Energy Performance and Climate Impact Assessment of Different Prefabricated Façade Systems.

A comparative study

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Master thesis in Energy-efficient and Environmental Buildings
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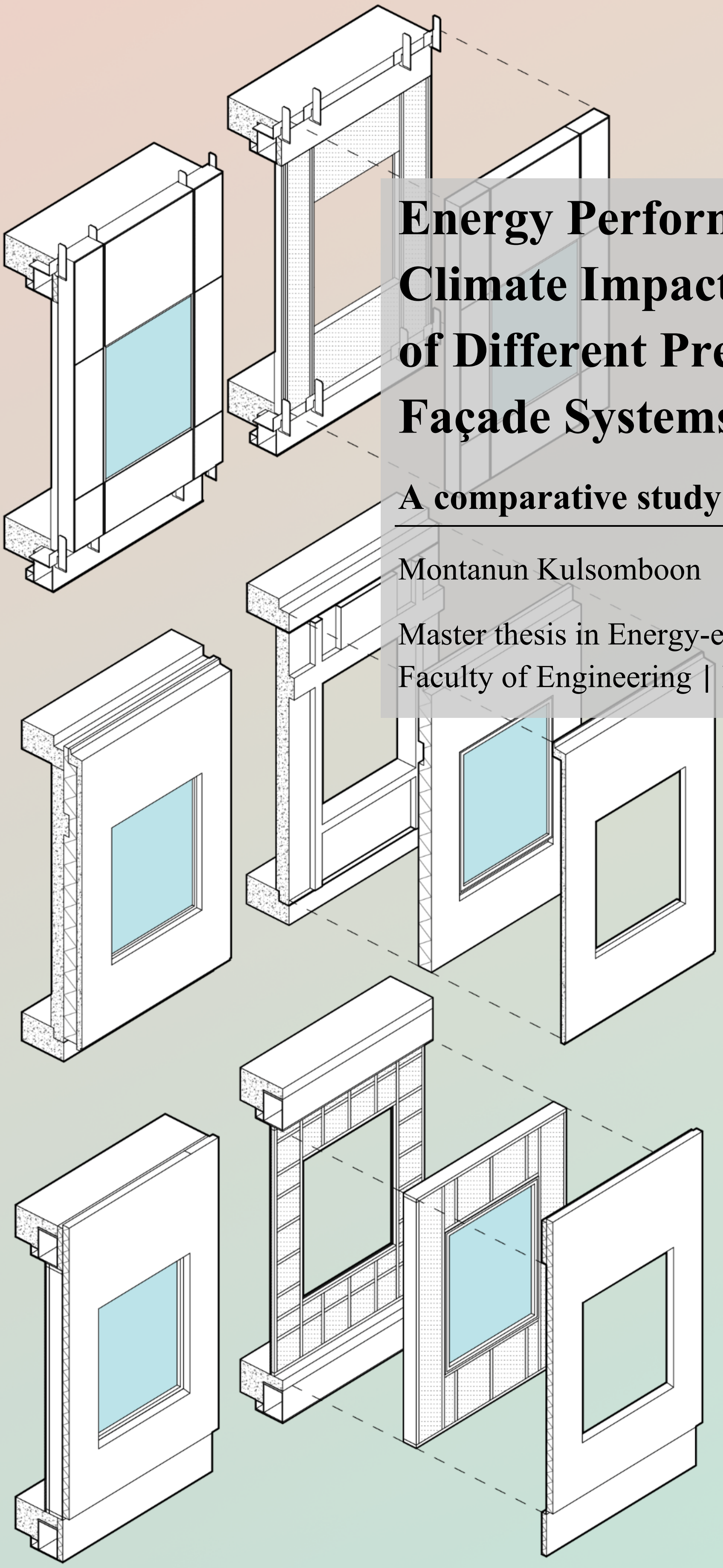

Lund University

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

The objective of the degree project was to assess the average thermal transmittance and the climate impact of the façade. The studied prefabricated façade panels were the aluminium frame one, the insulated concrete sandwich and the wooden frame panel. The research approach was consisted of five steps: the physical and thermal requirement of the panel was established; then the initial U-Value of each panel was calculated with a goal to have relatively comparable panels; the thermal bridges and average U-Value were assessed; at the same time Life Cycle Assessment for the designed façade from each system were evaluated; lastly, the comparative studies were conducted for alternative joints or structure in each system in both thermal performance and climate impact aspects. The results, while specific to the designed façade, provided some insight into the differences between three materials. The wooden frame panel had the best performance, thermal wise, followed by aluminium frame panel and insulated concrete sandwich panel. The Life Cycle Assessments suggested that the insulated concrete sandwich panel had the lowest Global Warming Potential, while the wooden frame façade system had slightly higher value, and the aluminium frame system had the highest Global Warming Potential – tripled that of the concrete system. The main structure for the wooden frame and aluminium frame façade proved to be very influential to the Climate Impact of each.

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Abbreviations

CO_2	Carbon dioxide
BBR 29	Swedish Building Regulations (Boverket byggregler) BFS 2020:4
BFS	Swedish Building Regulations (Boverkets byggregler (föreskrifter och allmänna råd))
EMS	European Modular System,
EPD	Environmental Product Declarations
GHG	Greenhouse gases
GWP	Global Warming Potential
GWR	Glazing-to-Wall Ratio
kg CO_2 eq.	Kilogram of Carbon Dioxide Equivalent
LCA	Life Cycle Assessment

Notations

R-Value	Thermal resistance, in $(m^2 \cdot K)/W$
U_m	The average heat transfer coefficient, according to BBR29, in $W/(m^2 \cdot K)$
U-Value	Thermal transmittance, in $W/(m^2 \cdot K)$
λ	Thermal conductivity, in $W/(m \cdot K)$
Ψ-Value	Linear thermal transmittance, in $W/(m \cdot K)$

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1 Introduction

In this study, the topics of material, prefabricated construction and Life Cycle Assessment have been covered. In this introduction section, the overview of each topic is given. The previous studies and articles relating to the topic were explored for deeper understanding of the topic.

1.1 Background

The building sectors directly and indirectly accounted for 30% of the total energy consumption and 55% of the electricity consumption globally (International Energy Agency, 2021). Approximately 20 – 40 % of energy use in developed countries, mainly European countries, and the United States of America, come from the energy use of the building. It was also indicated that 10 – 20 % of the total energy use from buildings in said region stem from the demand for thermal comfort in the building (Pérez-Lombard et al., 2008).

The attempts to reduce the energy consumption from the building sector majorly focuses on the energy use during the operational phase of the building. It was only in the recent years that Life Cycle Assessment has been used to evaluate the energy use of the building throughout its life cycle. Several studies have reported that the operational phase has the greatest share of the primary energy consumption and carbon emissions in the total life cycle of the building, the percentage varies depending on the energy supply system used in the project. (Gustavsson et al., 2010; Scheuer et al., 2003). The embodied energy and emissions of a conventional building was reported to be taken less share of the life cycle assessment.

However, as the building with low operational energy has become the focus of the building regulations and many environmental certification systems: a crucial factor to reach the lower number in operational energy use is the thermal performance of the building envelope, which typically required more material than the conventional construction. A study by Gustavsson and Joelsson (2010) suggested that the primary energy use for the production of the material and construction of the building could be as high as 60 % of the total life cycle primary energy use. Another study assessing the life cycle energy demand of passive houses also suggests that the operational energy demand of the house was less than 40 % of the total energy consumption by the house. The study mentioned that more construction material is required to achieve the level energy efficiency of the passive house standard, which adds up to the embodied energy of the house, offsetting the benefit gaining from the reduced operational energy (Stephan et al., 2013). In a study utilizing Life Cycle Assessment to evaluate a design strategy for an energy efficient residential building, it was discussed that additional insulation was beneficial to the building from the life cycle energy standpoint. But the balance between embodied energy, i.e., the amount of insulation, and operational energy, i.e., the reduction of energy use, over the expected lifetime of the building should be thoroughly assessed (Fay et al., 2000)

If the focus of the building and construction sector still dwells on the energy performance during the operational phase, the embodied energy and carbon emissions of the building could grow to be a significant contributor to global emission. According to International Energy Agency (2021), 40% of the emissions in the global material production come from materials used in the construction. The embodied energy and carbon emissions have only recently been discussed with the growing realisation that focusing on the operational energy alone is not enough to solve the rising energy consumption and greenhouse gas emissions.

In the Global roadmap for buildings and constructions during 2020 – 2050, created by the collaboration between Global Alliance for Buildings and Construction, International Energy Agency and the United Nation Environment Programme (2020), decarbonisation and creating efficient and resilient buildings are the prioritized goal for both existing buildings and new constructions. The suggested actions included developing decarbonisation strategies, implementing mandatory building codes, developing embodied carbon databases, promoting the use of low carbon materials, and increase disclosure of embodied carbon. Pomponi and Moncaster (2016) published a review article analysing the academic knowledge on embodied carbon mitigation and reduction in the built environment, concluding that the collaborative effort from the academic world, the construction sector and the policy makers are crucial to the carbon mitigation, and the pluralistic approach is required. Among seventeen mitigation strategies identified in the review, the implementation of policy and regulations by governments, the reduction, re-use and recovery of embodied energy and carbon intensive construction materials and the increased use of prefabricated elements or off-site manufacturing were listed.

1.1.1 Life Cycle Assessment (LCA) and Environmental Product Declaration (EPD)

Life Cycle Assessment (LCA) is one of the techniques being developed for the purpose to better understand and address the importance of environmental protection and the possible impact associated with products (European Committee For Standardization, 2006a). The principles and framework for LCA is defined by the International Organization for Standardisation (ISO) in ISO 14040 (European Committee For Standardization, 2006a). LCA is a systematic and scientific method to evaluate the impact on the environment that products or services has made throughout its life cycle stages; from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end-of-life treatment and final disposal. The economic and social aspects and impacts are generally outside the scope of the LCA. According to ISO 14040, LCA consist of four stages: Goal and scope definition, Inventory analysis, Impact assessment, and Interpretation. The involved details and decision made in each stage must be clearly stated in the study. The result of the assessment would provide an overview of the product or service, which could be used to assist in decision-making processes.

Although, LCA is a framework that could be implemented to any product or service, there is a specific calculation for environmental performance assessment of the buildings described in EN 15978: 2011 (European Committee For Standardization, 2011) and one for construction products in EN 15804: 2012 (European Committee For Standardization, 2021).

In EN 15978, the building assessment information has been separated into four stages of building life cycle and one supplementary stage beyond the building life cycle. Within the stage, the information modules are listed and defined as follow:

1. **Product stage**, including module A1 – raw material extraction and processing, processing of secondary material input, A2 – transportation the material from extracting processing site to the manufacturer, and A3 – manufacturing process.
2. **Construction process stage**, including module A4 – transportation to and from site, and A5 – construction installation process.
3. **Use stage**, including module B1 – use or application of the installed product, B2 – maintenance, B3 – repair, B4 – replacement, B5 – refurbishment, B6 – operational energy use, and B7 – operational water use.
4. **End-of-life stage**, including module C1 – de-construction and demolition, C2 – transport to waste processing, C3 – waste processing for reuse, recovery and/or recycling, and C4 – disposal.
5. **Supplementary information beyond construction works life cycle**, including module D – benefits and loads beyond the system boundary.

The modular information for different stages is as depicted in *Figure 1*.

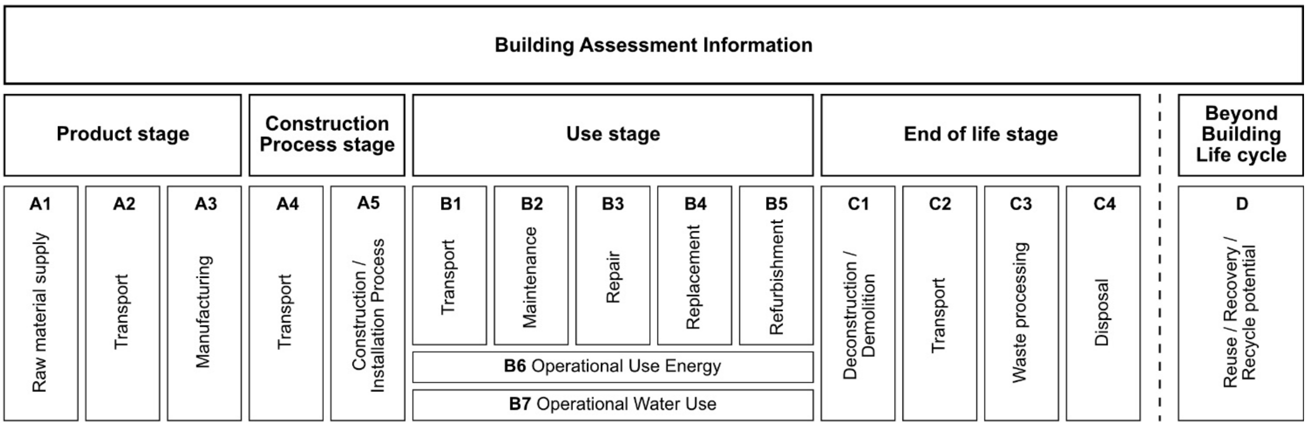


Figure 1 Display of modular information for the different stages of the building assessment. Illustrated based on Figure 6 from SS-EN 15978:2011

Whilst in EN 15804, the standard defines the information and details of the sustainability assessment of the construction products or services, which could be reported in form of Environmental Product Declarations (EPD). The EPD is a document providing quantified and verifiable environmental data related to the product or service. The manufacturer could use the EPD to provide information about their products. The types of EPD could be as follow:

- Cradle-to-gate (A1 – A3), which is the minimum to be declared for all construction products,
- Cradle-to-gate with options (A1 – A3 with A4 and/or A5)
- Cradle-to-gate with module C1 – C4 and module D (A1 – A3, C and D),
- Cradle-to-gate with options, module C1 – C4 and module D (A1 – A3 with A4 and/or A5, C and D),
- Cradle-to-grave and module D (A1 – A5, B1 – B7, C1 – C4 and D)

There are several standards related to the construction of EPD of the building construction material: EN ISO 14040, EN ISO 14025, EN ISO 15804 and EN ISO 21930. For the EPD of a certain material to be created, it should follow the specific rules of the product, which is called Product Category Rules (PCR). PCR was described in EN ISO 14025: 2006 as the set of specific rules, requirements and guidelines for developing EPD for one or more product categories (European Committee For Standardization, 2006b). In other words, the PCR delineates how the EPD of each product should be constructed, including the predetermined parameters for LCA and system boundaries. There are several published PCR for building materials, such as PCR for thermal insulation products, for windows and doors, for flat glass products, for wood and wood-based construction products, etc. (EPD International, 2022a). However, some PCRs of construction material are still being developed, such as the PCR for flexible sheets for water proofing, for steel and aluminium structural products, etc. (EPD International, 2022b).

For the building and construction sector, EPDs could provide important and comparable information regarding the environmental impacts of the products. The details in the EPD support the decision-making process for architects and engineers with incentives to lower carbon emissions of the construction and building. It also encourages the manufacturer of the products to develop the competitive construction products, too.

1.1.2 Swedish Building Regulations and Climate Declaration

In 2017, the Swedish parliament has decided to introduce the climate framework with a climate act for Sweden, with a goal to have zero net emissions of GHG by 2045 (Regeringskansliet, 2021). Sweden's territorial emissions must be reduced by at least 85 percent by 2045, while the remaining maximum 15 percent may be covered by "supplementary measures".

In response to the national climate goal, the Swedish National Board of Housing, Building and Planning (Boverket) has implemented the new regulation regarding the Climate Declaration (Klimatdeklaration) of the new building in January 2022, with the goal to reduce the climate impact of the new buildings (Boverket, 2021a, 2021b) The 'climate impact' is calculated as Global Warming Potential (GWP) – Greenhouse Gas (GHG), which includes the overall effect of greenhouse gas emissions, excluding the biogenic CO_2 storage of the material. The greenhouse gas emissions are converted to the equivalent amount of global warming potential as CO_2 emissions (CO_2 equivalent or CO_2 eq.).

One of the focuses of the regulation is to encourage the building material manufacturers to publish EPDs for their products to build a good quality climate database (Klimatdatabas), which is crucial to the calculation. As for the building sector, the regulation requires that the climate impact of the new building in the construction stage (A1 – A5) should be declared in the Climate Declaration. It is a starting point as Boverket also intent to expand the declared stage to cover other modules and implement the 'Limit Value' for the climate impact of the building in 2027 (Boverket, 2020). The Limit Value would be gradually reduced, creating a transition towards net-zero climate impact construction. With the Limit Value, the limitation in climate impact of each building would also lead to the design process that is more aware of the resulting climate impact. The construction material must push the development of their product to have lower climate impact in preparation for the Limit Value. But as of now, every party in the building construction project should be aware of the climate impact that is a result of the material choice and method of construction.

Boverket not only introduce the importance of climate impact in the building via Climate Declaration, but also consistently updating the operational energy use requirement of the building through the Boverket's Building Regulation (BFS and BBR). Boverket has a section specifically for Energy Management of the building in the building code, which stated the limit for energy performance of the building and the thermal transmittance of the building envelope. In the most recent version of the building regulation, BBR29 in accordance with BFS 2020:4, the Energy performance for a commercial building that has the heated floor area larger than 50 m² should not exceed 70 kWh/m² when expressed in Primary Energy number (EP_{PET}), and the average heat transfer coefficient (U_m) of the building envelope should not exceed 0.5 W/m²K (Boverket, 2021c).

1.1.3 Building material

Globally, approximately 70 % of the industrial CO_2 emissions are generated in the production of chemicals, steel, and cement. The building construction and operating phrases contributed to 37 % of the global CO_2 emissions. The percentage of CO_2 included the emissions from material productions from the energy use in production and the emissions from the process itself. The manufacturing of cement and steel being the main contributors in 2019 (International Energy Agency, 2021).

Concrete is the most used material in building and infrastructure industry. It is reported that concrete is the second-most consumed substance on Earth, following only water (Global Cement and Concrete Association, 2021). Concrete requires cement as a binding agent. Cement production is one of the highest CO_2 emissions and energy consumption industries. The emissions come from the heating that is required in the production process and the direct emission from the chemical reaction of the process itself (International Energy Agency, 2021). Concrete and steel are used together as reinforced concrete, which is common in modern construction but resulted in high GHG emissions (Hertwich et al., 2019). According to the Global Cement and Concrete Association (GCCA) 2050 roadmap, there are several actions that could lead to carbon neutral concrete (Global Cement and Concrete Association, 2021). Carbon capture and storage is one that has the potential to reduce the carbon emissions by 36 %. Carbon Cure is a Canadian company that realised this action by using a technology that injects captured CO_2 into concrete during mixing (Carbon Cure Technologies, 2019). Norwegian government also intend to commence operation of the CO_2 capture facility in 2024 (Heidelberg Cement Group, 2020; NorCem, 2021). Saving cement and binders proved to be another alternative in that could potentially reduce the carbon emission by 9 %. The Swedish cement manufacturer, Cementa, has introduced 'Anläggningscement FA' in 2019: By reducing the clinker content and replacing them with fly ash, the carbon footprint could be reduced from 15 % up to 20 % (Cementa, 2019a). Decarbonisation of electricity that is used in cement plants and in concrete production could also lead to a reduction of 5 %. Cementa and Vattenfall, Swedish power distributer, have launched CemZero project with the objective to electrified cement production by utilising a fossil-free electricity from Swedish energy system (Cementa, 2019b; Vattenfall, 2019).

The concrete industry in Sweden aims to have climate-neutral concrete on the market by 2030 and to have all concrete in Sweden climate neutral by 2045. The industry is currently having several ongoing research. The concrete industry is also in the process of implementing and integrating new technologies, one of which is a technological transition of the cement industry. As of now, it is already possible to achieve up to 50 % reduction in carbon emission from concrete by using climate-improved concrete, depending on the construction type (Fossilfrit Sverige, 2019).

Aluminium is one of the common building materials, found in the element such as window frames in residential buildings, curtain wall mullions in commercial buildings, aluminium frames for dry wall construction and aluminium composite cladding panels. Aluminium has a great benefit for being a material with high strength-to-weight ratio, high durability, and corrosion resistant, thus it is frequently used as on an external element. However, aluminium is an energy-intensive material and consequently has high greenhouse gas emissions for the mass of it. The CO_2 emissions associated with aluminium stems from the aluminium smelting and refining process, contributing to 40 % of primary aluminium production direct emissions. While there was a downward trend in both processes in 2014 (International Energy Agency, 2017), the technologies that would reduce the smelting process emissions and electricity consumption are still in the developing stage (International Energy Agency, 2021). In one study that the comparison of the aluminium, carbon steel and glulam timber mullion were made, it was recognised that while the aluminium mullion was 51 % and 55 % lighter than the steel and timber mullions, its GWP was 690 % and 694 % of carbon steel and glulam timbers (Azari-N and Kim, 2012). Another study also reported that, based on the study conducted to the residential building in China, the aluminium alloy used in the project is only 1.4 % of the mass but contributed to 17 % of material related GHG emissions (Yang et al., 2018).

Nevertheless, aluminium is a versatile material with high potential for recycle (Brown and Buranakarn, 2003). The significant of recycling and reusing waste building material was realised in one study on embodied energy use in a high-rise commercial building in Hong Kong, where the use of recycled steel and aluminium may lead to up to 50 % reduction in embodied energy when compared to the use of virgin materials (Chen et al., 2001). The result from top-down and bottom-up analysis study claimed that 33 % of aluminium used in the current products could be reused. The potential for reusing the aluminium extrusions – normally used as curtain walls and window frames – are dominant, but the components would face the limitation in compatibility if the elements' design were not standardised. Aluminium cladding could also be reused, but the thermal performance of the component might be viewed as 'inferior' in comparison to the new components and to the building regulations, limiting the use of the component to building where lower properties are acceptable (Cooper and Allwood, 2012). Another study suggested that aluminium as building materials has 81 % of recyclable content, but it still requires high reproducing energy. The option of reusing the element that has a large content of aluminium, such as window frames, is reported to be preferable energy-wise (Ng and Chau, 2015). A case study of using aluminium in prefabricated lightweight houses indicated that, if properly designed, aluminium is apt for the use in long life structure; the design for disassembly concept could be adapted when designing the aluminium elements; and the proper material management when the useful life stage is finished are required to reduce the environmental impact in the material flow (Mrkonjic, 2007).

Wood is a construction material that is renewable and often sourced locally, widely known to have high potential for reducing greenhouse gases emission. The wood products used in construction can be in a form of light-frame construction, mass timber construction, or a mixed of both constructions. Light-framing system is a conventional method of construction using standard dimension lumber While the mass timber construction uses thick wood products as a load-bearing structure of the building. Conventionally, the timber used in the mass timber construction are sawn from the tree trunk, but now there are engineered wood systems available in the market for mass timber construction as well, such as Cross-Laminated Timber (CLT), Glued Laminated Timber (Glulam), Nail-laminated Timber (NLT) and Parallel Strand Lumber (PSL). A review of the studies conducted in Sweden and Norway stated that, in the perspective of GHG emissions, wood, in forms of timber and lumber, is a better alternative in comparison to other building materials, while being economically competitive (Petersen and Solberg, 2005). The manufacturing of timber construction products requires less energy and has less CO_2 emissions in comparison to the production of other materials, such as concrete, mortar and structural steel (Gustavsson et al., 2006; Upton et al., 2008; Lippke et al., 2010). A study acknowledged wood building products to be better than others due to the energy recovering from material residue: the biomass residues recovered throughout its lifecycle can be used as a fossil fuel substitution (Gustavsson et al., 2010). Although another study, emphasising on the carbon storage property of wood construction products throughout their lifetime, suggested that the most beneficial options for disposal from the GHG emission perspective would be landfill (Ximenes and Grant, 2013).

1.1.4 Prefabricated construction

Prefabricated construction, also referred to as 'prefab', is a method of construction that utilises the off-site manufacturing location or factory to produce the building components and then transports the components to be assembled on the main construction site. Prefabricated construction has several benefits in comparison to the conventional construction: it increases construction quality and safety, while reduces the construction time, overall costs, material wastes and environmental impacts. Prefab methods in modern construction now also include construction technologies, such as the Building Integrated Modelling (BIM), Computer Numeric Control (CNC) machines and 2D laser cutting devices, to optimise the manufacturing process and increase the precision of the construction. Though, to strive for the most efficient way of construction, the collaborative effort from each party in the project is required in the design stage. A special evaluation of the project's effectiveness should also be made in the design stage to reduce the factor that could increase the investment cost (Cai, 2020). Prefabricated construction could be categorised by the degree of prefabrication, varying on the level of customisation and flexibility, the bulk of the element, and the level of construction on-site: the categories are component, panelised structure (2D panels), modular structure (3D volumetric module), hybrid structure, and the whole building unitisation (Boafo et al., 2016).

Precast concrete, a form of prefabrications in concrete construction, refers to reinforced concrete that is manufactured in an environmentally controlled factory and later transported to assemble on site. It has several benefits in comparison to the conventional cast-in-situ concrete construction, including high-quality control, reduction of construction period, cost-efficiency and precise dimensions (Hong, 2020). Though precast concrete has its constraints in formwork, transportation, handling, and erection (Ochshorn, 2010). Precast concrete could be used as a prefabricated element, a prefabricated panel or as a prefabricated modular unit. It is commonly used in the construction as the precast element itself, such as beams, staircases or load bearing façade, or could be used in the semi-precast construction, where the precast element is used both as the form for the cast-in-situ concrete and as the main structural element along with the cast-in-situ layer (Poon et al., 2003). Several studies have presented that the precast concrete construction has lower environmental impacts than the conventional concrete construction. There are factors affecting the lower impacts. The environmental controlled manufacturing place leads to shorter fabrication times. The precast concrete is also cast in steel formwork, whereas a conventional concrete construction normally uses wood formwork. The steel formwork can be reused up to 100 times, thus, reducing waste generation and waste treatment in the casting process compared to the conventional concrete construction. Additionally, precast component could be optimized to use less material while having the same structural strength as its equivalent component produced by a conventional method (Dong et al., 2015; Dong and Ng, 2015; Wang et al., 2018). However, the locations of the precast factory and the construction site could lead to complications in the transportation stage. The transportation emissions of the precast components, in some cases, could be higher than the transportation emission of the conventional construction due to several conditions, such as the distance from factory to site, the size of the building, the size of the precast component and the number of the modules that could fit in the vehicle. Although the precast concrete may be an alternative solution in reducing the CO_2 emissions, it still required an in-depth design for the components and the logistic plan in order to successfully reduce CO_2 emissions of the whole construction (Dong and Ng, 2015; Wang et al., 2018; Neuman, 2021).

