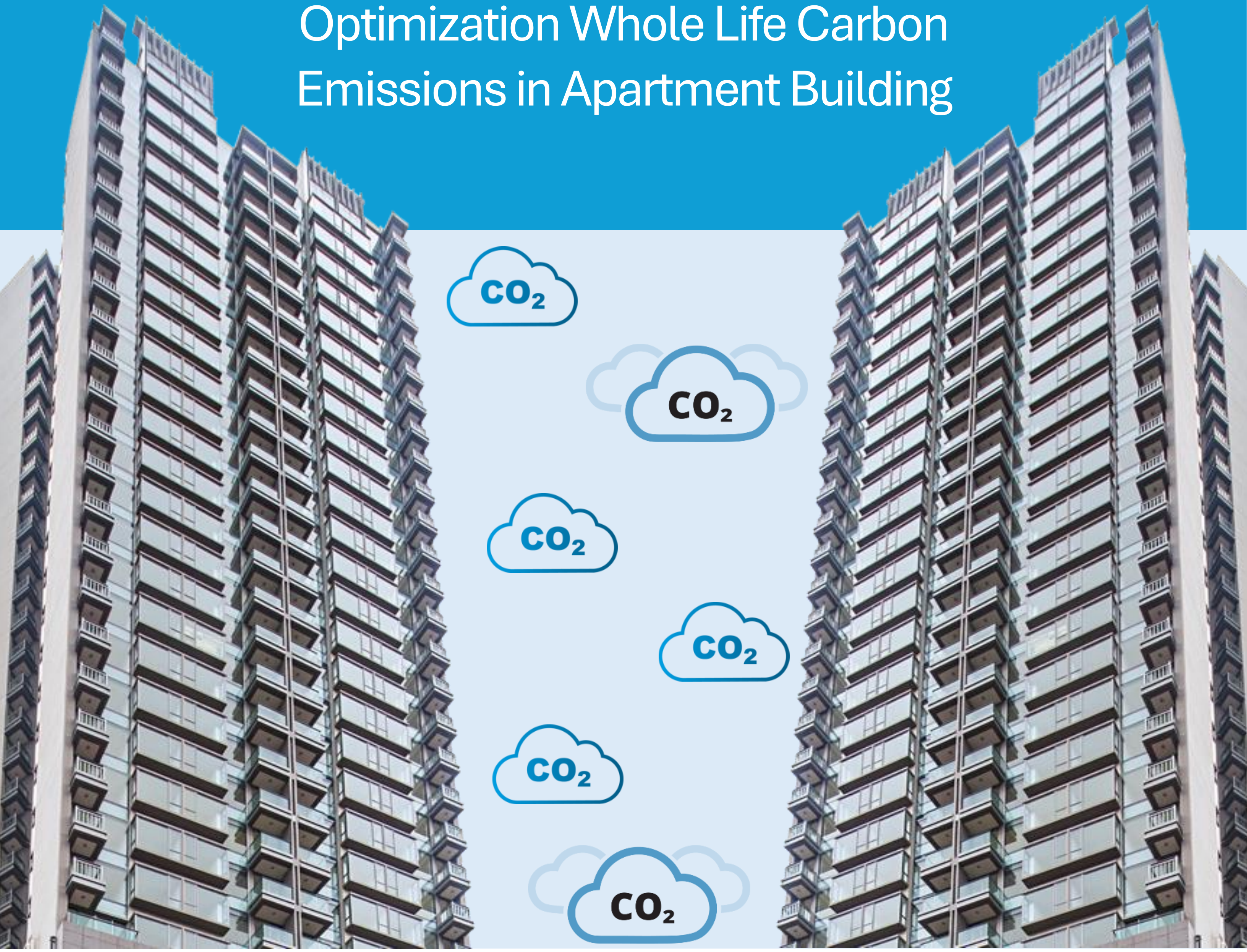
Optimization Whole Life Carbon Emissions in Apartment Building



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MSc Construction Management and Engineering

In collaboration with

MSc. THESIS REPORT

Optimizing Whole Life Carbon Emissions in Apartment Building

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Last but not least, through this thesis, I realize that our journey to create a more sustainable earth is far from over. I hope my thesis can benefit both the academic and practical worlds. May everyone who reads this report gain valuable insights and contribute to a broader landscape.

Alexander Francis Zen
Delft, May 2024

Abstract

As concerns about climate change increase, which can harm the environment, all kinds of businesses face a challenge called sustainability. In the construction sector, one way to be more sustainable is to design and build buildings with low carbon emissions. Some authors have discussed this challenge by conducting research on the portion between embodied and operational carbon and the methodology to calculate each type of carbon emission in buildings. Having an understanding of the design's performance against this challenge will provide more opportunities for design optimization. However, there are only a few authors who discuss the methodology to optimize these whole-life carbon emissions, especially for apartment buildings in the Netherlands.

This thesis project aims to address the research gap by closely examining the relationship between embodied and operational carbon in practice and achieving optimized designs for buildings to minimize whole-life carbon emissions. To tackle this, the main research question for this graduation project has been formulated as follows:

"How to optimize whole life carbon emissions in the apartment building?"

This is further divided into the following four sub-questions:

SQ1 : What factors contribute to the embodied and operational carbon?

SQ 2 : How to calculate embodied and operational carbon emissions?

SQ 3 : How do embodied carbon and operational carbon emissions influence each other, and impact overall carbon levels in order to optimize and achieve the best results in building design?

SQ 4 : How does the proposed framework help the designer?

The research was conducted in collaboration with TU Delft, Quake, and ABT. Quake and ABT are part of the Oosterhoff group, a Dutch consultancy and engineering company.

To address the research question, this study begins with a literature review and analysis to define the factors and methodologies for calculating embodied and operational carbon emissions. Next, a case study is conducted using a simple model through Excel and IES software to calculate both carbon. Optimization is then achieved using Rhino 7 and Grasshopper. Subsequently, a framework is developed containing the steps in Rhino 7 and Grasshopper to achieve optimization and analyze the results. Finally, interviews are conducted for validation and evaluation of the framework and its results.

The results yield several outcomes where some materials with higher embodied carbon can result in lower operational carbon, and conversely, materials with lower embodied carbon can lead to higher operational carbon. Moreover, increasing the thickness can effectively decrease operational carbon and lead to a decrease in whole-life carbon emissions, but only until Rc 4; above that, the effectiveness diminishes. Furthermore, above Rc 4, materials with high embodied carbon are no longer beneficial and result in higher whole-life carbon emissions, even though operational carbon decreases, but it is not proportional to the increase in embodied carbon. Lastly, each Rc of the façade has its own optimal façade opening, and window frame material only influences a small amount of the embodied carbon and has no influence on operational carbon. However, this result is based on Dutch circumstances and specific MEP inputs, such as the embodied carbon factor reflecting the Dutch market and the operational carbon factor aligned with the Dutch energy mix, using the Netherlands' weather file and assuming 100% efficiency in heating and cooling. Therefore, these results will differ if different locations and MEP inputs are used.

Through the framework, designers will receive guidance to achieve an optimal solution in apartment building design. Additionally, this framework has already been tested by expert respondents in this field, as detailed in Chapter 5. In the final section, recommendations will be provided for future research along with considerations for anyone wishing to further develop this research into a more comprehensive study.

Keywords: *Whole life carbon emissions, embodied carbon, operational carbon, optimization, IES, Rhino 7, grasshopper, TU Delft, Quake, ABT*

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Abbreviations

- BFS (Building Floor Space)
- BIM (Building Information Modeling)
- CEF (Carbon Emissions Factor)
- CEI (Carbon Emissions Intensity)
- CO_2 (Carbon Dioxide)
- EC (Embodied Carbon)
- ECF (Embodied Carbon Factor)
- EPD (Environmental Product Declaration)
- EUI (Energy Use Intensity)
- GBCS (Green Building Certification System)
- GHG (Green House Gas)
- GWP (Global Warming Potential)
- HR (Heat Reflective)
- IES (Integrated Environmental Solution)
- IPCC (Intergovernmental Panel on Climate Change)
- LCA (Life Cycle Assessment)
- LCCE (Life Cycle Carbon Emissions)
- OC (Operational Carbon)
- OE (Operational Energy)
- Rc (Thermal Resistance)
- U (Thermal Conductivity)
- WLC (Whole Life Carbon)

1. Introduction

This chapter aims to introduce the research topic and outline the study's objectives. It is divided into five sections: first, it provides the background of the research topic; second, it presents a review of previous literature relevant to this topic that supports the study; third, it identifies the problem that this study aims to address; fourth, it defines the research design, including the objectives, scope, questions, and methodology; and finally, it summarizes the outline of this thesis report for the reader's benefit.

1.1. Background

All kinds of businesses, including construction, are now dealing with a big challenge called "sustainability" (Miyatake, 1996). The things businesses do can harm the environment in different ways (Lash & Wellington, 2007). Society aims for sustainability to make sure that meeting our current needs does not make it tough for future generations to meet their own (Zimmermann, Althaus, & Haas, 2005).

The report on climate change published by the Intergovernmental Panel on Climate Change (IPCC) (2014), clearly states that continued emissions of carbon will lead to a drastic change in climate and increase in temperature by 1.5^0C - 2^0C by the end of 21st century. CO_2 emissions linked to human activities are recognized as a key contributor to global warming and the adverse impacts of climate change. Given the ongoing trend of emissions associated with construction, the construction industry is considered a sector with significant potential for reducing carbon emissions (Heydari & Heravi, 2023). In Europe, building accounts for 40% of the total final energy consumption and contributes to 36% of the overall CO_2 emissions (Ouldboukhitine, Belarbi, Jaffal, & Trabelsi, 2011). Therefore, saving energy and reducing the CO_2 emissions from building sector are urgent needs (Liu, et al., 2019).

While most of the energy consumption in a traditional building arises from operational energy (OE) consumed in heating, air-conditioning, lighting, and powering appliances and equipment, a significant portion is attributed to embodied energy (EE) (Imran, et all., 2022; Kumar, et all., 2022). Embodied energy (EE) is utilized directly in construction and transportation processes. Additionally, it is indirectly consumed through construction materials not only during the initial construction phase but also throughout the occupancy period in maintenance and replacement activities (Deepak, K, & Arvinder, 2022; Ng, et all., 2022). By employing carbon factors specific to the energy source, the life cycle operational energy (OE) and embodied energy (EE) consumption can be converted into life cycle operational carbon (OC) and embodied carbon (EC) impacts (Lotteau, et all., 2017; Sadowski, 2023).

1.2. Research Background

Whole life cycle carbon of a building is defined as the cumulative sum of operational and embodied carbon emissions over its entire life cycle (Nawarathna, Fernando, & Perera, 2017). Numerous studies have provided a breakdown of the ratio of embodied and operational emissions throughout the life cycle of various buildings.

A study conducted by RICS (2012) within the UK context reveals that certain building types, such as supermarkets, offices, and semi-detached houses, contribute to 70-80% of the operational carbon in the overall life cycle emissions. In a comprehensive review, Sartori and Hestnes (2007) analyzed 60 case studies from diverse countries, reporting that embodied emissions could range from 2-38% of the total life cycle emissions, with a larger proportion attributed to operational carbon. Ramesh et al. (2010) critically reviewed 73 case studies across 13 countries for residential and office buildings, concluding that operational emissions constituted 70-80%. Lin (2013) also noted that in China, carbon emissions during the operational stage accounted for 60-80% of the total life cycle building emissions. Consequently, operational carbon emissions outweigh embodied emissions in conventional buildings.

In contrast to typical buildings, RICS (2012) noted that low-energy incentive facilities, such as warehouses, only contribute to 20% of operational carbon emissions. This finding aligns with Sartori and Hestnes (2007), who stated that low-carbon buildings contribute to 9-46% of embodied carbon, with operational carbon remaining at a lower value. Unlike typical and low-carbon buildings, zero-carbon buildings emit no operational carbon, with the total carbon emitted being in the form of embodied carbon (RICS, 2012).

Furthermore, a study conducted by Zheng et al. (2023) reviewed the whole-life carbon emissions of similar buildings, using 145 residential properties in the UK. The study concluded that one of the major significant factors influencing carbon emissions is the number of occupants in the building. Lastly, a study conducted by Rossi et al. (2012) reviewed life-cycle assessment of residential building in three different European locations. The study stated that in Sweden, despite the very cold weather leading to a significant heating demand, the environmental impact remains relatively low.

Table 1 Research Background

Title	Highlights	Author
Methodology to calculate embodied carbon of materials	- Within the UK context reveals that certain building types, such as supermarkets, offices, and semi-detached houses, contribute to 70-80% of the operational carbon in the overall life cycle emissions. - Low-energy buildings, such as warehouses, only contribute to 20% of operational carbon emissions. - Zero-carbon buildings emit no operational carbon, with the total carbon emitted being in the form of embodied carbon	(RICS 2012)
Energy use in the life cycle of conventional and low-energy buildings: a review article	- Analyzed 60 case studies from diverse countries, reporting that embodied emissions could range from 2-38% of the total life cycle emissions, with a larger proportion attributed to operational carbon. - Low-carbon buildings contribute to 9-46% of embodied carbon, with operational carbon remaining at a lower value	(Satori & Hestnes, 2007)
Life cycle energy analysis of buildings: an overview	- 73 case studies across 13 countries for residential and office buildings, concluding that operational emissions constituted 70-80%.	(Ramesh et al., 2010)
Variations in whole-life carbon emission of similar buildings in proximity: An analysis of 145 residential properties in Cornwall, UK	- The study concluded that one of the major significant factors influencing carbon emissions is the number of occupants in the building	(Zheng et al., 2023)
Life-cycle assessment of residential buildings in three different European locations	- In Sweden, despite the very cold weather leading to a significant heating demand, the environmental impact remains relatively low.	(Rossi et al., 2012)

1.3. Research Gaps

After recognizing the urgency of addressing CO2 and reviewing previous research, the current challenge is to optimize both embodied and operational carbon to achieve the lowest possible carbon emissions for a building. This research sets itself apart from other studies that only focus on specific aspects of embodied and operational carbon emissions. The thesis aims to explore the relationship between embodied carbon and operational carbon, considering their mutual impact on each other and on the overall carbon emissions of the apartment building. The objective is to optimize both types of carbon to minimize the apartment building's overall carbon emissions.

Moreover, according to the study by Rossi et al. (2012), it is interesting to investigate the embodied and operational carbon of identical houses situated in radically different climates. This thesis research will also seek to understand how factors such as the orientation of apartment building influence carbon emissions in buildings for each orientation. For instance, optimizing the carbon footprint of a building on the south side will be different from the other side. Consequently, these variations will impact the energy usage in each orientation, influencing the overall optimization strategy.

1.4. Research Design

1.4.1.Research Objectives

The objective of this research is to optimize whole-life carbon emissions in apartment buildings. Through this study, companies and construction communities can design future buildings that are more sustainable, characterized by lower carbon emissions, and understand the relationship between embodied and operational carbon.

1.4.2. Research Scope

This research specifically concentrates on embodied carbon and operational carbon. The section on embodied carbon delves into material production, starting from raw materials to construction. The operational carbon section focuses on energy use. The study case will be confined to apartment building projects only, as buildings present a diverse range of material elements, along with unique challenges and opportunities for sustainable construction.

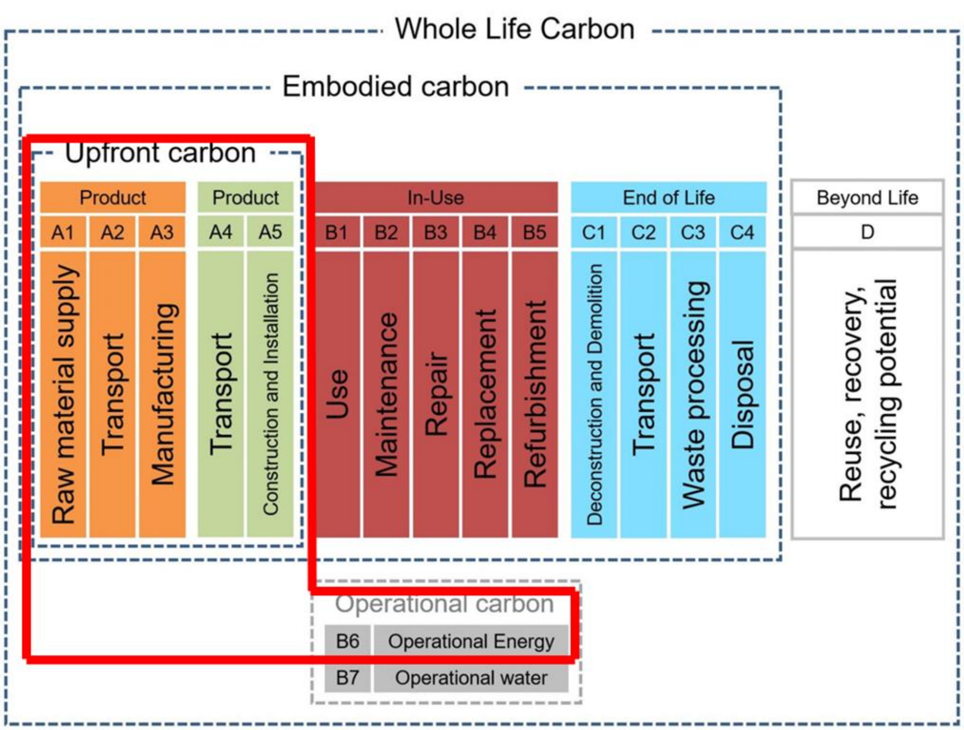

Figure 1 Research Scope

1.4.3.Research Question

"How to optimize whole life carbon emissions in the apartment building?'

Sub-questions:

1. **What factors contribute to the embodied and operational carbon?**

   This sub-question is crucial for determining the parameters that need to be addressed. It must be answered before moving on to the next sub-question. Understanding this parameter is essential for defining the goals that must be achieved. This sub-research question will be addressed based on the literature review.

2. **How to calculate embodied and operational carbon emissions?**

   After identifying the parameters of embodied and operational carbon emissions, this sub-question represents the initial step in collecting data for use in the optimization phase. The findings for this sub-question will be gathered from the literature review.

3. **How do embodied carbon and operational carbon emissions influence each other, and impact overall carbon levels in order to optimize and achieve the best results in building design?**

   This sub-question is crucial for understanding the relationship between embodied and operational carbon, which will be utilized in the optimization process. It will be addressed through scenario studies and the identification of opportunities for design improvement.

4. **How does the proposed framework help the designer?**

   This sub-question is intended to validate the proposed framework. The answer to this sub-question will be obtained through interviews with experts in the company.

1.4.4. Research Methodology

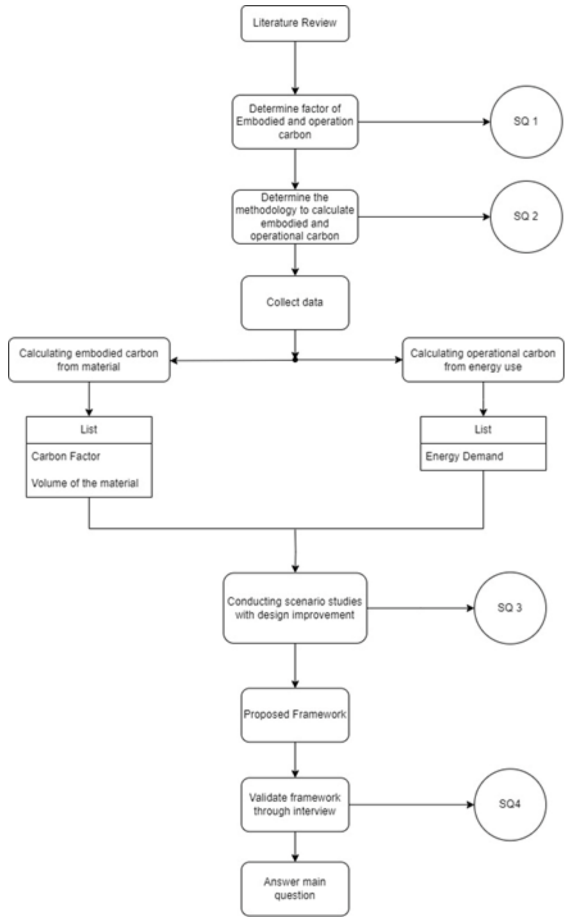

Figure 2 Research Methodology

The methodology for this research involves a literature review, data gathering, scenario studies, and interviews.

The literature review consists of explanations about whole life carbon, focusing on embodied and operational carbon. It will help determine factor for both embodied and operational carbon, as well as establish the methodology for calculating both.

Data gathering consists of environmental data derived from calculating each carbon emission. This data will be utilized for scenario studies and optimization.

Scenario studies consist of conducting scenarios using a building model with the same shape but different materials, energy use, and the orientation of the apartment building. Within these scenarios, the apartment building's orientation will provide different energy use. For example, a comparison between the west and north will be made. Different orientations will impact the optimization of carbon emissions, thereby influencing the energy use of each orientation.

Interviews will be conducted to validate the proposed framework and the results of the scenario studies by interviewing the project teams within the company. The framework must be efficient and useful. Finally, the main question will be answered.

1.5. Thesis Outline

In this chapter, a brief explanation of the final report's contents will be provided. The report's contents are as follows:

1. Thesis Cover

   This part will consist of the title, details of the researcher and supervisors, and the institutions involved.

2. Abstract

   This chapter offers a brief overview of the entire research, covering the background, theory, problem statement, methodology, and results of the research.

3. Introduction

   Preliminary information will be provided in this chapter, starting with an outline of the context and the broad subject of this study. This research's significance will be discussed in terms of the gaps and issues currently experienced.

4. Literature Review

   Significant theories related to the research, such as the definitions of life cycle analysis, whole life carbon, embodied carbon, operational carbon, optimization, and apartment building emissions will be explored in this chapter. This chapter's outcomes can be used to determine the factors that result in embodied and operational carbon, and the methodology to calculate both carbons. Therefore, the first and second sub-questions can be addressed in this section.

5. Methodology

   This chapter starts with the collection of data obtained from the calculation of embodied and operational carbon, followed by an analysis of the calculations.

6. Finding and result

   This chapter starts by presenting the outcomes of scenario studies. Various scenario studies are conducted to optimize varying materials, energy use, and orientations. Following this, a proposed framework is presented. Hence, the third sub-question can be answered in this chapter.

7. Evaluation

   This chapter focuses on discussing the findings and results. The next phase involves evaluation the results of scenario studies and the proposed framework through interviews with experts in the company. The framework must be useful and efficient. This section addresses the last sub-question.

8. Conclusion

   This chapter will summarize all the discussions made and answer the main research questions. It will end with some recommendations on what should be done by the next researcher and potential future research to enhance the content of this research.

9. Bibliography

   All the references used in this research will be listed in this chapter.

2. Literature Review

This chapter presents theoretical constructs essential for understanding the research objectives and addressing the first and second sub-questions. It integrates relevant theories to provide a comprehensive background for the study. By clarifying key concepts, this chapter establishes a strong theoretical foundation, guiding the following analysis and methodology part.

2.1. Life Cycle Assessment of Building

This chapter will discuss the definition and basic principles of life cycle assessment (LCA) in the context of buildings. This understanding will facilitate the author's comprehension of whole life carbon emissions, which are essential components of LCA. Therefore, to grasp whole life carbon emissions and design the framework of this research, it is advisable to first understand the life cycle assessment of buildings.

Life Cycle Assessment (LCA) is a standardized approach for evaluating the prospective environmental consequences and resource utilization associated with a structure. In the realm of the building sector, LCA plays a pivotal role in evaluating the environmental sustainability of structures (Birgisdottir & Rasmussen , 2016). By adopting a long-term outlook, it guarantees the incorporation of impacts spanning the entire life cycle of the building, encompassing the manufacturing of construction materials, transportation, installation, upkeep, replacements, material processing during end-of-life stages, and operational energy consumption throughout the building's lifespan (Zimmermann, Andersen, Kanafani, & Birgisdottir, 2021).

Over the past ten years, people have been looking for a lot at how buildings affect the environment using something called Life Cycle Assessment (LCA). This is because buildings have a big impact on the environment. Lots of different parts of this topic are being studied to try and figure out how to make it better, so it is a field of study that keeps on growing (Anand & Amor, 2016). This trend coincides with an increased emphasis on life cycle thinking, the establishment of building sustainability certification systems, and the concurrent advancement of standards and methodologies for LCA in various sectors (Goldstein & Rasmussen, 2017). Nowadays, Life Cycle Assessment (LCA) is integrated into the European standards for sustainable construction, specifically within the Construction Products Regulation (CPR) (Birgisdottir & Rasmussen, 2016).

Despite the growing significance of construction materials in contribution analyses, particularly with the emergence of low-energy buildings, energy consumption during the operational phase remains a key factor (Blengini & Carlo, 2010). Additionally, the lifespan of buildings significantly influences their contribution during the usage phase (Thormark, 2002). Buildings are anticipated to endure and accommodate human activities for several decades, typically ranging from 15 to 50 years for commercial buildings and 50 to 100 years for residential ones (Aktas & Bilec, 2012). Throughout this timeframe, both the climate and energy sources are expected to evolve, with potential changes including the development of renewable energies and the possibility of nuclear phase-out. These evolving parameters collectively impact the overall life cycle performance of buildings (Roux, Schalbart, Assoumou, & Peuportier, 2016).

EN 15978 outlines an approach for the LCA of buildings, delineating various life cycle stages: production and construction (A), use (B), and end-of-life (C), with an additional stage (D) addressing external benefits and burdens, such as recycling. To streamline the process and reduce workload, many building LCA studies utilize predefined datasets for materials or components, with dedicated databases (Hollberg, et al., 2021).

The utilization of predefined datasets the life cycle inventory (LCI) and life cycle impact assessment (LCIA) into a single, simplified step (Lasvaux, et al., 2013). Many aspects of the goal and scope, such as the functional unit or reference study period, are specified in national standards or guidelines for Green Building Certification Systems (GBCS). Additionally, these standards define the environmental indicators required as results; for example, Sweden mandates only the reporting of Global Warming Potential (GWP), while Switzerland considers GWP, Primary Energy Non-Renewable Total (PENRT), and a composite indicator known as environmental impact points (UBP) (Hollberg, et al., 2021).

