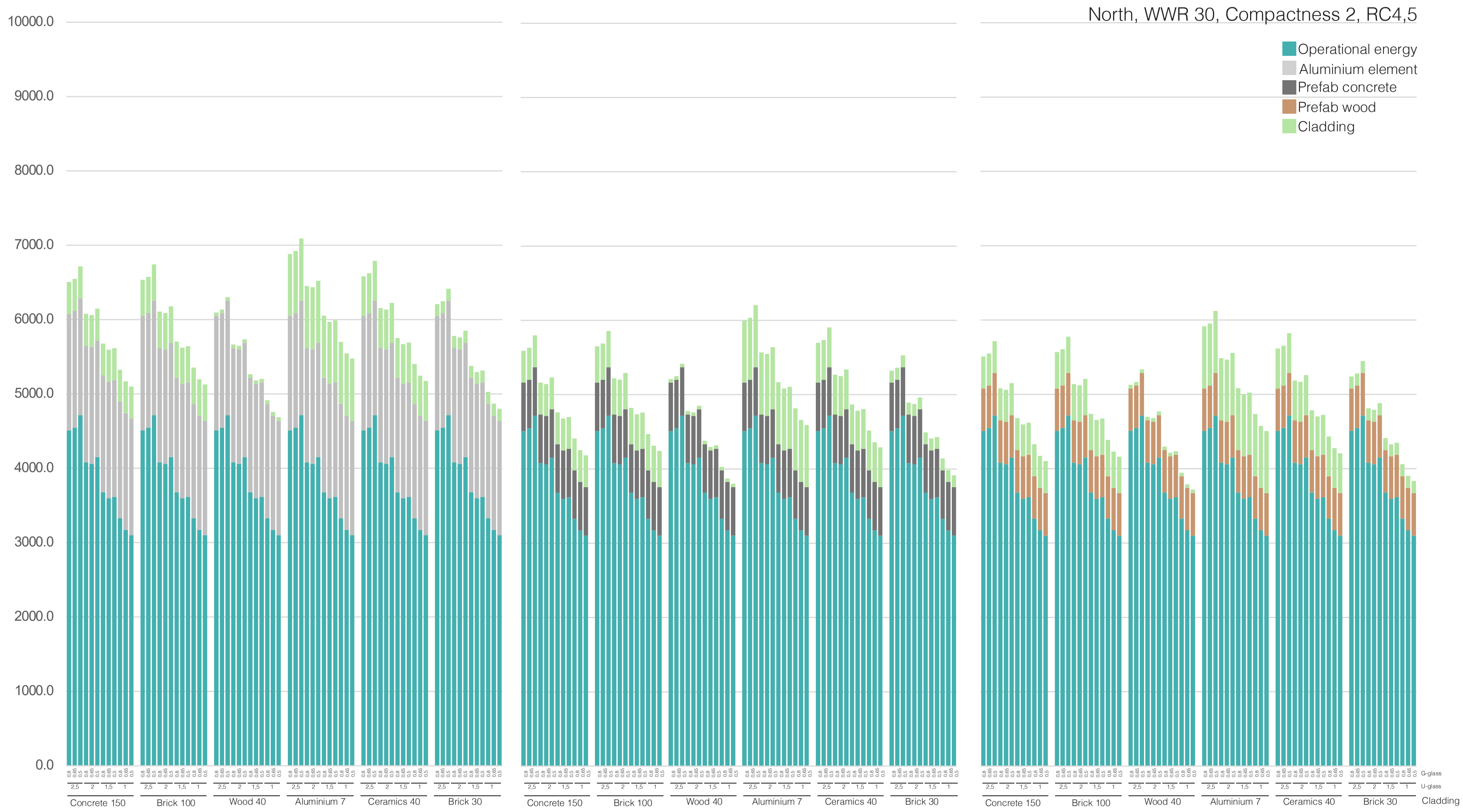




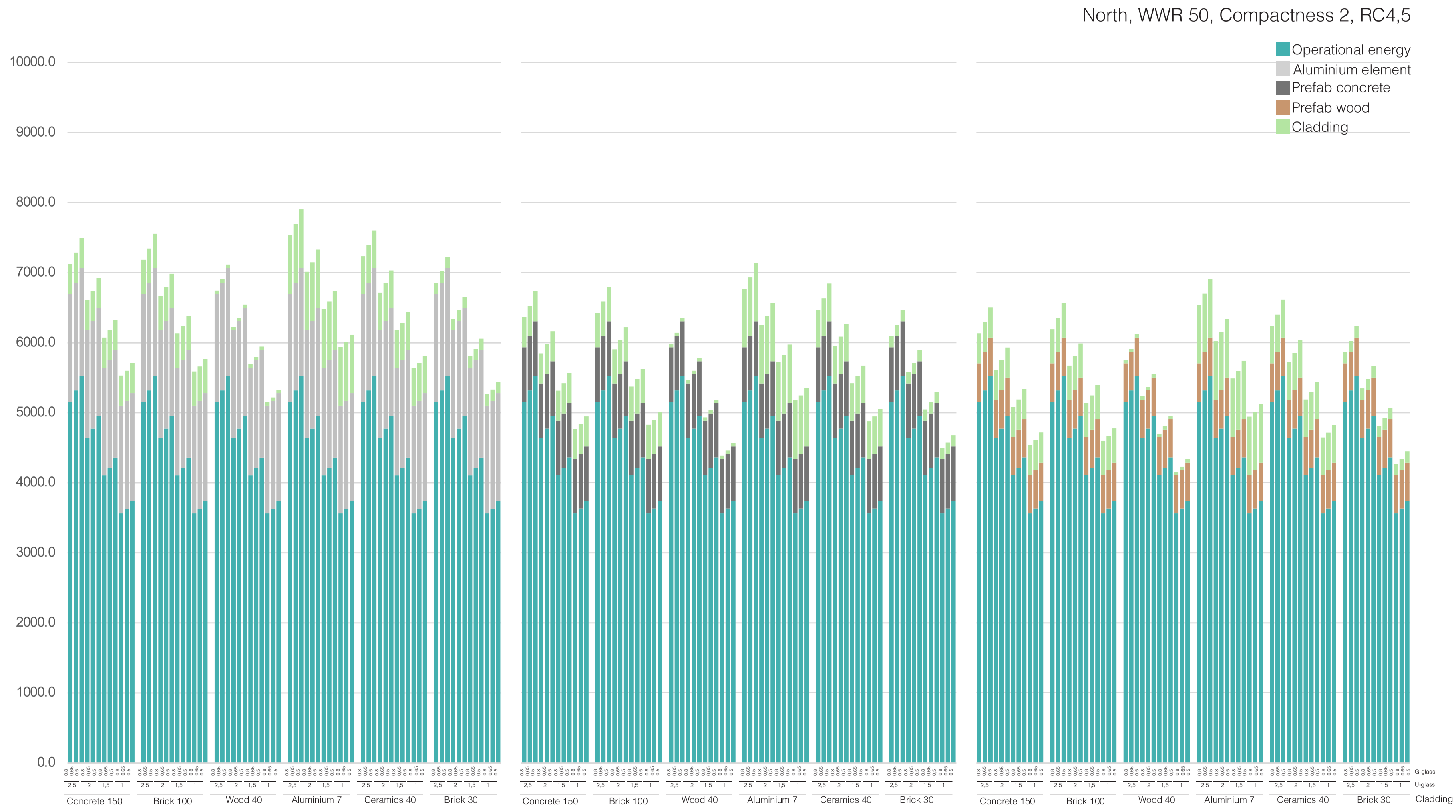
North operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr70