Aluminium is generally a flexible material leading to the opportunities for creative design. Therefore, aluminium in prefabricated construction could be found several categories of prefabrications. For prefabricated elements, aluminium is commonly used in the structural glazing element of the building, as a curtain wall or glass roofing. Prefabricated aluminium stairs, platforms, ladders, and long-span roof systems are also available and easily manufactured. Aluminium extrusions could be used as framing in the infill, non-load bearing wall panel or assembled the modular housing.

Prefabricated wood construction can be in a form of light-frame construction or mass timber construction. For the light-frame construction, the required lumbers and building materials that are forming the infill wall would be send to the prefabricated factory, where the wall would be assembled in an environmental-controlled factory, eliminating the moisture problems. The manufacturer would assemble from the exterior layer ready for cladding up to the inner wooden studs, ready for the installation of pipes and electrical elements on-site. The wall panels would be weather-sealed and then delivered to the construction site on the truck. The inner insulation and gypsum board would be installed on-site after other systems have finished their work in the wall. The prefabrication of the outer and main stud layer would reduce the on-site construction time greatly.

For the mass timber construction, the use of the engineered wood system along with computer numeric control (CNC) machines allows for versatility in the design and precision for the construction. The prefabricated engineered wood used as the load bearing structure of the building has advantages in CO_2 emissions compared to concrete and steel. One study suggested that the versatility and the low CO_2 emission of the CLT panels makes it a suitable building material for multi-storey buildings in the range of 4-8 stories height (Lehmann, 2013). Another study conducting LCA and comparing life cycle energy use and GWP of four similar office buildings with different materials: concrete, steel, timber design using prefabricated Laminated Veneer Lumber (LVL) and TimberPlus design that increased the use of wooden products in architectural features. The study concluded that the timber and TimberPlus buildings have significantly lower embodied energy and embodied carbon. While TimberPlus building has the relatively lowest overall embodied energy, embodied GHG emissions, total primary energy use over life cycle and GWP emissions over life cycle (John et al., 2009). A study by (Dodoo et al., 2014) analysed the lifecycle carbon emissions of three timber-frame multi-story building systems – massive wood system using CLT elements, beam-and-column system using LVL and glulam elements, and prefabricated modular system using light-frame elements – with conventional design and low-energy design. The results showed that the beam-and-column system required more concrete, and steel compared to other systems, resulting in the higher carbon emission in the production stage. While the CLT has the lowest GWP when the residues from the production stage is considered to be replacing fossil fuel (Dodoo et al., 2014). Though the use of prefabricated wooden products in building construction has consistently proven to have an environmental benefit, there are still concerns regarding the acoustic performance, moisture safety, fire safety and earthquake performance – some of the concerns are not perceived to be sufficiently proven or still in the research stage (Hemström et al., 2011; Lehmann, 2013; Izzi et al., 2018).

1.1.5 Decision making in early design stage

In a construction project, there are six main phases according to Royal Institute of British Architects (RIBA), which are Pre-design phase, Design phase, Construction phase, Handover phase, In use phase and End of life phase. The plan of work may differ in different countries, but the goal of the plan is still the same, which is to provide the project team with a consistent road map from one stage to the next. In RIBA's Plan of Work 2020 overview, the design phase was sub-divided into three stages with varying details of construction: Concept design, Spatial coordination, and Technical design (Royal Institute of ritish Architects, 2021). Whereas the Architects' Council of Europe (ACE) suggested to divide the design phase into Preliminary design, Design development and Production of construction documents, instead (Architects' Countil of Europe, 2020). Although there are sub-stages in the design phase as a basic division, there are still some overlapping works once the project starts. The early design stage naturally refers to the Concept design in RIBA's Plan of Work, and to Preliminary design stage in ACE's division. In Sweden, where the building regulations demands buildings to have a low-operational energy, the aspects of energy efficiency and daylight performance are generally integrated to the project in an early stage with the aim to be most influential.

The prefabricated construction, when it is fully optimized, is a system that would technically be streamlined to be the most efficient. The prefabricated construction requires a high level of collaboration between the disciplines to achieve the maximum competency. Often, the decision to utilise prefabricated construction are introduced to the project in the later design stages (Technical design or Production of construction documents) which make the adaptation to the prefabrication harder and more complicated, and might result in less efficient construction and more cost (Cai, 2020)

1.2 Objectives

The objective of this study was to compare the different types of prefabricated façade system to understand the resulting climate impact and average thermal performance transmittance (U-Value) of each system. By conducting a Life Cycle Assessment (LCA), U-Value calculation and thermal bridge assessment, the study aim to provide an overview regarding prefabricate façade systems for the decision-making process.

The specific objectives of this research were as follow:

- Comparing the average thermal transmittance of the prefabricated façade panel by:
  - Analysing the initial average thermal transmittance of the panel,
  - Assessing the possible thermal bridges in the panels and in conjunction with the other building elements,
  - Evaluating the average thermal transmittance, that included the effects of thermal bridges, of the façade system.
- Conducing the LCA with the production stage to transportation stage (A1-A4) of each designed façade system and comparing the results.
- Provide an overview of the relation between the thermal transmittance and LCA of the studied façade system.

2 Methodology

The methodology in this project is presented in an order of the approach diagram, presented in *Figure 2*. The processes, assumptions, and limitations would be stated within this chapter.

The type of prefabricated façade systems considered were an aluminium frame panel, an insulated concrete sandwich panel, and a wooden frame panel. These three façade systems were based on the products that are already available on the market and commonly used in the building construction in Sweden. More details on the three prefabricated panels are presented in the section called *'The prefabricated façades general information'*.

The panel property was set by defining the physical characteristics and the thermal transmittance of the generic façade. It was established as a 'common ground' for a fair comparison between systems. In the initial U-Value stage, the calculation for the thermal properties of the panel would be conducted so that the panel itself could reach the expected U-Value. The amount of material and thermal properties of each material in the panel would be used in the next stage. After that, the thermal bridges assessment of the joints within the panel would be done. The results of thermal bridges assessment were then included into the average U-Value calculation of each façade system. Simultaneously, once the material of each system was specified, the Life Cycle Assessment was conducted to the designed façade. The results of each part were assessed, then the comparative standpoints for each system and each aspect were built from the original result.

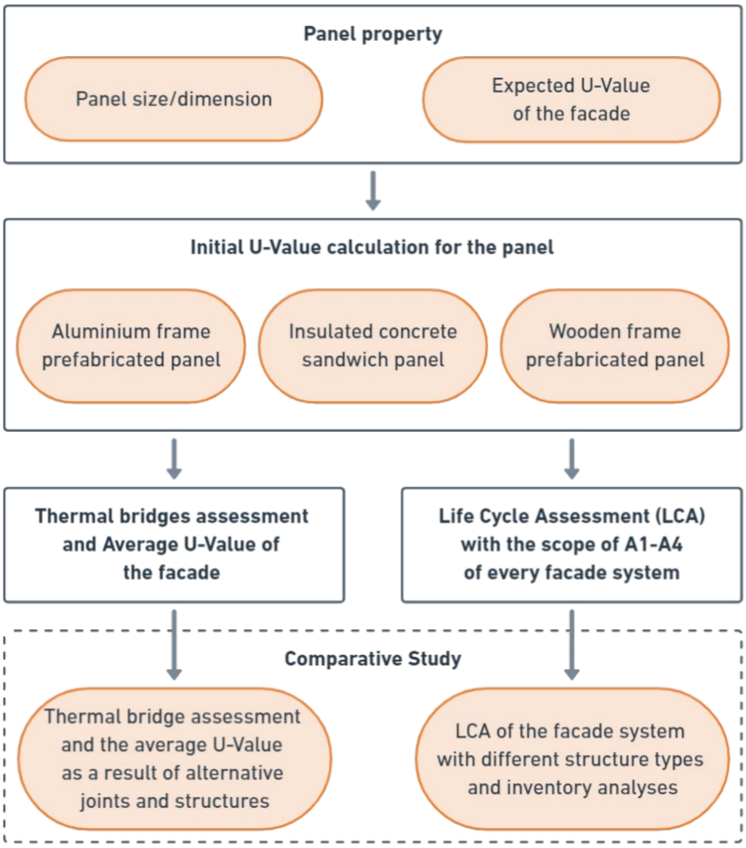


Figure 2 The approach in this study

The information within this chapter were gathered from the manufacturers, the building regulations, ISO standards, relevant research, and the available database. The information related to the practical aspects were gathered from the manufacturer and from the practitioners at FOJAB.

2.1 The general information of prefabricated façade systems

As aforementioned, three types of prefabricated façade systems analysed in this study were as followed: an aluminium frame panel, an insulated concrete sandwich panel and a wooden frame panel. The details and informations of the aluminium and concrete panels were gathered from two referenced buildings, which entailed one specific manufacturer for each panel type. The details of buildings that utilized the wooden frame façade were not available. Though, one manufacturer for a wooden frame panel was contacted to provide the information related to a wooden frame façade panel.

As there were only three manufacturer for three façade panels, the information gathered from them could be specific to one company. The information of the same product from other manufacturers might be different, which posed as a limitation to this study. However, because of the time constrain, the study was conducted using the information from these three specific manufacturers.

In this study, only the 'main core' of the façade system was analysed. The materials included in this study were those that was considered a part of the thermal envelope. The cladding material and the material required to install the cladding were excluded from this study, as they were not a part of the thermal envelope of the building. The prefabricated façade also required interior finishing treatment, i.e., interior painting. However, as the type of paints used in the building also depends on the space requirement and the aesthetic aim, the interior finishing was not included in the study.

2.1.1 Aluminium frame panel

The details and information of the aluminium frame panel in this project came from a reference building, which was a hospital, located in Malmö. The reference building has several types of cladding, but the main part of the façade remains consistent throughout the project. The profile of the aluminium frame used in the project was designed to fit both the opaque panel and the glazing part.

The opaque part of the prefabricated part consisted of two mineral wool insulation layers with an air gap slotted in between, enclosed by an aluminium alloy plate facing out and a steel plate facing the interior. The referenced construction has an additional layer of steel studs and mineral wool insulation on the inside, and gypsum boards as interior finishing. The additional inner steel studs with insulation and gypsum boards layers were assembled on-site and was not a part of the prefabricated panel. The additional layer served to complete the thermal resistance layer of the façade and functioned as a space to install the electrical, piping and other mechanical equipment. The details of the prefabricated panel and on-site panel was presented in *Figure 4*.

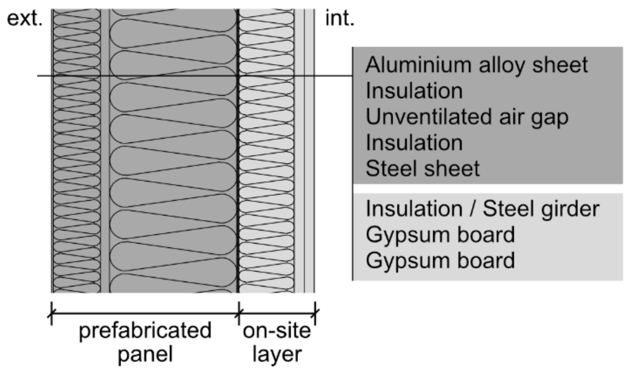


Figure 3 A section of the aluminium frame panel.

The profile of the aluminium frame was designed to be used as the installation point for both the frame of the operable window and the edge of the fixed glazing pane. For the fixed glazing, once installed, there would be no visible frame edge from outside. The glazing in the project, both operable and fixed, were all triple-paned.

The prefabricated aluminium panel were assembled in a factory located in one of Central European countries. The windows, both operable and fixed, were also installed to the panel at the same location. Once the panel and window were fully assembled, it would be loaded on to the trailer, then delivered to the construction site. The materials to assemble the panel were sourced within the region. The list of materials used in the panel and its provider was kindly provided by the manufacturer. The contractor was responsible for the materials that were assembled on-site, namely steel girders, glass wool insulation and gypsum boards. All the on-site materials were sourced from the providers within Sweden.

The aluminium frame façade in the referenced project does not have a load-bearing capacity, thus, it was labelled as a 'non-load bearing panel' in this study. The main structural element of the referenced building was a frame structure with steel columns, steel beams and concrete floor (both prefabricated plank and cast-in-situ concrete, depending on the functional requirement of the space). The aluminium façade panel would be attached to the anchor pieces which were welded to the steel beam.

In this study, both the prefabricated part and on-site wall layer were adapted to the study. The structural elements in the reference project were also adapted to this study as the main load-bearing structure for all non-load-bearing wall panels.

2.1.2 Insulated concrete sandwich panel

The insulated concrete sandwich panel can have varieties of details and thickness, depending on the design and the requirement of the project. The details and information used in this study was based on a reference building, which is an office building located in Helsingborg.

The insulated concrete sandwich panel consisted of the outer concrete layer, the insulation layer, and the inner concrete layer. The inner and outer layers of concrete were linked together with steel connectors and anchors embedded within the panel. The anchors and connectors would penetrate through the insulation layer. The inner concrete layer of the sandwich wall panel also functioned as a load-bearing element of the building. According to the manufacturer, the outer concrete layer normally has a thickness in the range of 70 mm to 80 mm. The insulation thickness has a range of 150 mm to 350 mm. The selection and thickness of insulation depends on the desired thermal resistance and the budget of the project. The inner concrete layer could have the thickness of 150 mm to 200 mm. The façade panel from the referenced project consisted of outer concrete layer with thickness of 80 mm, a G-EPS insulation layer with the thickness of 200 mm, and a 200-mm-thick inner concrete layer. The depiction of the design could be seen in *Figure 5*.

The sandwich wall panel also normally has a lifting element, which was a location where the hook from the crane would be attached to. The lifting element would be embedded at the top of the panel. In the reference building, the position where the lifting element was cast in has thinner insulation layer.

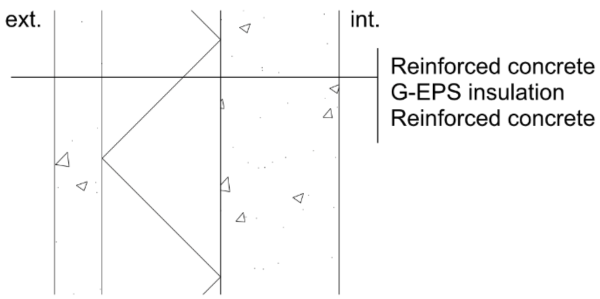


Figure 4 A section of the thermal envelope of the insulated concrete sandwich panel.

The sandwich panel would be cast at the manufacturing site, then delivered to the construction site. The installation of the panel would require some preparations at the assigned place where the panel would be installed. Steel bars should be cast in place on the ground level or should be threaded through the hollow core slab from the top of the lower-level panel. At the bottom of the panel, there are slots for the steel bars to be threaded into at the installation. The panel would be lifted with the crane and placed onto the lower structure while aligning the slots with the bars. Then concrete would be cast into those slots to seal the joints, and the panel would be supported by steel elements throughout the duration that it required to properly cured. The process would be repeat until the top floor. The window of the panel would be delivered to the site from the window provider. The installation of the window would be done at the construction site after the panel was fully cured.

The referenced building has two types of exterior finishing: painted concrete and corrugated metal cladding underneath every window. The corrugated metal façade influenced the joints at the bottom and top of the panel. However, as this study excluded the exterior cladding, the opaque wall would be taken to have a consistent thickness in this study, though the details from the referenced project were adapted to the study. The window used within this study was a fixed triple-pane wooden frame with aluminium cladding, sourced within the Nordic region.

The interior of the sandwich panel in the reference project was also treated as interior finishing, requiring only paint finishing. The electrical wirings were cast into the panel. This required high level of coordination between the disciplines as the electrical system was very specific to the usage of the space. In this study, the electrical elements that could be embedded in the panel was not included.

2.1.3 Wooden frame panel

There was no case study building for the wooden frame wall panel. Thus, the details of the panel used in this study mainly relied on the product sheet, product website, and from the available construction details from the same manufacturer. The wall panel was originally designed to include the exterior finishing, but the exterior finishing and its supporting element was excluded in this study.

The opaque part of the wall consisted of three insulation layers: the external rigid insulation, the main insulation layer in between the wooden studs, and the inner insulation layer in between the wooden studs. The wooden studs used in the panel were all standard lumber size in Sweden. The wall layer of a wooden frame panel is presented in *Figure 6.* The panel would be assembled at the factory, including the installation of the window. The innermost stud layer would be assembled at the factory, but the filling insulation and the gypsum boards for interior finishing would be installed at the construction site, after the mechanical, electrical and plumbing elements were put in place. The panel would be delivered in a weather sealed package on a delivery vehicle and would be lifted to install in place by the crane.

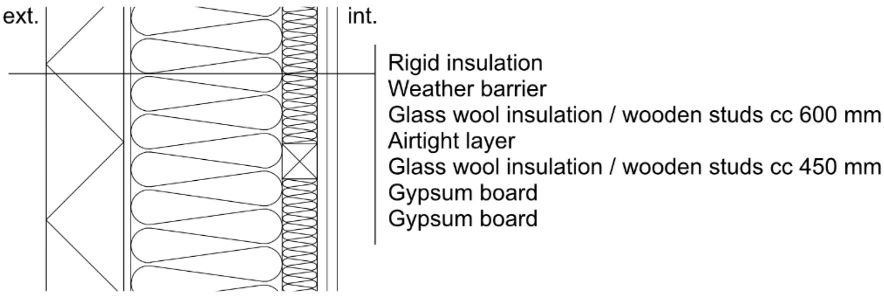


Figure 5 A section of the thermal envelope of the wooden frame panel.

The wooden frame panel could be used as either a load-bearing element or an infill wall. The manufacturer promoted the use of the wooden frame panel as a load-bearing wall for a residential building. In a case of a residential building, the panel would fit in between two load-bearing concrete interior wall and would also act as a casting form for concrete floor of the upper level, meaning that the wooden frame panel would not be the only load-bearing element of the building. In this study, the wooden frame was adapted as a non-load bearing panel, thus requiring the main structure. The main structure was adapted from the aluminium panel reference construction, as a frame structure with steel beams, steel columns and concrete floor. Although the slab edge and the steel beam would intrude more into the wall layer because of the details of the wooden element.

The window used with the panel was a fixed triple-pane wooden frame with aluminium cladding, sourced with in Nordic region, which was the same type of window as in the insulated concrete sandwich panel. The materials related to the installation was also the same. Though, the window and its installation materials would be delivered to the wooden frame panel assembling factory instead of the construction site.

2.2 The panel property

Although these prefabricated façade systems could theoretically be utilized in any type of building project. In this study, an office building was chosen. The location of the building was set to be in Malmö.

Several aspects were taken into consideration when establishing the panel's physical and thermal property, from the theoretical guideline, the building regulations, the practical limitations, and the standard practice. All of which would be explained within this section.

The panel property would be used as a guideline to adhere to when designing each façade panel. Eventually, every panel types would have same physical properties, i.e., the same width, the same height, the same glazing area. The thermal property was also established, with an intention to create a comparable energy performance between the three panels.

2.2.1 The panel size and dimension

As the panel in this study was to be used on an office building. The building regulations related to the design of the work premises were reviewed. The Swedish building regulations (Boverkets byggregler or BFS 2011:6 with BFS 2020:4 – BBR 29) stated that the room height in the 'work premises section' should not be less than 2.40 m, but in the premises intended for many people, the room height is required to be no less than 2.70 (Boverket, 2021c). In practice, offices tend to be designed with open plan layout, and the office building is designed to be rented out to companies that could have different space requirements. Thus, to maximise the flexibility, the room height – in other words, the ceiling height – was designed to have the minimum requirement of 2.70 m.

There are no minimum or maximum limit for floor-to-floor heights, according to BBR. The height commonly used for the office building in the early design stages varies from 3.80 m to 4.20 m upon the project's requirements, according to the practitioners.

As for the window size and position, a study stated that the position of windows that is high on and in the middle of the wall proved to have better performance in daylight metric overall, while the square-shape window was recommended (Vogiatzi, 2018). Another study also suggested the optimal glazing-to-wall ratio (GWR) for an office building located in Sweden is between 20 % to 40 % when considered both daylight and energy aspects (Dubois and Flodberg, 2013). These general window placements and GWR were taken into consideration when coming up with the comparable façade

However, there were other factors taken into consideration when defining the panel dimension. These factors, which would be discussed in the following sections, could pose as limitations when designing with prefabricated construction but could also be explored and optimized the construction solution for the best efficiency. The information presented in the next sub-section were based on e-mail correspondences with the three panel-manufacturers.

2.2.1.1 Transportation limitation

The method of delivery from the factory to the construction site depends on the location of the factory. If the factory was in Sweden, then the transportation would involve semi-trailer or trailer trucks. If the factory was located elsewhere in Europe, then it may include sea-going-vessels. In this project, it was verified that all the factories are located where the on-land vehicle could reach. Thus, the limitation would directly involve the size and weight limitation of the truck. Although there were several types of vehicles being used for delivery of construction materials.

The European Modular System for road freight transport stated that the total length of the vehicle should be less than 25.25 m, which based on combining the 7.82 m largest loading platform under CEN standards and 13.60 m of the semi-trailer and the longest vehicle under EU regulations in a road train. The gross height is limited to 4.00 m and the width to 2.55 m (Åkerman and Jonsson, 2007). In Sweden, the modular system was also adapted for the length limitation (Swedish Transport Agency, 2018). There is no specific height limitation in Sweden, but the normal clearance height of the underpass is 4.50 m. The Swedish regulation has a clear weight restriction based on the bearing capacity classes (Bärighetsklasser – BK) and the distance between the first and last axle of the vehicle or road train.

The transportation within the construction on site was also limited by the load capacity of the crane. Tower cranes with lifting capacity of 20,000 kg (20 tonnes) are commonly used in the construction site. Cranes with higher lifting capacity was avoided as it was not cost-effective (60% more expensive than the renting of the 20-tonnes crane) (Liew et al., 2019).

As the aluminium frame manufacturer is located in a Central European country, it was found that the width aluminium frame was limited to a maximum of 2.55 m from a logistic point of view. While the aluminium frame panel was a lightweight panel overall, the weight of the element was not a main issue.

The concrete manufacturer stated that the main limitation of the panel production was directly related to the transportation. The main concern being the weight of the element, which would affect the handling in the factory, the delivering transportation and the transportation within construction site. A concrete wall element could weight from seven to twelve tonnes; thus, bigger elements would be impossible to be transported because of the weight limitation of the vehicle.

The wooden frame panel manufacturer mentioned that the maximum transportation height including the truck was 3.80 m, meaning that the wall element height would normally be kept below 3.20 m. If the element is taller, it would be laid down on its side when it is being delivered, thus, the maximum width of the element would be limited to 3.00 m.

2.2.1.2 Manufacturing limitation

The process of making prefabricated panel were gathered from the company representation and general knowledge. The prefabricated façade panel are made on welding or casting table. The size of the table determines the size of the panel.

The aluminium panel manufacturer stated that the factory has a capability to build up to 13-metre-long element with extra consideration of the panel structural integrity. Though the width of the element was mainly determined by the transportation, as aforementioned.

For precast concrete, the size of the panel or any casted element varies from one manufacturing site to another. Most factories in Sweden can cast the element with the width of 3.70 m and the length of 7.50 m. Some of the factories can cast bigger elements, for example, the elements with a width of 4.20 m and a maximum length of 9.00 m. The concrete element also required to have 500 mm band around the border of the element to be opaque wall for handling and structural integrity purpose. In practice, there were several ways to design around this limitation.

As for the wooden frame panel, there was no apparent limitation in terms of manufacturing. Although the height of the element would normally be limited by the transportation, it is possible to produce an element that is taller than 3.20 m, according to the manufacturer.

2.2.2 The expected Average U-Value

In the latest version of Swedish building regulation, BBR 29 (2020), a building that has the heated floor area larger than 50 m² is required to meet a certain primary energy number (EP_{PET}) and a certain average heat transfer coefficient (U_m) value. In commercial buildings (lokaler), the average heat transfer coefficient should be lower than 0.50 W/(m²·K) (Boverket, 2021c).

In practice, the expected average U-Value of each element would normally be given by the energy consultant in the early design stage, in consideration of the prospect U_m. The calculation for the average heat transfer coefficient according to BBR could be seen in *Appendix A*. Each energy consultant has their own procedures and different U-Value for each project, depending on the building's heated floor area and envelope areas. However, the façade of the building is normally more exposed to the heated space in comparison to the roof and the ground. The façade, both opaque wall and glazing area, make up most of the building envelope area in many cases, including the two reference buildings. Therefore, the attempt to keep the U-Value of the façade area lower is more prominent among the practitioners. In this study, the expected average U-Value of the façade panel was set to be 0.40 W/(m²·K), which would increase the chance of U_m being lower than the limit stated in BBR.

2.3 Initial U-Value of the panel

The initial U-Value of the panel was calculated, assessing only the façade. The connection of the façade to the main construction and its heat loss would be addressed later in the process. The aim of the initial U-Value was to construct a façade with enough thermal insulation layer to reach the expected U-Value of 0.40 W/(m²·K), as mentioned in *The panel property*, and establish the amount of material in each façade system, which would later be used in the next stage of the study: *Life Cycle Assessment (LCA)*.