Extending the scope of LCA, life cycle carbon emissions (LCCE) specifically examine carbon dioxide emissions generated throughout the building's life cycle (Chau, Leung, & Ng, 2015). LCCE accounts for all carbon equivalent emissions produced at various stages of the building's life cycle (Cai, et al., 2022). Additionally, life cycle cost (LCC) analysis is commonly employed to accurately ascertain the total costs linked with such investments over a defined period (Giuseppe, Iannaccone, Telloni, D'Orazio, & Perna, 2017). As building construction progresses, the expenses related to design alterations tend to rise. Therefore, it is crucial to comprehend how to evaluate LCCE and LCC early in the design phase (Chen, Tsay, & Zhang, 2023).

2.2. Whole Life Carbon

This chapter will discuss the general knowledge of whole life carbon emissions and the factors that contribute to carbon emissions in the building sector. Moreover, this chapter will contribute to answering the first sub-question.

A crucial tool in advancing towards a zero-carbon building industry is Life Cycle Assessment (LCA), which is increasingly prioritizing the evaluation of Whole-Life Carbon (WLC) in buildings (Futas, Rajput, & Schiano-Phan, 2019). Whole-life cycle carbon footprint of a building refers to the combined operational and embodied carbon emissions generated throughout its entire lifespan. A building's life cycle typically comprises four primary stages: production, construction, operation, and end-of-life. (Nawarathna, Fernando, & Perera, 2017). Whole-Life Carbon emissions are directly affected by the kinds and quantities of resources utilized in constructing, maintaining, and operating a building. This indicates that whole-life assessments are not only about carbon emissions but also about resource efficiency. Consequently, these assessments play a crucial role in addressing two significant environmental challenges: global warming and resource depletion (Sturgis, 2017).

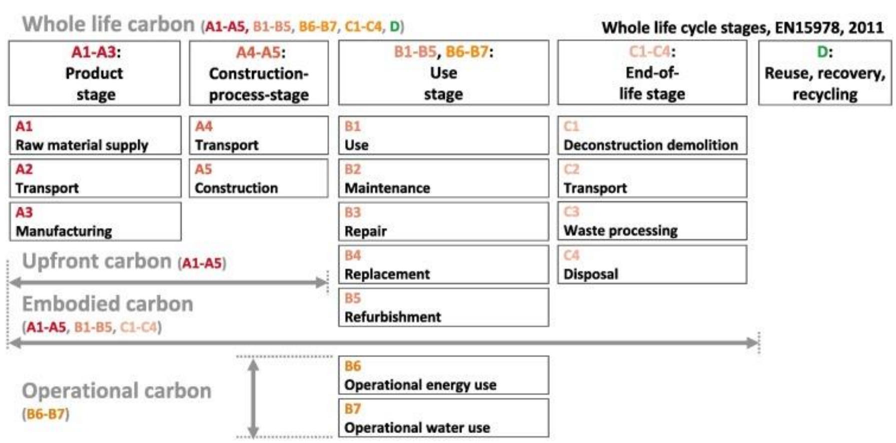

Figure 3 Whole Life Carbon

Source: (Shindo, et al., 2023)

2.3. Embodied Carbon (A1-A5)

This chapter will explore the definition of embodied carbon, explain the factors that influence it, and detail methodologies for its calculation that will be beneficial for the methodology chapter. These discussions will address the first and second sub-questions. Furthermore, this chapter will be a crucial component in the framework design, as embodied carbon significantly impacts whole life carbon emissions in buildings.

2.3.1. Definition

Embodied CO_2 (EC) represents the total CO_2 emissions resulting from raw material extraction, transportation to and from factories, building construction, maintenance, and refurbishment (Schwartz, Raslan, & Mumovic, 2018). EC can be classified into three categories: Initial EC, which includes CO_2 emissions from raw material extraction, manufacturing, transport, and construction; recurring EC, encompassing in-use CO_2 emissions such as repair, maintenance, and replacement; and Demolition EC, which refers to CO_2 emissions during demolition (Fernando, Victoria, & Ekundayo, 2018).

As embodied emissions increasingly become a focal point for reduction efforts, it will become imperative for traditional construction firms to quantify and disclose the emissions linked with their projects. This endeavor has the potential to enable comprehensive evaluation of the sector's emissions and facilitate a more accurate allocation of responsibilities for national emissions as a whole (Hamilton-Maclaren, Loveday, & Monjour, 2009). Moreover, by reporting the embodied emissions of projects, building engineers can supplement existing measures of operational emissions, offering a more comprehensive understanding of the environmental impact of completed endeavors (Ibn-Mohammed, et al., 2013). Incorporating considerations of embodied emissions can further contextualize operational emissions savings and spur well-informed initiatives aimed at achieving positive carbon reduction outcomes (Ibn-Mohammed, et al., 2013).

2.3.2. Calculation Embodied Carbon

A Life Cycle Assessment (LCA) serves as a tool for determining embodied carbon (Mohebbi, Bahadori-Jahromi, Ferri, & Mylona, 2021). The process of computing the embodied carbon of a building can be segmented into a cradle-to-gate LCA (A1–A3) (Hsu, Ochsendorf, & Veneziano, 2010). When conducting an LCA within the A1–A3 boundary, Equation (1) may be utilized for calculating the embodied carbon of materials (Gibbons & Orr, 2020). This calculation requires two sets of input data gathered during the Life Cycle Inventory (LCI) stage.

$$\text{Material quantity (Kg)} \times \text{Carbon factor (KgCO}_2\text{e/Kg)} = \text{Embodied Carbon (KgCO}_2\text{e)} \quad (1)$$

The calculation of material weight can vary depending on the stage of construction at which the LCA is conducted. If the LCA is conducted as a case study after construction, a Process LCA (PLCA) approach, which involves identifying and tracing the physical flow of all aspects (Omar, et al., 2014), can be adopted to gather all necessary data. Conversely, if the LCA is conducted before construction begins, material weights can be obtained from Building Information Modeling (BIM) (Mohebbi, Bahadori-Jahromi, Ferri, & Mylona, 2021).

The second set of input data needed for calculating embodied carbon consists of carbon factors. These factors offer an estimate of the Global Warming Potential (GWP) impact of individual products or processes. Securing precise and reliable values is crucial for conducting an LCA effectively. Carbon factors can be sourced from various secondary outlets for assessment purposes. These may encompass (Richardson S. , 2017):

- Environmental Product Declarations (EPD) (Butcher, 2021)
- Industry-specific data
- Government-provided data
- Factors from commercial LCA databases (e.g., ICE database)
- Carbon footprints compliant with PAS 2050 standards
- Factors derived or aggregated from literature.

The most precise data is typically sourced from EPDs. EPDs involve evaluations conducted by manufacturers by BS EN 15804:2012 and A2:2019 standards. Additionally, the production process of EPDs must adhere to ISO 14044 standards. According to EN 15804 requirements, EPDs are mandatory only within the A1–A3 boundary, while assessments for all other life cycle stages are optional (Mohebbi, Bahadori-Jahromi, Ferri, & Mylona, 2021).

Moreover, A4 emissions primarily relate to the transportation of materials and products from the factory to the construction site, generally accounting for less than 10% of the total embodied carbon of a structure. The A4 embodied carbon footprint (ECF) varies depending on the transportation mode and distance traveled. Similar to A1–A3 ECFs, the A4 ECF is calculated by multiplying it by the material quantity. A5 emissions are expected to represent a modest yet notable portion of the structural embodied carbon throughout the lifecycle of a project. These emissions fluctuate based on construction techniques, material selections, and site arrangements, and are categorized into two components. Emissions linked to materials wasted on-site are labeled as A5w emissions, while emissions resulting from on-site activities such as construction machinery and site offices are categorized as A5a emissions. The A5w emissions factor encompasses the carbon emissions released throughout the production, transportation, and disposal of wasted material. This factor represents the estimated percentage of material brought to the site that ends up as waste, denoted by the waste factor (WF), allowing the A5w factor to be applied to the same material quantity used in the A1–A3 calculations (Orr, Gibbons, & Arnold, 2020). The A5w factor is calculated by multiplying the WF by the sum of relevant ECFs, given by:

$$A5w = WF \times (A13 + A4 + C2 + C34) \quad (2)$$

Where:

- WF represents the waste factor, determined based on the anticipated percentage waste rate.
- A13 denotes A1–A3 emissions related to the production of the wasted material.
- A4 corresponds to emissions associated with transporting the wasted material to the site.
- C2 accounts for emissions linked to transporting the wasted material away from the site.
- C34 represents C3–C4 emissions related to processing and disposing of the waste material.

Below is a figure from Hammond and Jones (2011) about Embodied CO2 and embodied energy for materials typically used in the construction industry.

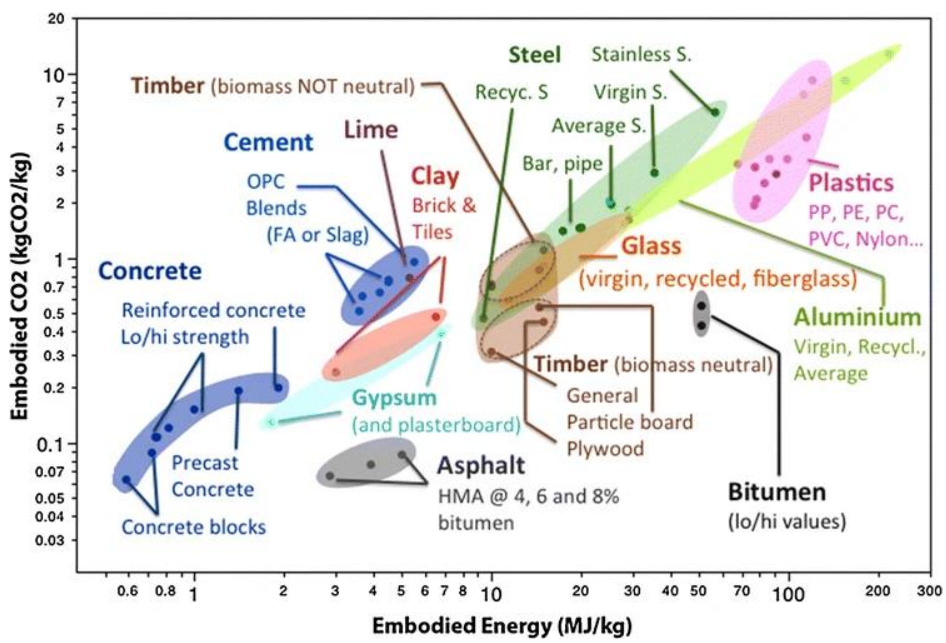

Figure 4 Embodied CO2 and energy from Hammond and Jones

Source: (Hammond & Jones, 2011)

2.4. Operational Carbon

Following the previous discussion on embodied carbon, this chapter begins an exploration of operational carbon. It starts by defining operational carbon and explaining the factors that affect it. Additionally, it will detail methodologies for calculating operational carbon, which will enhance the content for the methodology chapter. These discussions aim to address the initial and secondary sub-questions effectively. Moreover, this chapter plays a critical role in the framework design, highlighting the significant impact of operational carbon on overall carbon emissions in buildings.

2.4.1. Definition

This section of the LCA addresses the utilization phase, excluding considerations for maintenance or repair (B1 to B5). The operational carbon emissions of a building are associated with the various equipment utilized by occupants, and their estimation can be facilitated through a variety of available energy simulation software (Gan, et al., 2018). These emissions are directly derived from daily energy consumption, considering energy types and their corresponding emission factors (Gan, et al., 2020).

2.4.2. Calculate energy use

To calculate the energy use, it needs to calculate the heating loss factor that can use below equation:

$$Heat\ loss\ factor = \sum_i [U_i A_i] \qquad (3)$$

Where U_i = Heat transfer coefficient of wall i (W/m^2K) and A_i = surface of wall

The calculation of the window's heat transfer coefficient varies, taking into account factors such as U_{glass} and U_{frame}. For each window within the building, the value of U_{window} is determined individually. The average heat transfer coefficient enables users to estimate the heat loss through each window. Heat conduction through walls can occur both inward and outward, depending on the temperature differential between the interior and exterior of the walls (Rossi, Marique, Glaumann, & Reiter, 2011).

The software IESVE 2023 is used for this research to calculate annually energy demand. The Integrated Environmental Solution (IES) is a comprehensive environmental design tool that combines a user-friendly 3-dimensional modeling interface with a wide range of performance analysis functions, including shading, thermal, lighting, energy, resource usage, and cost considerations. IES offers performance analysis that is straightforward, precise, interactive, and visually engaging (Crawley, et al., 2004). The IESVE software is capable of simulating various outcomes related to energy flow and environmental conditions within a building. It possesses the ability to determine heating and cooling loads, as well as calculate energy consumption. IESVE generates a three-dimensional representation of the building, allowing for the attachment of characteristics to building elements. ApacheSim serves as the simulation engine, offering dynamic thermal simulation and mathematical modeling of heat transfer processes (Nikpour, Kandar, & Mousavi, 2013). Beevor (2010) suggested that IES can be employed for estimating the energy performance of buildings. Furthermore, Beevor (2010) conducted a comparison between experimental measurements and simulations regarding air temperature, solar heat gain, and heating and cooling loads, affirming the accuracy of IES results (Beevor, 2010).

2.4.3. Calculate Operational Carbon

To calculate operational carbon emissions, the Intergovernmental Panel on Climate Change (IPCC) developed a calculation model that combines activity levels and emissions factors (IPCC, 2019). Figure 4 illustrates the IPCC's calculation model.

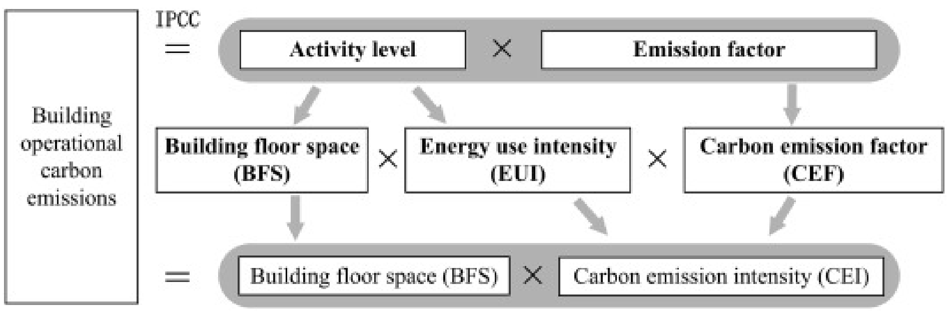

Figure 5 Calculation Model from IPCC

Source (Liang, et al., 2022)

Equation (3) outlines the primary method for computing building carbon emissions, wherein the carbon emission intensity (CEI) is multiplied by the building floor space (BFS). Meanwhile, the emission intensity of operational carbon is determined by the energy use intensity (EUI), as demonstrated in Equation (4). This involves multiplying the EUI of each energy source type (e.g., electricity and natural gas) by the corresponding carbon emission factor (CEF) to derive the CEI, where:

$$CE = BFS \; x \; CEI \qquad (3)$$

$$CEI = \sum_s (EUI_s \; x \; CEF_s) \qquad (4)$$

- CE is the building carbon emission ($kgCO_2$)
- BFS is the building floor space (m^2)

- CEI is the carbon emission intensity ($kgCO_2/m^2$)
- s is the different type of energy sources (e.g., electricity)
- EUIs is the energy use intensity of source (kWh/m^2 for electricity)
- CEFs is the carbon emission factor of source s ($kgCO_2/kWh$ for electricity)

2.5. Apartment building carbon emissions

This chapter explores the factors influencing carbon emissions from apartment buildings, alongside an investigation into various facade materials intended for use in the methodology part. Through this examination, it aims to provide a comprehensive understanding of both embodied and operational carbon emissions within apartment structures, which will assist in developing the proposed framework.

In the face of increasing concerns surrounding greenhouse gas (GHG) emissions, particularly carbon emissions, and their impact on climate change, extensive research has focused on the interplay between household consumption and environmental effects (Zhu, Shen , & Huang, 2011). This is because residential energy usage has emerged as the second-largest contributor to global energy consumption under a consumption-based GHG accounting framework, with an annual consumption of 70 EJ (22% of global energy use) in the mid-1990s (IEA, 2000). By 2015, residential energy use still accounted for 17% of the world's energy consumption, as estimated by the International Energy Outlook (2014). Additionally, it is recognized that individual characteristics such as household size, income, employment status, education, and age are often linked to emissions through household consumption (Baiocchi, Minx, & Hubacek, 2010). Moreover, O'Doherty et al. (2008) observed that newer homes typically incorporate energy-saving features, yet they often accommodate a greater number of appliances. Additionally, larger homes with more floor space may require increased energy for heating, cooling, and lighting. Holloway & Bunker (2006) highlighted that houses, encompassing detached, semi-detached, and townhouses, consume an average of 74% more electricity compared to residential units.

Residential carbon emissions can be divided into two main categories: first, direct emissions stemming from household energy usage such as cooking, heating, and hot water; second, indirect emissions resulting from the production processes of non-energy goods and services consumed in residential settings, which release carbon during production rather than afterward (Zhu, Peng, & Wu, 2012). The size of the household population thus correlates positively with household carbon emissions but negatively with per capita carbon emissions (Batih & Sorapipatana, 2016). According Elnakat et al (2016), individuals residing in homes with property ownership tend to consume more energy than renters.

2.5.1.Façade Materials for Apartments

a. Concrete

Concrete is a mixture of aggregates combined with water and cement (Damme, 2018). Concrete is acknowledged as a material with high carbon intensity, with cement, its primary component, compared to other industries, the cement sector carries a notable carbon footprint, accounting for approximately 8% (Environment, Scrivener, John, & Gartner, 2018). Concrete as a building material is considered environmentally friendly compared to materials like steel and glass. However, using concrete in large amounts has outweighed its sustainability benefits, as it requires a significant amount of resources for production and use in construction and renovation projects (Adesina, 2020). Nowadays, there are two methodologies for producing cement: on-site and precast. The on-site construction process represents another significant source of carbon emissions, primarily stemming from fuel consumption in heavy equipment, transportation of materials, embodied carbon in temporary materials, and waste management (Dong et al., 2015). On the other hand, precast concrete refers to concrete that is cast at a centralized location and then transported to its intended destination for use, making it a portable material (Richardson, 2003). Precast concrete components offer numerous benefits, such as shortened construction periods, cost-effectiveness, rigorous quality control, swift and precise assembly, and environmental conservation. These components help minimize on-site construction time while ensuring exceptional construction quality (Hong, 2020).

Wong and Tang (2012) compared the precast and cast-in-situ concrete with the system boundary from 'cradle to site' and concluded that the precasting method can reduce carbon emissions. If 'cradle-to-end of construction' processes are considered, the environmental benefits of precast concrete can also be detected (Dong & Ng, 2015). However, concrete blocks have an embodied carbon footprint ranging from 0.059 kgCO2/kg (8 MPa) to 0.1 kgCO2/kg (13 MPa), while precast concrete has an embodied carbon footprint ranging from 0.168 kgCO2/kg (40/50 MPa) to 0.229 kgCO2/kg (40/50 MPa) with reinforcement (Hammond & Jones, 2011).

b. Bricks

For thousands of years, bricks have played a crucial role in the realm of building and construction due to their exceptional attributes, including remarkable durability, high strength, and cost-effectiveness. The inception of brickmaking by humans dates back to 10,000 BCE, with the earliest known brick discovered in Egypt (Campbell, 2013) . During that era, clay block bricks were crafted by hand and left to dry in the sun. Clay bricks emerged as the primary construction material in the ancient city of Ur (modern Iraq) around 4000 BCE. Records from as early as 5000 BCE indicate the use of fire in brick production to enhance their performance. Subsequently, the brick industry experienced significant growth and evolution, particularly with the advent of modern machinery such as robust excavation equipment, motors, and tunnel kilns. These technological advancements notably bolstered brick production capacity. As of 2015, the global annual production of fired bricks was estimated at 1500 billion units. Typically, the modern brick firing cycle consists of six phases: moisture evaporation (20–150 °C), dehydration (149–650 °C), oxidation (300–982 °C), vitrification (900–1316 °C), flashing (1150–1316 °C), and cooling (1316–20 °C) (Zhang et al., 2018).

In terms of the carbon emission from bricks, brick kilns stand out as a primary source of pollution and the release of harmful gases within the construction sector, especially considering that brick manufacturing ranks among the fastest-growing industries globally (Khan et al., 2019). Research indicates that the brick firing process can lead to the emission of harmful polluting gases to the atmosphere, such as carbon dioxide (CO_2), carbon monoxide (CO), chlorine (CL2), ammonia (NH3), sulphur dioxide (SO2), nitrogen oxide (NO), hydrogen cyanide (HCN), and fluorine (F) (Ukwatta et al., 2018). According to Hammond and Jones (2011), bricks cost 0.23 kgCO2/kg of embodied carbon.

c. Timber

Wood, despite its ancient history in construction, has attracted renewed attention due to sustainability concerns (Correa, Krieg, & Meyboom, 2019). The increased use of wood and engineered timber products in the building sector has been identified in many market reviews, as presented by Hildebrandt, Hagemann, and Thrän (2017). This contributes to more sustainable buildings and to the achievement of the European climate policy targets (Arkar, Domjan, & Medved, 2018). As a naturally occurring resource with low energy requirements for conversion into construction material, timber emerges as a top choice for energy-efficient construction. Its excellent thermal conductivity properties make it particularly advantageous compared to alternative construction materials. Additionally, timber plays a crucial role in decreasing CO2 emissions, possesses favorable mechanical attributes, and contributes to creating a comfortable indoor living environment (Leskovar & Premrov, 2011). General timber cost 0.3_{fos} + 0.41_{bio} kgCO2/kg of embodied carbon (Hammond & Jones, 2011).

d. Double Glass

The double-glazed window system is widely utilized in contemporary buildings, with its energy efficiency frequently enhanced through the application of low-emission coating that reduces radiation heat loss (Gloriant, Tittelein, Joulin , & Lassue, 2015). A double-glazed unit requires about two times as much glass as a single-glazed unit. However, double-glazing reduces heat and cooling loads over single glazing which saves energy and emissions. Double-glazed units provide significant thermal benefits, which in most cases outweigh the additional carbon investment for extra glazing panes. However, the balance depends on the windows being kept in service for many years. The advancement of double-glazed units with low emissivity coatings reduces heat loss by 75% compared to single glazing, and by 40% compared to conventional double glazing (Westbroek et al., 2021). Cetiner and Özkan (2005) compared the energy and cost efficiency when the double-skin glass façade and the single-skin glass façade were used in a region of moderate climate, such as Istanbul. Whereas the double-skin glass façade was about 22.84% more energy-efficient than the single-skin glass façade, it was about 24.68% less cost-efficient than the single-skin glass façade.

e. Wool

Enhancing energy efficiency requires significant attention to the thermal insulation of buildings. The most common thermal building insulation materials today are mineral wool, expanded polystyrene, and polyurethane. Mineral wool encompasses both glass wool (fiberglass) and rock wool, typically manufactured in the form of mats and boards, although sometimes utilized as filling material as well. Glass wool is derived from borosilicate glass, created at temperatures around 1400°C, where the heated mass is extruded through rotating nozzles to form fibers. Rock wool, on the other hand, is produced by melting stone (such as diabase or dolerite) at approximately 1500°C, where the heated mass is spun out from a wheel or disk to create fibers. In both glass wool and rock wool production, dust abatement oil and phenolic resin are added to bind the fibers and enhance product properties. Typical thermal conductivity values for mineral wool range between 30 and 40 mW/(mK) (Jelle, 2016). The embodied carbon of wool is approximately 5.53 $kgCO_2/kg$ (Hammond & Jones, 2011). Expanded polystyrene (EPS) is crafted from small polystyrene beads derived from crude oil, incorporating an expansion agent (e.g., pentane C_6H_{12}) that enlarges them when exposed to water vapor heat. These expanded beads are fused together at their points of contact. The insulation material is formed into boards or produced continuously on an assembly line. EPS possesses a partially open pore structure. Typical thermal conductivity values for EPS fall within the range of 30 to 40 mW/(mK) (Altin & Yildirim, 2022). Polyurethane (PUR) is generated through a reaction between isocyanates and polyols (alcohols containing multiple hydroxyl groups). Throughout the expansion process, closed pores are infused with an expansion gas like HFC, CO_2, or C_6H_{12}. The insulation material is manufactured as boards or continuously on a production line. Additionally, PUR can be utilized as an expanding foam at construction sites, for instance, to seal around windows and doors or to fill various voids. Typical thermal conductivity values for PUR range between 20 and 30 mW/(mK), significantly lower than those of mineral wool, polystyrene, and cellulose products. However, the loss of pore gases and subsequent air permeation into the pores due to diffusion or degradation over time may elevate the thermal conductivity beyond these values. The thermal conductivity of PUR fluctuates with temperature, moisture content, and mass density. PUR products can be perforated, cut, and adjusted at the construction site without compromising their thermal resistance (Jelle, 2016). In addition, the embodied carbon of PUR is approximately 3.76 $kgCO_2/kg$ (Hammond & Jones, 2011)

f. Frame

Aluminum windows, crafted from lightweight and durable hollow extruded profiles, are assembled using mechanical fasteners. Due to aluminum's high thermal conductivity, a thermal break, typically composed of plastic, is integrated into the frame to diminish direct heat transfer between the interior and exterior components of the window. This raises the temperature of the internal surface of the framing, thereby mitigating its susceptibility to surface condensation to some extent (Carmody et al., 1996)

Timber is a conventional choice for window frames due to its ready availability and ease of processing. With the lowest thermal conductivity among frame materials(4), wood offers excellent insulation properties. Various wood species such as pine, cedar, and redwood are commonly utilized for window frames. However, timber is susceptible to moisture, which may cause warping or twisting over time. Consequently, timber windows require periodic painting or staining and regular maintenance every few years (Asif, Davidson, & Muneer, 2002).

In conclusion, this literature review has already addressed the first sub-question, which is the factors influencing embodied carbon. These factors include the type and quantity of materials used, the distance and mode of transport from the manufacturer to the site, and material waste. Conversely, the factors influencing operational carbon include energy demand, which encompasses heating and cooling loads, and the carbon emission factor derived from the energy mix of the country under study, in this case, the Dutch energy mix. Additionally, the answer to the second sub-question has been provided in sections 2.3.2 and 2.4.3, covering the calculation of embodied carbon and operational carbon respectively. Thus, the objective of the literature review has been achieved, aligning with the research methodology diagram presented in Chapter 1.4.4.