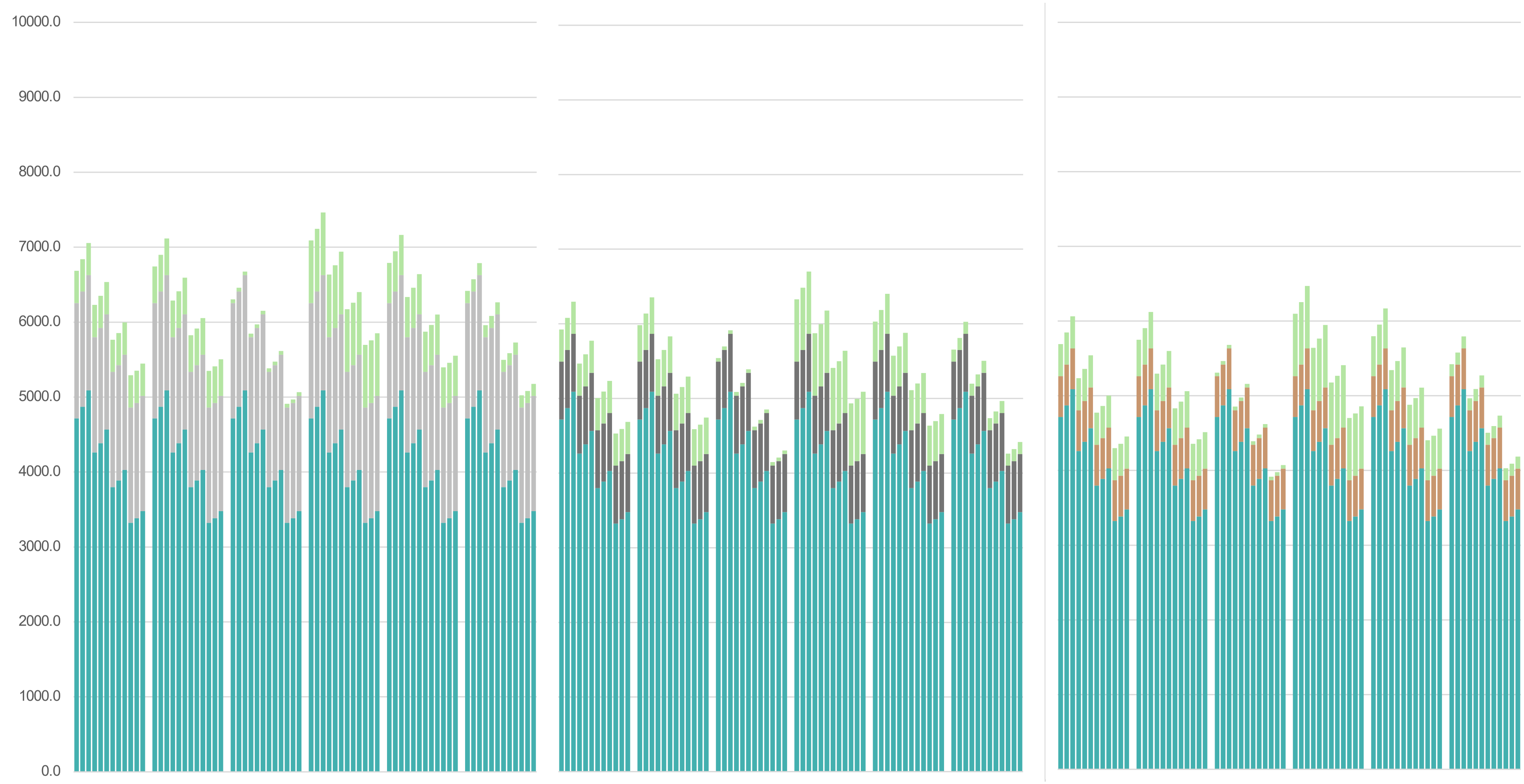
East operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr70



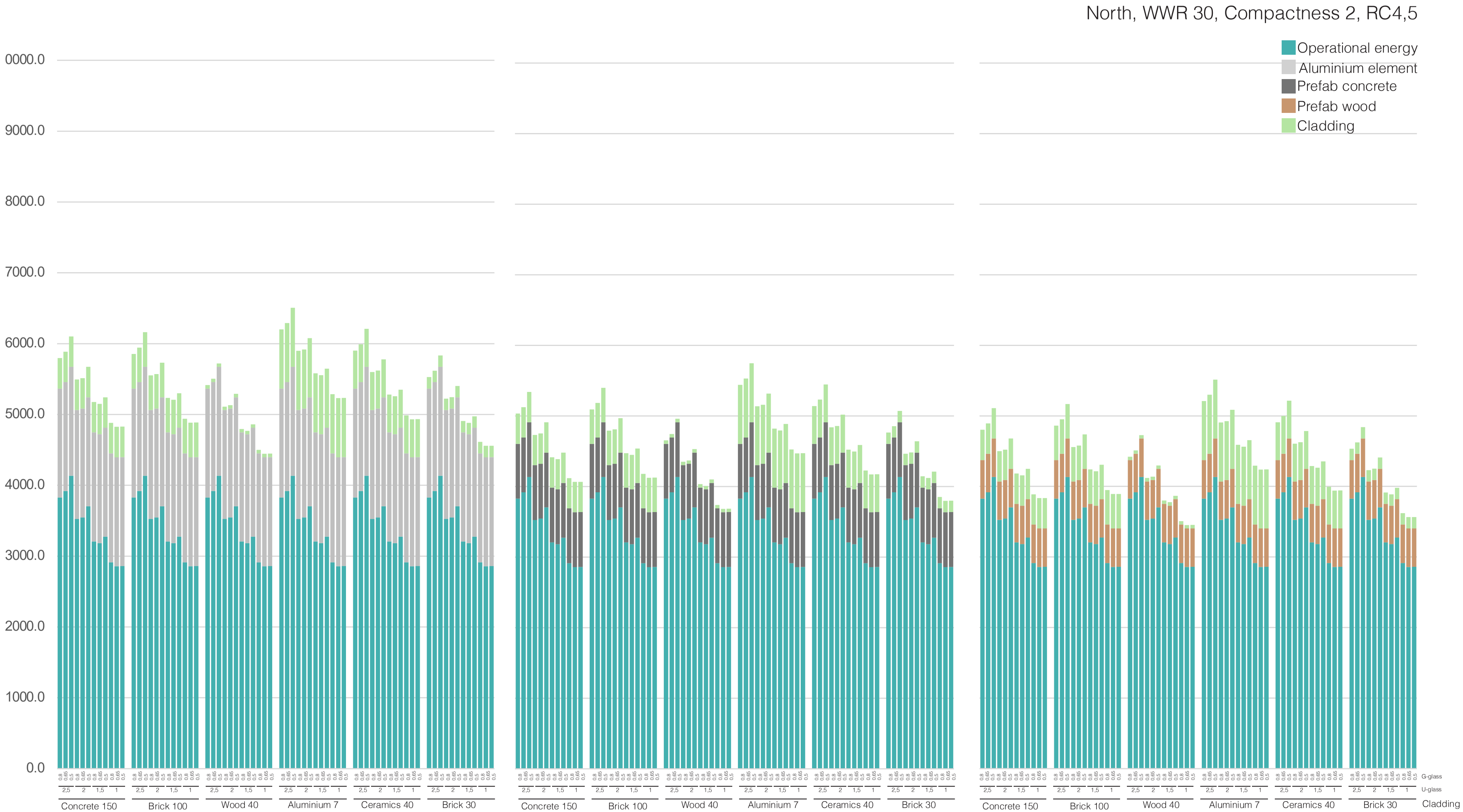
South operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr70



North operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr50



East operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr40


North, WWR 30, Compactness 2, RC4,5
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Aluminium element
Prefab concrete
Prefab wood
Cladding
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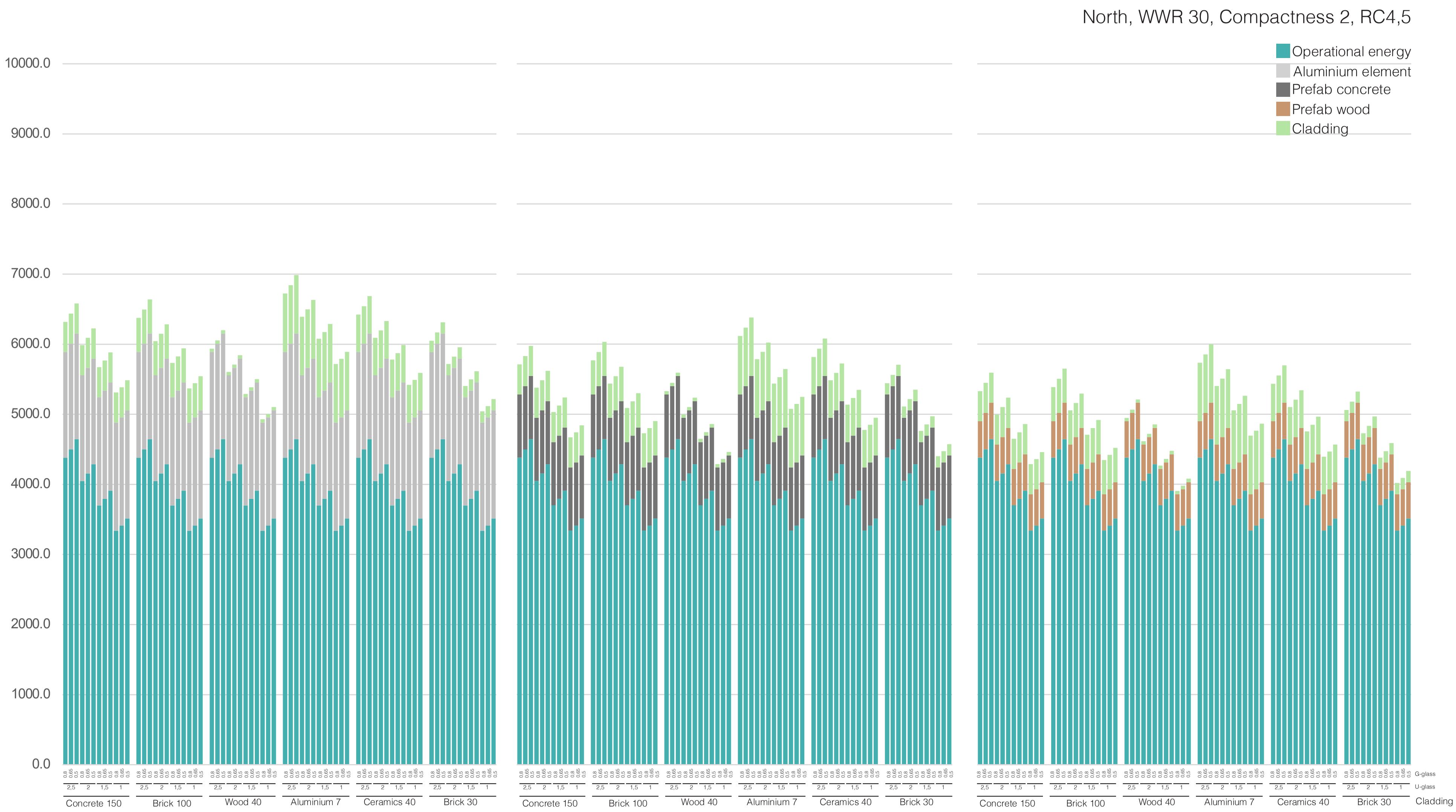
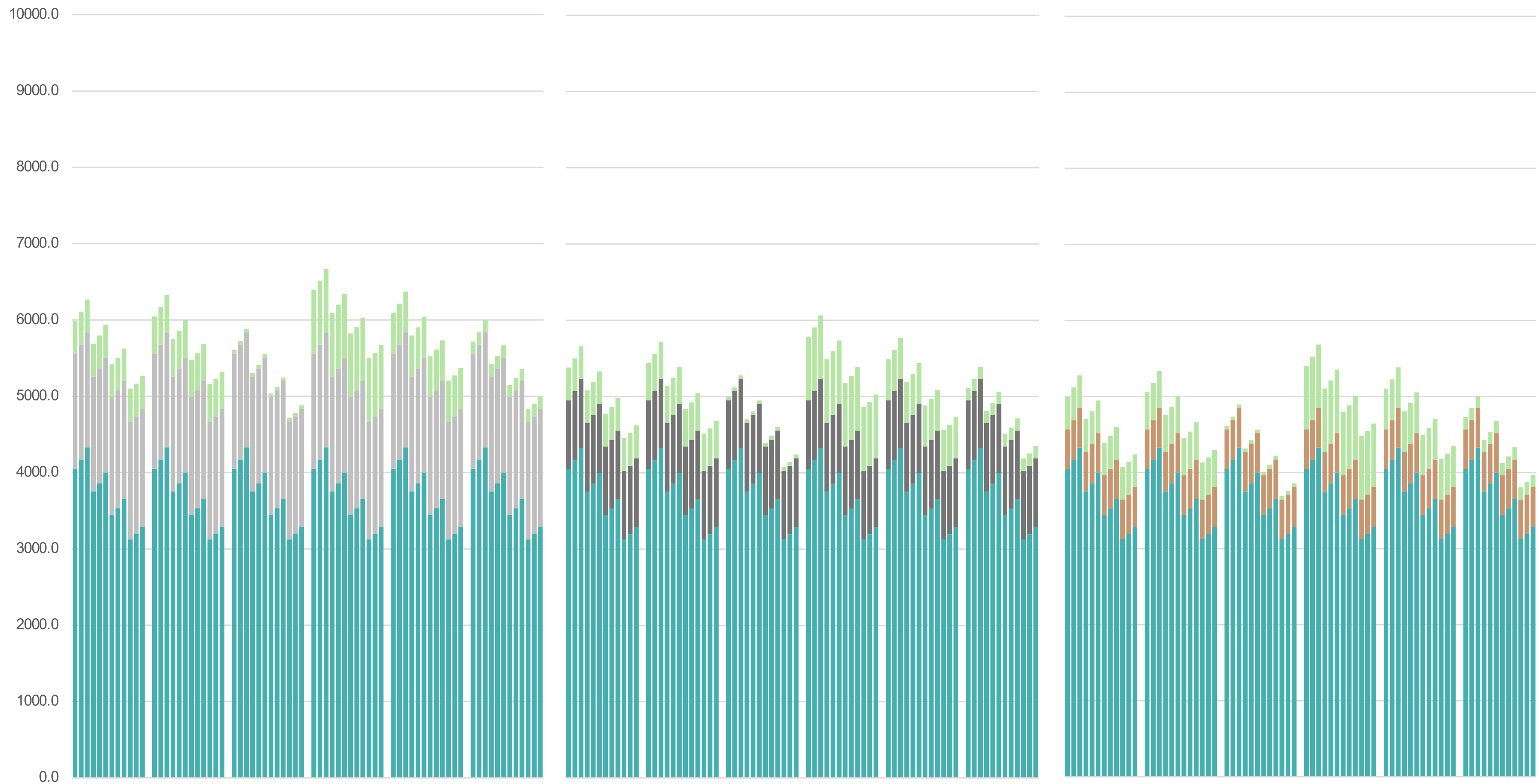