Because of the different types of façades, the three façade panels did not have the exact same method of calculating the U-Value. The aluminium frame panel was categorized as a curtain wall element, which required a different method of assessing the heat loss through the panel. Whereas the insulated concrete panel and the wooden frame panel could be manually calculated according to another standard for building components and building elements.

2.3.1 Initial U-Value of the aluminium frame panel

The U-Value calculation for aluminium frame construction fell under EN ISO 12631: 2017 standard, which described the calculation of thermal transmittance of curtain walling element (European Committee For Standardization, 2017a). The standard proposed two types of thermal transmittance calculations for a single element curtain wall: the area-related thermal transmittance method (U_{TJ}) and the length-related linear thermal transmittance method (Ψ_{TJ}). Both methods require the thermal modelling to determine the actual heat flow. However, with the limited information of the aluminium profile details, the calculation done by the manufacturer for the reference building was adapted to studied panel instead.

The calculation method that the manufacturer used was the area-related thermal transmittance method (U_{TJ}). The areas used in this method would be taken from the visible areas of the curtain walling system. The overlapping of the glazed area by the gasket is ignored. The calculation of the thermal transmittance of the curtain wall element (U_{CW}) in the area-weighted average of all the thermal transmittances of joints, glazing units and panels was calculated according to *Equation (1),* using *Figure 7* as an area definition.

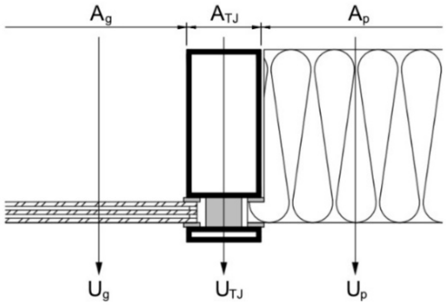


Figure 6 The definition of the areas when using U_{TJ}, illustrated based on Figure 7 in EN ISO 12631:2017

$$U_{CW} = \frac{\sum A_g U_g + \sum A_p U_p + \sum A_{TJ} U_{TJ}}{\sum A_g + A_p + \sum A_{TJ}} \tag{1}$$

Where A_g is the glazed area, in m²;
U_g is the thermal transmittance of the glazing, in W/(m²·K);
A_p is the opaque panel area, in m²;
U_p is the thermal transmittance of the opaque panel in W/(m²·K);
A_{TJ} is the thermal joint area, in m²;
U_{TJ} is the thermal transmittance of the thermal joint, in W/(m²·K);

The design of the aluminium frame panel façade would be described under *'Aluminium frame panel'*, in the result chapter. The U-Value of the glazing, the opaque panel, and the thermal joint (U_g, U_p, and U_{TJ}) from a comparable panel from the reference project were used to calculate the U-Value of the designed façade. The thermal transmittance of the thermal joint from the reference panel was assigned to the similar details in the designed façade, as shown in *Figure 8.* The thermal transmittance of the thermal joints would be listed in the result section – *Initial average U-value, Aluminium frame panel* – in a breakdown of the calculation. The thermal conductivity and the thickness of the materials that were grouped for the opaque part was as shown in *Table 1.*

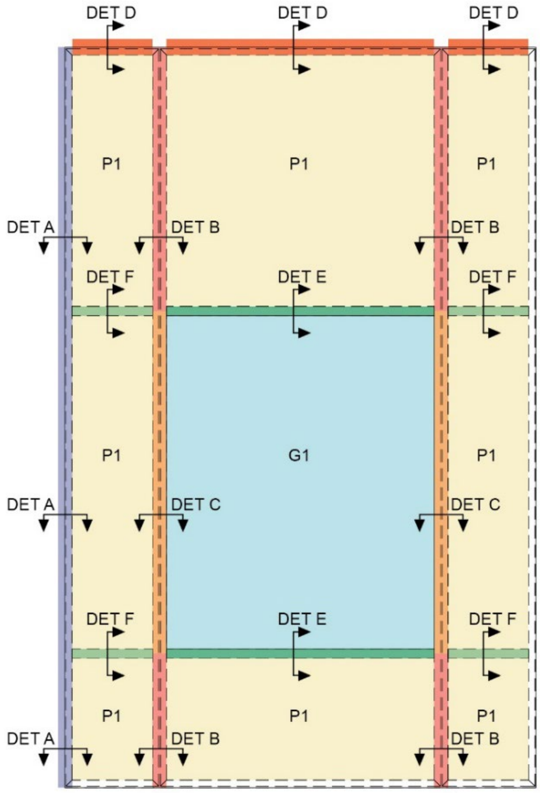


Figure 7 The designed façade, labelled with the adapted details for the calculation

Table 1 The thermal conductivity and the thickness of the material from the outer layer to the inner layer.

Material layer	Material	Thickness (mm)	Thermal Conductivity (W/(m·K))
1	Aluminium alloy sheet	2.0	160.000
2	Rockwool insulation	60.0	0.035
3	Air layer - unventilated	12.0	0.076
4	Rockwool insulation	160.0	0.035
5	Steel sheet	1.0	60.000
6	Stone wool insulation	70.0	0.035
	Steel girders	70.0	60.000
7	Gypsum board	12.5	0.220
8	Gypsum board	12.5	0.220

2.3.2 Initial average U-Value of the insulated concrete sandwich and wooden frame panel

The initial U-Value of the aluminium frame panel included every heat loss happening through the panel, including the heat loss around the perimeter of the glazing area. The calculation for the initial U-Value of the insulated concrete sandwich and wooden frame panel would adapt to include the linear thermal transmittance (Ψ-Value) around the window perimeter. Thus, the initial average U-Value of the two panels could be calculated according to *Equation (2)*.

$$U_{AVG} = \frac{\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k}{A_{facade}} \tag{2}$$

Where U_i is the heat transfer coefficient for façade component i, in W/(m²·K);
A_i is the area of the façade component i's surface, in m;
Ψ_k is the heat transfer coefficient for the linear thermal bridge k, in W/(m·K);
l_k is the length of the linear thermal bridge k, in m;
A_{facade} is the total façade area, in m.

Although, it must be mentioned that the calculation for initial average U-value only included the U-Value of the opaque part, the total U-Value of the window, and the linear thermal transmittance around the window perimeter. The effect of the heat loss where the panel was attached to the main structure would be later described in *'Thermal bridges assessment'* and *'Average U-Value of the façade'* sections.

The U-Value of the total window was set as 0.90 W/(m²·K), as the calculation of the total window U-Value was not in the scope of the study. The Ψ-Value around the window perimeter was taken from the default value listed in EN ISO 14683 (2017) – a standard that describes the thermal bridges in building construction. The default value for the joint of lightweight wall construction and window frame, assuming that the window frame would be in the middle position, was 0.10 W/(m·K) (European Committee For Standardization, 2017b).

The design of the concrete frame panel and the wooden frame panel would adhere to the panel property. The full description of the panel property, the design of the concrete and wooden panel could be found under *'The panel property'* in Results chapter. Though, the properties related to the initial U-Value calculation were the same for the insulated concrete panel and wooden frame panel. The panel properties are as follows:

- Area of the opaque part (A_{opaque}) was 7.255 m²,
- Area of the window (A_{window}) was 2.945 m²,
- The perimeter of the window (l_{window}) was 6.900 m,
- Total area of the panel (A_{facade}) was 10.200 m².

The U-Value of the opaque part of these two panels would be calculated taken different approaches as they were not the same type of wall. The calculation would be presented in the next sections.

2.3.2.1 Insulated concrete sandwich panel U-Value

The calculation method for thermal resistance of the sandwich panel is in accordance with the EN ISO 6946 (2018) – a standard describing calculation methods for thermal resistance and thermal transmittance f building components and building elements. The opaque part of the insulated concrete sandwich panel was taken as a homogeneous building material. The thermal resistance of homogenous layers (R-Value) could be calculated using the design thermal conductivity and the thickness of the material layer, as shown in *Equation (3)*

$$R = \frac{d}{\lambda} \tag{3}$$

Where	R	is the thermal resistance, in (m²·K)/W;
	d	is the thickness of the material layer in the component, in m;
	λ	is the design thermal conductivity of the material, in W/(m·K)

The total thermal resistance of a building component consisting of homogeneous layers (R_{tot}) can be calculated following *Equation (4)*. In this case of the concrete panel, there would only be three layers of material. The internal and external surface resistance (R_{si} and R_{se}) were taken according to EN ISO 6946; where the internal and external surface resistance for horizontal heat flow was 0.13 (m²·K)/W and 0.04 (m²·K)/W, respectively.

$$R_{tot} = R_{si} + R_1 + R_2 + \cdots + R_n + R_{se} \tag{4}$$

Where	R_{tot}	is the total thermal resistance, in (m²·K)/W;
	R_{si}	is the internal surface resistance, in (m²·K)/W;
	$R_1, R_2 \ldots R_n$	are the design thermal resistances of each layer, in (m²·K)/W;
	R_{se}	is the external surface resistance, in (m²·K)/W.

Finally, the U-Value of the opaque part of the panel could be determined using a simplified calculation as stated in *Equation (5)*.

$$U = \frac{1}{R_{tot}} \tag{5}$$

Where	U	is the thermal transmittance, in W/(m²·K);
	R_{tot}	is the total thermal resistance, in (m²·K)/W.

The thermal property of the material in the insulated sandwich panel could have slight variation depending on the requirement of each project. The manufacturer stated that there are several options for the insulation material: from the material with thermal conductivity of 0.020 W/(m·K) to 0.035 W/(m·K). The thickness of the insulation material ranged from 150 mm to 300 mm. Though, as the construction details of the insulated concrete panel were referring those of the reference building, the thickness and the thermal property of the material also followed those in the reference building. However, the thermal conductivity of the concrete used in the reference project was not provided. Thus, it was established as follows:

In EN 13369 (2018) – a standard defining common rules for precast concrete products, it stated that the design thermal conductivity and the specific heat capacity of the materials may also be obtained from tubulated values in EN ISO 10456, and the thermal resistance and transmittance of concrete products may be calculated in accordance with EN ISO 6946 (European Committee For Standardization, 2018). In EN ISO 10456: 2007, which is a standard for hygrothermal properties of building materials, the design thermal values for concrete as building materials were listed as in *Table 2* (European Committee For Standardization, 2008).

Table 2 Design thermal values for materials in general building applications. Excerpt from Table 3 in SS-EN ISO 10456:2007.

Material		**Density** (kg/m³)	**Design thermal conductivity** (W/(m·K))	**Specific heat capacity** (J/(kg·K))
Concrete	Medium density	1800	1.15	1000
		2000	1.35	1000
		2200	1.65	1000
	High density	2400	2.00	1000
	Reinforced (with 1 % of steel)	2300	2.30	1000
	Reinforced (with 2 % of steel)	2400	2.50	1000

In the concrete sandwich panel, which is a load-bearing structure, there are reinforcement steels and multiple types of steel cast-in-elements. Though EN ISO 13369 did not specifically mention how to include the thermal bridges effect of these elements in a manual calculation method. It is worth mentioning that the percentage of steel embedded in sandwich elements ranges from 2.1 % to 5.1 % (including both reinforcement steels and other steel cast-in-elements) based on the Environmental Product Declarations (EPDs) from several prefabricated concrete manufacturers (*Table 3*). The sources of the EPDs could be found in *Appendix B*.

Table 3 Reinforcement and cast-in-material weight percentage from eight different manufacturers

	EPD A	**EPD B**	**EPD C**	**EPD D**	**EPD E**	**EPD F**	**EPD G**	**EPD H**
Reinforcement and cast-in-element per total weight of the insulated concrete element (%)	2.9	3.0	4.0	3.5	2.9	2.3	2.1	5.1

This indicated that the thermal conductivity of the concrete layer in the sandwich element, when included all the embedded steels, might be higher than 2.5 W/(m·K) that is the maximum from EN ISO 10456 standard (Reinforced concrete with 2 % of steel, as stated in *Table 2*). However, the validation of the thermal conductivity of precast element was not in the scope of this study. Therefore, the thermal conductivity of 2.5 W/(m·K) was used for the concrete layer in the sandwich element. It was noted that the heat loss from the steel connectors and anchors, which penetrated through the insulation layer to connect the inner and outer concrete layers together, were not included in the calculation.

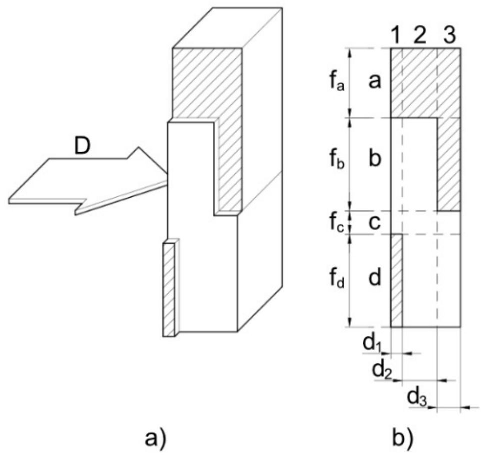
Thus, the material properties that were used to calculate the U-Value of insulated concrete panel were as listed in *Table 4*: the thickness of each layer and the insulation property were based on the referenced project.

Table 4 Material property in insulated concrete sandwich panel, from outer to inner layer

Layer	Material	Thickness (mm)	Thermal conductivity (W/(m·K))
1	Concrete (outer layer)	80	2.500
2	Graphite EPS	200	0.031
3	Concrete (inner layer)	200	2.500

2.3.2.2 Wooden frame panel U-Value

The type of wall layer used in the wooden frame infill panel was categorized as an inhomogeneous wall, as the wooden studs were sitting in between the insulation material. The calculation for the wall U-Value was taken according to the method listed in EN ISO 6496: 2017. The diagrammatic sections and layers of a thermally inhomogeneous component used in the standard calculation could be depicted as *Figure 9*.



Key
D is the heat flow direction
a, b, c, d are the sections
1, 2, 3 are the layers

Figure 8 The sections and layers of a thermally inhomogeneous component, illustrated based on Figure 1 in SS-EN ISO 6946:2017.

The inhomogeneous layers in the wooden frame façade were identified to be the two inner insulation layers. The 195 mm-thick layer of glass wool insulation had 45×195 mm wooden studs placed 600 mm (centre-to-centre) apart vertically as the bridging material. The inner 45 mm-thick layer of glass wool insulation had 45×45 mm wooden studs placed 450 mm (centre-to-centre) apart in both vertical and horizontal directions as the bridging material. The total resistance of the inhomogeneous component could be calculated by following *Equation (6)*.

$$R_{tot} = \frac{R_{tot;upper} + R_{tot;lower}}{2} \tag{6}$$

Where R_{tot} is the total thermal resistance of a component, in (m²·K)/W;
$R_{tot;upper}$ is the upper limit of the total thermal resistance, in (m²·K)/W;
$R_{tot;lower}$ is the lower limit of the total thermal resistance, in (m²·K)/W;

The property of the material in the wooden frame façade and the ratio of the material in the inhomogeneous layer was as listed in *Table 5*. The ratio of the wooden studs to insulation for the stud placement 600 mm and 450 mm were taken as 0.12 and 0.14 according to the studs percentage from the calculation manual instructed by the manufacturer (ISOVER, 2022).

Table 5 Material property in wooden frame façade, from outer to inner layer.

Layer	Material	Thermal conductivity (W/(m·K))	Thickness (mm)	Ratio of material (-)
1	Rigid insulation	0.032	100.0	-
2	Weather barrier	0.250	9.0	-
3	Glass wool insulation	0.035	195.0	0.88
	Wooden studs (45×195 mm), cc 600 mm	0.140	195.0	0.12
4	Airtight layer	-	-	-
5	Glass wool insulation	0.033	45.0	0.86
	Wooden studs (45×45 mm), cc 450 mm	0.140	45.0	0.14
6	Gypsum board	0.250	12.5	-
7	Gypsum board	0.250	12.5	-

The upper limit of the total thermal resistance ($R_{tot;upper}$) was calculated using *Equation (7).*

$$\frac{1}{R_{tot;upper}} = \frac{f_a}{R_{tot;a}} + \frac{f_b}{R_{tot;b}} + \frac{f_c}{R_{tot;c}} + \frac{f_d}{R_{tot;d}} \quad (7)$$

Where $R_{tot;upper}$ is the upper limit of the total thermal resistance, in (m²·K)/W;
$R_{tot;a}, R_{tot;b}, \dots, R_{tot;d}$ are the total thermal resistance from environment to environment for each section, calculate using *Equation (4)*, in (m²·K)/W;
$f_a, f_b, \dots, f_d$ Are the fractional areas of each section.

With the ratio stated above, the $R_{tot;upper}$ calculation, since there were two layers with inhomogeneous material, the fractional areas of each sections were calculated mathematically by multiplying the ratio of each material. The total R-Value of each fraction was also calculated using *Equation (4).* The results that were used in the calculation were as shown in *Table 6.*

Table 6 The ratios and R-Values of each fractional area.

Fraction	Material in the area	Multiplying ratio (-)	Multiplied ratio (-)	Total R-Value of the fraction ((m²·K)/W)
f_a	Stud cc 600 mm – Stud cc 450 mm	0.12 × 0.14	0.0168	5.145
f_b	Stud cc 600 mm – Insulation 33	0.12 × 0.86	0.1032	6.187
f_c	Insulation 35 – Stud cc 450 mm	0.88 × 0.14	0.1232	9.324
f_c	Insulation 35 – Insultion 33	0.88 × 0.86	0.7568	10.366

For the lower limit of the total thermal resistance ($R_{tot;lower}$), an equivalent thermal conductivity of the layer would be calculated by using *Equation (8)*, where the equivalent thermal conductivity of the inhomogeneous layer would be calculated with *Equation (9)*. The ratio of the wooden studs to insulation of each layer was as aforementioned. Then the total lower limit ($R_{tot;lower}$) could be calculated the same way as a homogeneous material, as mentioned in *Equation (4)*.

$$R_j = \frac{d_j}{\lambda_{eq;j}} \quad (8)$$

Where R_j is an equivalent thermal resistance, in (m²·K)/W;
d_j is the thickness of the layer, in m;
$\lambda_{eq;j}$ is the equivalent thermal conductivity, calculated according to *Equation (9)*, in W/(m·K)

$$\lambda_{eq;j} = (\lambda_{aj} \cdot f_a) + (\lambda_{bj} \cdot f_b) + \dots + (\lambda_{qj} \cdot \lambda_q) \quad (9)$$

Where $\lambda_{aj}, \lambda_{bj}, \dots, \lambda_{qj}$ are the thermal conductivity of each material in the layer, in W/(m·K);
$f_a, f_b, \dots, f_q$ are the ratio of each material in the layer.

Once the R_{tot} of the wooden frame infill wall was calculated, then the U-Value could be calculated using the same method as the homogeneous material, as mentioned in *Equation (5)*.

2.4 Thermal bridges assessment

The thermal bridge assessment was done with two-dimensional thermal model in HEAT2 program, which is a program validated with the standard EN ISO 10211 and EN ISO 10077-2 (BLOCON, 2016). In the thermal model, the exterior boundary was set to have a constant temperature of -10 °C, while the interior boundary was set to have a constant temperature of 20 °C. The top and bottom part of the wall were modelled to have the same length, measuring from the edge of the interrupted structure. Every element was modelled to have the minimum interior facing length of 1.00 m. The top and bottom boundaries of the wall were set to be adiabatic. The materials used in the thermal model was manually added to the material library with the exact thermal property of the material from each façade system.

The insulated concrete panel and the wooden frame panel both had window installation. The window was modelled in the exact same manner for the two panels. The window frame was modelled to have a thickness of 105 mm and a thermal conductivity of approximately 0.231 W/(m·K) to achieve the U-Value of 1.600 W/(m²·K). While the glazing part of the window was modelled to have a thickness of 40 mm, sitting in the middle of the frame, with the thermal conductivity of 0.027 W/(m·K) to achive the U-Value of 0.600 W/(m²·K). For the installation of the window, there would be a 20 mm band of glass wool insulation and a rubber sealant (bottninglist) wrapped around the perimeter of the window. The thermal conductivity of the glass wool insulation was 0.039 W/(m·K), while it was 0.140 W/(m·K) for a rubber sealant.

The result from the thermal modelling calculation was exported via 'the boundary flows results' and 'the thermal bridges calculation' function of HEAT2. The resulting thermal coupling coefficient was compared to the transmission heat loss calculation of the uninterrupted construction of the same length. The resulting linear thermal transmittance (Ψ-Value) would be used in the calculation for average U-Value of the façade. The average U-Value calculation would include the calculated U-Value of the opaque wall, U-Value of the total window, the Ψ-Value from different joints of the construction, calculated using *Equation (10),* according to the standard EN ISO 10211: 2017 (European Committee For Standardization, 2017c).

$$\Psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \tag{10}$$

Where Ψ is the linear thermal transmittance, in W/(m·K);

L_{2D} is the thermal coupling coefficient obtained from a 2D calculation of the component separating the two environments being considered, in W/(m·K);

U_j is the thermal transmittance of the 1D component, j, separating the two environments being considered, in W/(m²·K);

l_j is the length of over which the value U_j applies, in m.

As the façade systems had different details, the analysed joints would be different and unique to the system, the approach of each system would be mentioned in the next sections. The joint between the panel to the next panel in horizontal direction were not assessed as it was assumed to be the same material thus having the same heat loss.

For the part of the panel that had already been included in the U-Value calculation, the thermal modelling of it would only include the main material of each layer, for simplification and partially because of the lack of information in some system. The materials or elements that were specific to the joint would be included in two-dimensional modelling to observe their effect on thermal bridges.

2.4.1 Aluminium frame panel

In the aluminium frame curtain wall system, the heat loss through glazing area and aluminium frames were included in its U-Value calculation. Essentially, the thermal bridges around the glazing area and aluminium frame were assessed. The only joint being modelled for the aluminium frame system was the joint between the panel and the floor element that consisted of a steel beam and concrete floor. The location and detail of the joints could be seen in *Figure 10*. The aluminium profiles presented in vicinity of the thermal bridge were not modelled to simplify the model and because of the lack of information. The main material of each layer was modelled with the properties presented previously in *Table 1*. The thermal conductivity of the steel beam being modelled was 50.00 W/(m·K), while the concrete floor was 1.70 W/(m·K).

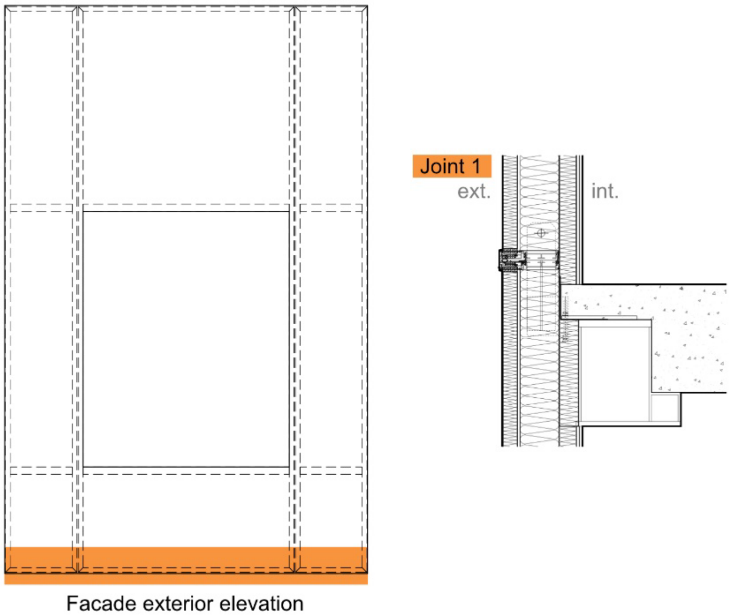


Figure 9 The aluminium frame panel's joint shown on facade elevation and its detail.

2.4.2 Insulated concrete sandwich panel

After observing the drawing of the concrete sandwich panel, the thermal bridges were analysed to be these following joints:

1. The joint at the top of the window
2. The joint at the top of the window, where the lifting element was located
3. The joints on the side and bottom of the window
4. The joint between the panel, the concrete floor and the panel below.

The details of the joint were based on the reference panel from the case study project. The details and locations of the joints could be seen in *Figure 11.* The thermal conductivity and the generic thickness of the material was modelled with values stated in *Table 4*. Concrete floor and PIR insulation were also materials being modelled around the window perimeter. The thermal conductivity of concrete floor was taken as 2.30 W/(m·K) while it was 0.022 W/(m·K) for PIR insulation. The properties of materials related to the window were as aforementioned. The embedded steel and cast-in-elements within the concrete layers were not modelled in the thermal bridge assessment as it was assumed that it was a part of the concrete layer.

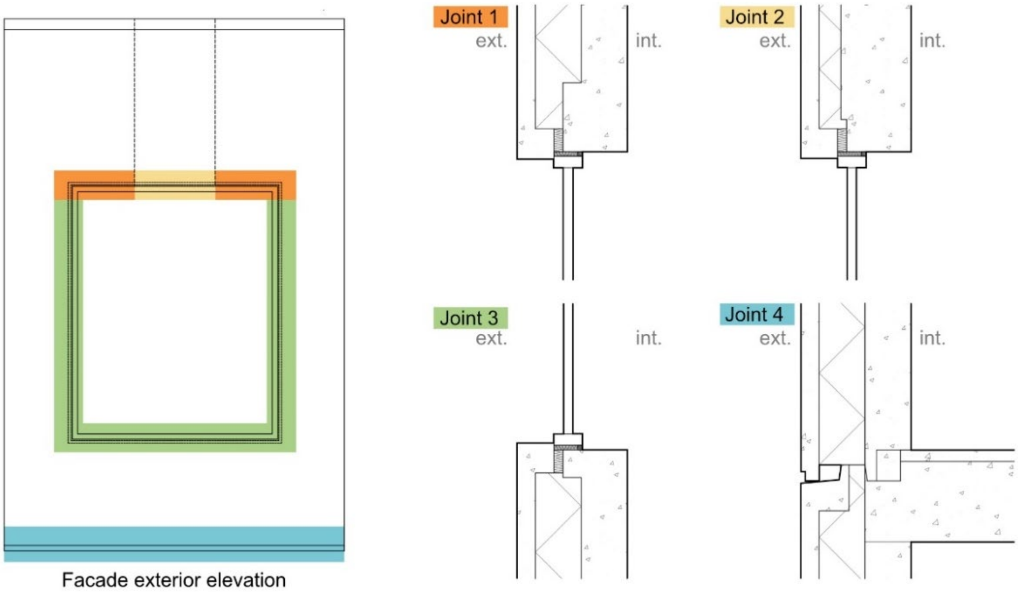


Figure 10 The insulated concrete sandwich panel's joints shown on facade elevation and its detail.