2.6. Multi-Objective Optimization

This part will discuss the definition of multi-objective optimization and the Grasshopper software, which will be used for optimization and sensitivity analysis.

The optimization process uncovers the best value or solution. It involves seeking either the highest or lowest value and can involve one or multiple objectives. Optimization problems can exhibit different characteristics, including continuous or combinatorial setups with either continuous or discrete decision variables. They may also be categorized as constrained or unconstrained, linear or nonlinear, static or dynamic (offline or online), and finally, as single or multi-objective optimization problems (Xu, 2013). When dealing with multiple objectives, it is called multi-objective optimization (MOO) (Gunantara, 2018). For multiple-objective problems, the objectives are generally conflicting, preventing simultaneous optimization of each objective. Many, or even most, real engineering problems do have multiple objectives, i.e., minimize cost, maximize performance, maximize reliability, etc. (Konak , Coit, & Smith, 2006). A solution that benefits one function may detrimentally affect another or multiple other functions. Consequently, finding a solution that meets all objective functions poses a significant challenge in multi-objective problems (Cui, Geng, Zhu, & Han, 2017).

The expressions used to describe various optimization objectives may differ, whether they are maximum functions or minimum functions. These two extreme functions can be transformed into each other using the following equation (Gong, Jiao, Yang, & Ma, 2009).

$$\max\{f(x)\} \leftrightarrow \min\{-f(x)\}$$

Therefore, any multi-objective optimization problem can be expressed as the following common mathematical model:

$$\min y = f(x) = [\, f_1(x),\, f_2(x), \ldots, f_m(x)]^T$$

$$g_j(x) \leq 0 \; (j = 1, 2, \ldots., p)$$

$$h_k(x) = 0 \; (k = 1, 2, \ldots., q)$$

$$x_i^{min} \leq \; x_i \; \leq x_i^{max} \; (i = 1, 2, \ldots., n)$$

$$x = [x_{1,}, x_2, \ldots., x_n]^T \in \theta$$

$$y = [y_{1,}, y_2, \ldots., y_n]^T \in \varphi$$

In this context, m represents the number of optimized objective functions, θ signifies an n-dimensional search space determined by the upper and lower bounds of decision variables. Meanwhile, φ denotes the m-dimensional vector space of objective functions, influenced by both Θ and the objective function. The equations g_j and h_k represent p inequality constraints and q equality constraints. Notably, if both p and q are equal to 0, the problem is simplified to an unconstrained multi-objective optimization problem (Rangaiah, 2016).

In multi-objective optimization problems, a key concern is the definition of solutions. Theoretical mathematics suggests that there isn't a single solution for such problems, but rather a set of solutions. In 1951, Koopmans (1951) introduced the concept of Pareto efficient solution set, which effectively characterizes solutions based on partial order relationships rather than total order.

Feasible solution: A solution vector denoted as x ∈ θ, if it satisfies both inequality constraints and equality constraints for all j = 1, 2, ..., p and k = 1, 2, ... , q, it is defined as a feasible solution, else it is a infeasible solution. All feasible solutions collectively form a set known as the feasible domain, denoted as Ω. Conversely, all infeasible solutions form the set referred to as the infeasible domain, denoted as Ω'. Clearly, Ω + Ω' = θ, where Ω and Ω' are θ (Cui, Geng, Zhu, & Han, 2017).

Pareto optimal solution: if the vector x* satisfies the condition x such that $f_i(x) \leq f_i(x^*)$ for all I and $f_j(x) < f_j(x^*)$ for at least one j, the x* is termed a global pareto optimal solution, or simply an optimal solution. The collection of all global Pareto optimal solutions a set known as the global Pareto optimal set, denoted as PS* (Caramia & Dell'Omo, 2020)

Pareto optimal front: The collection of Pareto optimal solutions represented in the objective function space is referred to as the Pareto optimal front, expressed as follows:

$$P\,F^* = \{\, f(x^*) \mid x^* \ \in PS^*$$

Non-dominant solution: During the computational evolution of evolutionary algorithms, the optimal solution within each generation of the evolving population is termed a non-dominant solution. The collection of all non-dominant solutions forms the set of non-dominant solutions (abbreviated as NDS). The objective of multi-objective optimization is to seek out these non-dominant solutions to approximate real optimal solutions (Pereira, Oliver, Francisco, Jr, & Gomes, 2022).

2.6.1. Rhinoceros 3D and Grasshopper plugin

Grasshopper software is extensively employed for translating natural inspiration into human technology. This is due to its ability to effectively measure and translate the diverse array of natural elements (Elshtwei, 2018). Grasshopper is a visual programming language that functions as an additional plugin within the Rhinoceros 3D modeling software. Rhinoceros 3D is a commercial Computer-Aided Design (CAD) software created by Robert McNeel & Associates, utilizing mathematical NURBS models as the foundation for geometry (Fink & Koenig, 2019). Within the plugin of Grasshopper in Rhinoceros 3D, this can enables the utilization of off-the-shelf compilers as commands. Specifically, in Grasshopper, modeling occurs through the arrangement of "components," which represent predefined commands (e.g., icons, connecting lines, and arrows). By connecting "components" with wires that link input and output parameters, modeling can be intuitively carried out in a seamless manner (Lee & Song , 2021). Parameter values can be input directly through components or easily adjusted by dragging the mouse pointer. Changes are instantly reflected in real-time on the Viewport of Rhino (Hsu, et al., 2015). In the field of architecture, Grasshopper stands out as the primary software for parametric design. It efficiently handles numerous parameters simultaneously and delivers rapid results compared to other parametric software such as 3D Max

(Eltaweel & Su, 2017). One benefit of utilizing Grasshopper is the ability to directly visualize algorithmic results within the 3D Rhino interface. Changes and details can be observed in real-time on Rhino's Viewport (Lee & Song , 2021).

Moreover, there are Honeybee and Ladybug plugins within Grasshopper facilitate model simulations for energy and daylight analysis (Roudsari et al., 2013). These open-source plugins allow access to the written code for materials, geometries, and constructions (Motamedi & Liedl, 2017). The underlying mechanism of plugins relies on OpenStudio and EnergyPlus for energy-related simulations, and Radiance and Daylighting simulations (Toutou et al., 2017). The Honeybee and Ladybug plugins, operating within Grasshopper, enable parametric building-related analyses (Norouzi et al.,2021). This functionality facilitates rapid simulation of models requiring frequent adjustments in coefficients and geometry. The weather data utilized in this study is sourced from EnergyPlus Weather files (EPW), accessible via this site (Ghasri et al., 2016). Furthermore, there is Colibri, the plugin within Grasshopper was utilized as the optimization method to automatically generate models. This plugin was specifically developed to facilitate the creation of datasets compatible with Design Explorer. Employing a 'Brute Force' algorithm within the Grasshopper environment, it systematically evaluates all possible alternatives to identify satisfactory solutions to the optimization problem (Valitabar et al., 2022). In addition, there is colibri plug in that can simulate a large number of parameters set, iterate a range of input values and export the simulations (Kim et al., 2020). The Colibri plug-in in Grasshopper is used to automatically iterate the process and save the results for the data visualization step and Design Explorer was used for interactive data visualization (Taheri et al., 2020).

2.7. Summary

This chapter provides an introduction to the concept of whole-life carbon emissions in apartment buildings. In the first part of this chapter (i.e., 2.1), a brief introduction to life cycle assessment in building is provided. This life cycle assessment is necessary because whole-life carbon emissions are part of it. Section 2.2 gives a brief introduction to Whole Life Carbon Emissions, including the definition and stages in building. Section 2.3 discusses Embodied Carbon, covering its definition and the methodology for calculating it in buildings. Section 2.4 discusses Operational Carbon, beginning with its definition and the software used for its calculation. Section 2.5 provides literature on carbon emissions from apartment buildings, concluding with materials used for the façade of apartment buildings. Lastly, Section 2.6 contains multi-objective optimization, starting with its definition, the formula, and the Grasshopper software used for optimization in this research.

3. Methodology

This chapter will discuss the methodology for calculating embodied carbon, operational carbon, and whole-life carbon emissions. Moreover, there will be some scenarios in this chapter to explore the relationship between each type of carbon, which will contribute to the next chapter, the findings chapter.

3.1. Model

The model represents a simple studio apartment room with an area of 50 m2 and one window covering an area of 4 m2. This model serves as the baseline for comparison with other scenarios. Below is the 3D model of the building created using IESVE software:

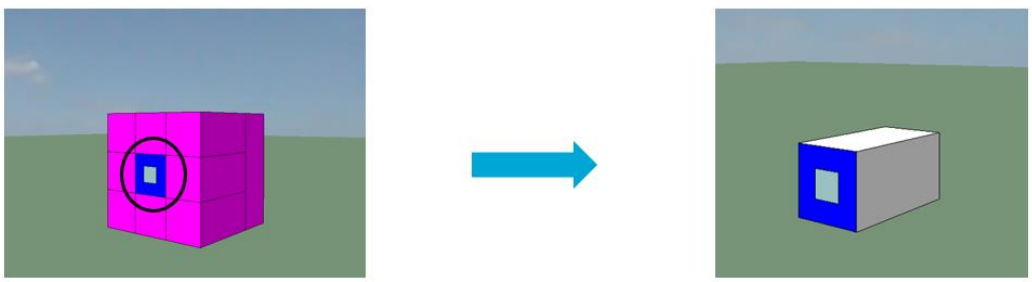

Figure 6 Building Model

3.2. Calculate the Embodied Carbon

In this research, calculating the embodied carbon is done using Microsoft Excel software. Firstly, it is necessary to collect the data on the embodied carbon factor for each material. Below are the embodied carbon factors from A1 to A5 for each material in every component of the model:

Table 2 Brick Material Properties

Brick Type	Carbon Factor	Unit	Density (kg/m3)	Source
Brick Masonry	0,152	KgCO2/kg	2000	GPR Materiaal. (n.d.). Materiaal.gprportaal.nl. Retrieved March 23, 2024, from https://materiaal.gprportaal.nl/b1d8e221-584b-45b2-bd9e-e8add0bcebce/component
Sand Lime Brick	0,113	KgCO2/kg	1750	
Concrete Block Masonry	0,084	KgCO2/kg	2000	

Table 3 Board Material Properties

Board Type	Carbon Factor	Unit	Density (kg/m3)	Source
Plasterboard	0,194	KgCO2/kg	1150	GPR Materiaal. (n.d.). Materiaal.gprportaal.nl. Retrieved March 23, 2024, from https://materiaal.gprportaal.nl/b1d8e221-584b-45b2-bd9e-e8add0bcebce/component
Gypsum Fiber Board	0,28	KgCO2/kg	1150	
Wood Chipboard	0,048	KgCO2/kg	600	
Beton C20/25 insitu, reinforcement 100 kg/m3	1,079	KgCO2/kg	2400	*Milieu Relevante Product Informatie* . (n.d.). Retrieved March 23, 2024, from https://www.mrpi.nl/
Beton C20/25 Prefab, reinforcement 100 kg/m3	1,11	KgCO2/kg	2400	

Table 4 Insulation Material Properties

Insulation Type	Carbon Factor	Unit	Density (kg/m3)	Source
Glass Wool	0,78	KgCO2/kg	200	*The Construction Material Pyramid* . (2019). Materialepyramiden.dk.
PUR Insulation	2,77	KgCO2/kg	170	

Table 5 Glass Material Properties

Glass Type	Carbon Factor	Unit	Source
Double Glass 6/12/6 mm	57,89	KgCO2/m2	GPR Materiaal. (n.d.). Materiaal.gprportaal.nl. Retrieved March 23, 2024, from https://materiaal.gprportaal.nl/b1d8e221-584b-45b2-bd9e-e8add0bcebce/component
Double Glas HR Coating 6/12/6 mm	60,8	KgCO2/m2	
Double Glass HR + Coating 6/15/6 mm	62,41	KgCO2/m2	
Double Glass HR ++ Coating argo 6/16/6 mm	62,88	KgCO2/m2	
Triple Glass 6/12/6 mm	73,07	KgCO2/m2	

Table 6 Frame Material Properties

Frame Type	Carbon Factor	Unit	Source
Alumunium Frame	53,24	KgCO2/m2	GPR Materiaal. (n.d.). Materiaal.gprportaal.nl. Retrieved March 23, 2024, from https://materiaal.gprportaal.nl/b1d8e221-584b-45b2-bd9e-e8add0bcebce/component
Timber Frame	18,6	KgCO2/m2	

The source is already based on the Dutch market and counts from A1 to A5. After collecting the data of the embodied carbon factor for each material, proceed to create the template for calculating embodied carbon in Microsoft Excel. The calculation formula for embodied carbon involves multiplying the volume or area of each material by its respective embodied carbon factor. By utilizing the template created in Excel, it becomes easier to obtain results for various scenarios with different dimensions of building areas and different materials. Below are the materials and dimensions that will be used for the baseline:

Table 7 Dimension of the Facade, Ceiling, Floor, and Interior Wall

Facade		
length facade	5,0	m
height facade	5,0	m
lenght opening	2,0	m
height opening	2,0	m
glass length	2,0	m
glass width	2,0	m
Amount glass	1	unit
Stud Length	100,0	mm
wall area	21	m2
opening area	4	m2
opening glass	4	m2

Ceiling		
Length Ceiling	10	m
Width	5	m
Ceiling thickness	58	mm
Ceiling Area	50	m2

Floor		
Length Floor	10	m
Width Floor	5	m
Floor thickness	58	mm
Floor Area	50	m2

Interior wall		
Length Interior Wall	10	m
Height Interior Wall	5	m
Interior thickness	58	mm
Interior Wall Area	50	m2

Table 8 Embodied carbon wall surface (baseline)

Wall Surface			
Brick	Type	Brick Masonry	
	Thickness	140	mm
	Volume	2,93943986	m3
	Density	2000	kg/m3
	Quantity	280	kg/m2
	Mass	5878,87972	kg
	GWP	42,56	kgCO2/m2
	Carbon Factor	0,152	kgCO2/kg
	Embodied Carbon	893,5897174	kgCO2
Insulation	Type	Glass Wool	
	Thickness	100	mm
	Volume	2,0995999	m3
	Density	200	kg/m3
	Quantity	20,00	kg/m2
	Mass	419,91998	kg
	GWP	15,60	kgCO2/m2
	Carbon Factor	0,78	kgCO2/kg
	Embodied Carbon	327,54	kgCO2
First Board	Type	Plasterboard	
	Thickness	19	mm
	Volume	0,398923981	m3
	Density	1150	kg/m3
	Quantity	21,85	kg/m2
	Mass	458,7625782	kg
	GWP	4,24	kgCO2/m2
	Carbon Factor	0,194	kgCO2/kg
	Embodied Carbon	89,00	kgCO2
Second Board	Type	Plasterboard	
	Thickness	19	
	Volume	0,398923981	mm
	Density	1150	m3
	Quantity	21,85	kg/m2
	Mass	458,7625782	kg/m3
	GWP	4,2389	kgCO2/m2
	Carbon Factor	0,194	kg
	Embodied Carbon	89,00	kgCO2
TOTAL GWP		66,64	kgCO2/m2
TOTAL FACADED EMBODIED CARBON		1399,13	kgCO2

Table 9 Embodied Carbon of Opening

Openings			
Window	Type	Double Glass 6/12/6 mm	
	Carbon Factor	57,89	kgCO2/m2
	Embodied Carbon	231,56	kgCO2
Frame	Type	Alumunium Frame	
	Carbon Factor	53,24	kgCO2/m2
	Embodied Carbon	0,21301324	kgCO2
TOTAL GWP		57,94	kgCO2/m2
TOTAL OPENING EMBODIED CARBON		231,77	kgCO2

Table 10 Embodied carbon of ceiling (baseline)

Ceiling			
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,95	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	1092,50	kg
	GWP	4,2389	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	211,95	kgCO2
Insulation	Type	Glass Wool	
	Thickness	58,00	mm
	Area	50,00	m2
	Volume	2,90	m3
	Density	200	kg/m3
	Quantity	11,6	kg/m2
	Mass	580,00	kg
	GWP	9,048	kgCO2/m2
	Carbon Factor	0,78	kgCO2/kg
	Embodied Carbon	452,40	kgCO2
TOTAL GWP		13,29	kgCO2/m2
TOTAL FACADED EMBODIED CARBON		664,35	kgCO2

Table 11 Embodied carbon of floor (baseline)

Floor			
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,95	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	1092,50	kg
	GWP	4,24	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	211,95	kgCO2
Insulation	Type	Glass Wool	
	Thickness	58,00	mm
	Area	50,00	m2
	Volume	2,90	m3
	Density	200	kg/m3
	Quantity	11,6	kg/m2
	Mass	580,00	kg
	GWP	9,048	kgCO2/m2
	Carbon Factor	0,78	kgCO2/kg
	Embodied Carbon	452,40	kgCO2
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,95	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	1092,50	kg
	GWP	4,24	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	211,95	kgCO2
TOTAL GWP		17,53	kgCO2/m2
TOTAL FLOOR EMBODIED CARBON		876,29	kgCO2

Table 12 Embodied carbon of wall right / left (baseline)

Wall Right / Left			
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,95	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	1092,50	kg
	GWP	4,24	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	211,95	kgCO2
Insulation	Type	Glass Wool	
	Thickness	58	mm
	Volume	2,9	m3
	Density	200	kg/m3
	Quantity	11,60	kg/m2
	Mass	580,00	kg
	GWP	9,05	kgCO2/m2
	Carbon Factor	0,78	kgCO2/kg
	Embodied Carbon	452,40	kgCO2
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,95	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	1092,50	kg
	GWP	4,24	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	211,95	kgCO2
TOTAL GWP		35,05	kgCO2/m2
TOTAL WALL INTERIOR EMBODIED CARBON		1752,58	kgCO2

Table 13 Embodied carbon of wall without window (baseline)

Wall Without Window			
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,48	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	546,25	kg
	GWP	4,239	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	105,97	kgCO2
Insulation	Type	Glass Wool	
	Thickness	58	mm
	Volume	1,45	m3
	Density	200	kg/m3
	Quantity	11,60	kg/m2
	Mass	290,000	kg
	GWP	9,05	kgCO2/m2
	Carbon Factor	0,78	kgCO2/kg
	Embodied Carbon	226,20	kgCO2
Board	Type	Plasterboard	
	Thickness	19,00	mm
	Volume	0,48	m3
	Density	1150,00	kg/m3
	Quantity	21,85	kg/m2
	Mass	546,25	kg
	GWP	4,239	kgCO2/m2
	Carbon Factor	0,19	kgCO2/kg
	Embodied Carbon	105,97	kgCO2
TOTAL GWP		17,526	kgCO2/m2
TOTAL WALL INTERIOR EMBODIED CARBON		438,15	kgCO2

With regards to the template already created, the blue cells represent inputs, the grey cells display the calculation results, the light blue cells indicate the embodied carbon for each material used in the baseline scenario, and the green cells show the embodied carbon for each component in the building. The total embodied carbon for the baseline scenario is 5362 kgCO2 or 107.24 kgCO2/m2

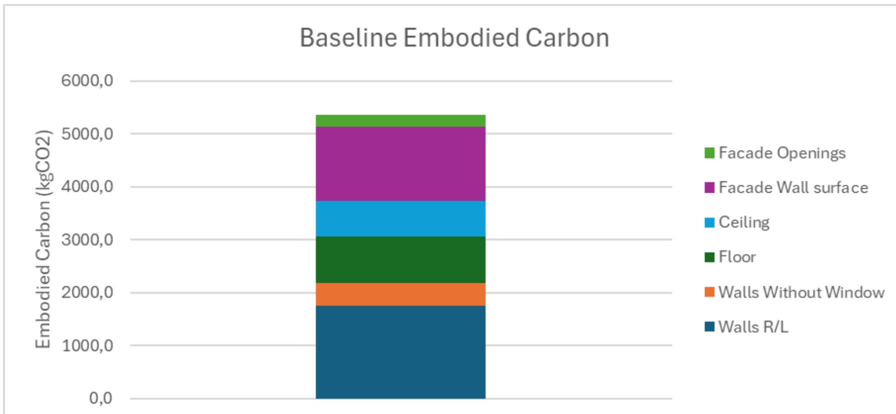

Figure 7 Embodied carbon (baseline)

3.3. Calculation Operational Carbon

To calculate the operational carbon in this research, IESVE software is utilized, as mentioned in Chapter 2.4. Firstly, it is necessary to create the building model within IESVE. Using the Apache tool within IESVE, all materials are inputted identically to those used in the baseline scenario, with the same dimensions. Based on the materials assigned for the baseline scenario, the thermal resistance (Rc) of the façade is calculated to be 3.685 m2K/W, and the U factor (thermal transmittance) of the window + frame is determined to be 2.7 W/m2K.

Subsequently, the weather file is inputted. In this research, the weather file location is set to Rotterdam. Furthermore, the thermal conditions are established. It is assumed that the efficiency od the heating and cooling is in the ideal condition or it means 100% efficiency, the dwelling heating set point is 19 °C, and the cooling set point is 24 °C. Heating and cooling operations are scheduled only from 00:00 to 08:00 and 18:00 to 24:00, as it is assumed that occupants are absent from 08:00 to 18:00 on weekdays. However, during weekends and holidays, the system operates continuously for 24 hours. Additionally, the outside air supply flow rate is set at 0.7 l/(s.m2). For energy consumption, it is assumed that there are 2 occupants in the room, each emitting 90 Watts.

Finally, the simulation is executed using ApacheSim. The results indicate that the total annual energy use is 2,518 MWh. The graph below illustrates the annual heating and cooling loads for the room:

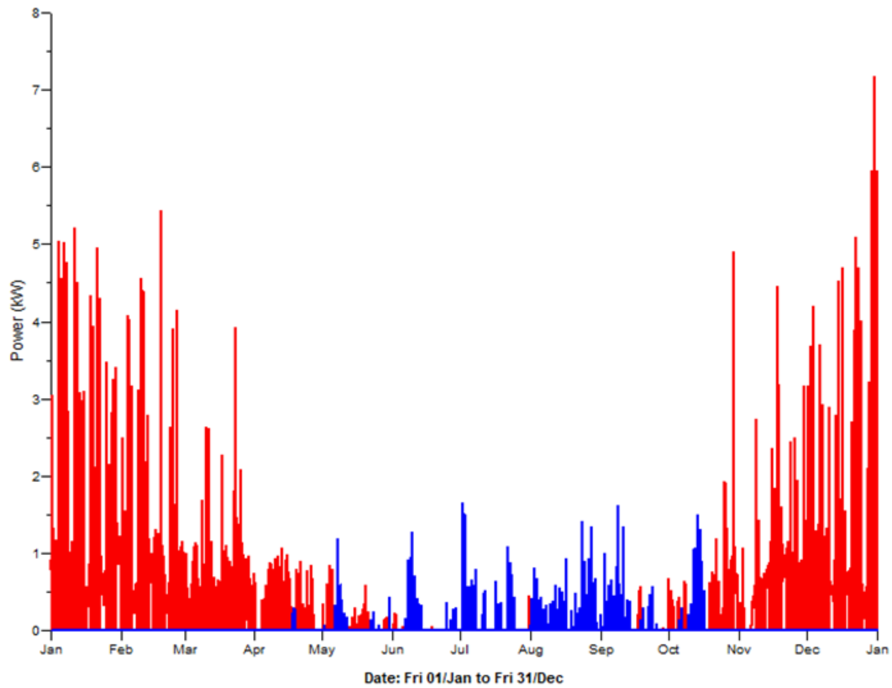

Figure 8 Energy use (baseline)

After calculating the energy demand, it is multiplied by the carbon emission factor to determine the total carbon emissions. This factor is dependent on the Dutch energy mix, which includes both fossil fuels and renewable sources, and varies annually from 2021 to 2050. Upon obtaining the operational and embodied carbon values for the baseline scenario, they are combined to yield a total emission of 13268 kgCO2 by 2050. The following section provides the carbon emission factors based on the Dutch energy mix from 2021 to 2050, alongside the total whole life carbon emissions:

Table 14 CO2 emission factor

Years	CO2 Emission factor (kg/kWh)	Source
2021	0,27	*Klimaat- en Energieverkenning 2023 | Planbureau voor de Leefomgeving* . (2023, October 26). Www.pbl.nl. https://www.pbl.nl/publicaties/klimaat-en-energieverkenning-2023
2022	0,25	
2023	0,23	
2024	0,21	
2025	0,19	
2026	0,17	
2027	0,14	
2028	0,12	
2029	0,09	
2030	0,07	
2031	0,07	
2032	0,07	
2033	0,07	
2034	0,07	
2035	0,07	
2036	0,07	
2037	0,07	
2038	0,07	
2039	0,07	
2040	0,07	
2041	0,07	
2042	0,07	
2043	0,07	
2044	0,07	
2045	0,07	
2046	0,07	
2047	0,07	
2048	0,07	
2049	0,07	
2050	0,07	

Table 15 Whole life carbon (baseline)

Year	CO2 Emission factor (kg/kWh)	Total Whole life Carbon (kgCO2)
2020	Embodied Carbon	5362,26
2021	Operational carbon	6042,12
2022		6671,62
2023		7250,76
2024		7779,54
2025		8257,96
2026		8686,02
2027		9038,54
2028		9340,70
2029		9567,32
2030		9743,58
2031		9919,84
2032		10096,10
2033		10272,36
2034		10448,62
2035		10624,88
2036		10801,14
2037		10977,40
2038		11153,66
2039		11329,92
2040		11506,18
2041		11682,44
2042		11858,70
2043		12034,96
2044		12211,22
2045		12387,48
2046		12563,74
2047		12740,00
2048		12916,26
2049		13092,52
2050		13268,78

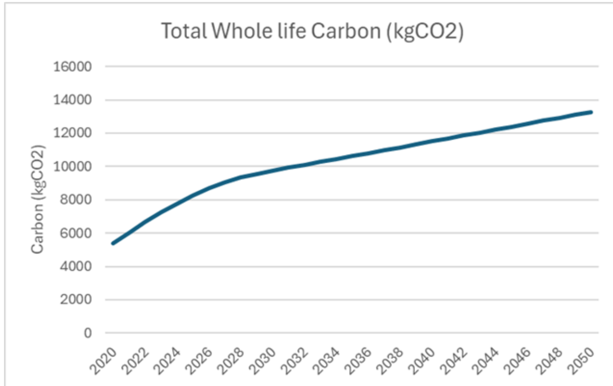

Figure 9 Whole life carbon (baseline)