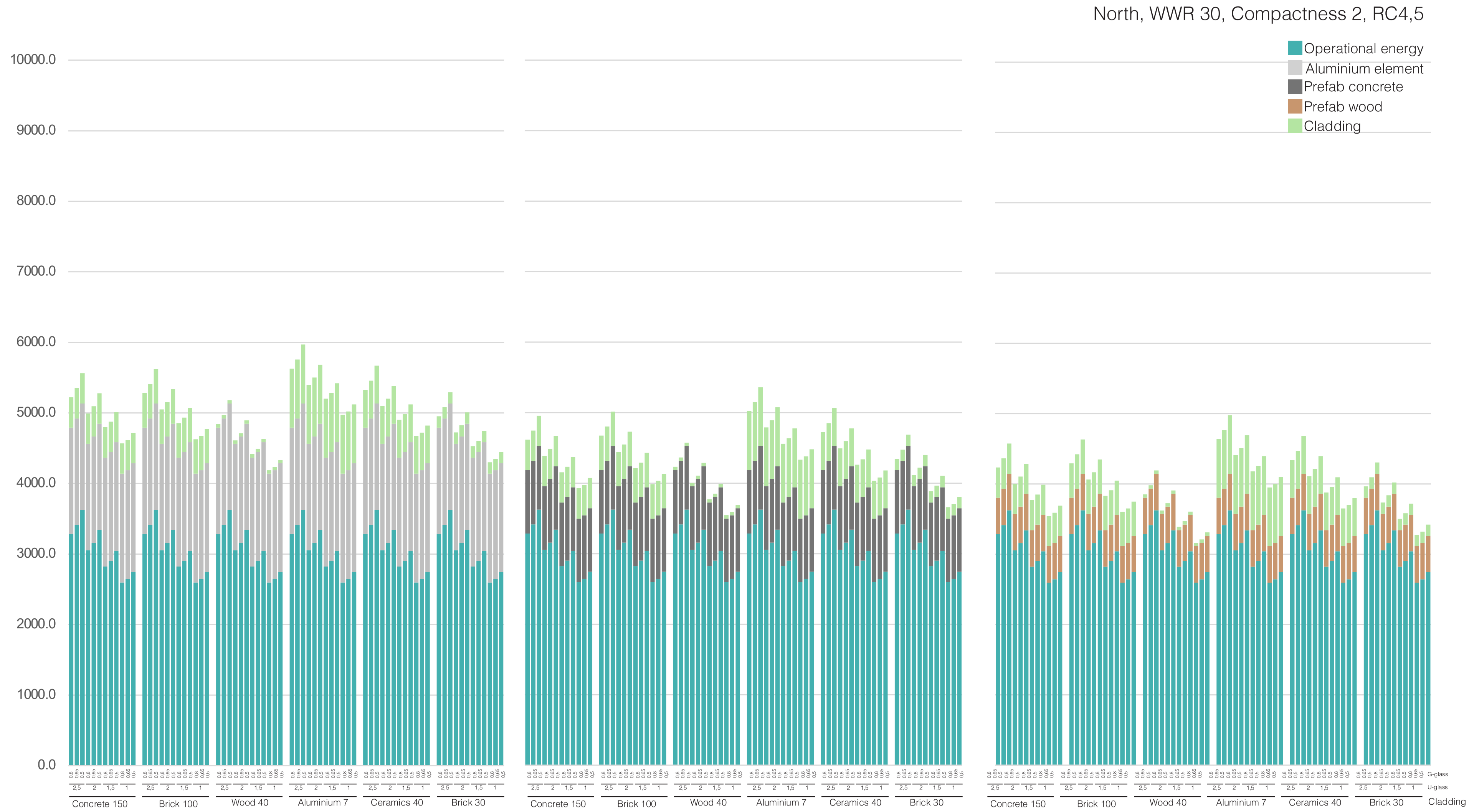


North operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr30



East operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr30



South operational carbon corrected for carbon decrease + embodied carbon facade types rc 4,5 + embodied carbon cladding wwr30