2.4.3 Wooden frame panel

After observing the details of the wooden frame panel, the thermal bridges were analysed to be these following joints:

1. The joint at the top and the sides of the window,
2. The joint at the bottom of the window,
3. The joint between the panel, the beam and the floor.

The details of the joints followed the standard details from the manufacturer. The details and the location of each joint were depicted in *Figure 12.* The two layers of inhomogeneous materials were modelled as one with an equivalent thermal conductivity of 0.044 W/(m·K), while other materials were modelled with the properties following those listed in *Table 5.* The materials related to the window and its installation were as mentioned before. The property for the steel beam and concrete floor were the same as what they were for *Aluminium frame panel*. The light steel frames located at the top and the bottom of the panel, were used when the panel was connected to different material. The light steel frames were modelled with the thermal conductivity of 50.0 W/(m·K).

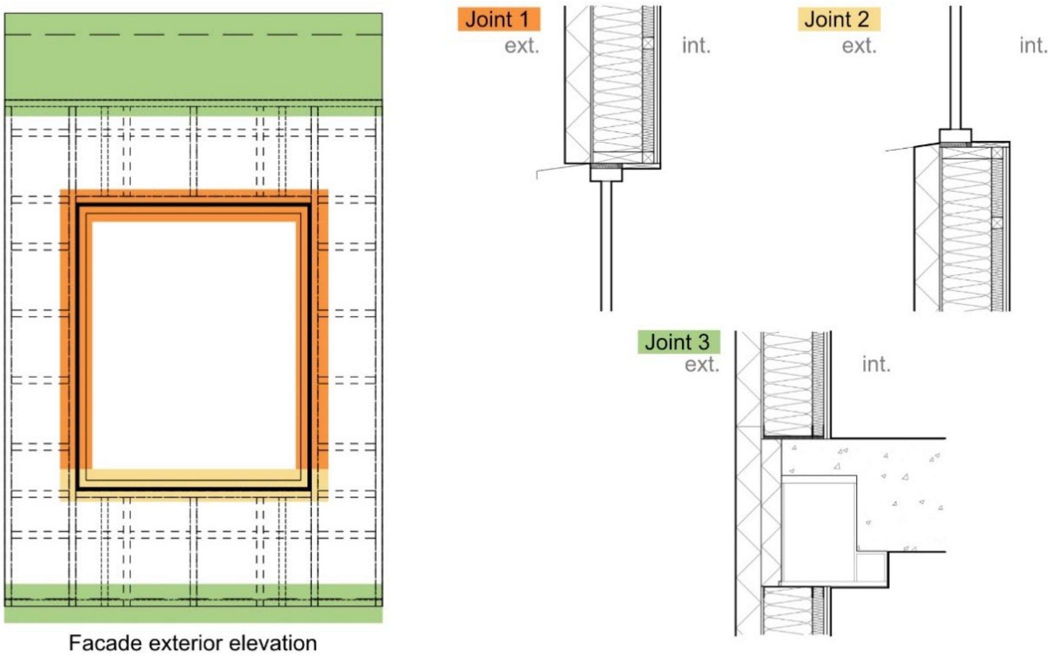


Figure 11 The wooden frame panel's joints shown on facade elevation and its detail.

2.5 Average U-Value of the façade

The average U-Value of the façade was set to include the heat losses happening through the panel, and the heat losses that happened where the panel made contact with the main structure. The calculation for the average U-Value of every façade system would follow *Equation (2)*, mentioned in *Initial average U-Value of the insulated concrete sandwich and wooden frame*. In the average U-Value of the aluminium and wooden frame panel, every linear thermal transmittance of the assessed thermal bridges would be included in the calculation instead of using the default value. The same process was done for the insulated concrete sandwich panel, but the U-Value of the concrete would also include the correction for mechanical fasteners, which would be mentioned in the next section.

In practice, there was a simplification method suggested in Miljöbyggnad 3.2 building certification to calculate the total heat loss of the building without assessing the linear and point thermal losses individually. The additional 30 % of the transmission heat losses through the building envelopes ($\sum U_i \cdot A_i$) would be included to get the total heat losses through the building envelope. Then the total heat losses would be divided by the total area of the building envelopes to get the average heat transfer coefficient (U_m) in accordance with BBR (Swedish Green Building Council, 2022).

In this study, the average U-Value of the façade would be compared to the initial average U-Value to observe the differences. Additionally, the comparison between the commonly practice method (additional 30 %) and the calculated average U-Value would be made.

2.5.1 The correction for mechanical fasteners in insulated concrete sandwich panel

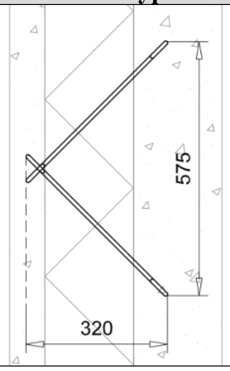
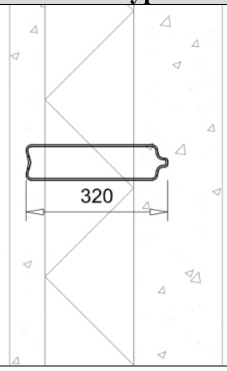
As aforementioned, the concrete sandwich panel had steel elements embedded in the panel. The steel elements fully embedded within the concrete layers were considered as reinforcements, thus the higher thermal conductivity used in this project. However, the steel connectors and anchors that penetrates through the insulation layer might cause additional heat losses. Thus, the correction for mechanical fasteners was calculated for the insulated concrete sandwich panel. The additional heat losses happening was accounted for by using the correction for mechanical fasteners calculation when the fasteners fully penetrate the insulation layer, *Equation (11)*, according to EN ISO 6946: 2017.

$$\Delta U_f = \alpha \cdot \frac{\lambda_f \cdot A_f \cdot n_f}{d_1} \cdot \left(\frac{R_1}{R_{tot}}\right)^2 \tag{11}$$

Where ΔU_f is the correction for mechanical fasteners, in W/(m²·K);
α is the coefficient. In the case where the fasteners fully penetrate the insulation layer, the coefficient was set to be 0.8.
λ_f is the thermal conductivity of the fasteners, in W/(m·K);
A_f is the cross-sectional area of one fastener, in m²;
n_f is the number of the fasteners per m²;
d_1 is the length of the fasteners that penetrates the insulation layer, in m;
R_1 is the thermal resistance of the insulation layer penetrated by the fasteners, in (m²·K)/W;
R_{tot} is the total thermal resistance of the component ignoring any thermal bridging, in (m²·K)/W;

The number and type of the anchors were taken from the referenced project. The anchors' material, diameter and dimension were according to the provider product's sheet (Halfen, 2020). The values used in the calculation could be seen in *Table 7*. Both anchors were made of stainless steel; thus, the thermal conductivity of the fasteners used in the calculation was 17 W/(m·K), according to the value of austenitic stainless steel listed in EN ISO 10456: 2007 (European Committee For Standardization, 2008).

Table 7 The values used in the calculation for each anchor.

	Anchor type 1	**Anchor type 2**
		
Diameter	9 mm	5 mm
Number of fasteners per m²	0.49	2.26
Length through insulation	0.28 m	0.20 m

2.6 Life Cycle Assessment (LCA)

2.6.1 The goal and scope

The goal was to conduct a LCA for each of the façade system, then compare and observe the result of the three systems. The functional unit in this study was defined as the average 1 m² of the designed façade. The scope of the analysis included the material of the designed façade area and its load bearing element. The assessment would include only one midpoint environmental impact category: the Global Warming Potential (GWP) with the unit of kg CO_2-equivalent. The calculation does not include the biogenic carbon according to Boverket's Climate Declaration (Boverket, 2021d). The expected lifespan of the façade system and the structure was taken as 50 years as it was recommended by Boverket (Boverket, 2021b), although the use stage modules (B1-B7) were not in the scope of this study.

Originally, the scope of the study included the five modules from the product stage to construction stage (A1 to A5) to fit with Swedish Climate Declaration. However, with the information regarding site energy for prefabricated façade specifically was limited, the scope was limited to cradle-to-gate with transportation (A1 to A4) instead. The original scope would have required extensive use of assumptions, limiting the robustness of the results. The result of the LCA study was used to compare between each system. Different variations of the assessment would be further analysed under the section called *'Comparative study'*.

As it would be stated in *'The panel property'* in *'Results'* chapter, each façade type was designed to cover the floor-to-floor height of 4.00 m with the panel width of 2.55 m. Each had the same glazing area. The same design was used to assess the total material amount in each system; thus, each panel would have the same 10.20 m² for façade area. The amount of materials required in each system was taken from the established façade that was used in calculations for *Initial U-Value of the panel*. All the materials were assumed to have the same lifespan as the building, which was 50 years. The difference in load-bearing capacity between each panel was also taken into consideration. Thus, the scope of the materials included in the designed façade of each façade panel was defined.

The aluminium frame and wooden frame panels were non-load bearing panels. Both panels required installation on the building's main structure. The structure for these two façades were adapted from the reference building of the aluminium façade: the steel columns and beams with concrete floor. The span of 7.00 – 9.00 m could be commonly found in office buildings. The column span in this study was set to be 7.65 m, so that it could fit exactly three panels perfectly. The column was a steel column with dimension of 450 mm by 250 mm, with the steel thickness of 16 mm. While the steel beam and concrete floor sizing could be seen in *Figure 13*.

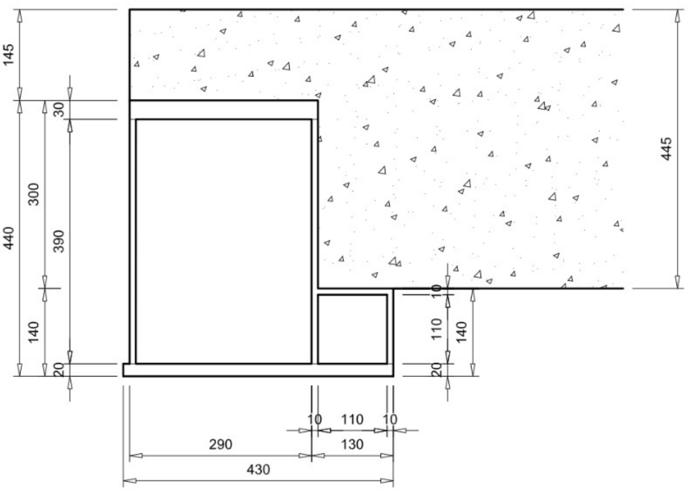


Figure 12 Section of the steel beam and concrete floor from the referenced building (Aluminium frame panel).

The designed façade of the aluminium and wooden frame panels could be seen in *Figure 14*: the designed façade area was the area within the red dotted line (4.00 m in height and 2.55 in width), the yellow area illustrated the opaque area of the façade, the blue indicated the glazing area. The orange area represented the beam and floor that directly take the weight of the panel, while the pink areas were the steel columns taken in as the load bearing structure of the façade. The column's volume would be divided by three, as the structure supported three prefabricated panel. The total environmental impact based on the element in the coloured areas were accumulated then divided by the area of the designed façade to achieve the environmental impact of 1 m² of the designed aluminium and wooden façade.

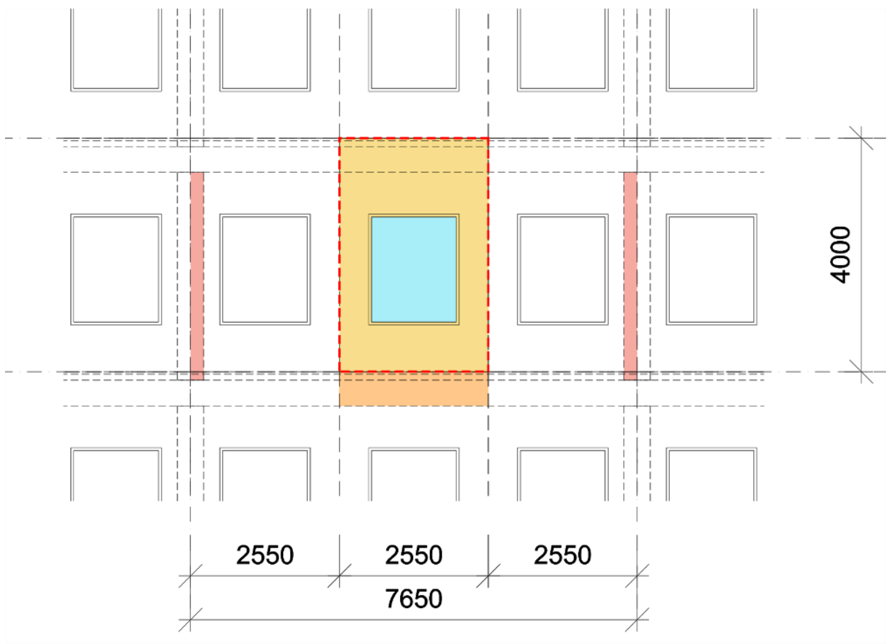


Figure 13 The elements included in the aluminium and wooden façade LCAs.

Whereas for the concrete panel, which functioned as both the façade and load bearing element of the building, the total environmental impact would be calculated based on the façade element – shaded in yellow, the glazing part – shaded in blue, and the concrete floor – shaded in orange *(Figure 15)*. Then the accumulated values would be divided by the area of the designed façade, outlined in red dotted box, to achieve the values per 1 m² of the designed concrete façade.

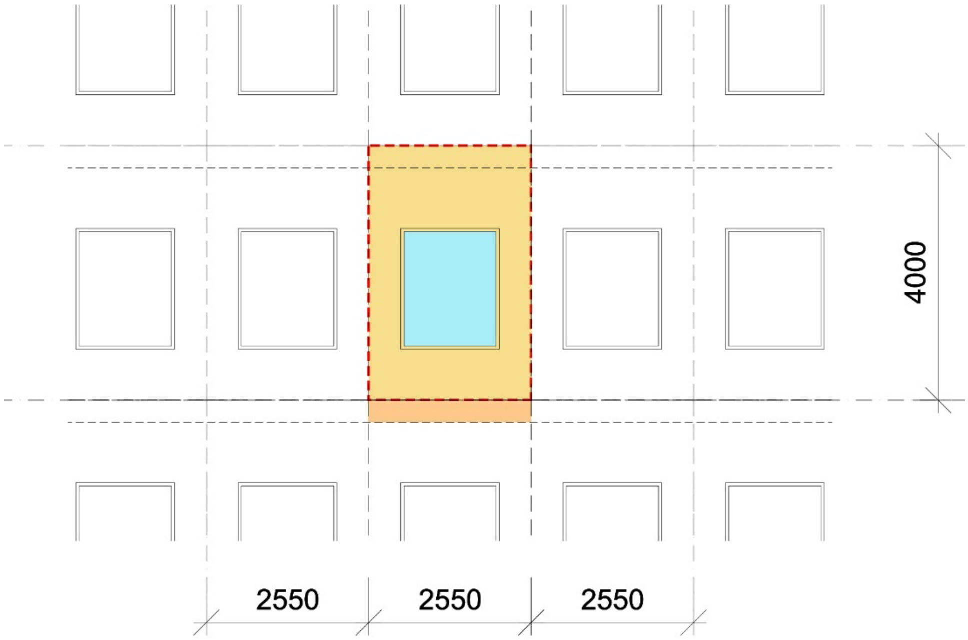


Figure 14 The elements included in the concrete façade LCA.

The illustration depicting the calculated elements of each system could be seen in *Figure 16* with the same colour coded as aforementioned. It could be noticed that although the steel beam and concrete floor supporting aluminium frame panel and wooden frame panel were taken according to the reference building, the different installation methods led to a dissimilar amount of calculated material.

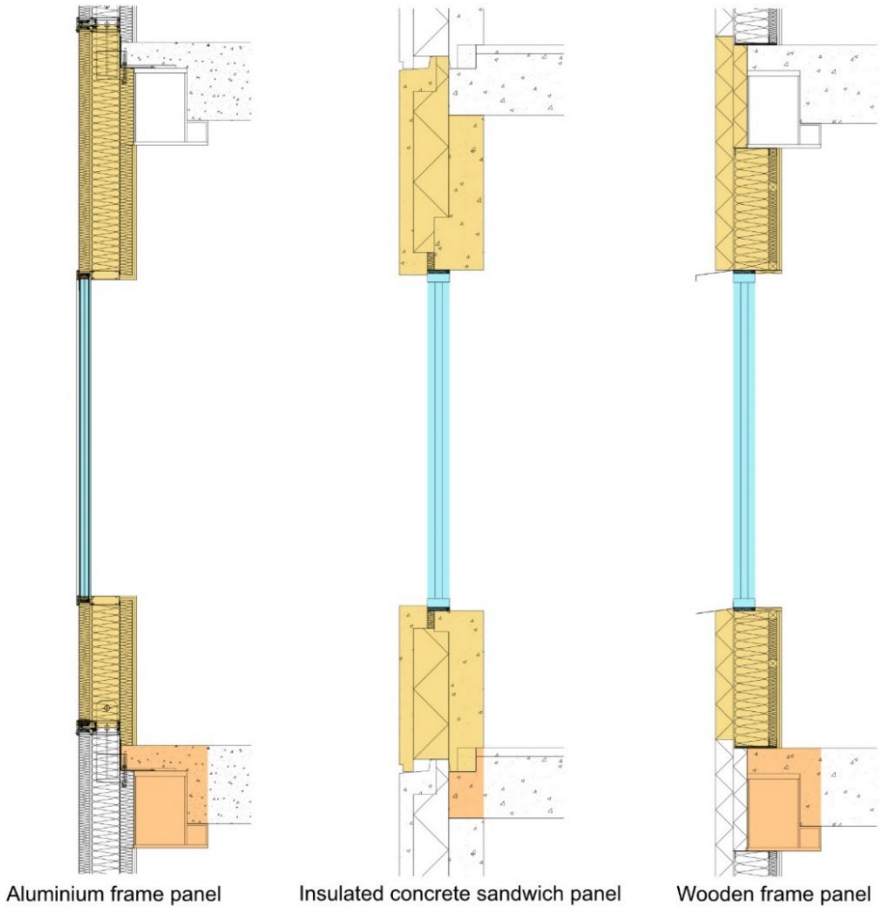


Figure 15 The calculated elements of each façade system. The yellow area signified the area of the opaque wall, the blue area signifies the glazing or window, and the orange area signified the structural elements.

2.6.2 Inventory analysis

The inventory analysis was conducted with the aid of One Click LCA database. In the product stage (A1-A3), the quantity of each material from each designed façade were used as an input to the calculation, pairing with the EPDs or the generic data available on One Click LCA database. The analysis was dependant on the available EPDs and material database on One Click LCA. The limitation of this method was that some of the EPDs re not available on the database. In the case where the EPD of the exact manufacturer was not available, another EPD of the same product by a different manufacturer that has similar geographical location was selected. In a case where the EPD of the product was not available, then the generic data from One Click LCA was selected to make the inventory analysis as complete as possible. The full list of One Click LCA building material input would be displayed in *Appendix C*.

As for the transportation stage (A4), the impact factor for the delivering vehicle would be taken directly from the EPD of the material. If generic data was used, then the 'trailer with 40 tons capacity' would be assigned to the material. The location of the construction site in this study was assumed to be Malmö. The transportation distance for each product was factor into the calculation. The distance for each product was found by using Google Maps to specify the distance from the manufacturing location stated in the EPD to Malmö. One Click LCA would automatically calculate the transportation environmental impact based on the weight of the material, the impact factor specific to the delivering vehicle and the distance between the manufacturing location and construction site.

In One Click LCA, these following parameters were set for the project: Technical service life was selected for Service life value. The transportation distance was selected to be European. The recommended option – v1.0 recommended – was selected for material manufacturing localization method. The end-of-life calculation method was not chosen as it was not within the scope of this study.

Each panel was built to have their own 'design' in One Click LCA. The building material would be selected based on the material in use. In the project basic information, every variation of the design was set to have the same setting and input as follow. The annual energy consumption was set to 0 kWh and the calculation period was set to 50 years, thought the operational period was not in the scope of the study. The building area, which was a mandatory section in One Click LCA, was set to be 10.20 m² of Gross Internal Floor Area. This was a way to work around the limitation, as this analysis was based on the façade area. Thus, the façade area was input as the Gross Internal Floor Area instead.

The environmental impact of each panel was then calculated in One Click LCA, which is also an automated life cycle assessment software (One Click LCA Ltd., 2015). However, as the input of the material was based on the total designed façade, the results of the assessment were also the total GWP of the designed façade. The results from One Click LCA were exported as a Microsoft Excel format, then divided by 10.20 m² to get the environmental impact per 1 m² of the designed façade in Excel. The relevant result presentation graphs were also created in Microsoft Excel based on results of the division.

2.6.2.1 Aluminium frame panel

The inventory analysis on the aluminium frame panel was broken down into several processes in order to calculate the environmental impact and embodied energy of the aluminium frame façade: the prefabricated panel that was delivered directly from the factory, the on-site part of the façade element, and the load-bearing structure. The main materials in the prefabricated panel were aluminium curtain wall profiles (the aluminium frame), glass wool insulations, the aluminium and steel sheet that covered the opaque part of the panel, and the insulated glass unit for the glazing area. The on-site part of the panel included steel girders, glass wool insulation and gypsum boards. The load-bearing element included the concrete floor and the steel beams and columns. The breakdown of the allocations could be seen in the diagram in *Figure 17*.

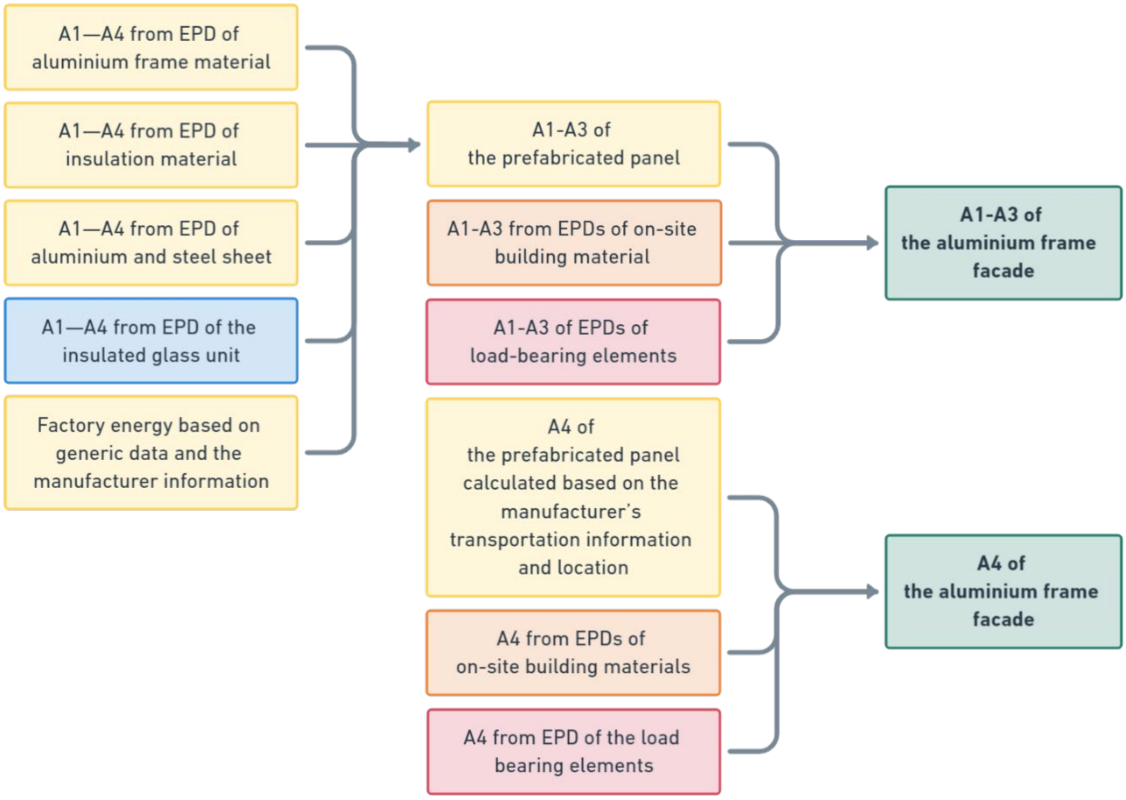


Figure 16 The inventory analysis diagram of the aluminium frame designed façade inventory.

The prefabricated aluminium panel did not have an EPD, thus the material list and amount were calculated for the designed façade, using the manufacturer's information and available drawings. The EPDs of the materials that were used to assemble the panel at the location in Central European were selected from the producer's EPD when it was available or chosen from the EPD of the same product within the region. The EPD of the exact aluminium profile that was used in the project was not available, so the EPD of similar aluminium profile from the same product provider was used in this analysis. The glazing EPD was selected with consideration of the U-Value of the glazing area. The information regarding annual energy use of the factory and the average time to assemble one panel were provided by the manufacturer. The energy use to assemble one panel was calculated based on the information, then was included into A1-A3 of the façade. As for the on-site and load-bearing materials, since the construction site was set to be in Malmö, the EPDs of the element were prioritized to be from the Swedish-based manufacturers.