3.4. Calculation other scenarios

For the 1-input scenario, Excel is used for the calculation of embodied carbon, and the software IESVE is utilized for the calculation of operational carbon. However, for the sensitivity analysis calculation that require more dept range of input and amount of input, it used Grasshopper. Moreover, to calculate energy demand, the Ladybug and Honeybee plugins are used, and for automation, the Colibri plugin is utilized. Using Grasshopper allows for faster generation of simulations with varying input amounts. Below are the Grasshopper models:

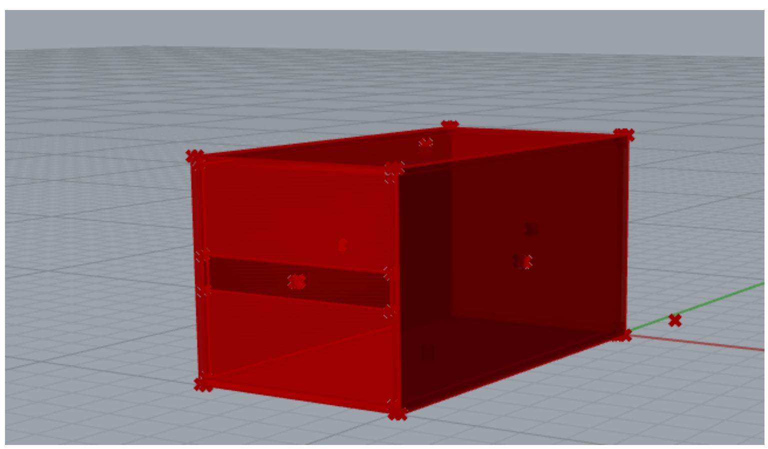

Figure 10 Baseline model (Rhinoceros 3D)

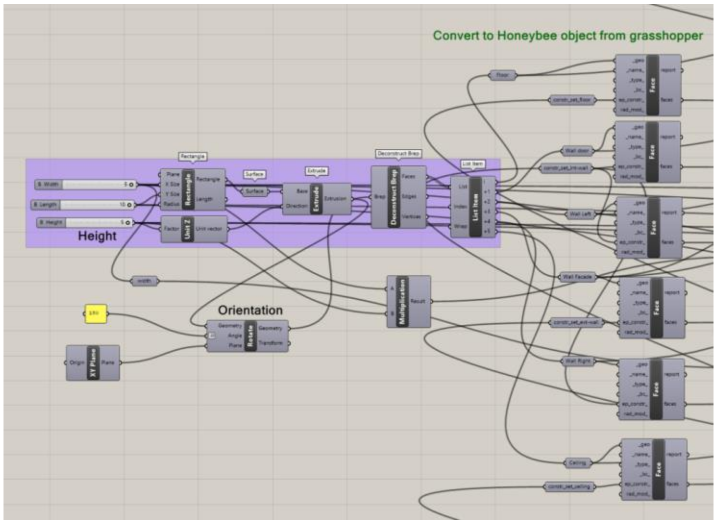

Figure 11 Grasshopper baseline model

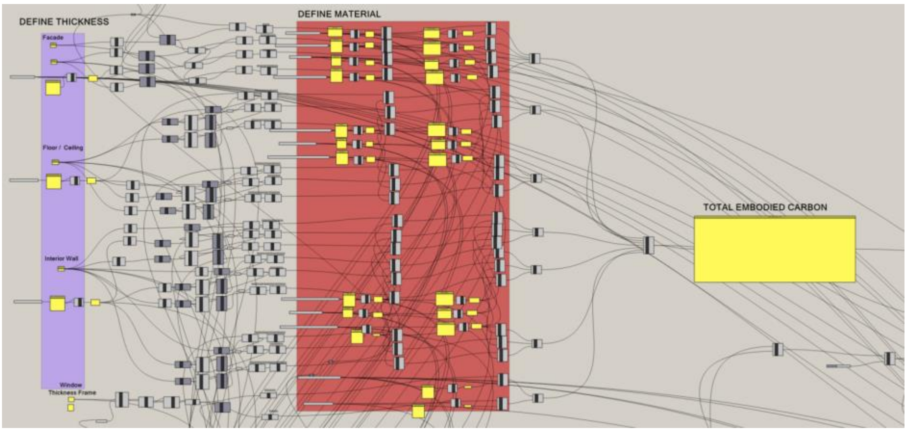

Figure 12 Embodied Carbon Calculation (Grasshopper)

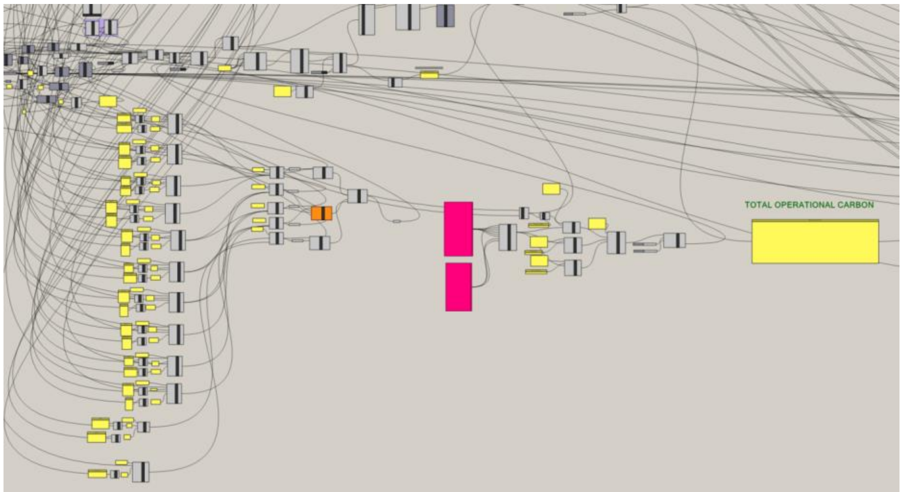

Figure 13 Operational Carbon Calculation (Grasshopper)

3.4.1. 1 Input Scenario (Excel and IESVE Software)

3.4.1.1. Different orientation

The first scenario will be compare the baseline which is the façade is in north face to other orientation. Therefore, the amount of embodied carbon will be same for each orientation because the material and dimensions that is used in baseline scenario will be same to each orientation. However, the energy demand will for each scenarios will be different, therefore the operational carbon for each orientation will be different. Below are the result of energy demand for each orientation and whole life carbon for each orientation:

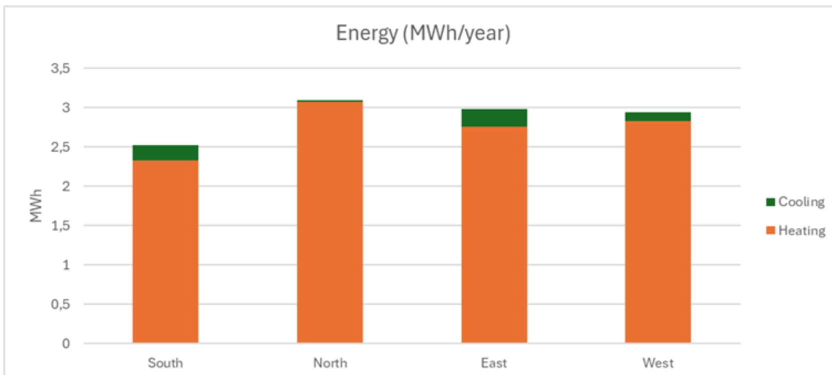

Figure 14 Energy Use for each orientation

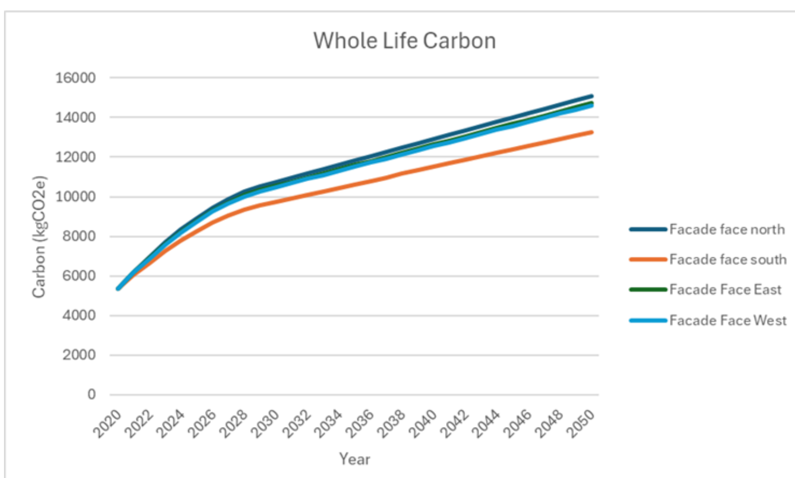

Figure 15 Whole life carbon each orientation

Based on the above results, since the location of the building is in the Netherlands, which is part of the northern hemisphere where the hemisphere tilts toward the sun, the Netherlands receives more direct sunlight, resulting in warmer summers. Therefore, when the south-facing facade receives direct sunlight throughout the day, it has the lowest carbon emissions because it can maximize the use of sunlight for natural heating during the winter. This can reduce the need for heating from fossil fuel heating systems, thus reducing carbon emissions. Additionally, they tend to require less energy for heating during the winter, as sunlight can provide sufficient warmth. Therefore, heating loads on the south-facing facade are the lowest among other orientations.

Conversely, on the north-facing facade, it will receive less sunlight, resulting in higher carbon emissions because it tends to require more heating during the long, cold winter. With less exposure to sunlight, these buildings rely on heating sources such as room heating systems, which may use fossil fuels or other non-renewable energy sources, leading to higher carbon emissions.

Lastly, on facades facing west and east, they provide relatively similar carbon emission results because they receive balanced sunlight exposure throughout the day, with peaks in the morning or evening. Although they do not receive direct sunlight all day like south-facing buildings, west or east-facing facades still require energy for cooling during the day and heating at night, depending on the season. Therefore, it can be concluded that orientation affects carbon emissions in apartment buildings and apartment buildings with south-facing facades are preferable as they result in the least carbon emissions compared to other orientations.

3.4.1.2. Comparison Different Material

a. Scenario 1

In the first scenario, the glass of the window is transitioned from double glass, measuring 6/12/6 mm, to triple glass, measuring 6/12/6/12/6 mm. Consequently, this alteration results in an increase in the embodied carbon, shifting from 107.24 kgCO2/m2 (5362 kgCO2) to 108.46 kgCO2/m2 (5423 kgCO2) for the triple glass configuration. Additionally, the U-factor of the window + frame experiences a reduction from 2.7 W/m2K to 0.9 W/m2K. This decrease in the U-factor signifies a notable decline in energy demand. Presented below are the outcomes of embodied carbon and whole-life carbon emissions employing triple glass:

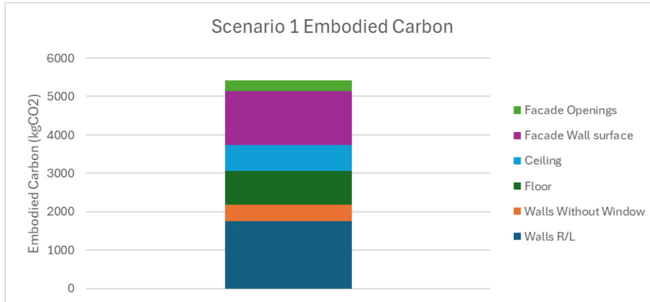

Figure 16 Embodied Carbon (Scenario 1)

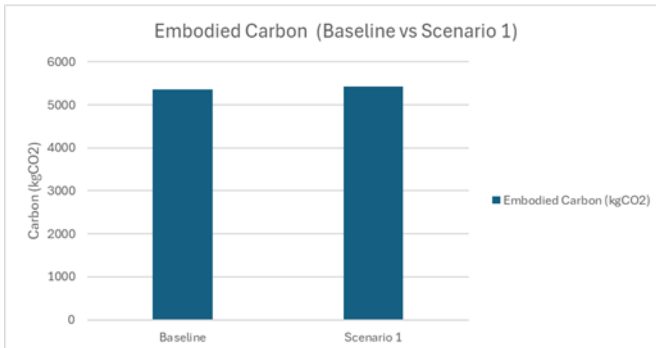

Figure 17 Embodied Carbon (Scenario 1 vs Baseline)

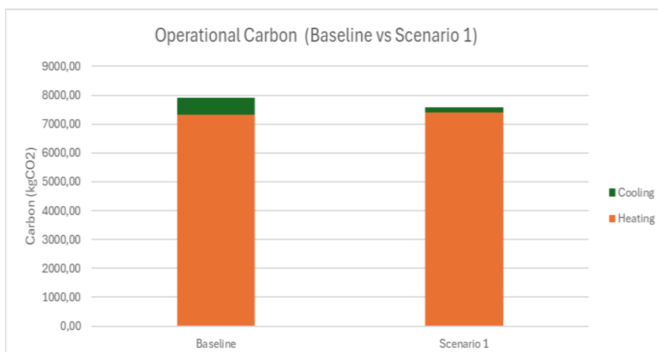

Figure 18 Operational Carbon (Scenario 1 vs Baseline)

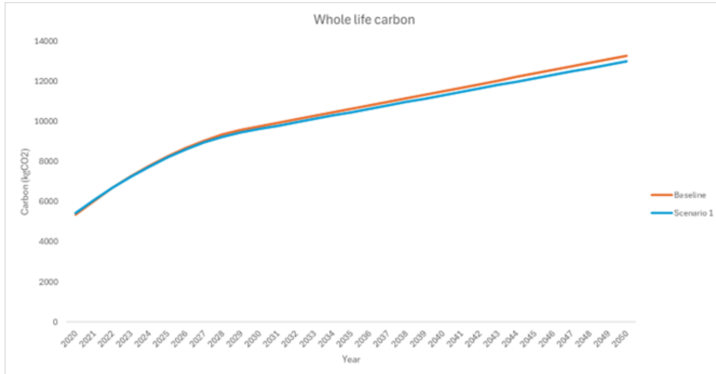

Figure 19 Whole Life Carbon (Scenario 1)

Based on the above results, while the change from general double glass to triple glass windows leads to an increase in embodied carbon, the effectiveness of triple glass in reducing energy demand has been evidenced, resulting in lower operational carbon emissions compared to general double glass. Consequently, in the year 2020, considering solely the embodied carbon, apartment buildings equipped with triple glass windows may exhibit higher carbon emissions than those with general double glass. However, when considering both embodied and operational carbon emissions, projecting forward to the year 2050, apartment buildings featuring triple glass windows demonstrate a reduction in carbon emissions compared to those with general double glass. Hence, it can be concluded that the utilization of triple glass is advantageous over double glass for future applications.

b. Scenario 2

In the second scenario, the thickness of the insulation will be increased three times. Consequently, the embodied carbon will increase from 107.24 kgCO2/m2 (5362 kgCO2) in the baseline scenario 120.34 kgCO2/m2 (6017 kgCO2) in the second scenario. This alteration results in an increase in the R-value of the facade from 3 to 8. However, as the window remains unchanged, the U-factor of the window + frame remains the same. Presented below are the results of embodied carbon and whole-life carbon emissions in the second scenario:

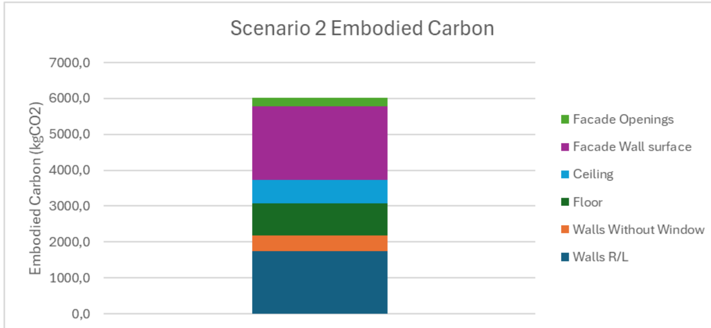

Figure 20 Embodied Carbon (Scenario 2)

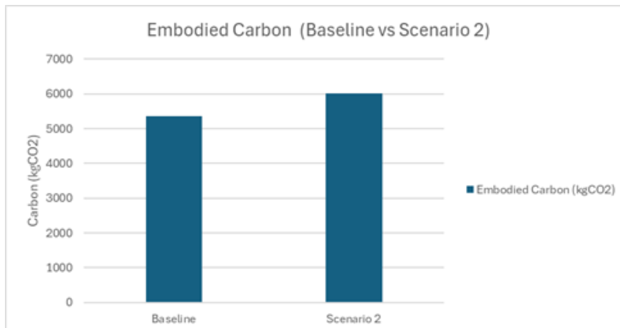

Figure 21 Embodied Carbon (Scenario 2 vs Baseline)

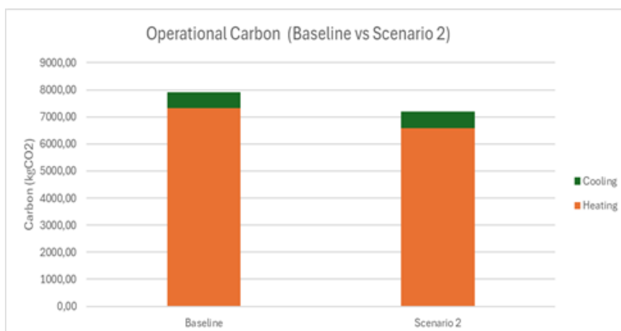

Figure 22 Operational Carbon (Scenario 2 vs Baseline)

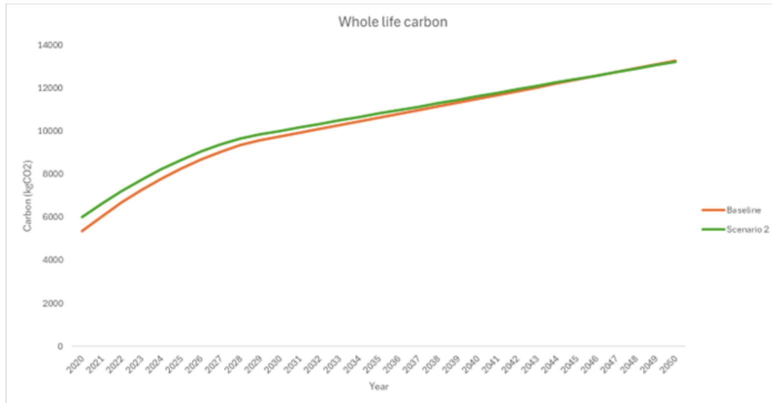

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Figure 23 Whole Life Carbon (Scenario 2)

Based on the above results, the change in insulation thickness significantly affects the increase in embodied carbon emissions. However, it can be observed that adding insulation thickness three times thicker enhances energy efficiency, resulting in smaller operational carbon emissions due to lower heating loads. Therefore, even though in the years 2020-2024, the whole carbon emissions generated from the increase in insulation thickness lead to higher emissions, it becomes evident as time progresses from 2025-2050 that carbon emissions with added insulation thickness decrease in the future. Thus, it can be concluded that insulation thickness influences the outcomes of whole-life carbon emissions and can reduce carbon emissions in apartment buildings.

c. Scenario 3

In the third scenario, the area of the window will be increase from 4 m2 to 16 m2. This will make decrease of the embodied carbon from 107.24 kgCO2/m2 (5362 kgCO2) to 105.14 (5257 kgCO2) for scenario 3. This changing result an increase in the energy demand from 2.518 MWh to 4.314 MWh for the third scenario. Below are the result of embodied carbon and whole life carbon emissions for the third scenario:

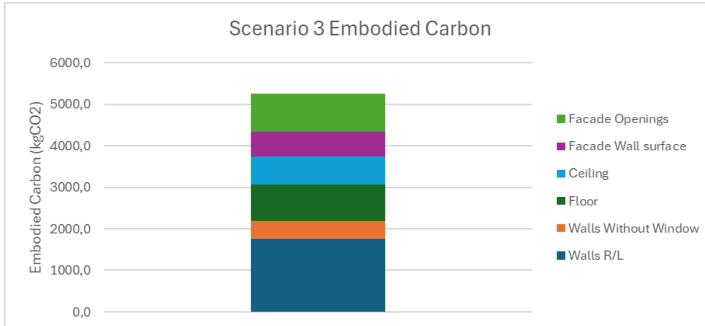


Figure 24 Embodied Carbon (Scenario 3)

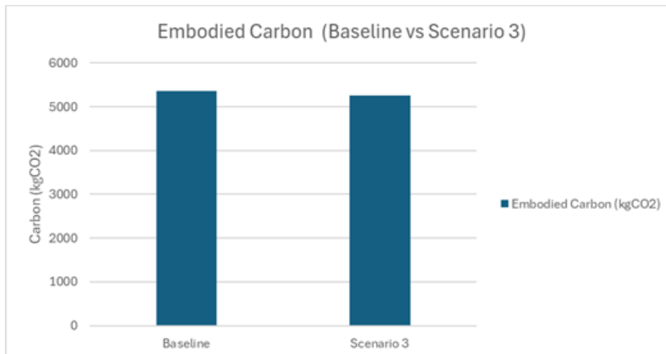


Figure 25 Embodied Carbon (Scenario 3 vs Baseline)

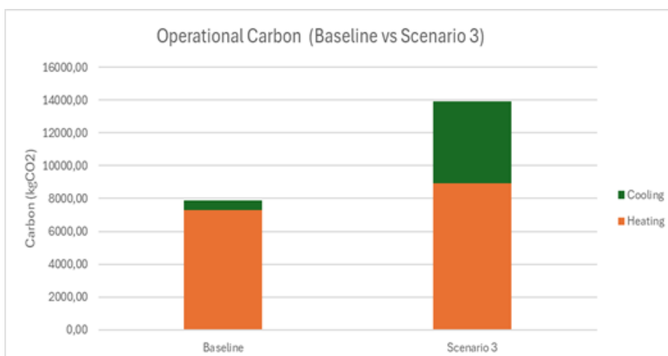


Figure 26 Operational Carbon (Scenario 3 vs Baseline)

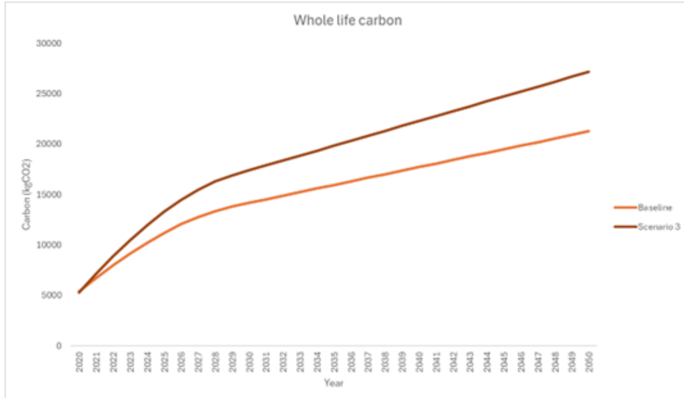


Figure 27 Whole Life Carbon (Scenario 3)

Based on the above results, larger window dimensions lead to a decrease in embodied carbon but an increase in operational carbon. The decrease in embodied carbon can be attributed to the larger size of the window and the smaller surface area of the facade wall, as the facade wall typically has a higher embodied carbon compared to the window. Therefore, increasing the window dimensions tends to decrease the embodied carbon. However, the increase in operational carbon is due to a significant rise in cooling loads, unlike in previous scenarios where the increase in cooling loads was not as pronounced. In this scenario, the increase is substantial.

This increase in cooling loads primarily occurs during the summer season. Larger window dimensions result in more direct exposure to sunlight due to the increased surface area of the window exposed to the sun. Additionally, during the winter season, there is also an increase in heating loads because larger windows allow more heat from indoors to escape to the outside environment, leading to increased heat loss from the room.

Furthermore, with larger window sizes, the surrounding insulated wall area becomes smaller. This can cause greater temperature differences between the inside and outside walls, necessitating more heating loads to achieve the desired indoor temperature, resulting in an increase in heating loads. Therefore, it can be concluded that increasing the dimensions of the window can impact whole life carbon emissions, ultimately leading to an increase in carbon emissions.

3.4.2. 1 Input Scenario (Grasshopper)

All the scenario is using the same HVAC system and with the efficiency of 100%.

a. Scenario 1

In this scenario, which is related to the second scenario of 1 dimension scenario with excel and IESVE software, it involves variations in Rc values due to different thicknesses of insulation. In this scenario, the Rc values range from Rc 0.5 (the least thicker insulation) to Rc 7 (The thickest insulation). These differences will impact both the embodied carbon, increasing from 5038 kgCO2 for Rc 0.5 to 5880 kgCO2 for Rc 7, and the operational carbon, decreasing from 12593 kgCO2 for Rc 0.5 to 7268 kgCO2 for Rc 7. Below are the results of the embodied carbon, operational carbon, and whole-life carbon emissions:

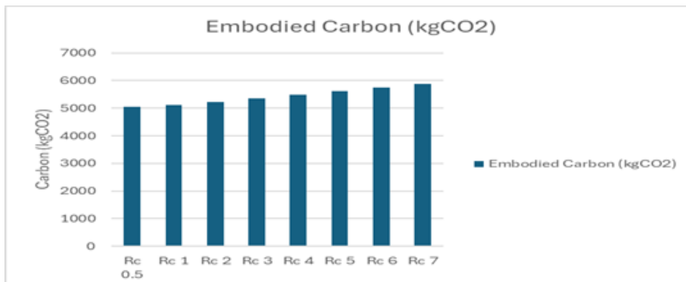


Figure 28 Embodied Carbon (Rc)

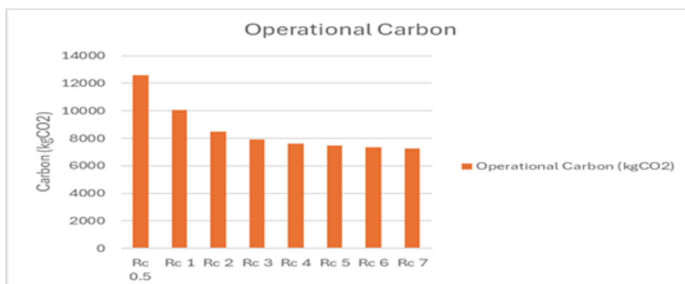


Figure 29 Operational Carbon (Rc)

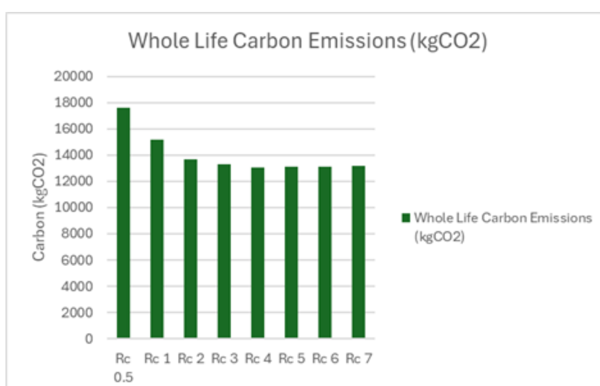


Figure 30 Whole Life Carbon Emissions (Rc)

Based on the above result, the thicker the insulation, the higher the embodied carbon increases. On the other hand, thicker insulation reduces operational carbon and overall carbon emissions. However, even though in the second scenario increasing insulation can efficiently reduce operational carbon emissions in apartment buildings, according to the above result, the efficiency decreases when the Rc value exceeds 4. Therefore, the most efficient thickness increase in insulation is only effective up to Rc 4, as it becomes less efficient beyond that point.

b. Scenario 2

In this scenario, which is related to scenario 3 of 1 dimension scenario with excel and IESVE software, variations in window area are considered, ranging from 0% façade opening (no) window to 100% façade opening (full window). This impacts the embodied carbon, increasing from 5397 kgCO2 for 0% façade opening to 5552 kgCO2 for 100% façade opening, and the increasing operational carbon, ranging from 8410 kgCO2 to 10123 kgCO2. Below are the results of the embodied carbon, operational carbon, and whole-life carbon emissions from this scenario:

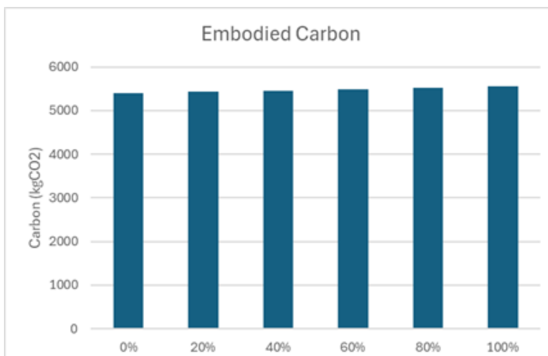


Figure 31 Embodied Carbon (Façade Openings)

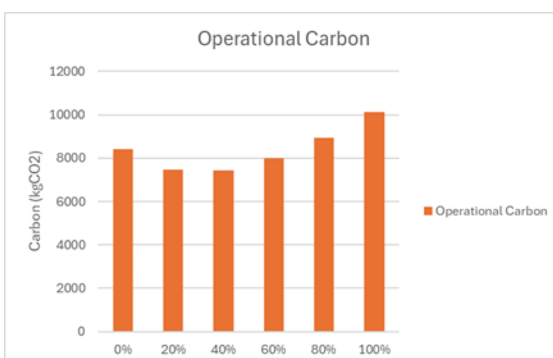


Figure 32 Operational Carbon (Façade Openings)

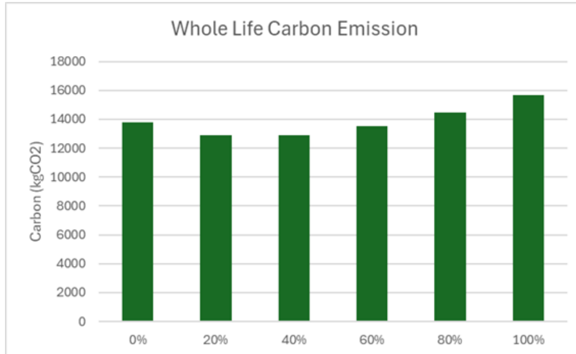


Figure 33 Whole Life Carbon Emissions (Façade Openings)

Based on the above results, a larger window area leads to higher embodied carbon and operational carbon emissions, this is different with the scenario 3 with excel and software IES because the different in the type of glazed, where in that case is using the double glazed that has much lower embodied carbon than triple glazed where it use in this case. Using double glazed make the wall surface more dominant as embodied carbon than window therefore with the double glazed where the window is increase it makes a decrease of embodied carbon from wall surface. On the other hand, using the triple glazed it makes that the window more dominant as embodied carbon than wall surface, therefore when increase the window, it will increase the embodied carbon.

Moreover, The lowest whole-life carbon emissions occur with a 40% façade opening. This happens because there's a balance between embodied and operational carbon. For instance, although a 0% façade opening results in the lowest embodied carbon, the operational carbon is not lower than 20%-60% façade opening. This explains the reason a 0% façade opening does not result the lowest whole life carbon emissions. However, the range between embodied carbon values is smaller than that of operational carbon. Therefore, the one that influence the result of whole life carbon emissions in this scenario is the operational carbon.

c. Scenario 3

In this scenario, different U factors are examined, which is related to the first scenario where general double glass is replaced with triple glass. These differences arise from the use of various types of glass. Five types of glass are tested in this scenario: double glass, double glass HR, double glass HR +, double glass HR ++, and triple glass. General double glass has the highest U factor of 2.7 W/m2K, followed by double glass HR with a U factor of 1.9 W/m2K, double glass HR + with a

U factor of 1.6 W/m2K, double glass HR ++ with a U factor of 1.2 W/m2K, and triple glass with the lowest U factor, which is 0.9 W/m2K. Below are the results of the embodied carbon, operational carbon, and whole-life carbon emissions:

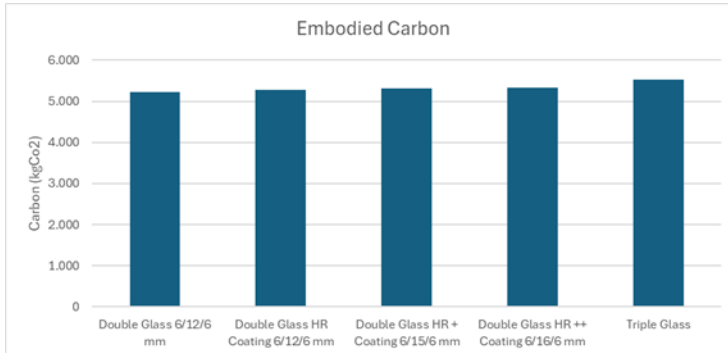


Figure 34 Embodied Carbon (U factor)

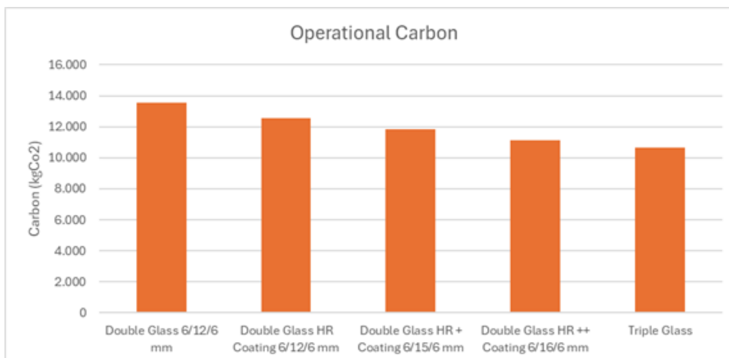


Figure 35 Operational Carbon (U factor)

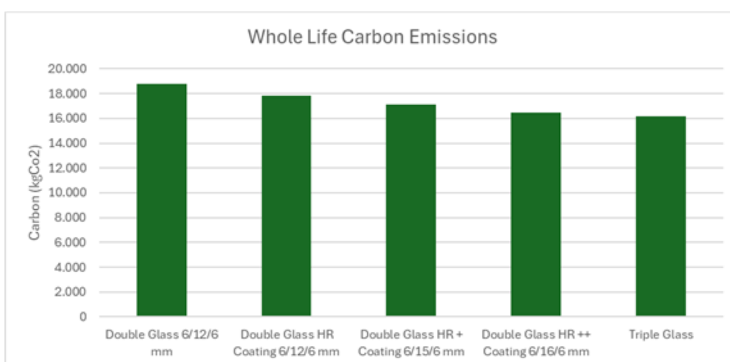


Figure 36 Whole Life Carbon Emission (U factor)

Based on the above results, although triple glass yields the highest embodied carbon compared to other materials, its operational carbon is remarkably efficient, being the lowest among them and leading to the lowest whole-life carbon emissions. This phenomenon can be attributed to the additional layers in triple glass, which create additional insulation space that slows down heat flow through the windows. Consequently, triple glass provides a higher level of insulation compared to double glass, thereby reducing heat leakage from the indoor space and decreasing the need for additional heating or cooling. This results in greater energy savings and higher long-term energy efficiency.

Thus, it can be concluded in this scenario that the results of embodied carbon are inversely related to the results of operational carbon, and operational carbon has a greater impact on whole-life carbon emissions. Therefore, in this scenario, triple glass, which has the lowest operational carbon, also exhibits the lowest whole-life carbon emissions.

d. Scenario 4

In this scenario, different dimensions of building model is implied. The input is 3 meter, 4 meter, and 5 meter for each width, length, and height. Below are the result of embodied carbon, operational carbon, and whole life carbon emissions:

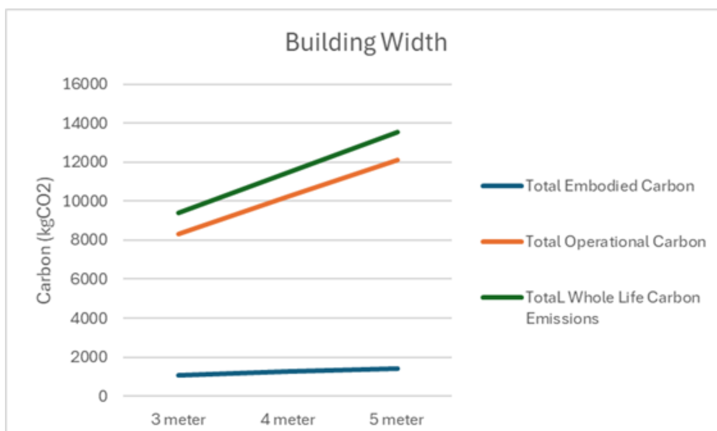


Figure 37 Building width

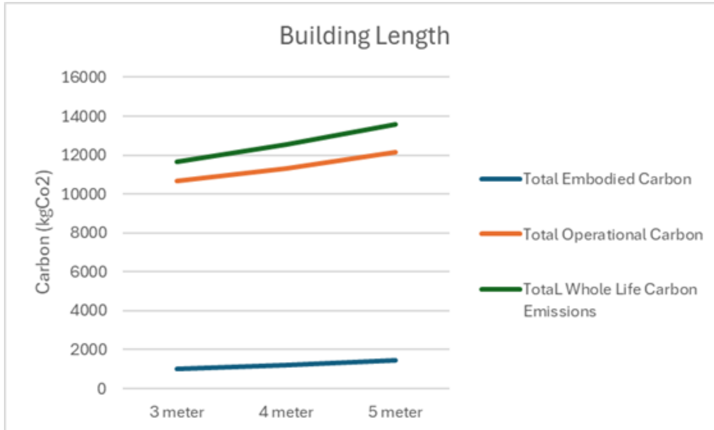


Figure 38 Building length

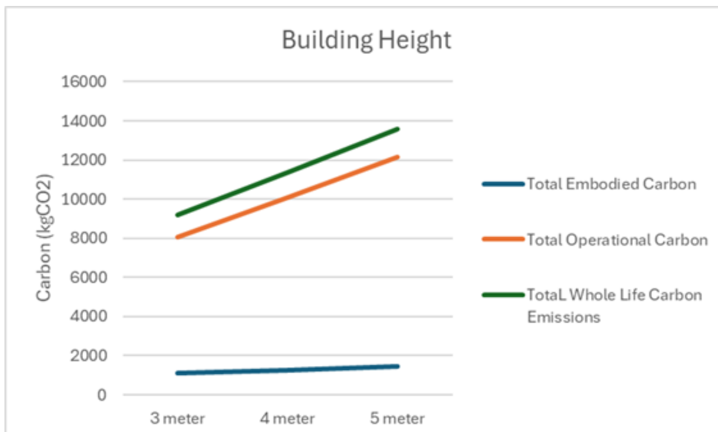


Figure 39 Building height

Based on the above results, higher dimensions of a building correspond to increased quantities of both embodied and operational carbon emissions, consequently leading to higher whole-life carbon emissions. This correlation arises from the fact that embodied carbon is directly influenced by the quantity of materials used, thus higher dimensions result in greater embodied carbon. Similarly, operational carbon, which is linked to energy demand, follows a similar trend; larger dimensions require more energy for heating or cooling due to the increased space to be conditioned.

Moreover, the analysis indicates that variations in building width and height have a more significant impact compared to changes in building length. This is attributed to the width and height being the façades directly exposed to the external environment. Consequently, it can be concluded that façades represent the most influential surfaces for carbon emissions.

3.4.3. 2 Input Scenario (Grasshopper)

a. Scenario 1

In this scenario the are 2 inputs which are different façade opening and different thickness of the façade insulation. However, the dimension of the building and the material are same. The material of the glazed is Triple glazed, which has 0.9 W/m2K and glass wool for their insulation. Below are the list of thickness, result of embodied, operational, and whole life carbon emissions:

Table 16 List of Thickness for facade insulation

Facade thickness insulation	Thickness (mm)	Rc	
		Glass wool	PUR
0	0	0,0	0,0
1	50	1,3	1,4
2	70	1,8	2,0
3	100	2,5	2,9
4	150	3,8	4,3
5	180	4,5	5,1
6	210	5,3	6,0

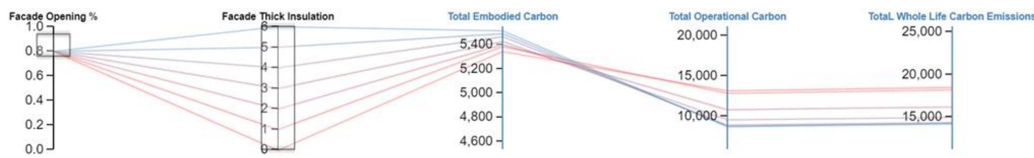


Figure 40 Facade opening 80% and Different Thickness Insulation

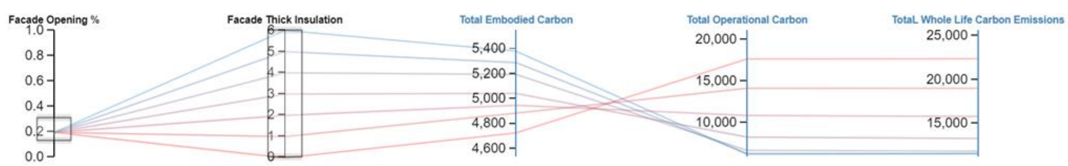


Figure 41 Facade opening 20% and Different Thickness Insulation

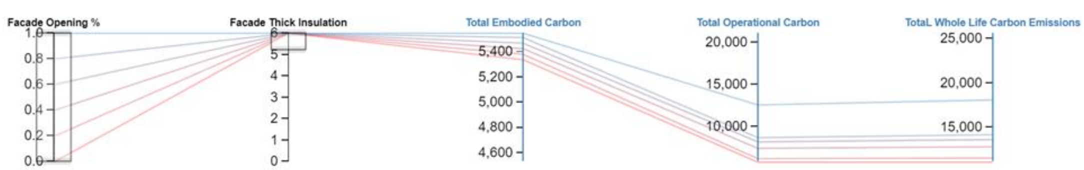


Figure 42 Thickness number 6 and Different Facade Opening

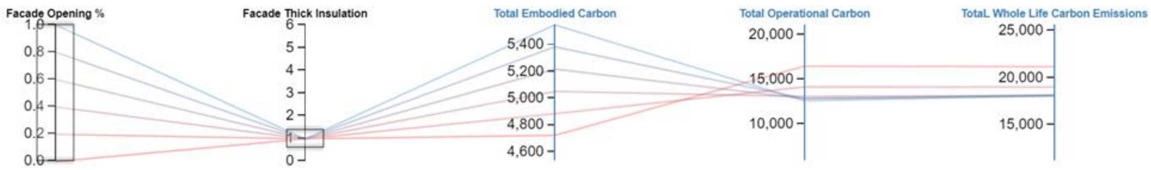


Figure 43 Thickness number 1 and Different Facade Opening

Table 17 Result scenario 1 (2 input)

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
0	0.0	4531.305	21064.219	25595.524
0	0.2	4729.67549	17645.073	22374.74849
0	0.4	4933.990624	15351.146	20285.136624
0	0.6	5138.305758	14051.5	19189.805758
0	0.8	5342.620892	13153.146	18495.766892
0	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
1	0.0	4726.305	16450.146	21176.451
1	0.2	4887.07247	14138.792	19025.86447
1	0.4	5052.621604	13083.281	18135.902604
1	0.6	5218.170738	12839.146	18057.316738
1	0.8	5383.719872	12830.354	18214.073872
1	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
2	0.0	4804.305	12978.719	17783.024
2	0.2	4950.031262	10885.281	15835.312262
2	0.4	5100.073996	10292.292	15392.365996
2	0.6	5250.11673	10440.5	15690.61673
2	0.8	5400.159464	10815.573	16215.732464
2	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
3	0.0	4921.305	9952.073	14873.378
3	0.2	5044.46945	8294.781	13339.25045
3	0.4	5171.252584	8390.708	13561.960584
3	0.6	5298.035718	8992.646	14290.681718
3	0.8	5424.818852	9568.208	14993.026852
3	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
4	0.0	5108.505	7387.792	12496.297
4	0.2	5195.57055	6698.719	11894.28955
4	0.4	5285.138324	7501.146	12786.284324
4	0.6	5374.706098	8329.792	13704.498098
4	0.8	5464.273872	8931.573	14395.846872
4	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
5	0.0	5225.505	6445.792	11671.297
5	0.2	5290.008738	6349.708	11639.716738
5	0.4	5356.316912	7422.646	12778.962912
5	0.6	5422.625086	8242.5	13665.125086
5	0.8	5488.93326	8792	14280.93326
5	1.0	5546.936026	12577.427	18124.363026

Facade Thick Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
6	0.0	5338.605	5809	11147.605
6	0.2	5381.298987	6227.719	11609.017987
6	0.4	5425.122881	7448.708	12873.830881
6	0.6	5468.946775	8216.281	13685.227775
6	0.8	5512.770669	8713.5	14226.270669
6	1.0	5546.936026	12577.427	18124.363026

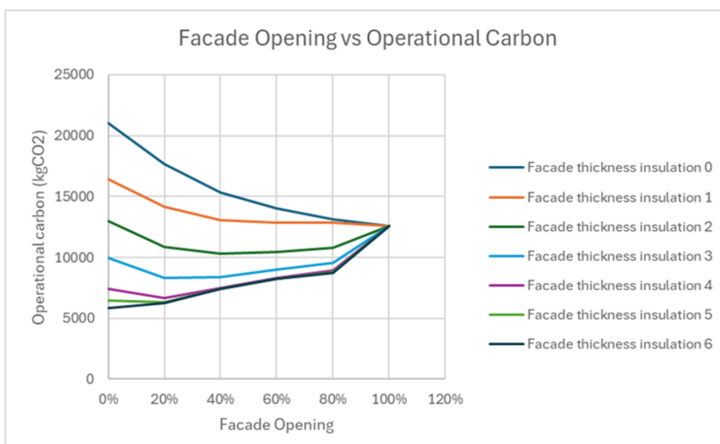


Figure 44 Facade opening vs Operational Carbon (scenario 1, 2 input)

The above results demonstrate that both inputs impact embodied and operational carbon emissions. However, operational carbon has a greater influence than embodied carbon on the result of whole life carbon emissions. This can be seen in Figures 40, 41, 42, and 43, where the ranking of operational carbon is the same as that of whole life carbon emissions.

Moreover, there are some findings from these two inputs. First, when the thermal resistance of the window is higher than that of the wall façade, indicating lower conductivity, this can be seen on the figure 43 and figure 44, where a larger window will result in lower operational carbon emissions compared to a smaller window. This is because it implies that the window becomes a better insulator than the wall surface (see thickness number 0 & 1). In scenarios where the triple-glazed window, which has 0.9 W/m²K, is used, and the thickness is at number 0 and 1, the conductivity of the façade wall surface is greater than that of the glazed window. This means their thermal resistance is lower than the window, therefore, a larger glazed window will decrease operational carbon. However, even though a 100% façade opening results in the lowest operational carbon for thickness number 1, the embodied carbon for a 100% façade opening is high, leading to higher whole-life carbon emissions. This can be seen in table 17, where for thickness number 0, the lowest whole-life carbon emissions occur with a 100% façade opening, while for thickness number 1, the lowest whole-life carbon emissions occur with a 60% façade opening.

Secondly, when the thermal resistance of the window is smaller than that of the wall façade (above thickness number 1), the optimal façade opening will vary. This can be seen on the figure 44 and table 17, where in higher façade thickness insulation the optimum result for façade opening is vary. This is because when there is no window at all, the heating loads are very high and the cooling loads are low. On the other hand, with a window, the heating loads decrease as the room receives support from sunlight, but the cooling loads increase during the summer due to the entry of heat into the room. However, a large window significantly increases the heating and cooling loads, which can lead to higher energy use and increased whole-life carbon emissions. This is illustrated in table 17, where for façade thickness above number 3, starting from a 40% façade opening, the operational carbon is higher than at 0% façade opening, leading to higher whole-life carbon emissions.

Lastly, when the façade is already Rc 4 and above (thickness number 4), increasing thickness is not as efficient anymore. This can be seen in the figure 44, when the façade thickness number 4, 5, and 6 has similar line. Therefore, different window sizes will more significantly affect the result of operational carbon and whole-life carbon emissions. This can be seen at façade thickness number 4, where increasing the thickness to number 6 with a 60% façade opening results in only a small decrease in operational carbon from 8329 kgCO2 to 8216 kgCO2. However, decreasing the opening of thickness number 4 from 60% to 40% decreases the operational carbon from 8329 kgCO2 to 7501 kgCO2, leading to a much higher reduction in whole-life carbon emissions as well.

b. Scenario 2

In this scenario there are 2 inputs which are Façade Openings and Glazed type. The thickness and the material of the façade insulation and the other surface is same. Below are the result of the embodied, operational, and whole life carbon emissions:

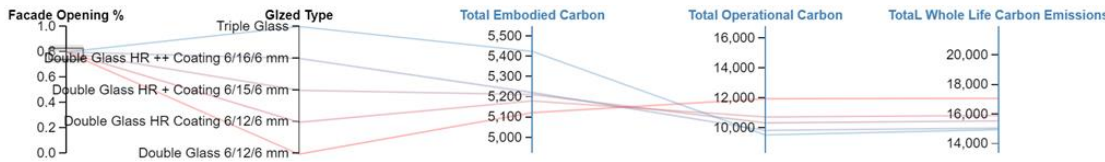


Figure 45 80% Facade Openings and Different Type of Glazed

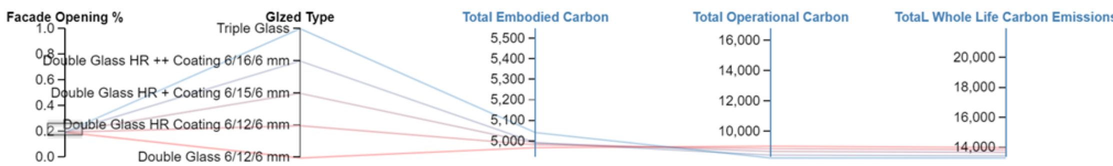


Figure 46 20% Facade Openings and Different Type of Glazed

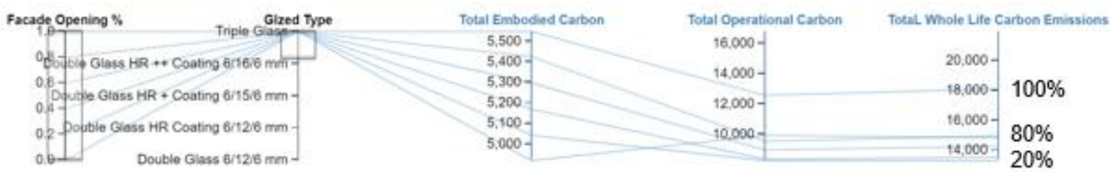


Figure 47 Triple Glazed and Different Facade Openings

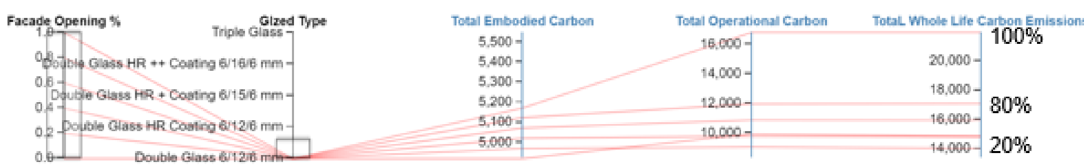


Figure 48 Double Glazed HR and Different Facade Openings

Table 18 Result of scenario 2 (2 input)

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	0.0	4921.305	9952.073	14873.378
Double Glass HR + Coating 6/...	0.0	4921.305	9952.073	14873.378
Double Glass HR ++ Coating 6...	0.0	4921.305	9952.073	14873.378
Double Glass HR Coating 6/12...	0.0	4921.305	9952.073	14873.378
Triple Glass	0.0	4921.305	9952.073	14873.378

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	0.2	4971.19177	9071.146	14042.33777
Double Glass HR + Coating 6/...	0.2	4992.88582	8722.292	13715.17782
Double Glass HR ++ Coating 6...	0.2	4995.29627	8486.792	13482.08827
Double Glass HR Coating 6/12...	0.2	4985.17238	8905.354	13890.52638
Triple Glass	0.2	5044.46945	8294.781	13339.25045

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	0.4	5022.430904	9803.708	14826.138904
Double Glass HR + Coating 6/...	0.4	5066.489954	8914.146	13980.635954
Double Glass HR ++ Coating 6...	0.4	5071.385404	8600.146	13671.531404
Double Glass HR Coating 6/12...	0.4	5050.824514	9158.281	14209.105514
Triple Glass	0.4	5171.252584	8390.708	13561.960584

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	0.6	5073.670038	10894.073	15967.743038
Double Glass HR + Coating 6/...	0.6	5140.094088	9620.646	14760.740088
Double Glass HR ++ Coating 6...	0.6	5147.474538	9254.208	14401.682538
Double Glass HR Coating 6/12...	0.6	5116.476648	9934.646	15051.122648
Triple Glass	0.6	5298.035718	8992.646	14290.681718

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	0.8	5124.909172	11975.646	17100.555172
Double Glass HR + Coating 6/...	0.8	5213.698222	10370.792	15584.490222
Double Glass HR ++ Coating 6...	0.8	5223.563672	9873.573	15097.136672
Double Glass HR Coating 6/12...	0.8	5182.128782	10763.292	15945.420782
Triple Glass	0.8	5424.818852	9568.208	14993.026852

Glzed Type	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	1.0	5171.482346	16772.781	21944.263346
Double Glass HR + Coating 6/...	1.0	5282.636396	14295.792	19578.428396
Double Glass HR ++ Coating 6...	1.0	5294.986846	13301.354	18596.340846
Double Glass HR Coating 6/12...	1.0	5243.114956	15080.792	20323.906956
Triple Glass	1.0	5546.936026	12577.427	18124.363026

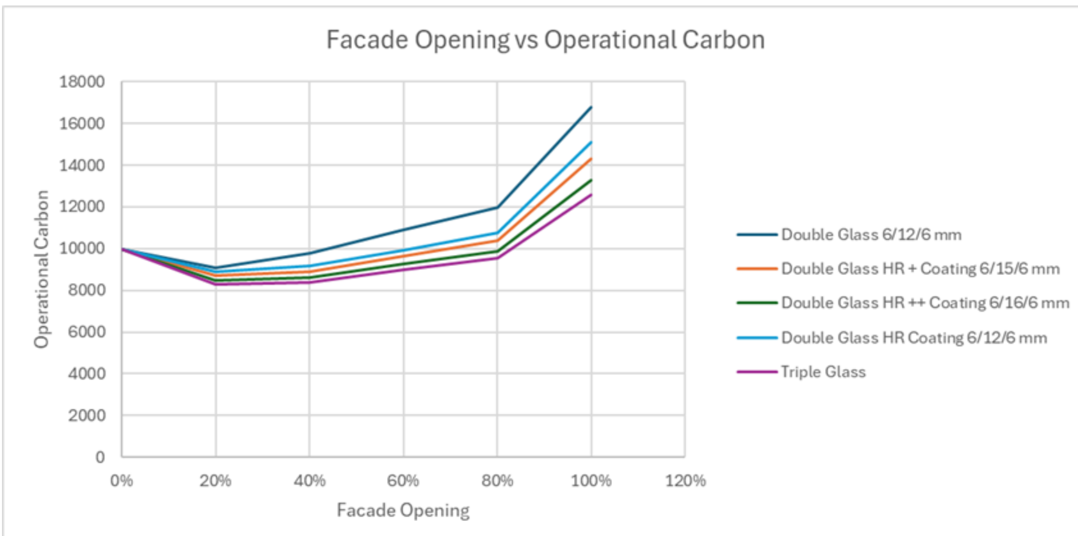


Figure 49 Facade opening vs Operational carbon (scenario 2, 2 input)

Based on the above results, both inputs impact embodied and operational carbon emissions. However, operational carbon has a greater influence than embodied carbon on the result of whole life carbon emissions. This can be seen in Figures 45, 46, 47, and 48, where the ranking of operational carbon is the same as that of whole life carbon emissions there are two findings.