The information of the structural steel was selected from the built-in generic value database in One Click LCA. Although steel products are a highly recyclable, and one Swedish steel manufacturer claimed that their steel products contain up to 97 % of recycled content, there was no direct statement about the average amount of recycled content for structural steel in Sweden. The generic structural steel with 80 % recycled content was assumed selected for the structural steel this project.

The amount of every material in the aluminium designed façade would be calculated and proportionated according to the declared unit in the EPD of that material. The material input for the aluminium frame designed façade could be seen in *Appendix Table 2.*

2.6.2.2 Concrete sandwich panel

The inventory of the concrete sandwich panel was conducted in a similar way to the aluminium panel. Albeit the concrete panel did not require an additional on-site process to complete the insulation layer unlike the aluminium panel. Thus, the analysis was broken down to two sections instead: the prefabricated materials and on-site materials. The on-site material only includes the concrete floor, which in practice could be a cast-in-place material or a precast floor, the window and materials related to the window installation. In this study, the concrete floor was assumed to be a generic concrete element. The allocation of the material in the inventory analysis of the concrete façade could be seen in *Figure 18.*

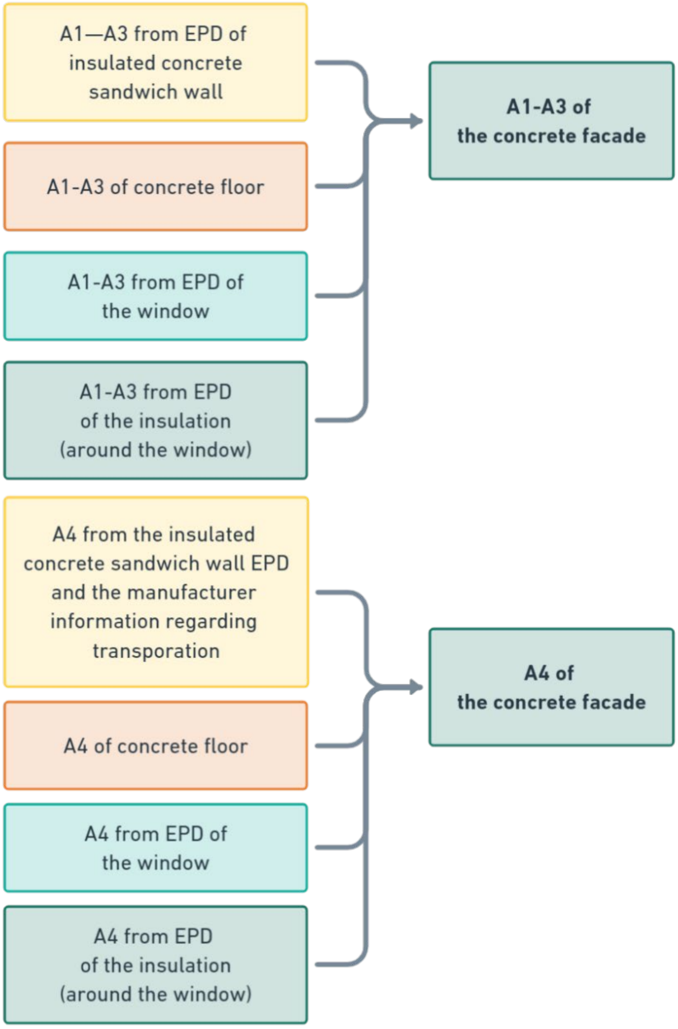


Figure 17 The inventory analysis diagram of the insulated concrete sandwich designed façade.

As there were several EPDs for insulated concrete sandwich wall, it was not necessary to create a detailed material breakdown of materials and elements embedded in the sandwich wall. The most detailed EPD – labelled as EPD A – was selected for the study. The source of the EPD was as listed in *Appendix B*.

The declared unit listed in EPD A was 1 ton of concrete insulated element (1000 kg). The declared product had the concrete strength of C30/37, the typical density of the product was approximately 1260 kg/m³ and the typical product consisted of inner layer concrete with thickness of 150 mm, the insulation layer with thickness of 200 mm and the outer panel concrete with 70 mm thickness. The EPD did not specify the type or the thermal property of the insulation or the total element. The designed concrete element in this study did not have the same thickness for the combined concrete layers: inner layer concrete with thickness of 200 mm, insulation layer with the thickness of 200 mm and 80 mm of outer layer concrete. It was also highly possible that the designed element did not have the same type of insulation nor the thermal property as the declared product in the EPD. Because of the lack of specific information, the volume of each main layer was calculated, then the density of the material was used to calculate the weight of the designed façade. The weight of the designed façade was used as an input to proportionate with the impact from EPD A. The breakdown of the material input could be seen in *Appendix Table 3.*

As for the window component, there was no EPD of a fixed window that had a U-Value that match 0.90 W/(m²·K) of total window U-Value used in the thermal assessment. The EPDs of a window that has in the similar U-Value were not from a fixed window, but from openable windows, which naturally have more components and might result in different climate impact. The available EPD of a fixed window came from a high-performance, low-energy product line with the total window U-Value of 0.74 W/(m²·K) which might also require more material and energy to manufacture. It was deemed that the EPD of a fixed window with lower U-Value would be used in the analysis as the type of product was found the most relevant to the one in this study. The declared unit of the window EPD was 1 m² of the window area, thus, the values from the EPD would be ratioed according to the area of the window in the designed façade. The same EPD and method would be applied in the inventory analysis of the wooden frame façade panel to keep the comparison equitable.

2.6.2.3 Wooden frame panel

Similar to the aluminium frame panel, the wooden frame façade was a non-load bearing panel and a panel that required on-site construction to complete the insulation layer. Typically, this would lead to three processes like the aluminium façade. However, the wooden frame wall had an EPD, which had already accounted for the impact of on-site materials. So, the inventory assessment of the wooden frame façade was only separated into two parts: the prefabricated panel and the main structure of the building. The allocation of the process could be seen in *Figure 19.*

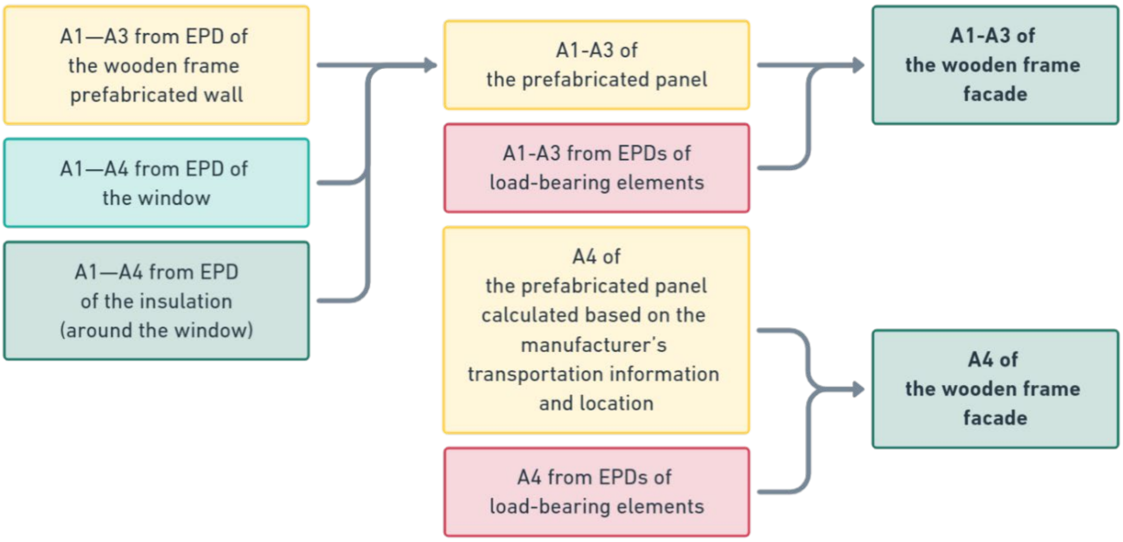


Figure 18 The inventory analysis diagram of the wooden frame designed façade.

The EPD of the wooden frame prefabricated wall stated that declared value was per 1 m² of the product with a thermal resistance of 7.70 (m²·K)/W. Therefore, in the calculation of the wooden designed façade, the value would not only be ratioed by the area of the opaque wall, but also by the specific thermal resistance of the façade. The specific thermal resistance of the panel was calculated according to the method mentioned in *'Wooden frame panel U-Value'*, and the results would be presented in the result chapter, under the section called *'U-Value of the wooden frame panel'*.

The methods and approaches for the inventory of the main structure element was the same as the one mentioned in the inventory analysis of *'Aluminium frame panel'* and the window were as previously mentioned in and in the inventory analysis of *'Concrete sandwich panel'*. The list of the material input for the study could be seen in *Appendix Table 4.*

2.7 Comparative study

This section described the further analysis of the façade systems regarding the thermal bridges and average U-Value and the different materials input of LCAs with the goal to provide more understanding to the façade systems.

2.7.1 Thermal bridges and average U-Value

The thermal bridges assessments, of which the results would be presented later in *'Thermal bridges assessment'* section of the result chapter, was based on the details from the reference building. Though there were alternatives that could be adapted into the design. The comparative study assessed these options to observe if it would bring any improvement to the building compared to the original calculations. The alternative details were modelled in HEAT2. The resulting thermal coupling efficient of the assessed detail was exported and then compared with the heat loss of an uninterrupted element to achieve the linear thermal transmittance value, which was later used to calculate the average U-Value of the façade. The resulting Ψ-Value and the average U-Value of the façade of the alternative was then compared with the original details.

2.7.1.1 Aluminium frame panel

Among three façade systems, the aluminium frame panel was the most complex panel, as it consisted of many materials and delicate details. The possible improvements regarding the thermal bridges within the panel were not explored. Only the joint between the façade and main structure could be explored; the other alternative in this case was replacing the steel beam and concrete floor to glulam beam and CLT floor. The depiction of the two structures could be seen in *Figure 20.*

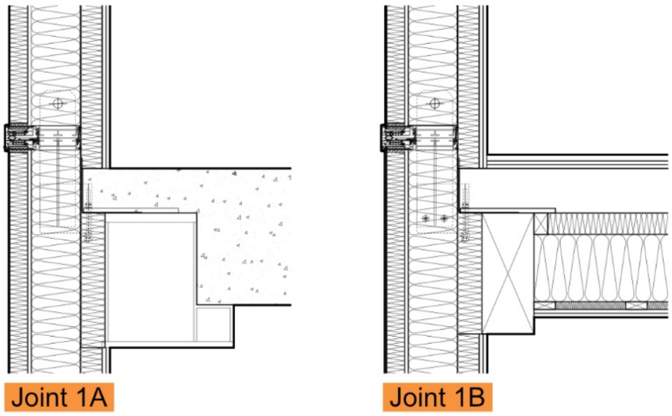


Figure 19 The joint comparison for two types of main load-bearing constructions

The thermal conductivity of the glulam beam and CLT floor were retrieved from the Swedish Wood handbooks as 0.13 W/(m·K) for both materials (Svenskt Trä, 2016, 2019). The insulation in between the beams were assumed to be glass wool with the thermal conductivity of 0.035 W/(m·K), and the acoustic insulation floor on top of the CLT floor was modelled with the thermal conductivity of 0.037 W/(m·K).

2.7.1.2 Insulated concrete sandwich panel

The detail of the joint used in the original calculation was based on the case study project. Though the insulated concrete sandwich has several types of joints that could be adapted to the building. The reference details were gathered from the project specific manufacturer's options and one manufacturer's product sheet and were used as comparison to possible alternatives. The comparison between the linear thermal heat loss between the different joints were made. The resulting average U-Value would also be compared.

The current joint between the panel, the concrete floor and the panel below was called the 'open joint' by the manufacturer from the case study. The open joint, labelled as Joint 4A, was designed to be water repellent although the joint would be left exposed to the outdoor air. Another alternative from the manufacturer was a 'soft joint', which referred to the same concrete detail, but the joint would be sealed with sealant from the exterior side, this joint was referred as Joint 4B in this study. The soft joint also had a possibility to be improved to have more insulation, dubbed as Joint 4C. The last option, Joint 4D, was the 'labyrinth' joint from the referenced product sheet from another company (Abetong, 2020). *Figure 21* illustrated the different joints being assessed in this comparison study. The change from one joint to another was highlighted in blue in every joint and circled in red for the smaller changes in Joint 4B and 4C.

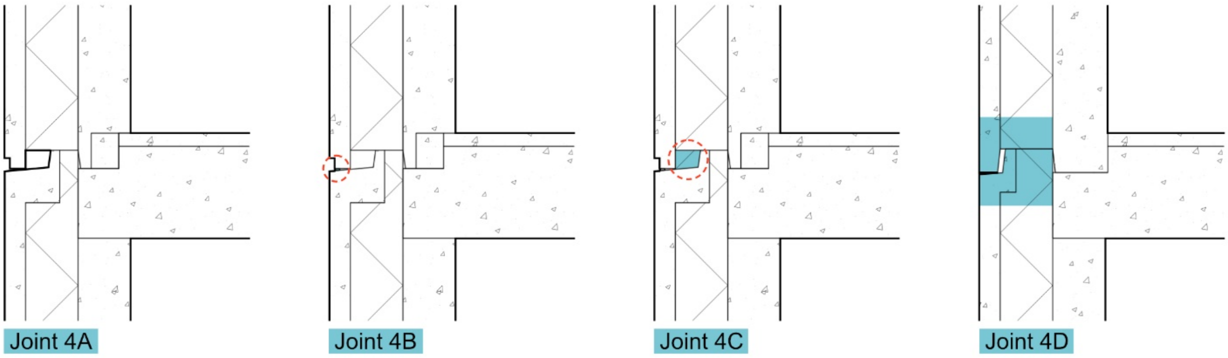


Figure 20 Variations of Joint 4 in the comparison study.

It was observed that the current joint used in the case study detail was rather similar to the labyrinth joint. The observation was confirmed by the manufacturer of the referenced panel; the detail was the same 'typical' detail, but because the reference building had a specific requirement in the design of the façade, the joint was adjusted to the current one (Joint 4A). Though it was said that there were certain typical details for the sandwich wall element, there was a flexibility to adjust the details to fit the aesthetic requirement of the building.

It was also noted that the thermal conductivity for concrete generally used in Swedish energy consultant practice was 1.70 W/(m·K) (Burström, 2007), which was lower than the thermal conductivity of 2.50 W/(m·K) that was used in this study. The lower thermal conductivity might signify that the effect of the reinforced steel in the concrete might be underestimated. The lower thermal conductivity was used to evaluate the thermal bridge based on the details mentioned in *'Insulated concrete sandwich panel'* section and calculate the average U-Value of the element with the same method as stated in *'Average U-Value of the façade'*. The result of the thermal conductivity of 1.70 and 2.50 W/(m·K) would be compared to observe the change in thermal performance of the panel.

2.7.1.3 Wooden frame panel

The focus of the comparison study for the wooden frame panel was on the joint where the panel was connected to the main construction. As the wooden frame façade panel had the same main structure as the aluminium system (Joint 3A), the alternative system such as glulam beam and CLT floor (Joint 3B) should also be adapted with the wooden panel to observe the difference in thermal bridges and average U-Value. Another alternative for the main structure was also a concrete floor (Joint 3C), which was suggested by the manufacturer. *Figure 22* depicted the different main structure types once adapted to the wooden frame panel.

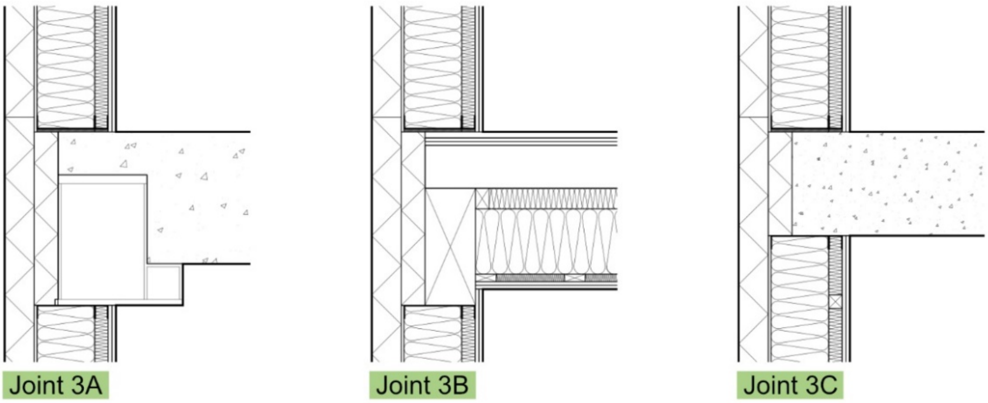


Figure 21 Variations of Joint 3 to different load-bearing elements in the comparison study.

2.7.2 Life Cycle Assessment

While the previously stated scope of LCA would provide a fair comparison of the system, different construction, and choice of EPD would also provide better understanding to the façade element. The original comparison was made for the façade system including the main structure of the building for the panel. However, the result of the main study was specific to the type of construction influenced by the reference building.

The first assessment explored the variations of possible main structure for the non-load bearing façade systems while using the same assessment scope. The frame structure options were the same as in the thermal bridges and average U-Value sensitivity analysis. The aluminium frame was paired with the glulam beam and CLT floor structure *(Figure 23)*. While the wooden frame panel was calculated in glulam beam and CLT floor scenario and the whole concrete floor scenario *(Figure 24)*. However, it was noted that the concrete floor structure for the wooden frame panel normally required to have two interior load-bearing walls, which was not included in the scope of the study.

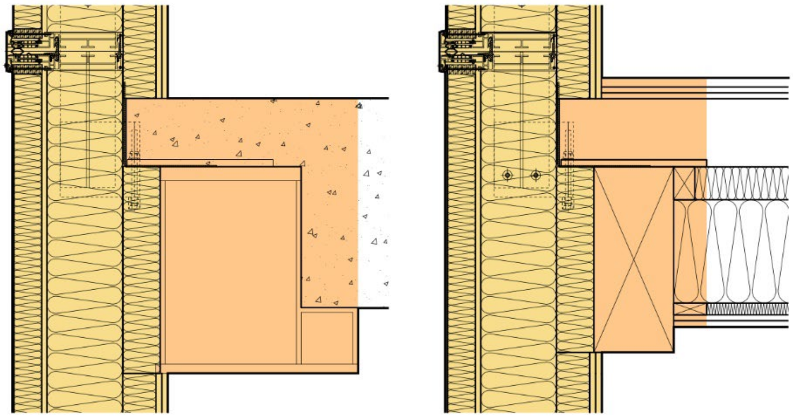


Figure 22 Two load-bearing structure option for Aluminium frame panel

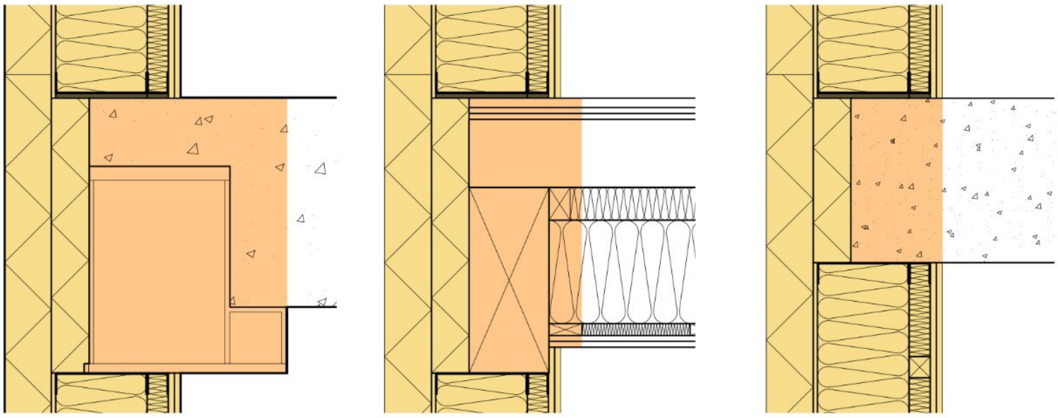


Figure 23 Three load-bearing structure options for the wooden frame panel

The second assessment investigated the possible results when the different EPD of the insulated concrete sandwich wall was used in the inventory analysis. As prior mentioned in *'Concrete sandwich panel'* section, there were several available EPDs for the insulated concrete sandwich wall element. Although these EPDs had the same declared unit (1 ton or 1000 kg mass of insulated concrete element), the material weight percentage differed from one EPD to another.

The EPD that was used in the main LCA study, which was referred as 'EPD A', was selected because of it being the most detailed EPD. Two other EPDs were selected to be compared with EPD A based on the percentage of reinforcement and steel elements in the prefabricated wall. One EPD, referred as 'EPD B', had 3.0 % of reinforcement and the other, 'EPD C', had 4.0 % of reinforcement in the element. All of the three EPDs related to real EPD of concrete sandwich wall. The sources of the three EPDs was stated in *Appendix* B. The details in the material composition from each EPD could be seen in *Table 8*. It was stated in all three EPDs that there are variations in the mix of materials depending on concrete mixes used in each project.

Table 8 Content declaration from three manufacturer EPDs

Material	**Weight-%**		
	EPD A	**EPD B**	**EPD C**
Cement	16.1	19.0	14.0
Aggregate	74.1	68.0	74.0
Additives	0.1	<1.0	<1.0
Water	6.0	9.0	8.0
Reinforcement	2.9	3.0	4.0
Cast-in-material	0.2	-	-
Insulation	0.6	<1.0	<1.0
Total	**100.0**	**100.0**	**100.0**

In this comparison study, EPD B and EPD C were used in two separate Life Cycle Assessments, which had the same scope as previously mentioned in the study. The EPD B and EPD C would replace EPD A to provide different product related environmental factor, while keeping the volume of the material the same throughout. The transportation distance was adjusted according to the manufacturing location listed in each EPD. The other materials that were included in the original LCA of the insulated concrete sandwich panel designed façade were kept constant in this comparison study.

3 Results

The presentation of the results begins with the general panel property that was created based on the practical transportation and manufacturing limitations. Then the panel from each material, which was a direct result of the general panel property, is presented, followed by the results from the calculations and assessments conducted according to the methods and scopes mentioned in the previous section.

3.1 The panel property

In this study, the floor-to-floor height of 4.00 m was selected, as it is within the range of 3.80 m to 4.20 m. With the variation in the panel width that could be manufactured and transported, the smallest width – 2.55 m from aluminium façade system – was selected. The fact that the panel size could be bigger and more optimized for efficient transportations for the concrete construction and wooden frame infill façade was acknowledged.

With all the limitation considered, the size of the panel was chosen to be 2.55 m wide, design for the floor-to-floor height of 4.00 m. The position of the window was 0.80 m off the finished floor, to leave a room to install heating equipment. The top height of the window would align with the ceiling level, 2.70 m, to maximize the daylight quality. With the limitation of the 0.50 m band around the border of the element, the window size was 1.55 m in width and 1.90 m in height. The frame thickness of the window was assumed to be 50 mm; thus, the glazing area was 1.40 m in width and 1.80 in height, resulting in the GWR of 25.6 %. The depiction of the generic panel could be seen in *Figure 24.*

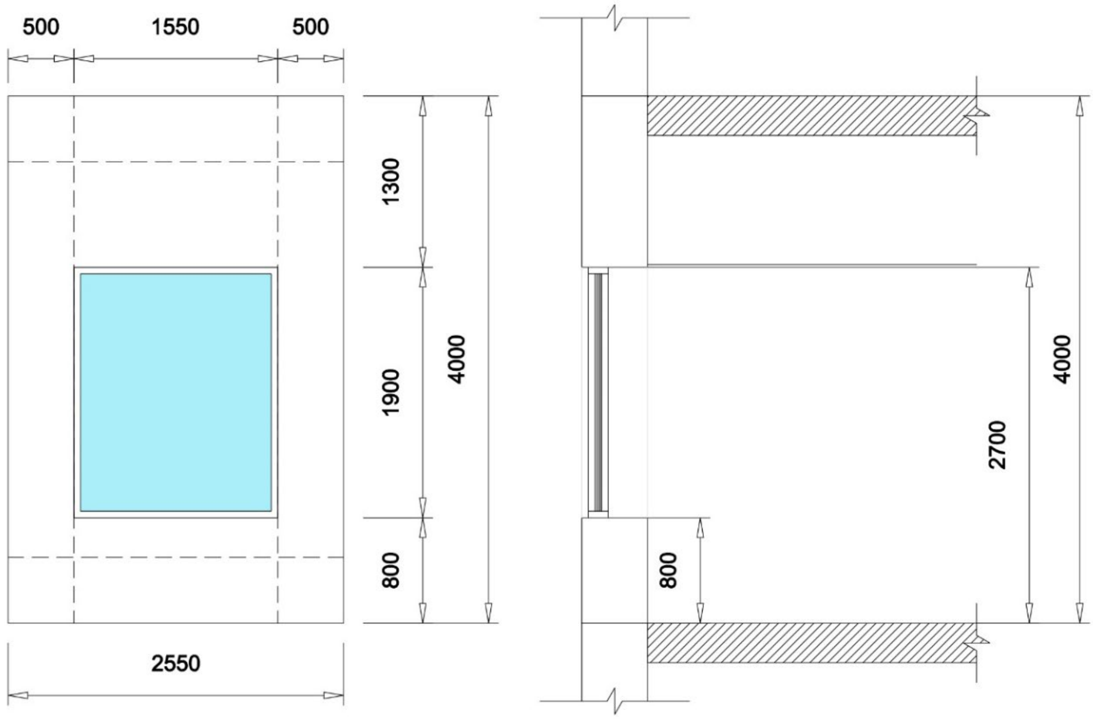


Figure 24 The elevation of the generic panel (Left) and the section of the generic panel (right)

3.1.1 Aluminium frame panel

Based on the general property, the details of the aluminium frame panel were as depicted in *Figure 28*. As mentioned in *'The general information of prefabricated façade systems'* section, once the insulated glass unit was installed, the frame edge would not be visible unlike the other two façade panels, where the window frame could be seen. The position and the area of the glazing in he designed panel was kept the same as other systems, resulting in a slight misalignment of the top of the 'window' and the ceiling.