Moreover, there are 2 findings from this scenario. First, the lower the conductivity, the smaller the result gap of façade openings. This can be seen in Figure 45, 46, and Table 18, where the operational carbon emissions for a 20% façade opening of triple glazing is 13,339 kgCO2, and for an 80% façade opening of triple glazing, it is 18,124 kgCO2. In contrast, for double glazing (6/12/6 mm), the emissions range from 14,042 kgCO2 at a 20% façade opening to 21,944 kgCO2 at an 80% façade opening. This is because the lower conductivity of the triple-glazed windows results in much less heat loss, meaning less energy is required to heat or cool the room. Therefore, the difference in operational carbon emissions between various façade openings is not as significant as with the higher conductivity double-glazed windows (6/12/6 mm).

Secondly, regardless of the size of the façade opening, triple glazing, which has the lowest conductivity, will result in the lowest operational carbon emissions and, consequently, the lowest whole-life carbon emissions. This can be seen in the figure 49, where the line of the triple glazed is below than the other types of glazed. This is because lower conductivity results in significantly less heat loss, meaning less energy is required to maintain the room's temperature. Consequently, this leads to substantial energy savings, thereby reducing overall energy use and carbon emissions.

c. Scenario 3

In this scenario, there are 2 inputs which are different types of window frame material and different types of glazed material. Below are the result are the result of embodied, operational, and whole life carbon emissions:

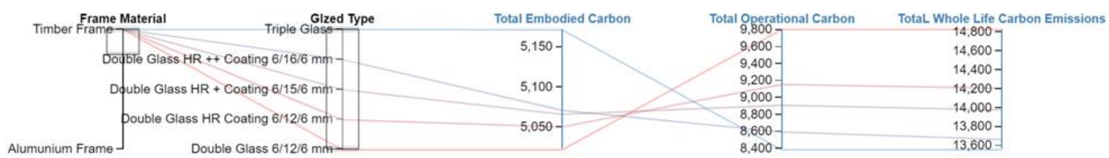


Figure 50 Timber Frame and Different Glazed Type

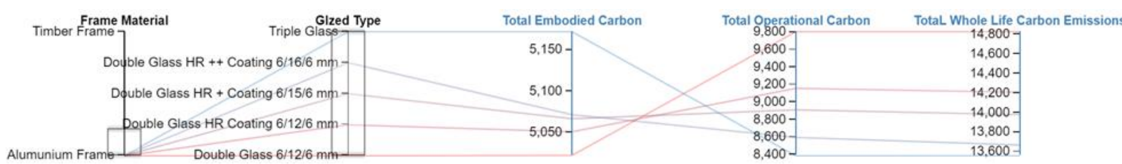


Figure 51 Aluminum Frame and Different Glazed Type

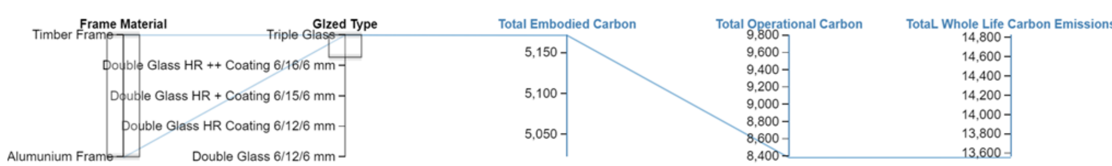


Figure 52 Triple glazed + and Different Frame Material

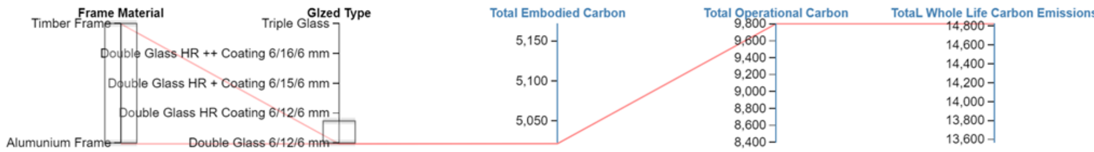


Figure 53 Double Glazed and Different Frame Material

Table 19 Result scenario 3 (2 input)

Glzed Type	Frame Material	Total Embodie...	Total Operatio...	TotaL Whole Li...
Double Glass 6/12/6 mm	Alumunium Fra...	5022.911013	9803.708	14826.619013
Double Glass 6/12/6 mm	Timber Frame	5022.430904	9803.708	14826.138904

Based on the above results, it is evident that the type of glazing has a more influence on both embodied and operational carbon emissions, while different types of frame materials do not have a significant impact or only exert a minimal influence due to the very small dimensions of the frame. It can be seen on the figure 50, 51, and table 19, where the different type of frame material not affect the operational carbon. Therefore, it can be concluded that the type of glazing material has a greater influence than the choice of frame material.

d. Scenario 4

In this scenario, there are 2 inputs which are Façade thick insulation and Façade Insulation Material. Below are the results of embodied, operational, and whole life carbon emissions:

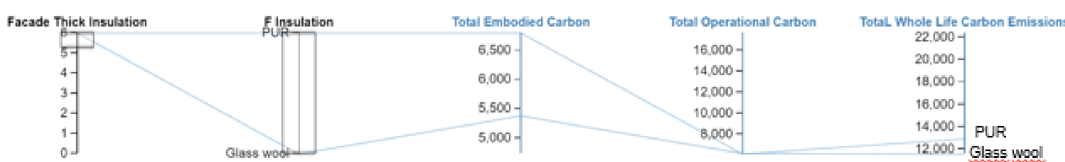


Figure 54 Thickness number 6 and Different Facade Insulation Material

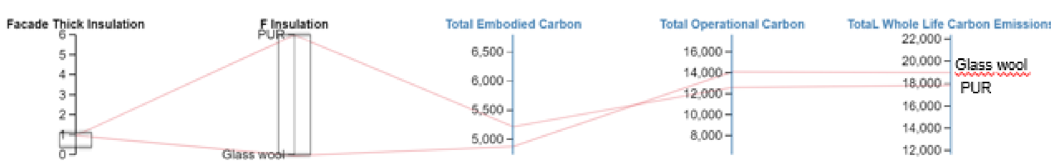


Figure 55 Thickness number 1 and Different Facade Insulation Material

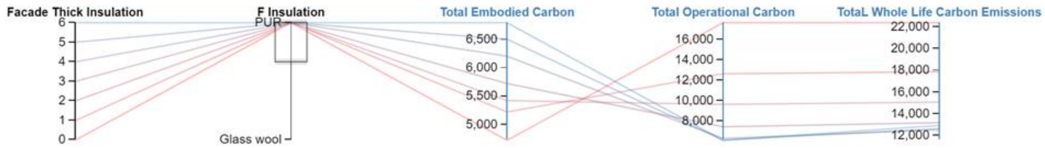


Figure 56 PUR and Different Rc

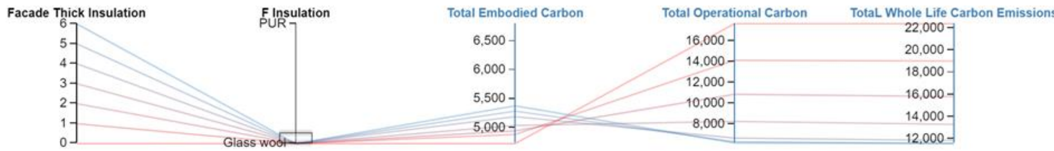


Figure 57 Glass Wool and Different Rc

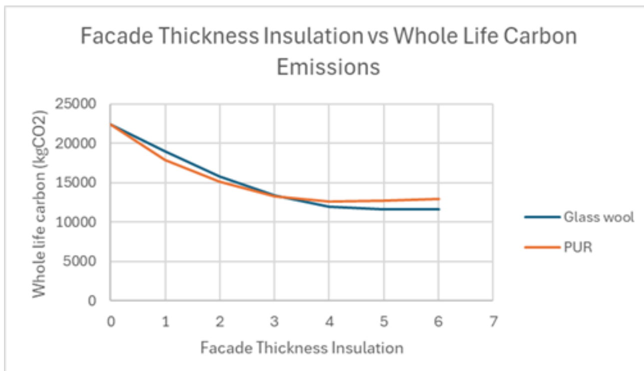


Figure 58 Facade thickness insulation vs Whole life carbon (scenario 4, 2 input)

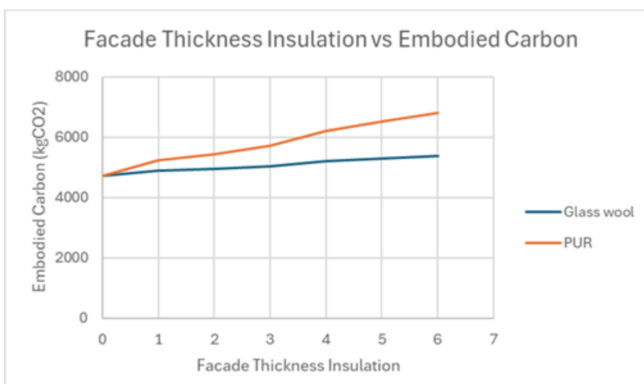


Figure 59 Facade thickness insulation vs Embodied carbon (scenario 4, 2 input)

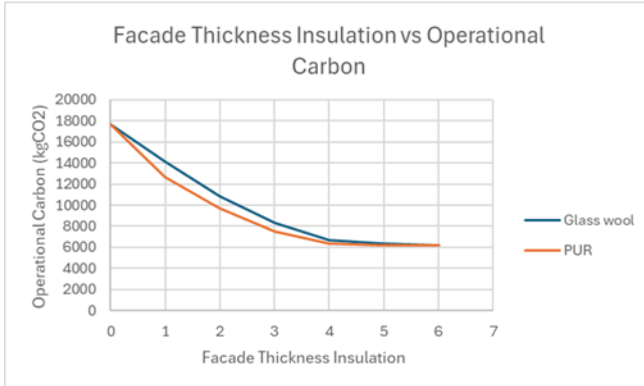


Figure 60 Facade thickness insulation vs Operational carbon (scenario 4, 2 input)

Table 20 Result scenario 4 (2 input)

Facade Thick Insulation	F Insulation	Total Embodie...	Total Operatio...	TotaL Whole Li...
1	Glass wool	4887.07247	14138.792	19025.86447
1	PUR	5229.386686	12655.927	17885.313686
2	Glass wool	4950.031262	10885.281	15835.312262
2	PUR	5429.271165	9672.927	15102.198165

Facade Thick Insulation	F Insulation	Total Embodie...	Total Operatio...	TotaL Whole Li...
5	Glass wool	5290.008738	6349.708	11639.716738
5	PUR	6508.647349	6175.281	12683.928349
6	Glass wool	5381.298987	6227.719	11609.017987
6	PUR	6798.479843	6166.646	12965.125843

Based on the above results, façade thickness insulation influences both embodied and operational carbon, but it has a greater impact on operational carbon compared to façade insulation material. Façade insulation material only influences embodied carbon emissions. This can be observed in Figures 54 and 55, where varying façade thickness insulation yields different results in operational carbon, affecting the overall life cycle carbon emissions. However, different façade insulation materials do not significantly modify operational carbon or the resulting whole life carbon emissions.

Moreover, PUR always has higher embodied carbon and lower operational carbon than glass wool, see figure 58 and 59. However, below Rc 4, PUR has lower whole-life carbon emissions than glass wool, but above Rc 4, PUR has higher whole-life carbon emissions, see figure 60 and table 20. This is because PUR's high embodied carbon and the reduced effectiveness of thick insulation for operational carbon lead to higher whole-life carbon emissions above Rc 4. This also can be seen in table 20, where at insulation thickness numbers 1 and 2, PUR has lower operational carbon and thus lower whole-life carbon emissions than glass wool. However, at insulation thickness numbers 5 and 6, while PUR still has lower operational carbon, it does not result in lower whole-life carbon emissions due to its high embodied carbon. Hence, it can be concluded that PUR is effective in decreasing whole-life carbon emissions when the façade's Rc is below Rc 4.

Furthermore, based on the first findings, façade thickness insulation has a more significant influence at lower thickness levels, particularly below Rc 4, than façade insulation material. This is evident in table 20, where with glass wool insulation at thickness level 1, increasing the façade thickness insulation to level 2 decreases operational carbon and thus whole-life carbon emissions, from 19,025 kgCO2 to 15,835 kgCO2. However, with the same façade thickness insulation (thickness number 1), changing the material from glass wool to PUR decreases operational carbon and whole-life carbon emissions from 19,025 kgCO2 to 17,885 kgCO2. Therefore, it can be concluded that façade thickness insulation is more effective in decreasing operational carbon and whole-life carbon emissions than the insulation material type when the Rc is below Rc 4.

e. Scenario 5

In this scenario, there are 2 inputs which are Façade opening and orientation of the building. Below are the results of embodied, operational, and whole life carbon emissions:

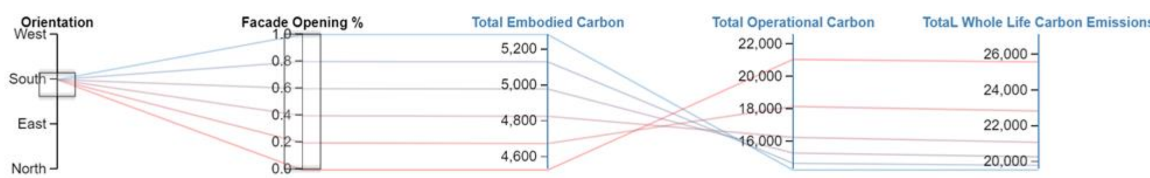


Figure 61 South Orientation and Facade Opening

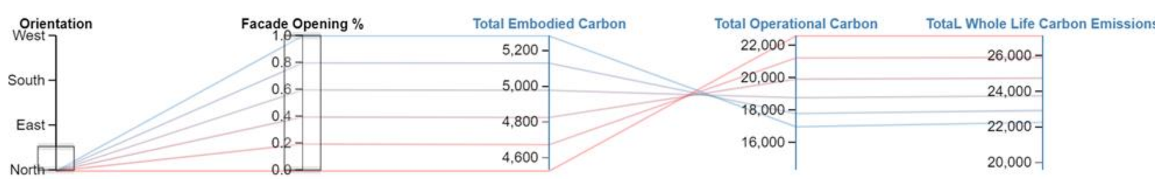


Figure 62 North Orientation and Facade Opening

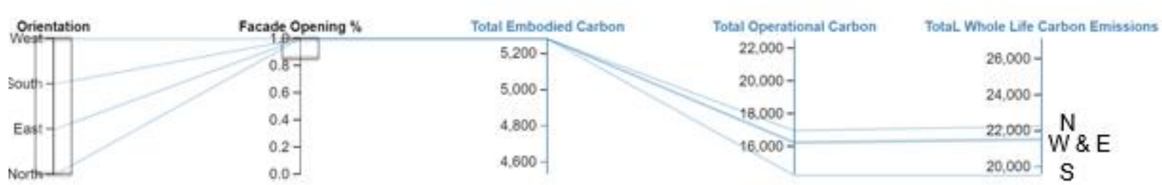


Figure 63 100% Facade Opening and Building Orientation

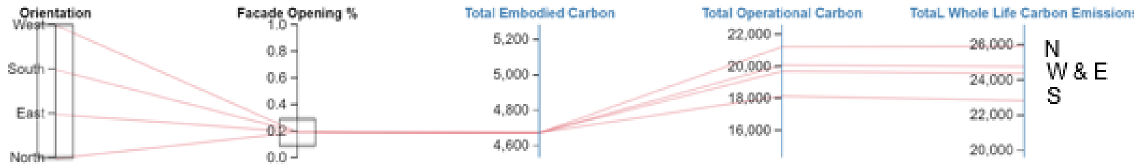


Figure 64 20% Facade Opening and Building Orientation

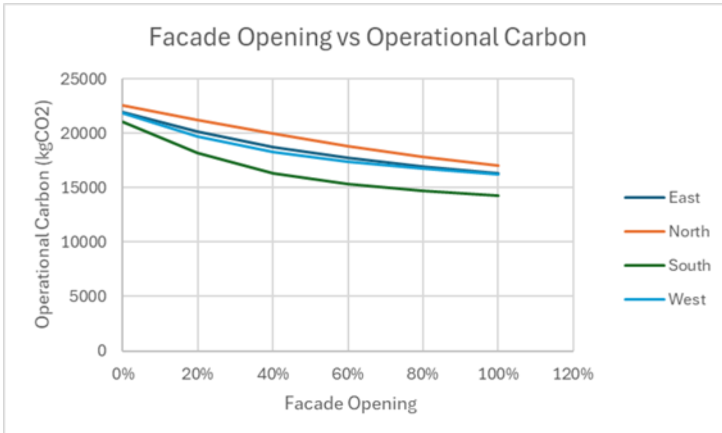


Figure 65 Facade opening vs Operational Carbon (scenario 5, 2 input)

Table 21 Result of scenario 5 (2 input)

Facade Opening %	Orientation	Total Embodie...	Total Operatio...	TotaL Whole Li...
1.0	North	5282.636396	17017.073	22299.709396
1.0	East	5282.636396	16328	21610.636396
1.0	South	5282.636396	14295.792	19578.428396
1.0	West	5282.636396	16249.5	21532.136396

Facade Opening %	Orientation	Total Embodie...	Total Operatio...	TotaL Whole Li...
0.2	North	4678.09186	21238.646	25916.73786
0.2	East	4678.09186	20113.427	24791.51886
0.2	South	4678.09186	18185.781	22863.87286
0.2	West	4678.09186	19720.927	24399.01886

Facade Opening %	Orientation	Total Embodie...	Total Operatio...	TotaL Whole Li...
0.0	South	4531.305	21064.219	25595.524
0.2	South	4678.09186	18185.781	22863.87286
0.4	South	4829.227994	16293.146	21122.373994
0.6	South	4980.364128	15333.719	20314.083128
0.8	South	5131.500262	14705.719	19837.219262
1.0	South	5282.636396	14295.792	19578.428396

Facade Opening %	Orientation	Total Embodie...	Total Operatio...	TotaL Whole Li...
0.0	North	4531.305	22590.573	27121.878
0.2	North	4678.09186	21238.646	25916.73786
0.4	North	4829.227994	19939	24768.227994
0.6	North	4980.364128	18796.354	23776.718128
0.8	North	5131.500262	17828.292	22959.792262
1.0	North	5282.636396	17017.073	22299.709396

Based on the above results, the facade opening has a greater impact on both embodied carbon emissions. In contrast, building orientation has no impact on embodied carbon emissions but does affect operational carbon emissions to some extent. However, regardless of the facade opening, a south orientation consistently results in the lowest operational carbon emissions, leading to the lowest whole-life carbon emissions. The reason for this is same as the first scenario that using the software IES and excel to calculate the whole life carbon emissions.

3.4.4.3 Input Scenario

a. Scenario 1

In this scenario, there are 3 inputs which are different façade openings, different façade thickness insulation and glazed type, but same glass wool as façade insulation material Below are the results of embodied, operational, and whole life carbon emissions of this scenario:

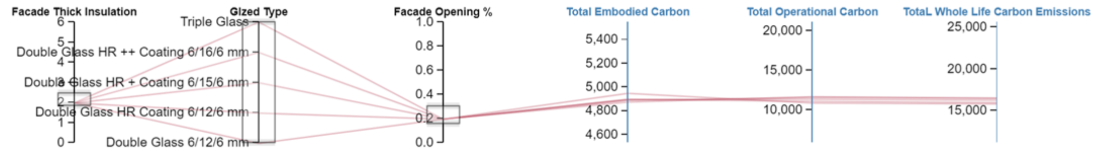


Figure 66 Different glazed type, façade thickness insulation number 2 and façade opening 20%

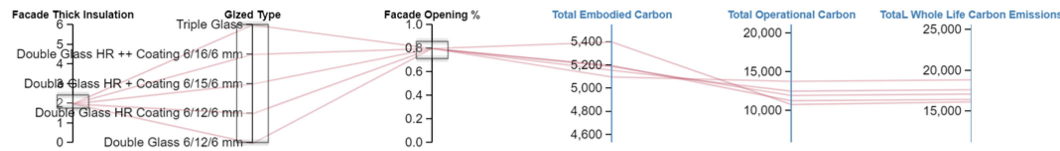


Figure 67 Different glazed type, façade thickness insulation number 2 and façade opening 80%

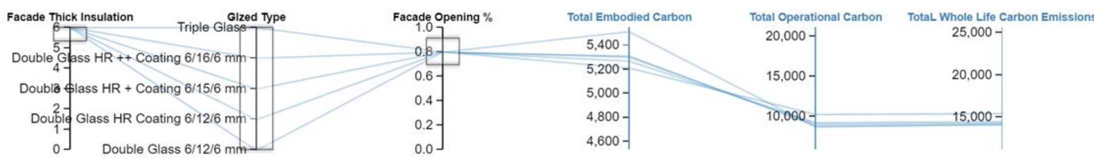


Figure 68 Different glazed type, façade thickness insulation number 6 and façade opening 80%

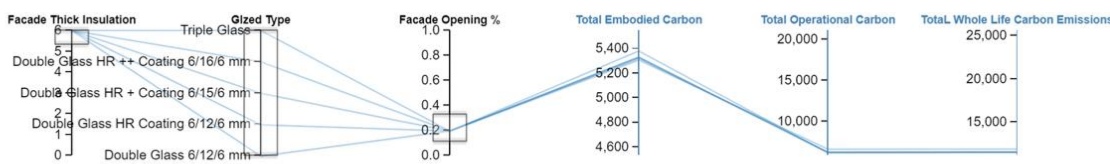


Figure 69 Different glazed type, façade thickness insulation number 6 and façade opening 20%

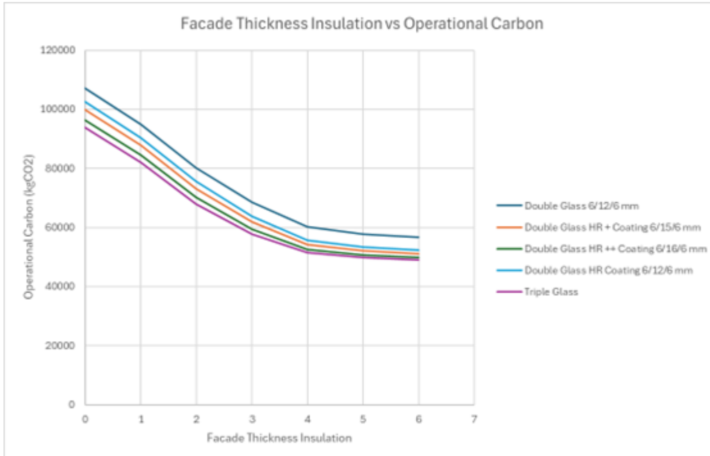


Figure 70 Facade thickness insulation vs Operational carbon (scenario 1, 3 input)

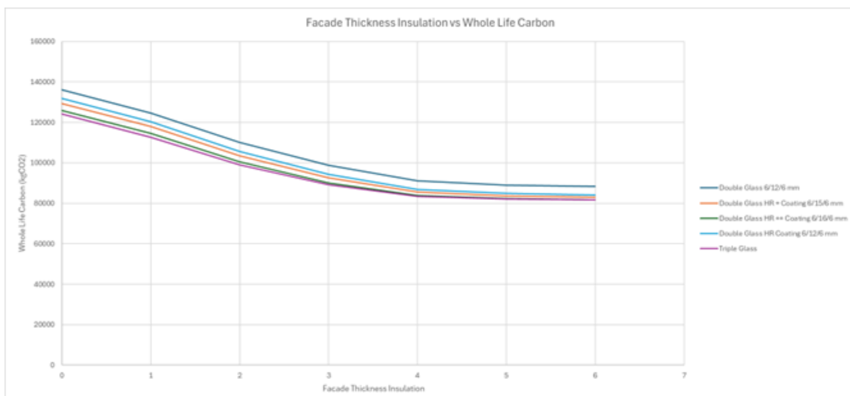


Figure 71 Facade thickness insulation vs Whole life carbon

Table 22 Result scenario 1 (3 input)

Facade Thick Insulation	scid	Glzed Type	Facade Openi…	Total Embodie…	Total Operatio…	TotaL Whole Li…
2	37	Double Glass 6…	0.2	4876.753582	11687.708	16564.461582
2	44	Double Glass H…	0.2	4890.734192	11600.573	16491.307192
2	51	Double Glass H…	0.2	4898.447632	11382.5	16280.947632
2	58	Double Glass H…	0.2	4900.858082	11094.719	15995.577082
2	65	Triple Glass	0.2	4950.031262	10885.281	15835.312262

Facade Thick Insulation	scid	Glzed Type	Facade Openi…	Total Embodie…	Total Operatio…	TotaL Whole Li…
6	146	Double Glass 6…	0.8	5212.860989	10266.073	15478.933989
6	153	Double Glass H…	0.8	5270.080599	9254.208	14524.288599
6	160	Double Glass H…	0.8	5301.650039	9053.719	14355.369039
6	167	Double Glass H…	0.8	5311.515489	8826.854	14138.369489
6		Triple Glass	0.8	5512.770669	8713.5	14226.270669

Facade Thick Insulation	scid	Glzed Type	Facade Openi…	Total Embodie…	Total Operatio…	TotaL Whole Li…
2	142	Double Glass 6…	0.8	5100.249784	13789.781	18890.030784
2	149	Double Glass H…	0.8	5157.469394	12533.781	17691.250394
2	156	Double Glass H…	0.8	5189.038834	11975.646	17164.684834
2	163	Double Glass H…	0.8	5198.904284	11304	16502.904284
2		Triple Glass	0.8	5400.159464	10815.573	16215.732464

Facade Thick Insulation	scid	Glzed Type	Facade Openi…	Total Embodie…	Total Operatio…	TotaL Whole Li…
6	41	Double Glass 6…	0.2	5308.021307	6663.708	11971.729307
6	48	Double Glass H…	0.2	5322.001917	6332.281	11654.282917
6	55	Double Glass H…	0.2	5329.715357	6280	11609.715357
6	62	Double Glass H…	0.2	5332.125807	6236.354	11568.479807
6		Triple Glass	0.2	5381.298987	6227.719	11609.017987

Based on the above results, regarding Figures 70 and table 22, no matter how thick is the thickness insulation or how big is the façade opening, triple glaze will has the lowest operational carbon. However, regarding figure 71, with low thickness insulation, regardless of the size of the façade opening, triple glazing will leading to the lowest whole-life carbon emissions. Conversely, Figures 71 and table 22, with very high thickness insulation (above Rc 4), regardless of the façade opening size, triple glazing will result in higher whole-life carbon emissions than double glazing HR++ due to its higher embodied carbon. This is also because, at this level of thickness, further increases in thickness are not as effective.

Therefore, it can be concluded that with lower thickness insulation, where façade thickness insulation is the most significant factor influencing operational carbon and whole-life carbon emissions, it is better to use materials that can decrease operational carbon emissions. However, when the façade thickness insulation is no longer effective in decreasing operational carbon, or when the room already has good insulation, it is better to use glazing that does not have high embodied carbon but still has low conductivity. This ensures the glazing remains a good insulator, helping to maintain room temperature and save energy.

b. Scenario 2

In this scenario, there are 3 inputs: different façade opening, façade thickness insulation, and façade material insulation. Below are the results of embodied, operational, and whole-life carbon emissions:

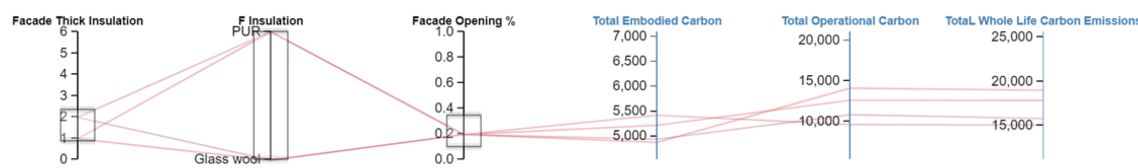


Figure 72 Different façade insulation material, thickness insulation number 1 and 2, 20% facade opening

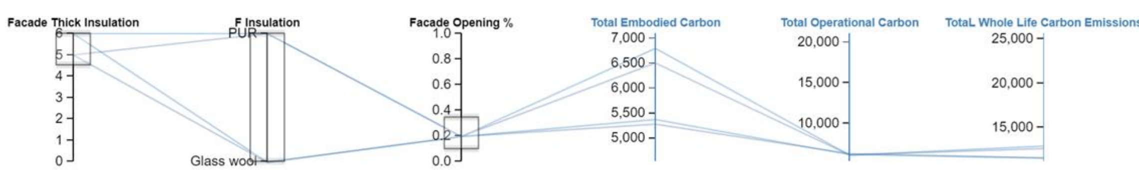


Figure 73 Different façade insulation material, thickness insulation number 5 and 6, 20% facade opening

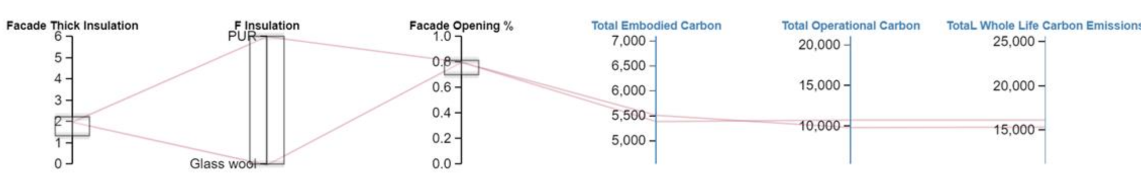


Figure 74 Different façade thickness insulation, thickness insulation number 2, façade opening 80%

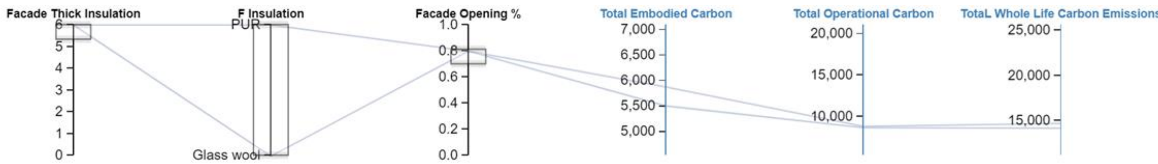


Figure 75 Different façade thickness insulation, thickness insulation number 6, façade opening 80%

Table 23 Result scenario 2 (3 input)

Facade Thick Insulation	scid	F Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
1	15	Glass wool	0.2	4887.07247	14138.792	19025.86447
1	22	PUR	0.2	5229.386686	12655.927	17885.313686
2	16	Glass wool	0.2	4950.031262	10885.281	15835.312262
2	23	PUR	0.2	5429.271165	9672.927	15102.198165

Facade Thick Insulation	scid	F Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
2	58	Glass wool	0.8	5400.159464	10815.573	16215.732464
2	65	PUR	0.8	5525.297006	9891	15416.297006

Facade Thick Insulation	scid	F Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
5	19	Glass wool	0.2	5290.008738	6349.708	11639.716738
5	26	PUR	0.2	6508.647349	6175.281	12683.928349
6	20	Glass wool	0.2	5381.298987	6227.719	11609.017987
6	27	PUR	0.2	6798.479843	6166.646	12965.125843

Facade Thick Insulation	scid	F Insulation	Facade Openi...	Total Embodie...	Total Operatio...	TotaL Whole Li...
6	62	Glass wool	0.8	5512.770669	8713.5	14226.270669
6	69	PUR	0.8	5882.820257	8870.5	14753.320257

Based on the above results, in Figures 72 and table 23, with a smaller window and lower thickness, PUR has lower operational carbon and consequently lower whole-life carbon emissions than glass wool. However, in figure 73 and table 23, with a smaller window and higher thickness, while PUR still has lower operational carbon, it results in higher whole-life carbon emissions than glass wool due to the high embodied carbon of PUR. This mirrors the scenario in Figure 4 with two inputs, where higher façade thickness insulation results in higher whole-life carbon emissions with PUR than with glass wool.

Conversely, in Figures 74 and table 23, with a larger window and lower thickness, PUR has lower operational carbon and thus lower whole-life carbon emissions than glass wool. However, in Figure 75 and table 23, with a larger window and higher thickness, PUR has higher operational carbon and higher whole-life carbon emissions than glass wool due to the increased cooling load, especially during summer. In a larger façade opening, more heat enters from outside, and high-thickness insulation retains the internal heat. Using high-performance insulation like PUR makes the room very hot, increasing the cooling loads. This leads to higher operational carbon compared to glass wool. Hence, from this scenario, it can be concluded that PUR is not suitable for higher thickness insulation.

3.4.5.4 Input Scenario

a. Scenario 1

In this scenario, there will be 4 inputs: different materials for brick, board 1, insulation, and board 2. Below are the results of embodied, operational, and whole-life carbon emissions:

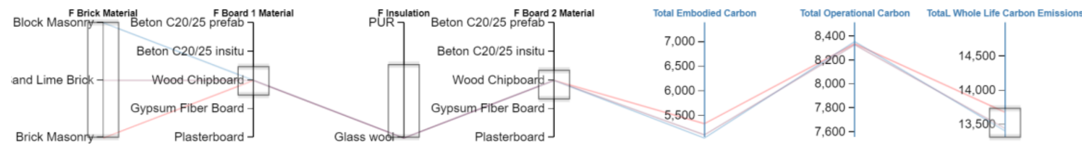


Figure 76 Different brick material but same material for the other façade component

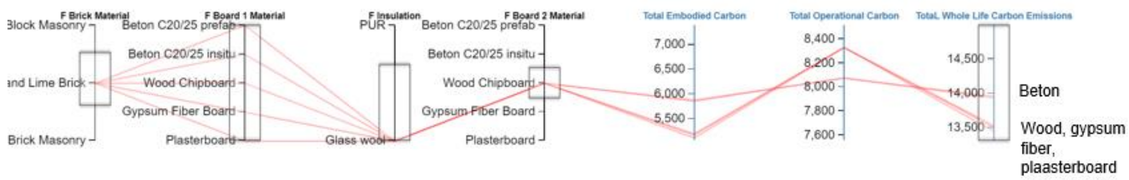


Figure 77 Different board 1 material but same material for the other facade component

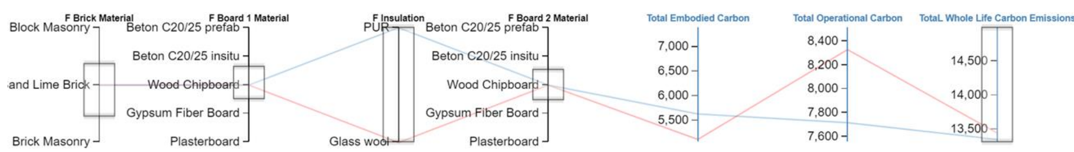


Figure 78 Different insulation material but same material for the other facade component

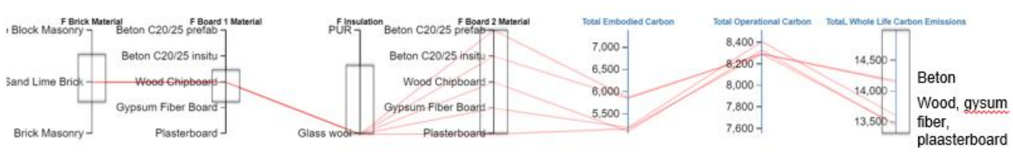


Figure 79 Different board 2 material but same material for the other facade component

Based on the above results, all materials with low thermal conductivity and high specific heat lead to lower operational carbon. This is because lower thermal conductivity results in less heat transfer, which helps maintain indoor temperature and reduces heating and cooling loads. This principle is similar to the U-value of glass, which indicates its heat transfer capabilities. Moreover, specific heat also affects operational carbon emissions, as a higher specific heat means the ability to store a larger amount of heat.

In the Netherlands, where winters are longer, materials with low thermal conductivity and high specific heat help minimize heat loss from indoors to the external environment, store more heating loads, and reduce the demand for heating. Similarly, during summer, low thermal conductivity helps reduce the entry of heat from the outside into indoor spaces, decreasing the need for cooling.

Moreover, it can also be seen that some materials with lower operational carbon have high embodied carbon. For instance, concrete has higher embodied carbon than timber but lower operational carbon. However, the decrease in operational carbon is not as significant as the higher embodied carbon of concrete compared to timber. Therefore, timber still has lower whole-life carbon emissions than concrete in this scenario. From this scenario, it can be concluded that selecting materials for buildings requires balancing embodied and operational carbon.

3.4.5.5. 5 input scenario

a. Scenario 1

This scenario involves multiple inputs: façade opening, façade thickness insulation, orientation, façade insulation material, and glazed type. The results provide the optimal solutions for each orientation and each façade thickness insulation. Below are the findings for embodied, operational, and whole-life carbon emissions for each orientation:

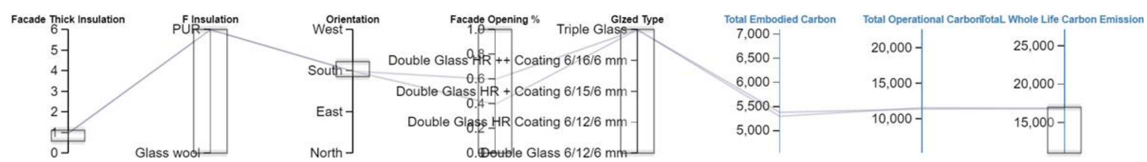


Figure 80 Optimization of south orientation

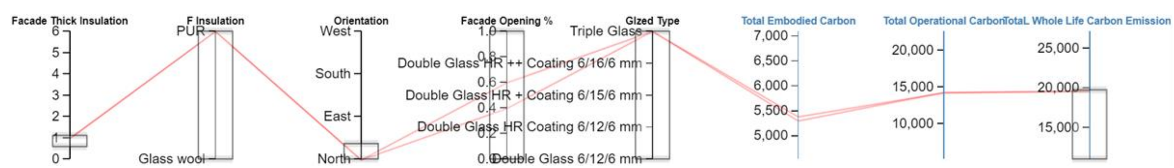


Figure 81 Optimization of north orientation

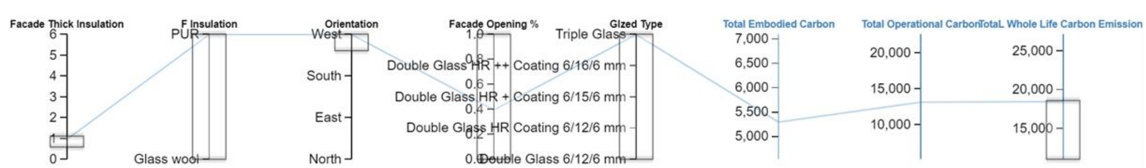


Figure 82 Optimization of west orientation

Figure 83 Optimization of east orientation

Based on the above result, for the south orientation with façade thickness insulation number 1, the optimal solution includes using PUR as the façade insulation material, a 60% façade opening, and triple glazing. For the north, west, and east orientations, the optimal solution for thickness number 1 involves using PUR as the façade insulation material, a 40% façade opening, and triple glazing.

The difference in façade opening between the south and the other orientations is due to the longer duration of sunlight on the south side and because, in this façade thickness insulation, the wall surface has better thermal resistance than the window, impacting operational carbon. However, for the north orientation, which also faces the sun directly but not as long as the south, the lowest operational carbon is also at the 60% façade opening. But due to the significantly higher embodied carbon of the 60% façade opening compared to the 40% façade opening, and the relatively smaller decrease in operational carbon, the 40% façade opening results in the lowest whole-life carbon emissions for the north orientation. On the other hand, in the west and east orientations, where the sun does not directly face these sides, larger windows are not optimal because they allow heat to enter and exit more easily, increasing energy use for the room. Since these orientations do not receive as much sunlight as the south, and do not directly face the sun like the south and north, larger windows let in more cooling energy from outside, increasing heating loads and leading to higher energy use.

However, not using windows at all is also not the best solution, as windows are still necessary to reduce heating loads by utilizing sunlight. Therefore, using this methodology, the optimal façade opening size can be determined for each orientation, balancing the need for natural light and thermal performance to minimize energy use and carbon emissions.

3.5. Summary

This chapter demonstrates all the calculations of embodied, operational, and whole carbon emissions, as well as conducting various scenarios. The first scenario involves using a combination of Excel and IESVE software to calculate embodied and operational carbon, as discussed in part 3.4.1. This scenario represents a simple input setup. Additionally, there are more complex scenarios discussed in parts 3.4.2 to 3.4.5, which involve multiple inputs and utilize Grasshopper for the calculation of embodied and operational carbon.

Furthermore, from all the scenarios, the relationship and optimization between embodied, operational, and whole-life carbon emissions can be observed, along with identifying the best materials for constructing buildings with low carbon emissions. These aspects will be further discussed in Chapter 4.

4. Finding and Results

This chapter will discuss the findings from the methodology chapter, and it will end with a proposed framework. Moreover, this chapter will address the third sub-question regarding the relationship between embodied carbon and operational carbon emissions.

4.1. Findings

Based on the scenarios conducted in the methodology chapter, it is evident that the relationship between embodied carbon and operational carbon can be divided into two aspects: type of material and quantity of material.

4.1.1. Type of material

In terms of material type, not all materials with high embodied carbon result in high operational carbon emissions. In fact, some materials with high embodied carbon can be more energy-efficient, resulting in lower operational carbon emissions. For example, in scenarios involving different types of glazing, triple glass, which has the lowest U-factor of 0.9 W/m²K, results in the highest embodied carbon but can lead to the lowest operational carbon emissions compared to other types of glazing with higher conductivity. Moreover, in scenarios involving different insulation materials, it is also observed that PUR, which has the lowest thermal conductivity and the highest specific heat, results in the highest embodied carbon and the lowest operational carbon emissions.

Secondly, in scenarios involving different façade component materials such as concrete block masonry and brick masonry, concrete block masonry has lower embodied carbon than brick masonry due to the production process of bricks requiring more firing and resulting in more CO_2 emissions. However, despite brick masonry having higher embodied carbon, it results in lower operational carbon emissions than concrete block masonry. When considering the whole-life carbon emissions until 2050, concrete block masonry emits less carbon than brick masonry because the difference in operational carbon emissions between the materials is smaller than the difference in embodied carbon emissions.

Furthermore, in scenarios involving different façade component materials like concrete and other board materials, concrete has higher embodied carbon than other board materials but results in lower operational carbon emissions. However, the reduction in operational carbon emissions is not as significant as the difference in high embodied carbon. Therefore, in terms of whole life carbon emissions, the wood chipboard still has the lowest overall carbon emissions.

From these examples, it becomes clear that the level of embodied carbon does not always directly correspond with operational carbon emissions. Additionally, thermal conductivity affects operational carbon emissions. Lower thermal conductivity results in less heat transfer, which helps maintain indoor temperature and reduces heating and cooling loads. This principle is similar to the U-value of glass, which indicates its heat transfer capabilities. Moreover, specific heat also affects operational carbon emissions, where a higher specific heat means the ability to store a larger amount of heat. In the Netherlands, where winters are longer, materials with low thermal conductivity and high specific heat help minimize heat loss from indoors to the external environment, store more heating loads, and reduce the demand for heating. Similarly, during summer, low thermal conductivity assists in reducing the entry of heat from the outside into indoor spaces, decreasing the need for cooling.

4.1.2. Quantity of Material

In terms of material quantities, in some scenarios, larger dimensions will result in higher embodied carbon and operational carbon emissions. This can be seen in the scenario of different building dimensions where the larger dimensions result in higher embodied carbon, as more material leads to increased CO2 emissions, and higher operational carbon emissions because larger rooms require more energy demand.

Moreover, this can be observed in the scenario of façade openings, where 0% façade opening results in higher embodied carbon and higher operational carbon compared to 100% façade openings. However, this only occurs when the embodied carbon of the glass is high enough, such as with triple glazing. When using double glazing (6/12/6 mm), larger windows will result in less embodied carbon. This is similar to the third scenario using Excel and IES software. This happens because, with double glazing, the embodied carbon is not as high and does not become the dominant factor influencing the overall embodied carbon result. In this case, the façade wall surface becomes the most influential factor. Therefore, using larger windows decreases the wall surface area, leading to a decrease in embodied carbon.

On the other hand, looking at operational carbon, larger windows will result in higher operational carbon if the wall surface has lower thermal resistance than the window. For instance, with zero façade insulation and triple glazing, larger triple-glazed windows will lower operational carbon because, in that case, the façade opening becomes a better insulator than the wall surface. However, if the façade has higher thermal resistance than the window, a very large window will result in high operational carbon because the increased surface area of windows exposed to sunlight leads to higher cooling loads, particularly during summer. During winter, larger window areas contribute to increased heat loss from inside to outside, resulting in higher heating loads.

However, not having any windows at all does not result in the lowest operational carbon. Using medium-sized windows can balance the façade opening by helping to decrease heating loads during winter and only slightly increasing cooling loads, leading to lower operational carbon. Hence, to achieve the optimum balance, it requires a balanced approach between the type of glazing and the size of the façade openings

Furthermore, another result emerges from the scenario of different façade thickness insulation, where an increase in insulation thickness leads to higher embodied carbon but lower operational carbon emissions. However, transitioning from Rc 0.5 to Rc 3 results in a significant decrease in operational carbon emissions, indicating high efficiency. Beyond Rc 3, especially from Rc 4 onwards, the decrease in operational carbon emissions is less noticeable compared to below Rc 3 but still present. This reduction in operational carbon emissions contributes to a decrease in whole-life carbon emissions. Therefore, from these three examples, it can be concluded that an increase in the quantity or dimension of material does not always result in an increase in embodied and operational carbon emissions but can vary.

4.1.3. Relationship to Whole Life Carbon Emissions

To establish the relationship with whole life carbon emissions, sensitivity analysis was conducted through scenario as outlined in the methodology chapter. In all scenarios, operational carbon comprises a larger portion of the whole life carbon emissions for lower thicknesses of insulation (Rc 0 to 4). This is evident in scenarios where triple glazing and PUR significantly decrease operational carbon, leading to lower whole life carbon emissions with lower insulation thickness. However, when the Rc façade is above 4, embodied carbon becomes more influential. For instance, using PUR in Rc 5 or 6 is no longer effective and leads to higher whole life carbon emissions because the room is already well insulated and does not require more advanced materials. Therefore, using glass wool is better than PUR at higher insulation thicknesses. Similarly, triple glazing becomes ineffective and results in higher whole life carbon emissions when the Rc of the façade is above 4. Thus, using double-glazed HR++, which has lower embodied carbon and is not as effective as triple glazing, is more efficient and results in lower whole life carbon emissions.

Furthermore, different façade insulation thicknesses significantly impact whole life carbon emissions due to their substantial effect on operational carbon. However, this impact is only significant until Rc 4; beyond that, the influence diminishes. This can be observed in Scenario 1 of the Grasshopper simulation, where increasing insulation thickness is not as effective in reducing operational carbon beyond Rc 4.

Additionally, there are conditions where the thermal conductivity of the façade wall is higher than that of the façade opening. In such cases, using larger façade openings results in lower whole life carbon emissions. This is seen in scenarios where the façade insulation thickness is 0; using 100% façade openings with triple glazing results in the lowest whole life carbon emissions because the glazing acts as a better insulator than the façade wall surface. However, if the façade wall surface has lower thermal conductivity than the glazing, larger windows do not reduce whole life carbon emissions. Nonetheless, not having any windows does not result in the lowest whole life carbon emissions either. Small windows help decrease heating loads and only slightly increase cooling loads. Therefore, a balanced approach is required for façade openings, insulation thickness, and glazing type.

Moreover, materials with lower conductivity and high specific heat usually lead to decreased operational carbon but have high embodied carbon. This advanced material is only effective with lower Rc values; above Rc 4, it is better to use medium materials that do not have the high embodied carbon as advanced materials. This can be observed in the case of PUR and Glass wool when the façade insulation thickness is 5 and 6. Although PUR has lower operational carbon, in those façade insulation thicknesses, Glass wool results in lower whole-life carbon emissions due to the high embodied carbon of PUR. Similarly, the same trend is observed with triple-glazed and double-glazed HR++ windows. In higher façade insulation thicknesses, it is better to use double-glazed HR++ than triple-glazed to achieve the lowest whole-life carbon emissions.

In addition, the frame material does not impact operational carbon but only affects embodied carbon. This is evident in Scenario 3 with 2 input, where different frame materials do not change the operational carbon results and only slightly affect embodied carbon due to the small dimensions of the frame material

Another influential factor on whole life carbon emissions is the orientation of the building, especially in comparisons between north and south orientations. As explained earlier, the Netherlands, being part of the northern hemisphere, receives more direct sunlight, leading to warmer summers. Therefore, buildings with south-facing facades experience lower carbon emissions as they can harness sunlight for natural heating during winter, reducing the need for fossil fuel heating systems and carbon emissions. Conversely, buildings with north-facing facades receive less sunlight, resulting in higher carbon emissions due to increased heating requirements during long, cold winters.