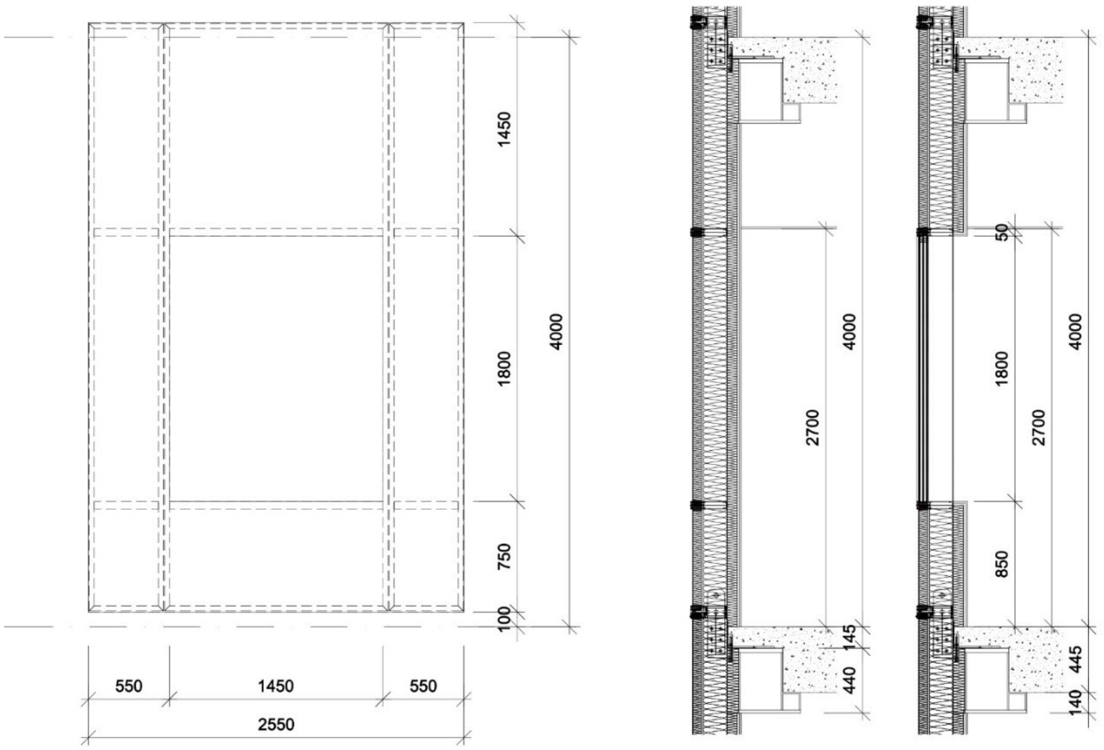


Figure 25 The elevation (left) and sections (right) of the aluminium frame panel used in this study.

3.1.2 Insulated concrete sandwich panel

The details from the reference office building were adapted to the dimensions specified in *'The panel property'* section, resulting in the panel depicted in *Figure 29.* The insulated concrete sandwich panel also included the lifting element, which had a width of 600 mm according to the reference building, embedded at the top of the panel in the middle position, directly above the window.

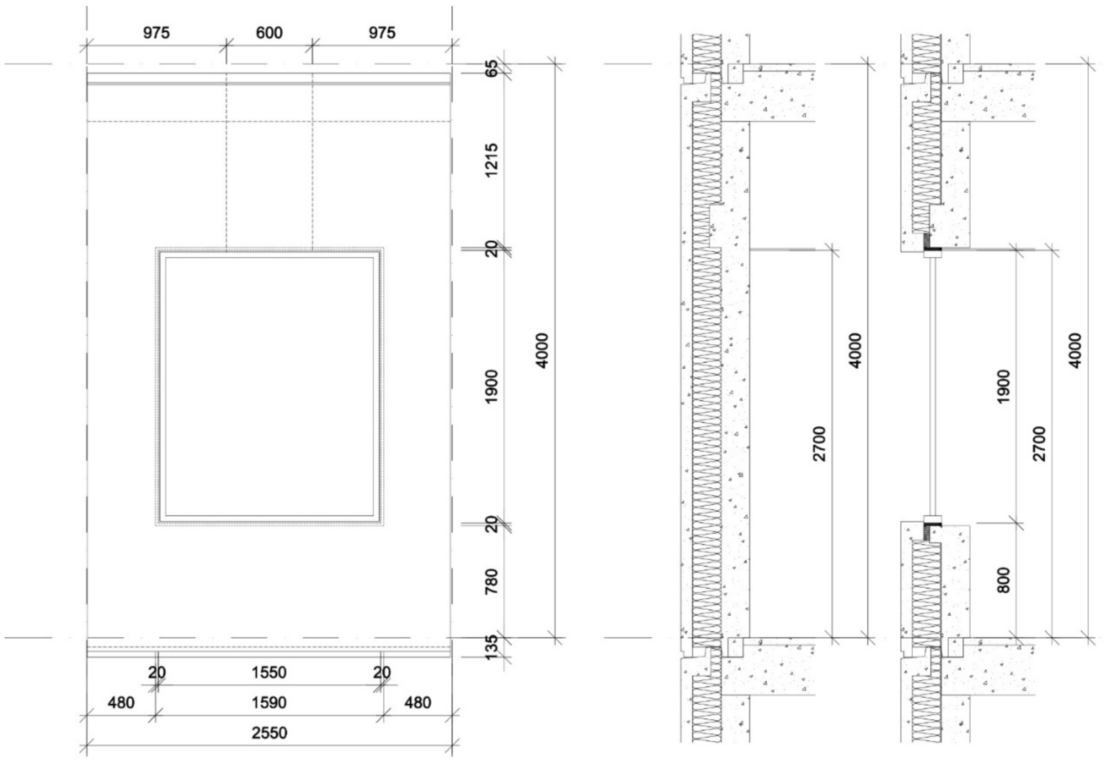


Figure 26 The elevation (left) and sections (right) of the insulated concrete sandwich panel used in this study.

3.1.3 Wooden frame panel

The details from the manufacturer were adapted to the general panel requirements. The depiction of the wooden frame panel used in this study could be seen in *Figure 27.* The lumber (wooden studs) frame would fit into the space between the top of concrete floor and the bottom of steel beam. The space in front of the beam and the floor was filled with the rigid insulation. Then the inner layer would be completely covered by weather barrier, then with outer layer of rigid insulation.

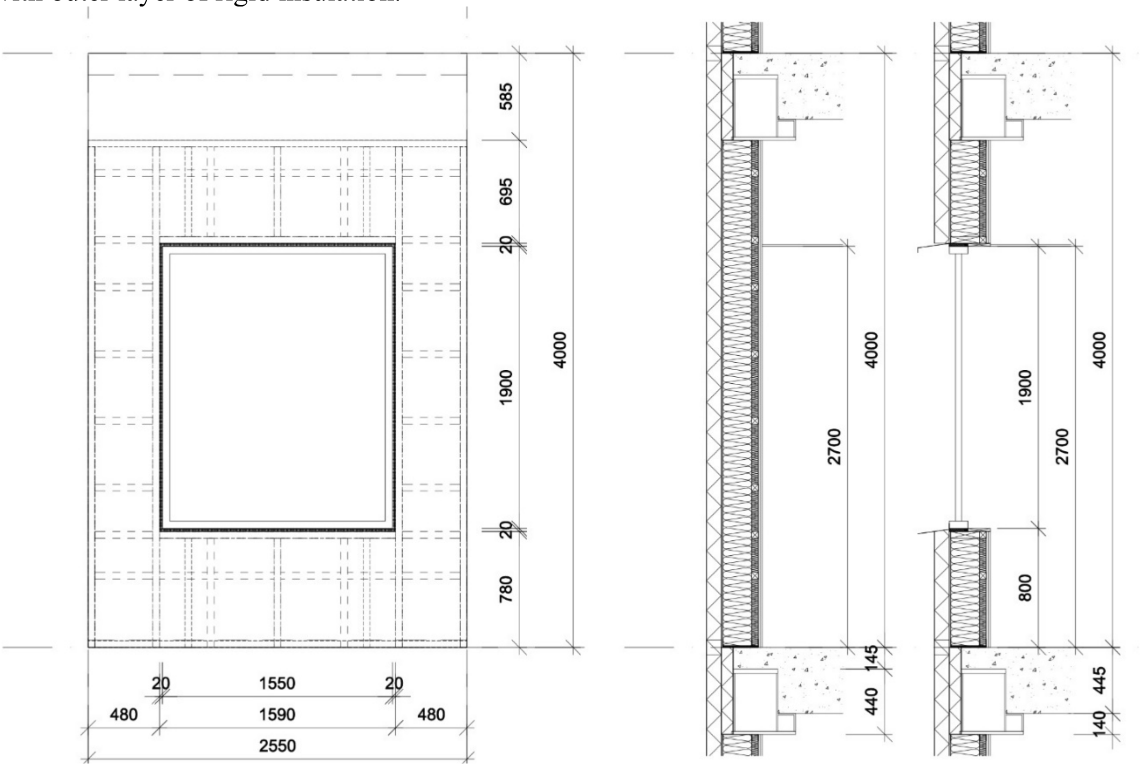


Figure 27 The elevation (left) and sections (right) of the wooden frame panel used in this study.

3.2 Initial average U-value

The calculation of each panel according to its respective standards would be shown in this section. The results of each panel type would be presented.

3.2.1 Aluminium frame panel

According to the calculation done by the manufacturer, the U-Value of the opaque panel, which consisted of the prefabricated panel and the on-site layer, was 0.129 W/(m²·K). The glazing used was a triple-glazed pane with a warm edge spacer. The U-Value of the glazing was stated to be 0.500 W/(m²·K). Combining with the area-related heat loss of each detail was gathered, the breakdown of the calculation was as shown in *Table 9*.

The total heat losses were calculated to be 4.039 W/K for the whole façade. With the total façade area of 10.20 m², the average U-Value of the aluminium frame panel was 0.396 W/(m²·K). Noted that this U-Value of the aluminium frame panel had covered all the heat losses within the panel.

Table 9 The breakdown of the aluminium frame panel average U-Value calculation.

Area		Width (m)	Height (m)	Area (m²)	U-Value (W/(m²·K))	A·U (W/K)
Panel	Glazing G1	1.450	1.800	2.610	0.500	1.305
	Panel P1	2.324	3.816	6.258	0.129	0.807
Thermal joints		**Width (m)**	**Height (m)**	**A_{TJ} (m²)**	**U_{TJ} (W/(m²·K))**	**A_{TJ}·U_{TJ} (W/K)**
Details	Det A	0.076	4.000	0.304	1.120	0.340
	Det B	0.150	2.149	0.322	0.991	0.319
	Det C	0.150	1.851	0.278	1.991	0.553
	Det D	2.324	0.082	0.191	1.207	0.230
	Det E	0.102	1.450	0.148	2.492	0.369
	Det F	0.102	0.874	0.089	1.293	0.115
Total heat losses through the façade				4.039	W/K	
Total façade area				10.200	m²	
Average U-Value of the façade				**0.396**	**W/(m²·K)**	

3.2.2 Insulated concrete sandwich panel

3.2.2.1 U-Value of the insulated concrete sandwich wall

From the material thickness and the thermal conductivity stated in *Table 4*, the total thermal resistance of the insulated concrete sandwich panel was calculated to be 6.734 (m²·K)/W. Thus, the U-Value of the insulated concrete sandwich panel was calculated to be 0.149 W/(m²·K), which represented the U-Value of the opaque part of the façade.

3.2.2.2 The initial average U-Value of the insulated concrete sandwich panel

With all the values known, the initial average U-Value of the insulated concrete sandwich panel could be calculated as 0.433 W/(m²·K). The breakdown of the values used in the calculation could be seen in *Table 10.*

Table 10 The breakdown of the values and the heat losses for the initial U-Value of insulated concrete sandwich panel

Façade panel	Area (m²)	U-Value (W/(m²·K))	U·A (W/K)
Opaque part	7.255	0.149	1.077
Window	2.945	0.900	2.651
		∑U·A	3.728
Thermal bridges	Length (m)	Ψ-Value (W/(m·K))	Ψ·L (W/K)
Perimeter of the window	6.900	0.100	0.690
		∑Ψ·L	0.690
Total heat loss through the panel		4.418	W/K
Total area of the panel		10.200	m²
Initial Average U-Value of the panel		**0.433**	**W/(m²·K)**

3.2.3 Wooden frame panel

3.2.3.1 U-Value of the wooden frame panel

For the upper limit of the total thermal resistance ($R_{tot;upper}$), once the fractional areas and its total thermal resistances *(Table 6)* were used in the calculated, the resulting in 0.1062 W/(m²·K) as the inverse of $R_{tot;upper}$. The calculation was as shown in *Equation (12)*.

$$\frac{1}{R_{tot;upper}} = \frac{f_a}{R_{tot;a}} + \frac{f_b}{R_{tot;b}} + \frac{f_c}{R_{tot;c}} + \frac{f_d}{R_{tot;d}} = \frac{0.0168}{5.145} + \frac{0.1032}{6.187} + \frac{0.1232}{9.324} + \frac{0.7568}{10.366} = 0.106\, W/(m^2 \cdot K) \quad (12)$$

Thus, the $R_{tot;upper}$ was calculated to be 9.419 (m²·K)/W.

To reach the lower limit of the total thermal resistance ($R_{tot;lower}$), the equivalent thermal conductivity of each inhomogeneous layer should be calculated first. The equivalent thermal conductivity of layer 3 – Glass wool insulation with wooden studs (cc 600 mm) and layer 5 – Glass wool insulation and wooden studs (cc 450 mm) were calculated to be 0.048 W/(m·K) and 0.048 W/(m·K). The calculations for both values could be seen in *Equation (13)* and *Equation (14)*. With the thickness of 195 mm of layer 3 and 45 mm of layer 5, the resulting equivalent thermal resistance of each layer were 4.097 (m²·K)/W and 0.938 (m²·K)/W respectively.

$$\lambda_{eq;3} = (0.035 \cdot 0.88) + (0.140 \cdot 0.12) = 0.048\, W/(m \cdot K) \tag{13}$$

$$\lambda_{eq;5} = (0.033 \cdot 0.86) + (0.140 \cdot 0.14) = 0.048\, W/(m \cdot K) \tag{14}$$

Thus, the $R_{tot;lower}$ was calculated to be 8.133 (m²·K)/W.

With the resulting upper and lower limit of the thermal resistance, the average resistance was calculated to be 8.942 (m²·K)/W. Thus, the U-Value of the wooden frame infill panel was 0.112 W/(m²·K), which represented the U-Value of the opaque part of the façade.

3.2.3.2 The initial average U-Value of the wooden frame panel

With all the values known, the initial average U-Value of the wooden frame façade could be calculated as 0.407 W/(m²·K). The breakdown of the values used in the calculation could be seen in *Table 11*.

Table 11 The breakdown of the values and the heat losses for the initial U-Value of wooden frame panel

Façade panel	**Area (m²)**	**U-Value (W/(m²·K))**	**U·A (W/K)**
Opaque part	7.255	0.112	0.811
Window	2.945	0.900	2.651
		∑U·A	3.462
Thermal bridges	**Length (m)**	**Ψ-Value (W/(m·K))**	**Ψ·L (W/K)**
Perimeter of the window	6.900	0.100	0.690
		∑Ψ·L	0.690
	Total heat loss through the panel	4.152	W/K
	Total area of the panel	10.200	m²
	Initial Average U-Value of the panel	**0.407**	**W/(m²·K)**

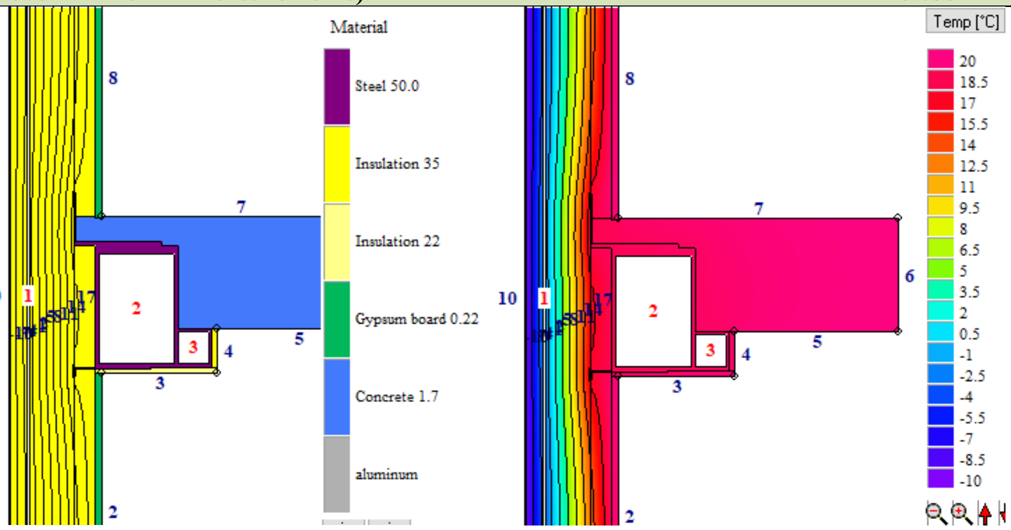
3.3 Thermal bridges assessment

3.3.1 Aluminium frame panel

There was only one thermal bridge assessment for the aluminium frame panel. The resulting Ψ-Value of the thermal bridges, for overall internal measurements, was 0.035 W/(m·K). The breakdown of the calculation and the HEAT2 results was as shown in *Table 12*, which also served as an example breakdown for every thermal bridge assessment.

Table 12 The calculation breakdown for the Psi-Value of the joint between the panel and the floor.

Results	**U-Value (W/(m²·K))**	**Length (m)**	**U·L**	
Aluminium frame wall	0.113	1.000	0.113	W/(m·K)
Aluminium frame wall	0.113	0.563	0.063	W/(m·K)
Aluminium frame wall	0.113	1.000	0.113	W/(m·K)
Total length		2.563		
Total heat losses, 1D			0.288	W/(m·K)
Total heat losses, 2D			**0.324**	W/(m·K)
Ψ-Value (for overall internal measurements)			**0.035**	**W/(m·K)**



HEAT2 Results:
∑ in: 9.7155 W/m
Heat flow for each BC type:

BC	q [W/m]	
[2]	9.7155	(T=20 R=0.13)
[3]	-9.7156	(T=-10 R=0.04)
∑:	-9E-005	

Bound	q [W/m²]	q [W/m]	Length [m]	BC
2	2.689	2.689	1	[2] T=20 R=0.13
3	1.1268	0.4676	0.415	[2] T=20 R=0.13
4	1.2242	0.1959	0.16	[2] T=20 R=0.13
5	1.3667	0.7995	0.585	[2] T=20 R=0.13
6	0.3748	0.1511	0.403	[2] T=20 R=0.13
7	2.8231	2.8231	1	[2] T=20 R=0.13
8	2.5892	2.5892	1	[2] T=20 R=0.13
10	-3.7907	-9.7156	2.563	[3] T=-10 R=0.04
∑:		-9E-005		

THERMAL BRIDGES ACCORDING TO EN ISO 10211:
Thermal coupling coefficient:
L^2D=q_in/dT=9.7155/30= **0.3238** **W/(m·K)**

Max error between exact and calculated U-values at cut-off planes is 1.844%.
Make sure that cut-off planes are not too close central element.

Thermal transmittance coefficient:
Psi=L^2D-U_1D*L=0.3238-0.1125*2.563= 0.0354 W/(m·K)

Average U-value for section:
U_avr=U_1D+Psi/L=0.1264 W/(m²·K)

Horizontal cut-off planes found.

U-values at cut-off planes [W/(m²·K)]:

	exact	calculated	error (%)
lower boundary:	0.1125	0.1109	1.4307
upper boundary:	0.1125	0.1105	1.844

Extreme temperatures and temperature factor f_Rsi:
Indoor Min: 19.028°C f_Rsi=f_0.13=0.9676 @ (x, y)=(0.335, 1.563)
Max: 20.075°C
Outdoor Min:-9.8613°C
Max:-9.8327°C
Indoor boundaries: 2 3 4 5 6 7 8
Outdoor boundaries: 10

3.3.2 Insulated concrete sandwich panel

The Ψ-Value of the joint at the top of the window (Joint 1) was evaluated to be 0.127 W/(m·K), while the joint at the top of the window with the lifting element (Joint 2) had a higher Ψ-Value of 0.242 W/(m·K). The resulting material and temperature isotherm from HEAT2 of the joints could be seen in *Figure 28*.

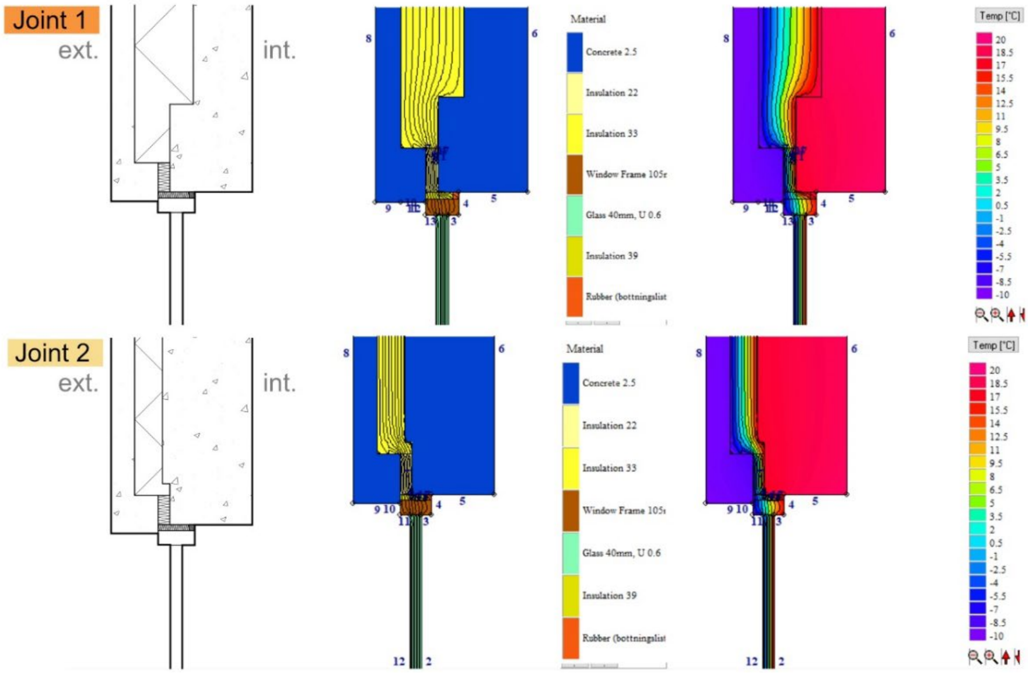


Figure 28 The resulting pictures from HEAT2 simulation for Joint 1 and Joint 2 of insulated concrete sandwich panel.

The Ψ-Value of the joint on the side and bottom of the window (Joint 3) was calculated to be 0.081 W/(m·K), which was lower than the initial default values used in the initial U-Value calculation (0.100 W/(m·K)). While the joint between the panel, the concrete floor and the panel below resulted in the Ψ-Value of 0.070 W/(m·K). The resulting material and temperature isotherm from HEAT2 of the joints could be seen in *Figure 29*.

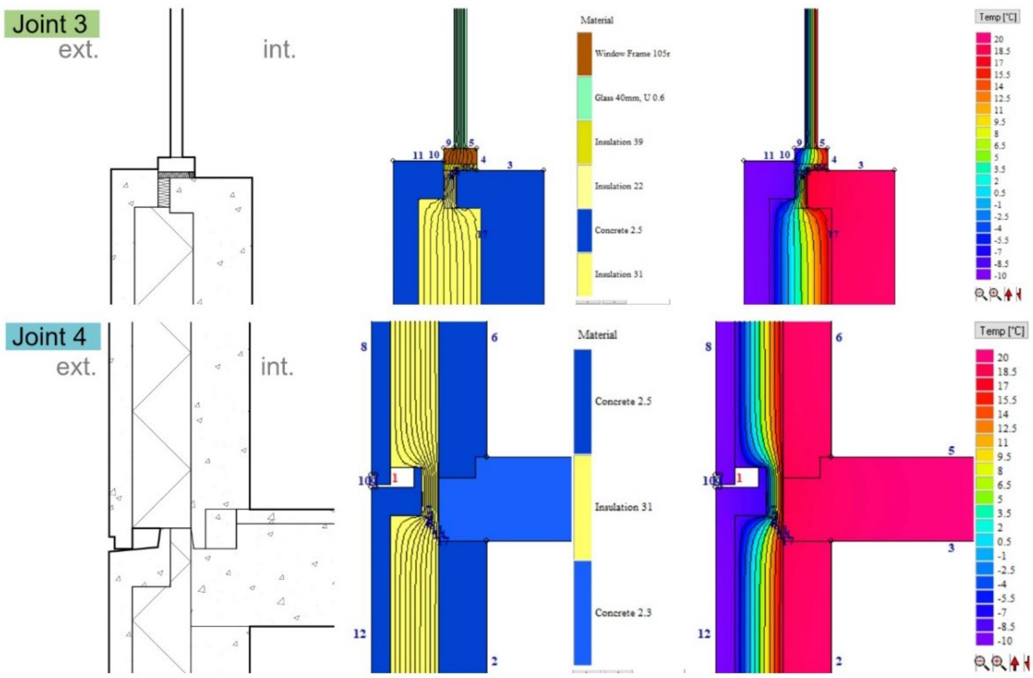


Figure 29 The resulting pictures from HEAT2 simulation for Joint 3 and Joint 4 of insulated concrete sandwich panel.