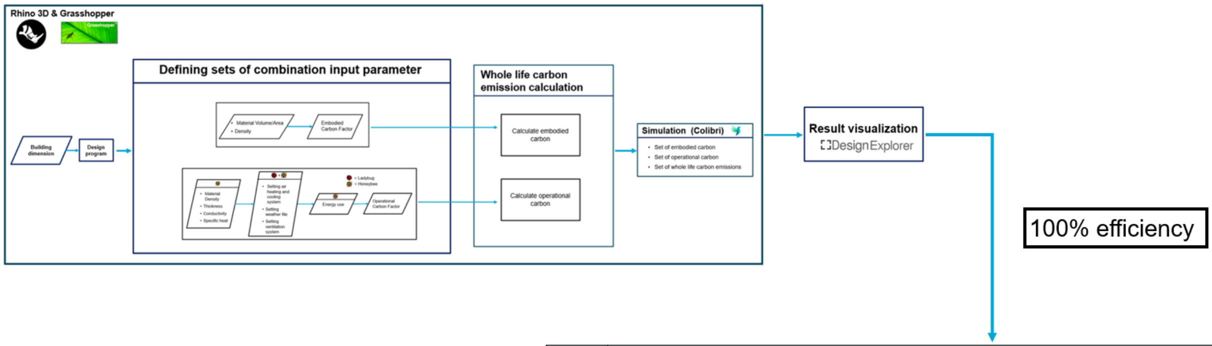
4.2. Optimization of Whole Life Carbon Emissions

After establishing the relationship between embodied carbon and operational carbon to whole life carbon emissions through sensitivity analysis by conducted scenarios, it can be concluded that achieving the most optimal result involves utilizing higher thickness until the Rc of the façade is 4, as thickness insulation is the most significant factor affecting whole life carbon emissions and above Rc 4 the effect is not that efficient anymore. However, different thickness levels will result in different Rc values, where each Rc value requires a different façade opening to achieve the optimum solution. Lower façade thickness insulation values necessitate larger façade openings. In this optimization, using the Rc 4 of PUR, need 20% façade opening for their optimal solution. Regarding glazed types, the most optimal choice is triple glazed with timber frame due to its high efficiency in reducing operational carbon. According, façade materials, the best option is using those with the lowest conductivity and highest specific heat, which in this research, concrete block masonry is used as the brick, wood chipboard as the board, and PUR as the insulation material. Lastly, for orientation the most optimal solution is on the south orientation.

In addition, using this methodology, the most optimum results or the lowest whole life carbon emissions can be obtained for each orientation and each façade insulation thickness. However, it must be remembered that these results are based on 100% efficiency; different efficiencies will yield different optimizations. In summary, achieving the most optimal solution requires considering the balance act between the embodied and operational carbon, and also multiple inputs for each parameter to better understand which factors are highly impactful and which are less so.

4.3. Proposed Framework

This chapter introduces a proposed framework aimed at optimizing whole-life carbon emissions in apartment buildings, drawing from the analysis conducted in part 4.1. Below outlines the proposed framework:



<table>
<tr><th rowspan="2">Orientation</th><th colspan="7">Facade thickness insulation (mm)</th></tr>
<tr><th>0</th><th>50</th><th>70</th><th>100</th><th>150</th><th>180</th><th>210</th></tr>
<tr><td>South</td><td rowspan="4">Maximize facade opening, triple glazed</td><td>60% facade opening, triple glazed, PUR</td><td>40% facade opening, triple glazed, PUR</td><td>20% facade opening, triple glazed, PUR</td><td>20% facade opening, triple glazed, Glasswool</td><td>20% facade opening, double glass HR ++ glazed, Glasswool</td><td rowspan="4">Minimize facade opening, Glasswool</td></tr>
<tr><td>North</td><td rowspan="3">40% facade opening, triple glazed, PUR</td><td rowspan="3">20% facade opening, triple glazed, PUR</td><td>Minimize facade opening, PUR</td><td rowspan="3">Minimize facade opening, Glasswool</td><td rowspan="3">Minimize facade opening, Glasswool</td></tr>
<tr><td>East</td><td rowspan="2">20% facade opening, triple glazed, PUR</td></tr>
<tr><td>West</td></tr>
</table>

Figure 84 Proposed Framework

The framework entails a methodology for optimizing whole-life carbon emissions in apartment buildings. Initially, building dimensions are selected or a model of the building is created, facilitated by Rhino 3D or Grasshopper commands, alongside programming in Grasshopper to choose the building orientation. Subsequently, materials for the building are chosen, with properties such as density, thickness, conductivity, and specific heat inputted, along with energy consumption data.

Following this, a Grasshopper program is developed to calculate embodied, operational, and whole-life carbon emissions. Embodied carbon emissions are determined by multiplying material quantities by the embodied carbon factor, while operational carbon emissions are computed using the Ladybug and Honeybee plugin to estimate energy use. Additionally, setting the ventilation system, air heating and cooling system, also setting the weather file (EPW file) corresponding to the building's location is necessary for the Ladybug plugin. The energy use is then multiplied by the operational carbon factor. Finally, whole-life carbon emissions are the sum of embodied and operational carbon emissions.

After establishing the environment or program in Grasshopper, different building dimensions or materials can be inputted. To compare and optimize building designs, the Colibri plugin can be utilized, and optimization results can be viewed on the Design Explorer website.

Furthermore, the table below shows the results obtained from the optimization for each orientation and each façade insulation thickness. The 100% efficiency mentioned refers to the ideal conditions of the air heating and cooling systems. If the efficiency of these systems differs, the results and recommendations will also differ. Therefore, this framework only applies to the same location or weather conditions of the building (South Netherlands) and assumes the same air heating and cooling system efficiency (100%).

In conclusion, this framework aims to support designers in developing apartment buildings with minimal whole-life carbon emissions under ideal conditions of air heating and cooling systems (100% efficiency) and the same location (South Netherlands).

4.4. Implementation to the Apartment

Based on the optimization results and framework, here is how to implement these findings in an apartment building context:

a. Façade Insulation Thickness and Opening Size:

- Utilizing higher insulation thickness until the Rc (thermal resistance) of the façade reaches 4 is optimal for reducing whole life carbon emissions. This finding can be applied to apartment buildings by ensuring that the insulation thickness meets or exceeds the recommended level.
- For the façade opening, the window area depends on the Rc of the façade; however, it is stated that higher façade needs a smaller window, and the lower Rc of façade needs a bigger window area.

b. Glazed Types:

- Triple glazed windows with timber frames are identified as the most optimal choice due to their high efficiency in reducing operational carbon. Apartment buildings can adopt this recommendation by selecting triple glazed windows with timber frames for their window installations.

c. Façade Materials:

- The research suggests using materials with low conductivity and high specific heat for the façade. Concrete block masonry for the brick layer, wood chipboard for the board layer, and PUR insulation for the insulation layer are identified as the best options. Apartment buildings can incorporate these materials into their construction to minimize whole life carbon emissions.

d. Orientation:

- South orientation is the most optimal orientation for reducing carbon emissions. Apartment buildings can be designed or oriented in the south orientation, allowing for passive solar heating and reduced reliance on heating systems during colder periods.

e. Implementation Considerations:

- The corner of the apartment, where the wall on the right or left also directly faces outdoors, requires better insulation for the surface facing the outdoors due to heat loss from the wall, not just the façade. Therefore, the material for the wall on the right or left will be similar to that of the façade. In this framework, heat loss from the wall on the right or left is not considered because it is very small due to the room's central position in the apartment.

- The ground floor, where the floor is near the land surface, must use material with good insulation, as heat loss also comes from the floor. The land itself has properties of storing and transmitting heat. During winter, the cold temperature in the ground can transfer to the floor, making the room colder. Conversely, during summer, the heat in the ground can transfer to the floor, making the room hotter. Good insulation can reduce the heat entering and leaving the room, thus saving more energy and leading to lower operational carbon. Therefore, the material used must be a good insulator for the floor.

- The top of the apartment directly faces the sun, so heat loss comes from the ceiling, not only from the façade. Since the ceiling receives the most direct sunlight, it is better to use material with good insulation for the ceiling. In the summer, when the sun shines longer than in other seasons, it makes the room hotter and increases cooling loads. Therefore, using material with better insulation can reduce the heat coming from the outside into the room, especially during the summer, and help maintain the room temperature, leading to less energy use.

- The air heating and cooling system affects efficiency and results in different energy usage, leading to different results for operational carbon. This model assumes 100% efficiency or ideal conditions for the air heating and cooling system.

- Overall, every surface that directly faces the outside needs better insulation due to increased heat loss. To optimize material selection, a framework utilizing Grasshopper can be employed. Grasshopper can help determine the most optimal material for the entire apartment building. However, in the author's model, only the façade is considered for heat loss, with other surfaces not directly facing the outside set to adiabatic. Therefore, for future research that examines the entire apartment building, attention must be given to the adiabatic settings. Essentially, each surface not directly facing the outside should be set to adiabatic.

Through the analysis above, it can be seen that the framework can be implemented for the apartment building to design for low whole-life carbon emissions, while still considering the factors examined in the analysis above.

4.5. Summary

This chapter presents the findings from Chapter 3 and proposes a framework based on these findings. It begins with an analysis of the relationship between embodied, operational, and whole life carbon emissions in part 4.1. It continues with the optimization of whole-life carbon emissions in part 4.2. Then, in part 4.3, the chapter introduces a proposed framework for optimizing whole-life carbon emissions in apartment buildings, aiming to assist designers in achieving low carbon emission factors, with evaluation to be discussed in Chapter 5. Finally, part 4.4, examines the approach to link the framework and optimization result to the apartment building with some consideration factor.

5. Evaluation

This chapter demonstrates the evaluation of the proposed framework through interviews with some experts in the company and university. At the end, the last sub-research question will be addressed in this chapter.

5.1. Interviews

The interview was conducted to evaluate the proposed framework, which can support designers and universities in designing apartment buildings with low carbon emissions. Table 85 provides an overview of their roles in their organizations. The results from these discussions are summarized in the following sections.

Interviewee code	Current role
B1	Building Physics Specialist
B2	Building Physics Specialist
B3	Building Physics Specialist
B4	Phd Candidate of Building Physics

Figure 85 Respondent of Interviewees

a. **Company Perspective**: In general, all the experts from the company agreed that the proposed framework will be very helpful, especially in the early design stages. It helps to understand the consequences of design decisions and provides insight into how material selections influence carbon emissions. Moreover, they also mentioned that the proposed framework, particularly the steps of calculation in Grasshopper, is still useful despite differences in location, air heating and cooling systems, or ventilation systems. This is because, in theory, one can simply change the settings in Grasshopper while the rest of the program remains the same. However, the table results in the framework will be most useful for countries with conditions similar to those in the Netherlands. In countries without a winter season, where insulation material is not used, the framework might be less useful.

b. **Academic perspective:** The proposed framework is very useful, especially the calculation steps in Grasshopper. These steps are logical and easy to follow. Additionally, the material itself is very reliable, and the results derived from it are also trustworthy. However, the table results in the proposed framework should be considered as evidence supporting the framework, rather than as part of the framework itself. This is because the tables are too specific to certain conditions, such as 100% efficiency and weather conditions. Therefore, the tables should be viewed more as proof of the proposed framework's validity rather than as a core component.

5.2. Summary

This chapter summarizes the results of the last phase of the research project, namely the evaluation of the proposed framework. The evaluation and validation indicate that, in general, all respondents agree that the proposed framework is very useful for designers, especially in the early stages. However, the table results within the framework are too specific, as they only apply under identical thermal conditions and building locations. The goal of this chapter is to address the last sub-research question, which will be discussed further in the conclusion chapter.

6. Conclusions

6.1. Conclusions

In this subchapter, the research's conclusions will be discussed in response to the research question in Chapter 1. To arrive at the answer to the main research question, 4 sub-questions were formulated. The following sections will summarize the results of the thesis per each research sub-questions.

SQ 1: What factors contribute to the embodied and operational carbon?

Based on the literature review, factors contributing to embodied carbon include material quantities (A1-A3), material transport (A4), and emissions from on-site activities such as material waste and construction machinery (A5). Operational carbon, on the other hand, arises from the energy use within the building, including heating and cooling energy use. These energy are influenced by heat transfer between the inside and outside of the building, thermal resistance of materials used, and energy gains from internal sources such as electricity for occupants.

SQ 2: How to calculate embodied and operational carbon emissions?

According to the literature review, the methodology to calculate embodied carbon involves multiplying the material quantities by the embodied carbon factor of each material. On the other hand, the methodology to calculate operational carbon involves multiplying the energy use by the carbon emission factor derived from the energy mix of the country, such as the energy mix in the Netherlands. Furthermore, to calculate the energy demand, the literature review suggests using either the IESVE software or Grasshopper from the Ladybug and Honeybee plugin.

SQ 3: How do embodied carbon and operational carbon emissions influence each other, and impact overall carbon levels in order to optimize and achieve the best results in apartment building design?

Based on Chapter 4, the relationship between embodied and operational carbon emissions can be categorized by material type and quantity. Interestingly, not all materials with high embodied carbon exhibit high operational carbon emissions; some, like triple-glazed windows and PUR, surprisingly reduce operational carbon even though they have high embodied carbon. Additionally, the quantity of materials also influences carbon emissions, although increasing the quantity does not always lead to higher levels of both embodied and operational carbon.

Furthermore, in relation to whole-life carbon emissions, operational carbon is the most influential factor for insulation thicknesses ranging from Rc 0 to 4. In this range, façade insulation thickness emerges as the most influential factor, despite having little impact on embodied carbon emissions. Façade openings also become one of the most influential factors in determining whole-life carbon emissions. Optimal façade opening varies for each Rc value to result in the lowest whole-life carbon emissions. Usually, materials with lower conductivity and high specific heat lead to decreased operational carbon but have high embodied carbon. This advanced material is only effective with lower Rc values; above Rc 4, it is better to use medium materials that do not have the high embodied carbon of advanced materials. Additionally, frame material only impacts a small amount of embodied carbon but not operational carbon emissions Lastly, building orientation primarily affects operational carbon emissions but has minimal influence compared to other factors. Orientations that receive more sunlight have lower operational carbon emissions, leading to lower whole-life carbon emissions.

SQ 4: How does the proposed framework help the designer?

According to Chapter 5, the proposed framework was evaluated and validated through interviews with experts from the company and university. Based on the interviews, all respondents agreed that the proposed framework will be helpful to designers, particularly in the early design stages. They also mentioned that the framework provides insights into how material selection influences carbon emissions. However, the table results in the framework are too specific, as they only apply under certain conditions, such as identical efficiency for air heating and cooling systems or the same weather conditions. It is suggested that the table results should not be considered part of the proposed framework but rather as evidence supporting the proposed framework, which consists solely of the calculation steps in Grasshopper.

And finally, to answer the main research question,

"How to optimize whole life carbon emissions in the apartment building?"

Based on the above analysis, it can be concluded that to optimize whole-life carbon emissions in apartment buildings, it is first necessary to identify the factors that contribute to each type of carbon and understand how to calculate each type of carbon emission. After understanding the manual calculations, a program should be developed to automate the calculations and analyze different input variants, which, in this case, involves using Rhino 7 and Grasshopper. This approach will help achieve optimized solutions and reveal the relationship between embodied and operational carbon. However, different heating and cooling efficiencies and varying locations will yield different results. Nevertheless, the steps outlined in the framework can be applied to different locations and varying efficiencies in apartment buildings.

6.2. Limitations

The first limitation of this study stems from the author's background, which is in construction management and engineering. This topic would be better suited for master's students in building technology or architecture because they already have basic knowledge from the beginning. Therefore, it takes quite a lot of time for the author to learn this basic knowledge. Furthermore, with a weak basic knowledge, the author is not aware that in the field, there is a possibility of ideal conditions in the air heating and cooling system or what can be called 100% efficiency. Changes in efficiency in the air heating and cooling system will affect the results of energy use and automatically influence the optimization results.

The second limitation is the limited time of the study; therefore, the study does not cover the entire apartment from foundation to roof, but only the studio room in the middle where the heat loss is greatest, mainly in the façade. However, this point can be a good starting point for further research that encompasses the entire apartment.

6.3. Recommendations for further research

The first recommendation for further research is to broaden the scope to encompass the entire apartment, from the foundation to the roof, It is recommended to use more than 100% efficiency for heating and cooling if the building is located in a low-temperature area. Moreover, it is advisable to take into account the considerations the author has already outlined in Chapter 4.4.

The second recommendation is to explore the financial sector as well. Instead of just optimizing the embodied and operational carbon, it is important to also consider financial viability. Advanced materials may come with a higher price tag but are beneficial for operational carbon, whereas materials with lower embodied carbon may result in lower operational carbon but are cheaper than advanced materials. Therefore, conducting an optimization that includes the financial sector would be interesting, as in this research, the author only focused on optimizing whole-life carbon emissions, meaning only the balance between embodied and operational carbon emissions was considered, without taking into account the reliability of financing.

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APPENDIX

Appendix A. Grasshopper's program

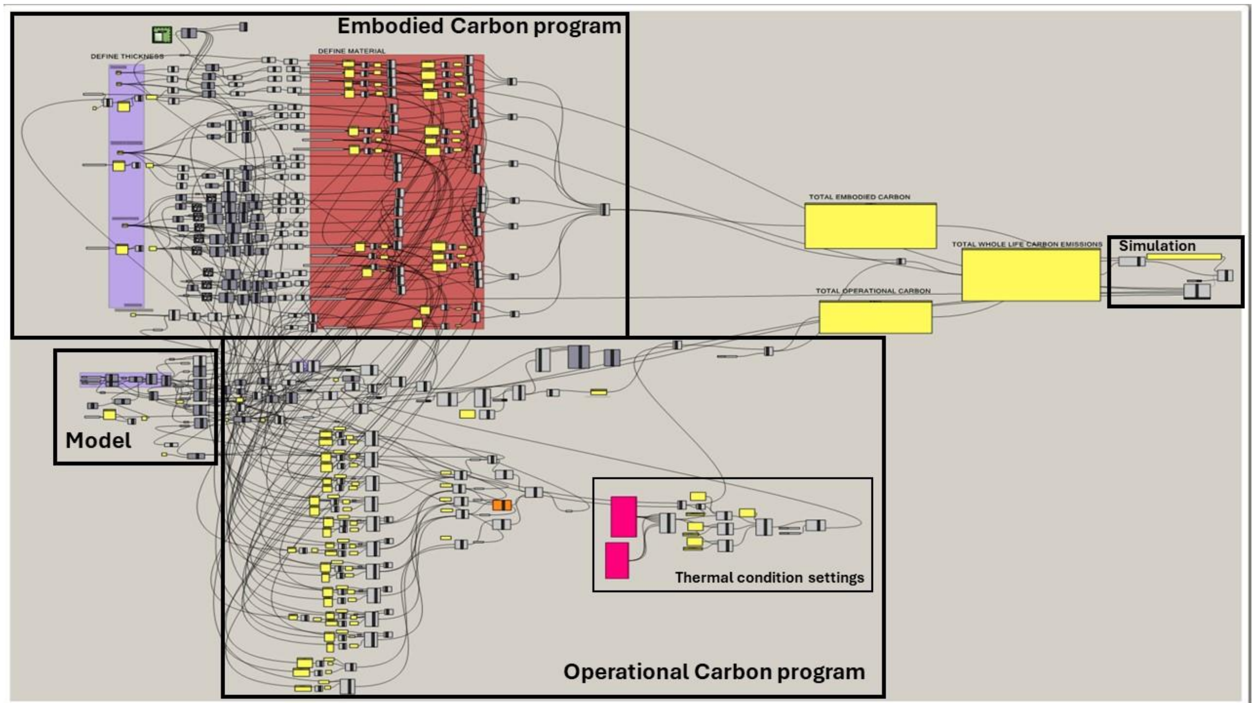

Figure 86 Overview of the graasshopper script

Appendix B. Interview Questions

Question of the interview for company:

1. What is your role at ABT?
2. What do you think about my proposed framework? Will it help the company or designer to reduce whole-life carbon emissions in apartment buildings?
3. What do you think about my proposed framework from an external perspective? (e.g., construction communities)
4. In other cases where the location of the building and the settings of the air heating and cooling system are different, do you think that my framework, especially the calculation steps in Grasshopper, will still be useful?

Question for the academic:

1. What is your role in university?

2. What do you think about my proposed framework from academic perspective?
3. In other cases where the location of the building and the settings of the air heating and cooling system are different, do you think that my framework, especially the calculation steps in Grasshopper, will still be useful?

Appendix C. Interview Result

Interviewee B1 – Company's expert

1. Building physics specialist.
2. The proposed framework is very helpful in early design stages. It helps to understand the consequences of design decisions, making it really valuable and helpful in assessments.
3. The contractor will be more focused on other aspects rather than optimizing whole-life carbon emissions. The client is more likely to look into this, as contractors tend to prioritize profit, and using advanced materials can increase costs. However, if the contractor has a wooden project, they might use this framework.
4. Yes, it is still useful because, in theory, it just changes the air heating and cooling system and weather file, but the rest of the program remains the same. However, this framework is best suited for countries with conditions similar to the Netherlands, not for countries without winter seasons, as they do not use insulation materials.

Interviewee B2 – Company's expert

1. Building physics specialist
2. Yes, it is absolutely useful, especially the calculation method in Grasshopper. It will help the designer, particularly in the early design stages.
3. It might not be that useful for contractors, but if they focus on materials, it could be somehow helpful.
4. Sure, it can still be useful because, as I see it, you have already included the step for setting adjustments. So, if there are any changes, just change those settings, and the rest of the program will remain the same.

Interview B3 – Company's expert

1. Building physics specialist

2. Yes it will help. Moreover, it can give the idea of how materials selection influence the carbon emissions.

3. For the contractor in practical might be not that useful, but for their knowledge it will be useful.

4. Yes, it can still be useful by just changing the weather file and the settings in the air heating, cooling, and ventilation system.

Interview B4 – Academic

1. Phd candidate in Building Physics

2. Yes, it will be useful. The material is very reliable, the steps are logical, and the steps in Grasshopper will work in general, but not the table results, as they are too specific and only applicable under certain conditions (e.g., same weather conditions, same air heating and cooling efficiency). Therefore, it is suggested that the proposed framework focuses on the calculation method in Grasshopper, while the table results serve more as validation of the proposed framework.

3. Yes, it is already mentioned to adjust the weather file and air heating and cooling systems. Therefore, for different locations, just change the weather file, and for different efficiencies, adjust the air heating and cooling systems.

Appendix D. Validation Result by Manual Calculation

Table 24 Validation result different facade thickness and material insulation

Different thickness, 20% opening, Triple glazed, South				
Facade Thickness Insulation (mm)	Glass Wool		PUR	
	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)
0	96,2	112,4	96,2	112,4
50	77,5	90,1	75,9	80,6
70	59,0	69,3	57,6	61,6
100	44,0	52,8	43,2	47,7
150	41,9	42,7	41,4	40,5
180	41,2	40,4	40,7	39,33
210	40,7	39,7	40,3	39,28

Table 25 Validation result different type of glazed

Different type of glazed, 20% opening, 150 mm, South				
Type of Glazed	Glass Wool		PUR	
	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)
Double Glazed	51,0	46,7	50,3	43,9
Double Glazed HR	47,4	44,9	46,8	42,1
Double Glazed HR +	45,7	44,2	45,1	41,6
Double Glazed HR + +	42,9	43,1	42,4	40,8
Triple Glazed	41,9	42,7	41,4	40,5

Table 26 Validation result different facade opening

Different facade opening, 150 mm, Double glazed, South				
Facade Opening	Glass Wool		PUR	
	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)
0%	53,3	47,1	52,8	42,4
20%	51,0	46,7	50,3	43,9
40%	61,0	53,9	60,8	50,5
60%	72,1	61,2	71,7	57,5
80%	83,2	68,1	83,0	63,8
100%	94,2	106,8	94,2	106,8

Table 27 Validation result different orientation

Different Orientation, 150 mm, 60% opening, Double Glazed				
Facade Opening	Glass Wool		PUR	
	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)
North	85,2	74,7	84,8	70,8
South	72,1	61,2	71,7	57,5
West	81,2	73,8	80,8	69,7
East	80,0	71,1	79,6	66,9

Table 28 Validation result different facade thickness and material insulation without 0.17

Different thickness, 20% opening, Triple glazed, South (without 0,17)				
Facade Thickness Insulation (mm)	Glass Wool		PUR	
	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)	Result from Excel (kwh/m2)	Result from Grasshopper (kwh/m2)
0	139,3	112,4	139,3	112,4
50	79,7	90,1	77,5	80,6
70	60,0	69,3	58,5	61,6
100	44,4	52,8	43,6	47,7
150	42,1	42,7	41,5	40,5
180	41,3	40,4	40,8	39,33
210	40,8	39,7	40,4	39,28

In the embodied carbon calculation, there is no difference between the results from Grasshopper and Excel (manual calculation) because the model in Grasshopper is based on the calculation formula from Excel. The difference between Grasshopper results and manual calculation lies in the operational carbon calculation, particularly in the energy use calculation. Grasshopper uses Ladybug and Honeybee plug-ins for the energy use calculation. According to the table above, tables 24, 25, 26, and 27, there are some differences in the results between Grasshopper and the manual calculation for energy use. However, the biggest differences is around 20% lower or higher compared to the Excel calculation, and the building technology lecturer from TU Delft said that it is fully acceptable if the difference is around 20%.

The first reason for the difference is that the manual calculation uses an average weather file for the Netherlands, while Grasshopper uses the actual weather file for Rotterdam over several years. Furthermore, the Excel calculation is based on the NEN 7120 and NTA 8800 standards, which are specific to the Dutch environment, whereas Grasshopper is more general. The difference lies in the utilization factors of heat gains and heat loss that affecting the calculation of energy use. Another reason is that in Excel, the formula for thermal conductivity is 1/(R+0.17), while some software uses 1/R, where R is the thermal resistance. At higher thicknesses, the 0.17 does not significantly affect the result, but at lower thicknesses, it does. Therefore, at lower thicknesses, the difference between results in Grasshopper and Excel calculations is larger than at higher thicknesses. This 0.17 value comes from the cavity construction, where all types of heat transfer occur within the cavity. The comparison results without using 0.17 can be seen in Table 28. In Table 28, the result from Excel is closer to Grasshopper result than using 0.17, especially on the façade thickness insulation 50 mm and 70 mm, but not at 0 mm. However, the difference without 0.17 at 0 mm façade thickness insulation is still around 20%, and as mentioned before, a difference of around 20% is fully acceptable. In addition, for the next student who would like to continue this research, it is recommended to include the 0.17 in the Ladybug and Honeybee plugins because it is reasonable to assume that every component, like walls, floors, and ceilings, has a cavity layer. Therefore, it must be considered that the cavity also has thermal resistance. Overall, it can be concluded that the results from Grasshopper have already been validated by the manual calculation.