3.3.3 Wooden frame panel

The Ψ-Value of the joint at the top and the sides of the window (Joint 1) and the joint at the bottom of the window (Joint 2) were both evaluated to be 0.038 W/(m·K), which was less the initial valued assumed. The joint between the panel, the beam and the floor was calculated to have the Ψ-Value of 0.124 W/(m·K). The resulting material and temperature isotherm from HEAT2 of the joints could be seen in *Figure 30*.

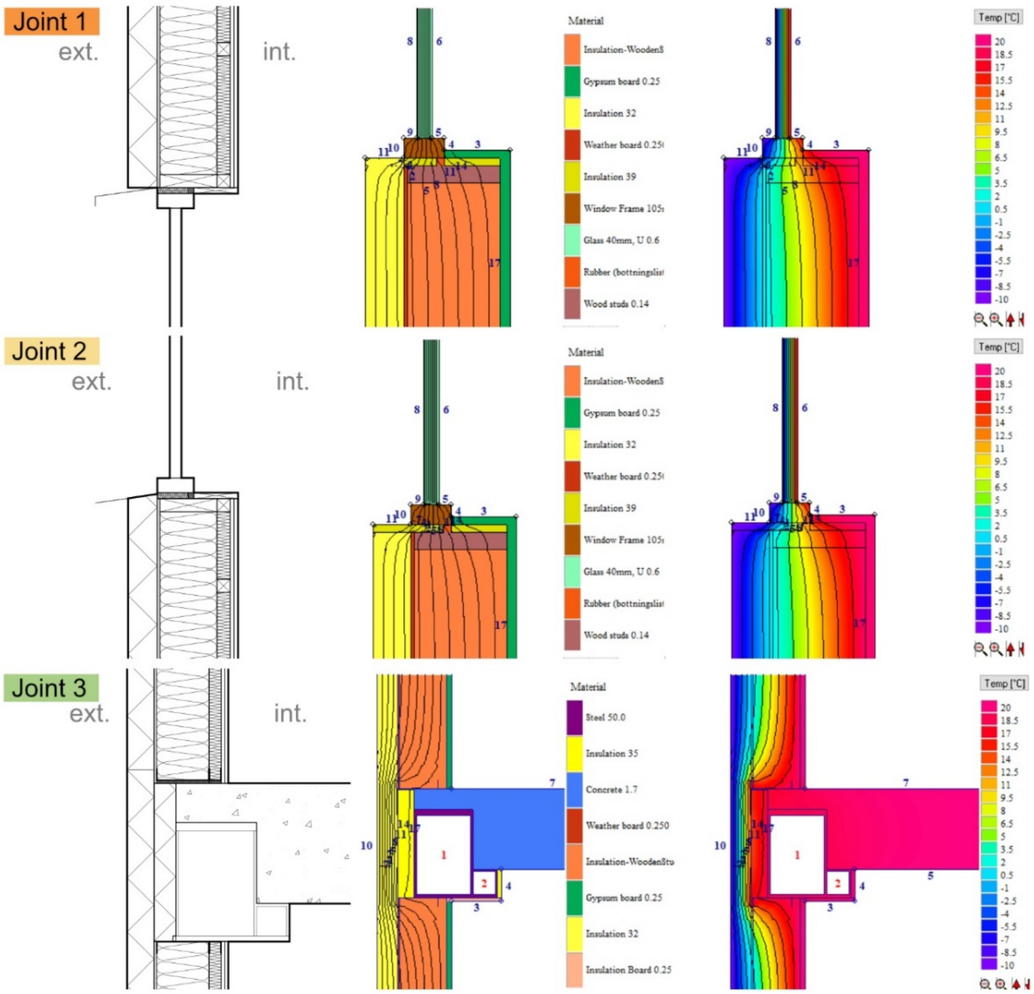


Figure 30 The resulting pictures from HEAT2 simulation for Joint 1, 2 and 3 of wooden frame panel

3.4 Average U-Value of the façade

3.4.1 Aluminium frame panel

As the initial U-Value of the aluminium frame panel had already considered all possible heat losses through the area of the façade, the only thermal bridges to be included here was where the panel was connected to the main structure of the building. Thus, the average U-Value of the aluminium frame panel was calculated to be 0.405 W/(m²·K), which was 2.24 % higher when compared to the initial U-Value. The breakdown of the calculation was as seen in *Table 13*.

Table 13 The breakdown of values used in the aluminium frame panel calculation

Façade panel	Area (m²)	U-Value (W/(m²·K))	U·A (W/K)
Aluminium frame panel	10.200	0.396	4.039
		∑U·A	4.039
Thermal bridges	**Length (m)**	**Ψ-Value (W/(m·K))**	**Ψ·L (W/K)**
1. Connection to structure	2.550	0.035	0.090
		∑Ψ·L	0.090
Total heat loss through the panel		4.129	W/K
Average U-Value of the panel		**0.405**	**W/(m²·K)**

3.4.2 Insulated concrete sandwich panel

The correction for anchor type 1 and type 2 were calculated to be 0.001 W/(m²·K) and 0.003 W/(m²·K), respectively. Once the Ψ-Values of the previously assessed joints were included into the calculation, and additional corrections for mechanical fasteners were included, thus, the average U-Value of the insulated concrete sandwich panel was 0.045 W/(m²·K) *(Table 14)*. The average U-Value was 5.20 % higher than the initial average U-Value. The total heat loss, including the losses through mechanical fasteners, was 4.648 W/K, which was 24.67 % higher than the transmission heat loss through the envelope, but was still within 30 % range.

Table 14 The breakdown of values used in the insulated concrete sandwich panel calculation

Façade panel	Area (m²)	U-Value (W/(m²·K))	U·A (W/K)
Opaque part	7.255	0.149	1.077
Window	2.945	0.900	2.651
		∑U·A	3.728
Thermal bridges	**Length (m)**	**Ψ-Value (W/(m·K))**	**Ψ·L (W/K)**
1. Top of the window	0.950	0.127	0.121
2. Top of the window – lifting element	0.600	0.242	0.145
3. Side and bottom of the window	5.350	0.081	0.433
4. Connection to the floor	2.550	0.070	0.178
		∑Ψ·L	0.877
Total heat loss through the panel		4.605	W/K
Average U-Value of the panel		**0.451**	**W/(m²·K)**
The total correction for mechanical fasteners		0.004	W/(m²·K)
Average U-Value of the panel including the correction		**0.455**	**W/(m²·K)**

3.4.3 Wooden frame panel

The average U-Value of the panel was calculated to be 0.396 W/(m²·K) *(Table 15)*, which was lower than the initial average U-Value by 2.71 %. The total heat loss was 4.039 W/K, which was 16.68 % higher than the transmission heat losses through the panel. The total heat loss was safely within 30 % range.

Table 15 The breakdown of values used in the wooden frame panel calculation

Façade panel	Area (m²)	U-Value (W/(m²·K))	U·A (W/K)
Opaque part	7.255	0.112	0.811
Window	2.945	0.900	2.651
		∑U·A	3.462
Thermal bridges	**Length (m)**	**Ψ-Value (W/(m·K))**	**Ψ·L (W/K)**
1. Top and side of the window	5.350	0.038	0.202
2. Bottom of the window	1.550	0.038	0.059
3. Connection to structure	2.550	0.124	0.317
		∑Ψ·L	0.577
	Total heat loss through the panel	4.039	W/K
	Average U-Value of the panel	**0.396**	**W/(m²·K)**

3.5 Life Cycle Assessment

The aluminium frame panel resulted in the highest GWP of 347 kg CO_2 eq./m² of the designed façade. The second highest GWP was from the wooden frame design façade, at 151 kg CO_2 eq./m². Then the concrete was the lowest one, resulting in 108 kg CO_2 eq./m². The results of the LCA of the three systems were presented in *Figure 31*. The graph was presented separating the impact from the materials that made up the façade (the prefabricated façade and the glazing part) and the impact from the structural parts. It could be noted that for the same façade area, the façade material of the wooden frame panel resulted in much lower GWP than the concrete. Though, because of the main structural material, the total GWP from the wooden frame designed façade was higher than that of the concrete sandwich panel. This observation prompted the comparative study in structural material in both non-load bearing façade systems.

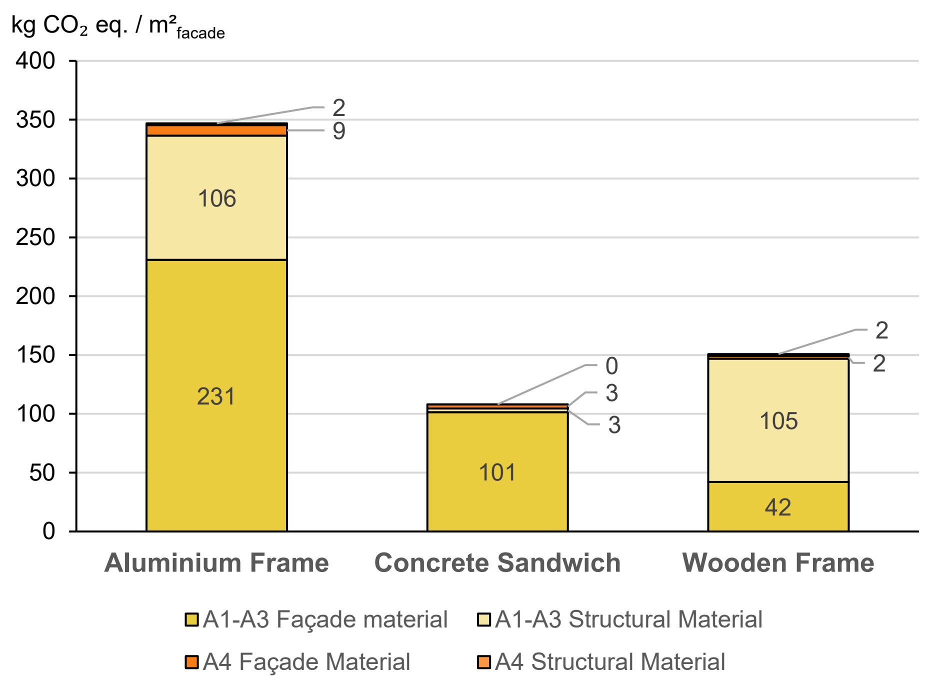


Figure 31 LCA results of the three facade systems: prefabricated and on-site materials

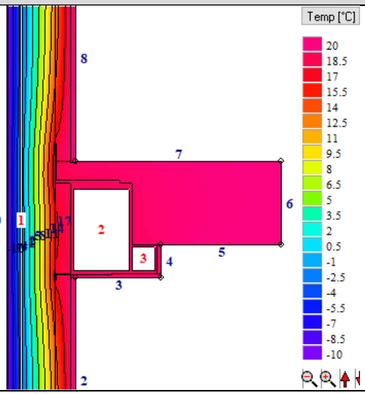
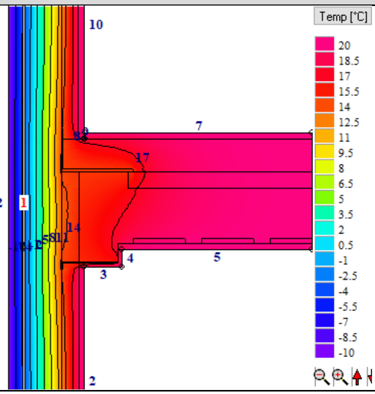
3.6 Comparative study

3.6.1 Thermal bridges and average U-Value

3.6.1.1 Aluminium frame panel

As previously presented before, the original Ψ-Value of the joint between the panel and the steel beam and concrete floor element was 0.035 W/(m·K), which results in the average U-Value of 0.405 W/(m²·K). The joint between the panel and the glulam beam and CLT floor resulted in the Ψ-Value of 0.011 W/(m·K). The average U-Value of the panel was reduced to 0.399 W/(m²·K), which was a reduction when compared to the original construction. The average U-Value from Joint 1B was only 0.68 % higher than the initial average U-Value of the panel itself. HEAT2 pictures and the summary of the results could also be seen in *Table 16.*

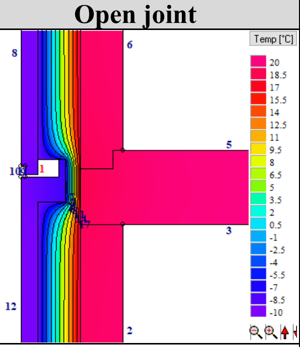
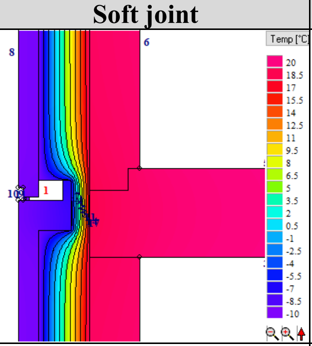
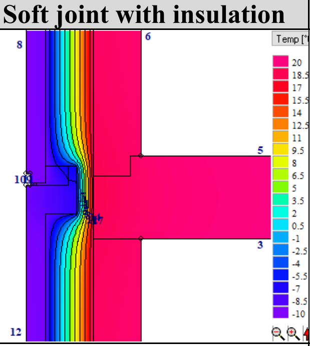
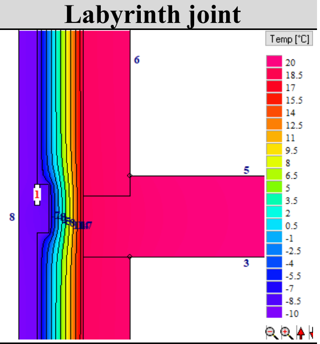
Table 16 Aluminium frame panel: Joint 1 comparison

Joint 1A Steel beam and concrete floor	Joint 1B Glulam beam and CLT floor
	
Ψ-Value: 0.035 W/(m·K) Average U-Value: 0.405 W/(m²·K).	Ψ-Value: 0.011 W/(m·K) Average U-Value: 0.399 W/(m²·K).

3.6.1.2 Insulated concrete sandwich panel

The Ψ-Value of Joint 4A was previously calculated to be 0.070 W/(m·K), resulting in the façade average U-Value of 0.455 W/(m²·K), including the correction factor. The Ψ-Value of Joint 4B and Joint 4C proved to have a slight reduction from the original joint, resulting in 0.069 and 0.066 W/(m·K), respectively. Once the linear thermal transmittance of the two joints were incorporated to the average U-Value calculation, the outcome of the calculation had no difference from the average U-Value of Joint 4A. The Ψ-Value of Joint 4D was calculated to be the lowest within the comparison, with 0.013 W/(m·K). The average U-Value, when using Joint 4D, was calculated to be 0.441 W/(m²·K), which was only 1.8 % higher than the initial average U-Value. HEAT2 pictures and the summary of the results could also be seen in *Table 17.*

Table 17 Insulated concrete sandwich wall: Joint 4 comparison

Joint 4A Open joint	Joint 4B Soft joint	Joint 4C Soft joint with insulation	Joint 4D Labyrinth joint
			
Ψ-Value: 0.070 W/(m·K)	Ψ-Value: 0.069 W/(m·K)	Ψ-Value: 0.066 W/(m·K)	Ψ-Value: 0.013 W/(m·K)
Average U-Value: 0.455 W/(m²·K).	Average U-Value: 0.455 W/(m²·K).	Average U-Value: 0.455 W/(m²·K).	Average U-Value: 0.441 W/(m²·K).

The comparison study between using the concrete thermal conductivity of 2.5 W/(m·K) and 1.7 W/(m·K) was conducted. All the calculation and thermal modelling were recalculated with concrete's thermal conductivity of 1.7 W/(m·K). The difference between the results were minimal. The smallest difference was the initial average U-Value with 0.19 % difference. The biggest difference was found in Ψ-Value of Joint 4, with 3.71 % difference. However, once the Ψ-Values were included to the average U-Value, these two thermal conductivities did not provide a significant variation, with 0.455 W/(m²·K) from 2.5 W/(m·K), and 0.452 W/(m²·K) from 1.7 W/(m·K). The resulting values of the two thermal conductivities could be seen in *Table 18*.

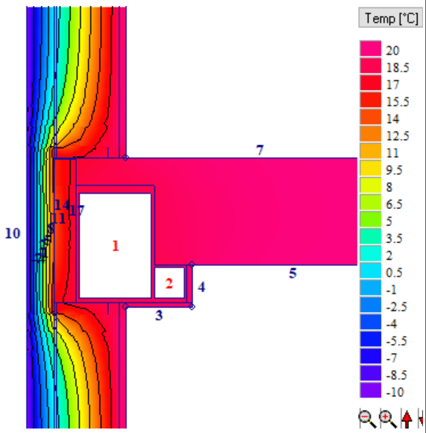
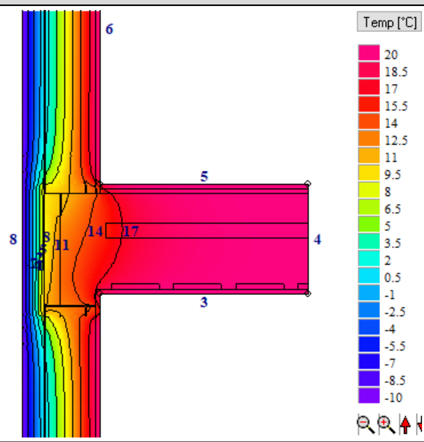
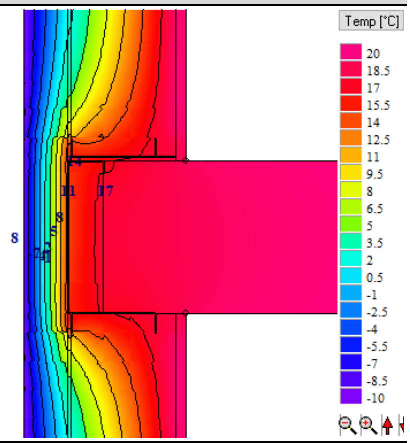
Table 18 The resulting values for every calculation for two different thermal conductivities of concrete.

The calculated value	Thermal conductivity of 2.5 W/(m·K)		Thermal conductivity of 1.7 W/(m·K)	
The U-Value of the opaque part	0.149	W/(m²·K)	0.147	W/(m²·K)
The initial average U-Value	0.433	W/(m²·K)	0.432	W/(m²·K)
Ψ-Value of Joint 1	0.127	W/(m·K)	0.123	W/(m·K)
Ψ-Value of Joint 2	0.242	W/(m·K)	0.233	W/(m·K)
Ψ-Value of Joint 3	0.081	W/(m·K)	0.078	W/(m·K)
Ψ-Value of Joint 4	0.070	W/(m·K)	0.067	W/(m·K)
Total correction for mechanical fasteners	0.004	W/(m²·K)	0.004	W/(m²·K)
The average U-Value of the panel	0.455	W/(m²·K)	0.452	W/(m²·K)

3.6.1.3 Wooden frame panel

As previously stated, the Ψ-Value of the steel beam and concrete floor joint, Joint 3A, was 0.124 W/(m·K), resulting in the average U-Value of 0.396 W/(m²·K). Whereas the glulam beam and CLT floor, Joint 3B, was calculated to have the Ψ-Value of 0.075 W/(m·K), reducing the average U-Value to 0.384 W/(m²·K). Lastly, the concrete floor, Joint 3C, was analyzed to have the Ψ-Value of 0.094 W/(m·K). Thus, its corresponding average U-Value was 0.389 W/(m²·K). The HEAT2 pictures and the summary of the results could also be seen in *Table 19*. Looking at the resulting linear thermal transmittance, it was noted that the Glulam beam and CLT floor structure outperformed the other joints, but the different in the average U-Value between the structure variations were not significant.

Table 19 Wooden frame panel: Joint 3 comparison

Joint 3A Steel beam and concrete floor	Joint 3B Glulam beam and CLT floor	Joint 3C Concrete floor
		
Ψ-Value: 0.124 W/(m·K) Average U-Value: 0.396 W/(m²·K).	Ψ-Value: 0.075 W/(m·K) Average U-Value: 0.384 W/(m²·K).	Ψ-Value: 0.094 W/(m·K) Average U-Value: 0.389 W/(m²·K).

3.6.2 Life Cycle Assessment

3.6.2.1 Variation of load-bearing structure for Aluminium and Wooden frame panels

With the Glulam beam and CLT floor, the overall GWP of the aluminium frame panel was 243 kg CO_2 eq./m², which was 104 kg CO_2 eq./m² less than the original steel beams, column and concrete floor. The results were as shown in *Figure 32*.

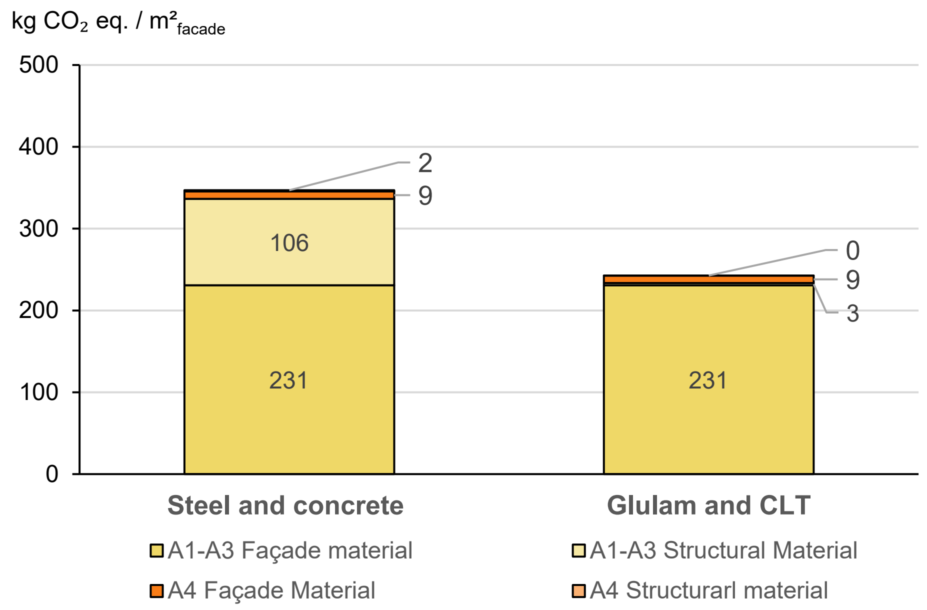


Figure 32 The main structural material comparison for Aluminium frame panel.

As for the wooden frame panel, the steel beam and concrete floor had the GWP of 151 kg CO_2 eq./m². By changing the load-bearing structural to Glulam beam and CLT floor and the concrete floor, the resulting impacts were 47 kg CO_2 eq./m² and 50 kg CO_2 eq./m², accordingly. Both options resulted in a drastic reduction of 103 kg CO_2 eq./m² and 101 kg CO_2 eq./m², respectively *(Figure 33)*.

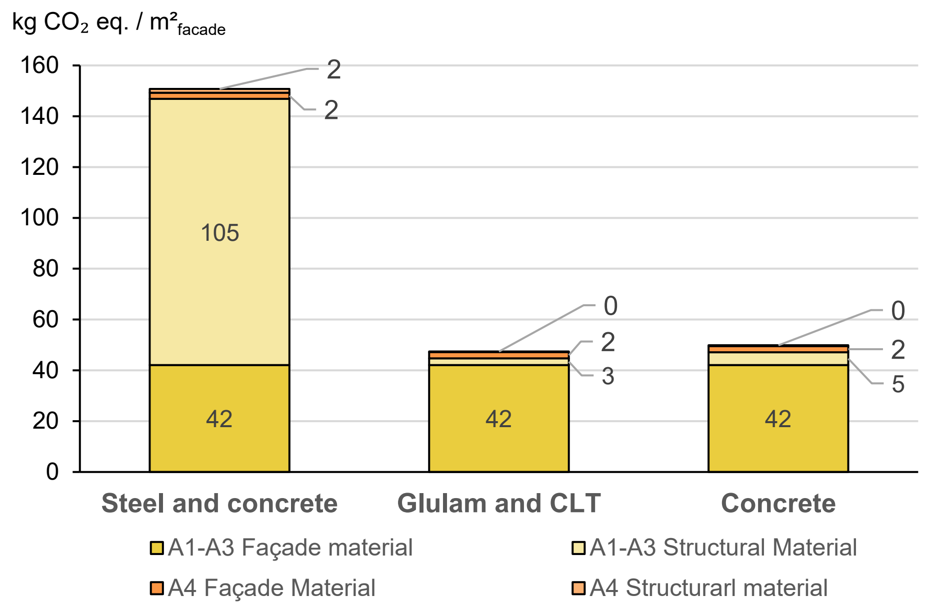


Figure 33 The main structural material comparison for Wooden frame panel.

3.6.2.2 Variation of EPDs for Concrete sandwich panel

The original result from EPD A had 107 kg CO_2 eq./m² for overall GWP. The impact of EPD B was calculated to have the total of 184 kg CO_2 eq./m², with 52 kg CO_2 eq./m² difference in the product stage of façade material and 24 kg CO_2 eq./m² higher in transportation of façade material when compared to EPD A.

EPD C resulted in the total of 159 kg CO_2 eq./m², that had 42 kg CO_2 eq./m² and 10 kg CO_2 eq./m² more in the façade material's product stage and transportation stage comparing to EPD A, respectively. The graph depicting the result from each EPD could be seen in *Figure 34.*

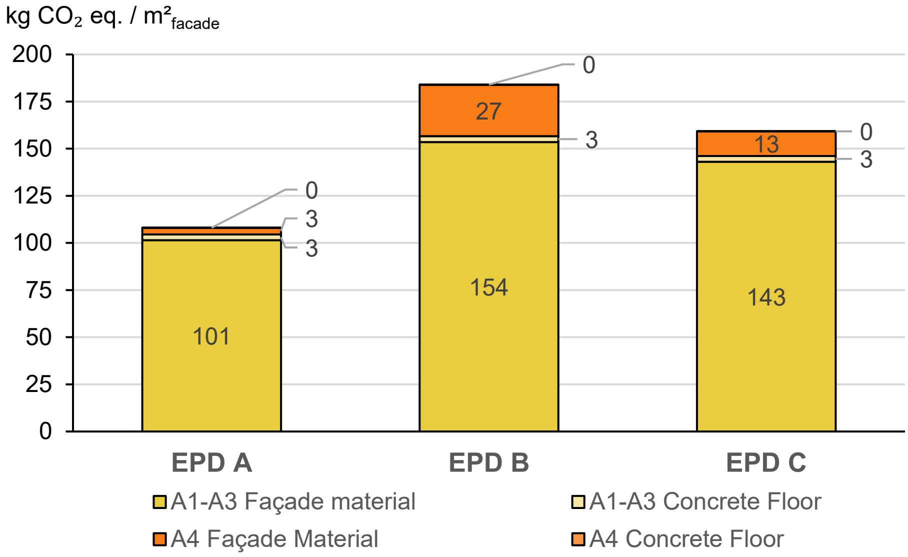


Figure 34 The comparison study of EPD for insulated concrete sandwich panel.

3.7 Summary of the study

An overview of the relationship between the thermal transmittance (Average U-Value) and the resulting Global Warming Potential (GWP) of the prefabricated design façades in the original study were as shown in *Figure 35*. In the first scope of the study, the insulated concrete element resulted in the highest average U-Value at 0.451 W/(m²·K), while the aluminium frame panel and its supporting system resulted in the highest GWP at 347 kg CO_2 eq./m².

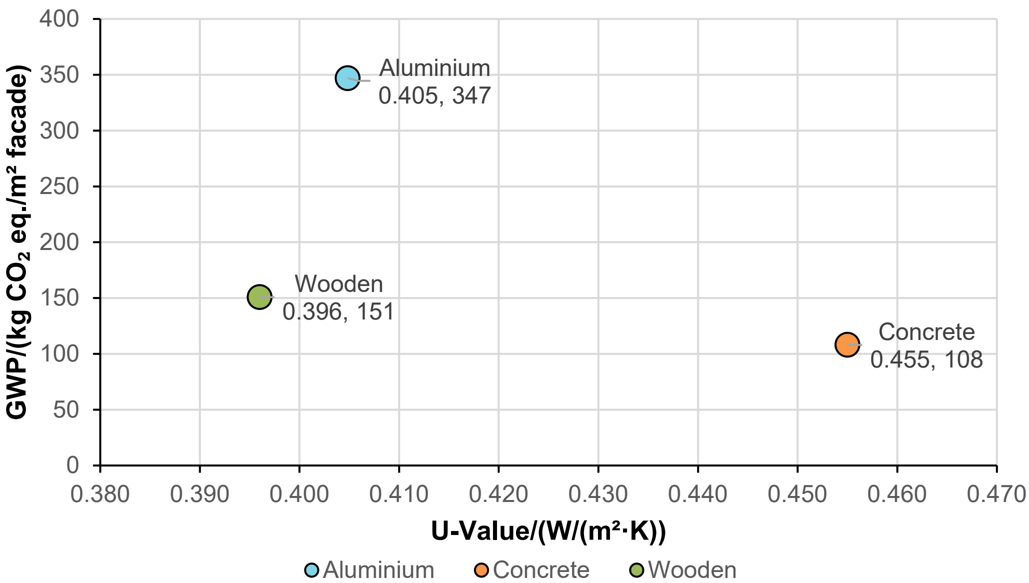


Figure 35 The relation between Average U-Value and GWP of the three prefabricated facade systems.

Once the results from the comparative studies were integrated into the summary *(Figure 36)*, it was clear that in the non-load bearing façade systems, the improvement in the main structure of the building not only effect the average U-Value, but also the greenhouse gases emissions. The comparative study for the insulated concrete system displayed a range of variation in the resulting GWP based on the EPD used for the sandwich panel, while the average U-value should technically be constant.

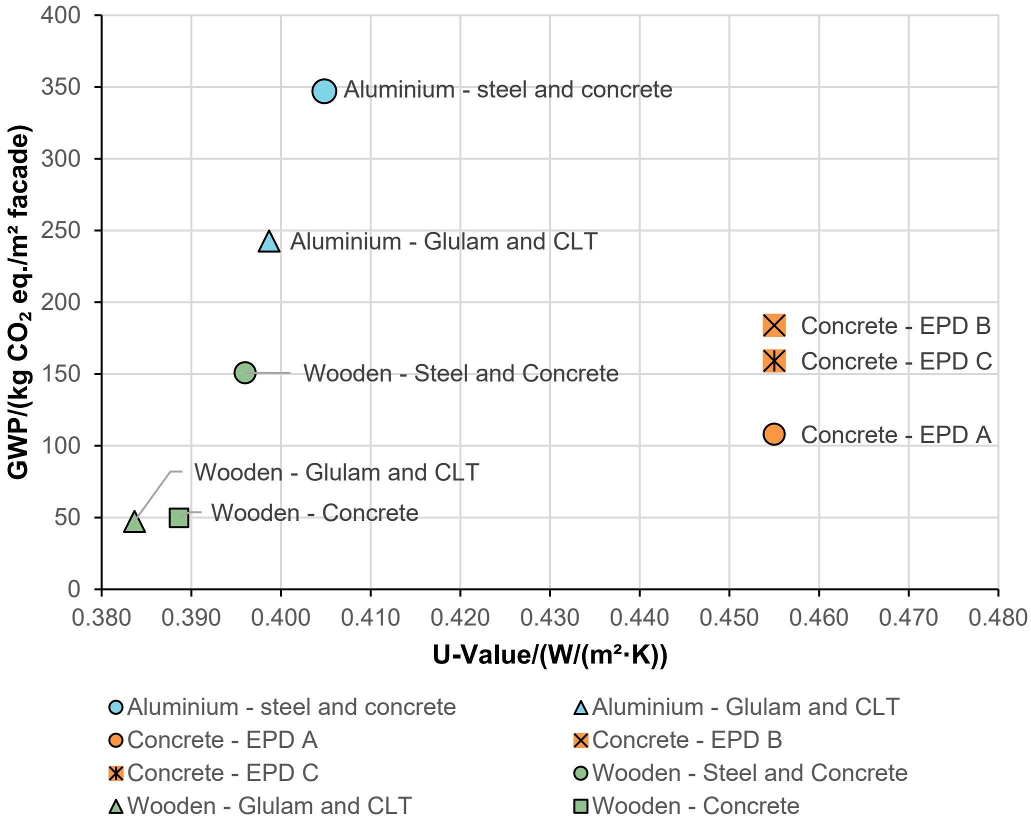


Figure 36 The relation between Average U-Value and GWP of the three prefabricated facade systems, including the results from the comparative study.

4 Discussion

In this chapter, the discussion of interesting findings from the study would be presented, along with the limitation of the study that could possibly influenced the results.

4.1 The thermal transmittance and thermal bridges

The aimed average U-Value of the façade was set at 0.400 W/(m²·K). In the initial U-Value, there was only aluminium frame panel that could reach below 0.400 W/(m²·K), the initial U-Values of the insulated concrete sandwich panel and wooden frame panel were higher than the expected U-Value. As for the average U-Value, the wooden frame panel was the only system that reach the expected U-Value. The aluminium frame system's average U-Value was not that different from the expected U-Value either. The average U-Value of insulated concrete panel, on the other hand, exceeded the expected layer by 0.055 W/(m²·K) *(Table 20)*.

The differences in initial U-Value and average U-value were the direct result of the linear thermal transmittance of each joint. The Ψ-Values of the joints around the window in the wooden frame panel were significantly lower than the standard Ψ-Value used to calculate the initial U-Value. Some Ψ-Values of the joints around the windows in concrete panel from thermal bridges calculation were higher than the default value, specifically where there was a local thickening of concrete for structural purposes. Thus, using the default values from EN ISO 14683 (2017) might over or underestimate the heat losses. If there was a strict guideline, such as BFS and BBR, then using the default values might not be precise enough for the heat losses calculation.

Table 20 The summary of the initial and average U-Value of each facade system.

Facade system	Initial average U-Value (W/(m²·K))	Average U-Value of the facade (W/(m²·K))
Aluminium frame panel	0.396	0.407
Insulated concrete sandwich panel	0.433	0.455
Wooden frame panel	0.407	0.396

In the comparative studies of the non-load bearing panels, the Glulam and CLT structure generally resulted in a reduction of linear thermal transmittance at the joint, which could possibly be the result of higher insulation content in the main structure and lower thermal conductivity of wooden element. It should be noted that the reduction of linear thermal transmittance of the joint was highly reliant on the type of structure used in the project, though the selection of the structural element might not be mainly motivated based on the thermal performance.

Within the variation of joints for insulated concrete panel, it was demonstrated that the improvement of the original joints (Joint 4B and 4C) did not bring a significant improvement for the Ψ-Value nor for the average U-Value. On the other hand, the optimal joint (Joint 4D) resulted in much lower Ψ-Values, leading to the lower average U-Value than the original case. The joint used in the case study project (Joint 4A) was heavily influenced by the façade's aesthetic design choice. The aesthetic decision effectuated a thermally less performing joint, based on the result in this study. If the aesthetic design is one of the key features of the building, then the designer should be aware that it might affect the thermal performance of the envelope. The details which were designed to fit the aesthetic elements should be thoroughly inspected and optimized, as they may risk compromising the otherwise good building thermal envelope.

The results from the comparative study of the thermal conductivity of the concrete also suggested that the difference between using the thermal conductivity of 1.7 and 2.5 W/(m·K) was apparent, though minimal. Considering that the thermal resistance of the insulated concrete sandwich panel was a direct result of the insulation layer, the resulting minimal difference was explainable. However, when calculating the thermal resistance for an element of which concrete was the main material, the difference might be more apparent, and, in succession, might affect the average U-Value of the building.

4.1.1 Limitations for thermal transmittance calculations

There were several limitations throughout the study that should be addressed. The original intention when establishing the same initial U-Value of each façade was to build a comparable standpoint, taking it as a way to assume that the façade system should have the same energy performance. However, as it could be observed from the results, the initial U-Value of each façade was not exactly 0.4 W/(m²·K) as intended because of these following factors:

Firstly, through establishing the aluminium frame panel, the initial approach to manipulate the thermal transmittance of the element was by adjusting the thickness of the on-site insulation layer while keeping the prefabricated panel as it was in the referenced study. However, it was noted that it required high level of details and specification for materials within the panel to replicate an accurate thermal modelling of the aluminium frame panel. The thermal model of the prefabricated panel along with the on-site layer should be created so that the following the area-related thermal transmittance method (U_{TJ}) from EN ISO 12631: 2017 can be used (as mentioned in *Initial U-Value of the aluminium frame panel*). Additionally, the on-site insulation layer of the aluminium frame panel consisted of steel girders and insulations, the layer was inhomogeneous. The method of calculating inhomogeneous component from EN ISO 6496: 2017 (as mentioned in *Wooden frame panel U-Value*) was clearly instructed that it was not applicable for metal bridging material in the standard (European Committee For Standardization, 2017d). There are other numerical modelling approaches proposed by Blomberg and Claesson (1998) and Gorgolewski (2007). Though the wall demonstrated within their research were not exactly the same as the steel girder wall that was in this study, their calculation methods could be adapted to this project. Nevertheless, with the time limitation of the project and information limitation of the thermal modelling for the aluminium frame façade, the calculation for thermal transmittance of the inhomogeneous component with steel girders was not explored.

Secondly, in EN 13369: 2018 – Common rules for precast concrete products – it was stated that the thermal resistance and thermal transmittance of concrete products may be calculated in accordance with the EN ISO 6946: 2017 or measured in a hot box in accordance with EN ISO 8990: 1994 or EN 1934: 1998 – the hot box approach required special equipment and laboratory setting for (European Committee For Standardization, 2018). The approaches taken in this project followed the calculations in EN ISO 6946: 2017. However, the specific numerical calculation for thermal transmittance for the insulated concrete sandwich panel was also not stated in any related standard and each manufacturer has their own calculation for the value. Although the calculation for this project was done as thorough as possible, this limitation might affect the accuracy of the results for the insulated concrete sandwich panel, as there were no clear instructions and there might be some parts where information was not available.

4.2 Life Cycle Assessment

Aluminium façade system had the highest GWP compared to other systems mainly because it was composed of energy and carbon intense materials. Not only just the aluminium frame itself, but also the other supporting and installing materials, such as the steel brackets, the steel and aluminium plates finish, the steel girder for the on-site layer.

While it was evident that the wooden prefabricated panel had a consequential role in reducing the climate impact of the façade system, the main structure of the building should also be included in the incentive to decrease the climate impact. The wooden frame panel with steel and concrete construction resulted in a higher GWP than the concrete sandwich system in the original comparison. When the low embodied carbon non-load bearing panel was paired with the low embodied carbon construction, such as Glulam and CLT, the carbon footprint of the building could be further reduced.

The comparative study using the EPDs of the same product also gave some insight into the details within the EPD itself. It was noted that majority of the EPDs of the insulated concrete sandwich wall did not mention the thickness of each layer or the whole element, nor the thermal properties or the density of the declared product. All of which was a fundamental property of the material used in the project and should technically be specific to each construction project. It was also observed that for the prefabricated element that has some flexibility of the material within the element (in this case, the insulated concrete sandwich panel has a range of thickness of each layer and varieties of option regarding the insulation used), the EPD, which was a form of generalized version of the product, might not be specific enough for a study that is as sensitive as LCA. A clarification from the manufacturer or the publisher of the EPD might be needed when the LCA was conducted for any building.

It should be stated again that the cladding was excluded from this study. Among three of the prefabricated façade systems, the insulated concrete sandwich element was the only system that did not require a cladding layer. If the cladding and its installation material were included into the LCA study, the result would not be the same as it was previously presented.

4.2.1 Limitations for Life Cycle Assessment

As aforementioned, the initial goal of the project was to cover the GHG emissions throughout the product stage to construction stage, which stemmed from the requirement of the Swedish Climate Declaration, along with the fact that prefabricated construction was highly advocated for its efficiency and less waste at the construction site, thus signifying the low emissions during construction stage. The approach for the construction and installation process (A5) was to obtain the recorded site energy from both referenced projects and the time that each project planned for the installation. However, it was later discovered that the site energy was recorded for the whole construction site. With various of processes going on and several machineries being occupied at the same time that there was a prefabricated façade installation, it was impossible to distinguish highly specific measures from the total site energy. Thus, the construction and installation module was unfortunately omitted from the scope of the study.

The design for steel girders used in the aluminium design façade was taken from the reference hospital building, which has an exceptionally high floor-to-floor height to fit various mechanical equipment. The minimum floor height from the referenced project was 4.80 m. The steel girder, being an easily bendable material, were doubled in each location to provide more structural stability. Since the floor-to-floor height in this project was assumed to be 4.00 m, the doubling of the steel girder might not be required. Thus, the doubling of the steel girder from the reference project might have made an effect on the GWP of the aluminium façade.

With the goal to create a result that could be used as in a decision-making process, it was implied that the study should lean more towards the 'generic' side of things. Despite the aim, the LCA did require a level of certainty of information used. As some part of the information used in the study came from a referenced project, i.e., the aluminium frame panel and the concrete sandwich panel, it was difficult to keep the results on the generic level. The results given in this study might not be universally applicable to the same façade system from a different manufacturer, but they still provide good insight into the LCA of the prefabricated façade system.

4.3 Other aspects

As the assessment of the façade system only evaluates the thermal performance of the building element. There were other aspects to be considered in the design process regarding the choice of the façade system.

One of the factors was the thickness of the façade system, i.e., the wall. In this study, the thickness of the façade required to achieve an arguably similar thermal performance was 330 mm for the aluminium frame panel, 480 mm for the insulated concrete sandwich panel, and 374 mm for the wooden frame panel. To achieve the final appearance, each system would have additional thickness added to it, which solely depended on the cladding material and the supporting structure for it. Although the insulated concrete was the thickness among the options, it was the system that required the least amount of work and material to reach the final appearance, if the designer choose to. While the aluminium frame and wooden frame panel still required a proper cladding material, which might add to the thickness of the wall. The thicker wall means that it would require bigger building area to achieve the same internal area.

The second factor to be mentioned was construction time. The concrete sandwich wall was a load-bearing element that supported the next floor plate. Thus, the construction would be built from one floor to the next. While for the lightweight system, the main load-bearing structure could be erected separately from the façade, which might provide more opportunity for other systems to be assembled or installed independently, without waiting for the façade.

The third factor, which was arguably the significant one, was the cost. The scope of the study did not cover the economical aspect of the prefabricated construction, which was crucial and could make the result of the study more holistic.

5 Conclusion and Future work

With the intention of the study to provide a basic information for decision making process, the starting point of the study was based on generalised value and design. But further along the study, it became apparent with the knowledge of the panel and each calculation that keeping the panel generalised was a hard feat when each calculation for both the thermal transmittance and LCA required specific values from the panel. Eventually, the resulted of the study could only be summarized based on the specific design of the façade.

When the average thermal transmittance was addressed, the wooden façade provided the lowest among the three, following by aluminium frame panel with a slightly higher value, while the insulated concrete sandwich panel had the highest average U-Value. The thermal bridge assessment and comparative study suggested that the joint of the concrete element should be thoroughly considered as it influenced the average U-Value of the façade. While the comparative thermal bridge studies from the non-load bearing panels focusing on the type of main structure indicated that the structure of the building also effect the thermal performance of the building envelope.

As for the LCA of the designed façade, the insulated concrete panel resulted in the lowest GWP, followed by the wooden frame designed façade, while the aluminium frame panel resulted in the highest GWP. The importance of the structural system was also highlighted, as the result from wooden designed façade was highly affected by the material for the main load-bearing structure. Alternatives structures were also explored, and the result suggested that there was a possibility to improve the GWP of the construction by choosing structures with lower climate impact.

It could be concluded from the study that both the prefabricated façade panel and the main structure of the building had an influence on the thermal transmittance of the building envelope. The climate impact of the lightweight panels that required the main structure was heavily influenced by the main structural elements of the building. The thermal transmittance could be reduced by using proper details to prevent thermal bridges. While the climate impact could be reduced by using low-carbon material alternatives for both the façade panel and for the structural elements.

5.1 Future work

The following topics could be explored to provide a holistic knowledge of prefabricated façade for decision-making process. For the thermal transmittance, the case study building could be established to be used for energy modelling and energy simulation, which could provide more insight into the thermal performance of the façade. Addressing the Life Cycle Analysis, since the current study only included the Global Warming Potential, the other environmental impacts could be explored. The other stages of the building assessment information could also be investigated: from the operational stage, the end-of-life, the effect of biogenic storage and the reusability of the material. The aspect of Life Cycle Costing could also be integrated to make the project more comprehensive and well-rounded.

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Appendices

Appendix A. The average heat transfer coefficient (U_m)

The average heat transfer coefficient (U_m) is the average heat transfer coefficient of the building components and thermal bridges, and is calculated according to the equation below, as defined in Boverkets byggregler BFS 2020:4, BBR29 (Svensson, 2020).

$$U_m = \frac{\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{p} \chi_j}{A_{om}}$$

Where	U_i	is the heat transfer coefficient for building component i, in W/(m²·K);
	A_i	is the area of the building component i's surface against heated parts of dwelling or premises, in m;
	Ψ_k	is the heat transfer coefficient for the linear thermal bridge k, in W/(m·K);
	l_k	is the length of the linear thermal bridge k, in m;
	χ_j	is the heat transfer coefficient for the point thermal bridge k, in W/K;
	A_{om}	is the total area of enclosed building components' surfaces against heated parts of dwellings or premises, in m.

Appendix B. Concrete EPD

The EPDs of the insulated concrete sandwich products mentioned in this study were the ones available on OneClick LCA and Environdec (EPD International AB) websites. The detail of each one was presented in *Appendix Table 1*.

Appendix Table 1 Insulated concrete sandwich product's EPD source.

EPD	EPD registration number	Upstream database	Source
EPD A	RTS_126_21	Ecoinvent, OneClick LCA	OneClick LCA
EPD B	S-P-03019	GaBi	OneClick LCA
EPD C	S-P-02988	GaBi	OneClick LCA
EPD D	S-P-04724	Ecoinvent, Agri-footprint	Environdec
EPD E	S-P-02098	Ecoinvent	Environdec
EPD F	S-P-01452	Ecoinvent	Environdec
EPD G	S-P-05208	Ecoinvent	Environdec
EPD H	S-P-01658	Ecoinvent	Environdec

Appendix C. Breakdown of the input for LCA calculation

The following tables would list out the materials and amount of them that was used as input for One Click LCA for every designed façade option, including the input for structural variation in the comparison study. The material composition of the aluminium frame designed façade, the concrete designed façade and the wooden frame designed façade could be found in *Appendix Table 2, Appendix Table 3,* and *Appendix Table 4 accordingly.*

Appendix Table 2 Input breakdowns for Aluminium frame designed façade.

Parts	Material	Input values	EPD registration number
Prefabricated panel	Aluminium alloy sheet, 2700 kg/m³	35.810 kg	EPD-GDA-2019129-IBG1-DE
	Rockwool insulation, medium density	1.337 m³	EPD-DRW-20180118-IBC1-DE
	Purenit, high density	106.942 kg	EPD-DRW-20180119-IBC1-DE
	Aluminium facade profile, 5.25 kg/m³	25.290 m	EPD-ADA-34.0
	Steel sheet, 7840 kg/m³	0.007 kg	n/a, generic data from One Click LCA
	Steel bar anchor	5.099 kg	NPD-1234-388-EN
	Adhesive, PUR based	29.595 kg	BREG EN EPD000008
	EPDM rubber sealant	0.448 kg	INIES_CMAS20180529_141850, 28454
	Insulating glass unit, triple glazed	2.693 m²	S-P-01739
	Electricity	103.440 kWh	n/a, generic data from One Click LCA
	Gas	60.540 kWh	n/a, generic data from One Click LCA
Opaque wall (on-site)	Steel girder, 7850 kg/m³	0.003 m³	EPD-AMC-20210146-CBB2-EN
	Glass wool insulation, λ = 0.035 W/(m·K)	0.501 m³	NEPD-2079-940-EN
	Gypsum board, thickness 12.5 mm	12.197 m²	S-P-02001
Main structure: Steel beam and column, and concrete floor			
	Structural steel, 80 % recycled content	0.071 m³	n/a, generic data from One Click LCA
	Structural steel, 80 % recycled content	0.025 m³	n/a, generic data from One Click LCA
	Generic concrete	0.274 m³	n/a, generic data from One Click LCA
Main structure: Glulam beam and CLT floor			
	Glulam, 430 kg/m³, for beam	0.183 m³	NEPD-456-318-NO
	Glulam, 430 kg/m³, for column	0.108 m³	NEPD-456-318-NO
	CLT, 430 kg/m³	0.116 m³	NEPD-2587-1314-EN
	Rockwool insulation, λ = 0.035 W/(m·K)	0.040 m³	n/a, generic data from One Click LCA
	Ceiling wooden stud	0.004 m³	NEPD-2547-1284-NO
	Gypsum board, thickness 12.5 mm	0.004 m³	S-P-00389, V.3
	Floor acoustic insulation, 40 mm	0.016 m³	NEPD-1696-683-EN
	Floor finishing, engineered wood flooring	0.011 m³	RTS_117_21

Appendix Table 3 Input breakdown for the insulated concrete sandwich designed façade.

Parts	Material	Input values	EPD registration number
Opaque wall	Insulated concrete element	4641.114 kg	RTS_126_21
	High-density PIR insulation, λ = 0.022 W/(m·K)	0.033 m³	n/a, generic data from One Click LCA
	Precast concrete C30/37	0.128 m³	n/a, generic data from One Click LCA
	Graphite EPS, λ = 0.031 W/(m·K)	0.137 m³	EPS-IVH-20140137-IBB1-DE
Glazing area	Window, triple glazed, U_w = 0.740 W/(m²·K)	2.945 m²	NEPD00245E
	Mineral wool, λ = 0.039 W/(m·K)	0.015 m³	NEPD-2966-1656-EN
	Butyl window sealant	0.003 m³	n/a, generic data from One Click LCA
Structure			
	Hollow core, concrete slab, C30/37	0.204 m³	n/a, generic data from One Click LCA

Appendix Table 4 Input breakdown for the wooden frame design façade

Parts	Material	Input values	EPD registration number
Opaque wall	Lightweight external wall, with wooden studs, R = 7.700 (m²·K)/W	2.424 m³	S-P-01255
	Glass wool insulation, λ = 0.035 W/(m·K), 45 kg/m³	0.119 m³	NEPD-1941-862-EN
	Glass wool insultion, λ = 0.032 W/(m·K), 62.5 kg/m³	0.149 m³	NEPD-2499-1246-EN
Glazing area	Window, triple glazed, U_w = 0.740 W/(m²·K)	2.945 m²	NEPD00245E
	Mineral wool, λ = 0.039 W/(m·K)	0.015 m³	NEPD-2966-1656-EN
	Butyl window sealant	0.003 m³	n/a, generic data from One Click LCA
Main structure: steel beam and column, and concrete floor			
	Structural steel, 80 % recycled content	0.071 m³	n/a, generic data from One Click LCA
	Structural steel, 80 % recycled content	0.025 m³	n/a, generic data from One Click LCA
	Generic concrete	0.247 m³	n/a, generic data from One Click LCA
Main structure: Glulam beam and CLT floor			
	Glulam, 430 kg/m³, for beam	0.183 m³	NEPD-456-318-NO
	Glulam, 430 kg/m³, for column	0.108 m³	NEPD-456-318-NO
	CLT, 430 kg/m³	0.089 m³	NEPD-2587-1314-EN
	Rockwool insulation, λ = 0.035 W/(m·K)	0.165 m³	n/a, generic data from One Click LCA
	Ceiling wooden stud	0.004 m³	NEPD-2547-1284-NO
	Gypsum board, thickness 12.5 mm	0.004 m³	S-P-00389, V.3
	Floor acoustic insulation, 40 mm	0.015 m³	NEPD-1696-683-EN
	Floor finishing, engineered wood flooring	0.012 m³	RTS_117_21
Main structure: Concrete floor			
	Generic concrete	0.174 m³	n/a, generic data from One Click LCA

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