# RENOVATION USING PREFABRICATED FAÇADE ELEMENTS

## A case study of a building in Linero, Lund Sweden

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

# Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

## Master Programme in Energy-efficient and Environmental Building Design

This international programme provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behaviour and needs, their health and comfort as well as the overall economy.

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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Keywords: Energy renovation, Swedish Million Programme, Prefabricated façade elements, TES, Multi-active, Alingsås, Energy efficiency building, WUFI Simulations, HEAT2 simulations

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# Work contribution done by the Author's was equally divided.

Contributing the author's work that was made by Mohamed Soliman & Aleksandra Milkova was a teamwork in the research of this thesis document. The work was made by them both equally divided the amount of work that had to be carried out to make this thesis research. During this thesis, various diverse options on prefabricated façade system were evaluated equally by both authors. Both authors also equally contributed to the WUFI, HEAT2 analysis as well as the drawings made in AutoCAD.

# Abstract

The building sector uses about 40% of the total global energy use. Sweden aims to reach its new goal to reduce the energy use in their residential sector as well as commercial sector by 20%, which should be reached by year 2020 and 50% by year 2050. To find a solution to this problem European Union (EU) collaborated with IVL (Swedish environmental Research Institute) and LKF (lunds Kommuns Fastighets AB) on a pilot project in Linero district, Lund. This master's degree thesis is a part of that pilot project.

This study is based on a literature review with a qualitative evaluation and the aim of the thesis was to identify a highly industrialized method of a façade that could provide a better additional insulation to the existing building façade to make it energy efficient. Moreover, this thesis observed the potentials of introducing the concept of prefabricated façade element onto the Swedish market for the renovation projects of the Swedish Million Programme.

The study scrutinized numerous facades available in the European market; as a result, a top selection was gathered of the 15 promising prefabricated facades in the European market. These 15 promising prefabricated facades were analysed and compared to determine the best fit for the Swedish climate. After thorough investigation three prefabricated facades from the European market were selected as most promising for the renovating the Million Programme of the Linero project.
To evaluate these options, the study employed various software tools such as WUFI, AUTOCAD, and HEAT2. Comprehensive analyses encompassed moisture risk assessment, attachment and fixation to existing structures, and thermal performance. While all three facades demonstrated commendable results suitable for future Million Programme renovations, one of them emerged as the top performer.

Keywords: Energy use, Reduce energy, EU, IVL, LKF, TES façade, Multi-active façade, Alingsås façade, Million Programme, Moisture risk analysis, Attachment, Thermal performance, WUFI, AUTOCAD, HEAT2

# Preface

This study was carried out as the final part of the master programme in Energy Efficient Building Design at Lund University. Further, the study was carried out as a collaboration between Lund University and IVL (Swedish Environmental Research institute).

# Acknowledgement

The authors of this thesis research would like to acknowledge their main supervisor Hans Bagge and second supervisor Jeanette Green from the company IVL. We got great support from IVL such who welcomed us to their office in Malmo City and gave us an access their facilities. IVL sustained us with an immense amount of information and details about the Linero case. Jeanette also introduced us to members of the Cityfied project (EU) and LKF (Lunds Kommuns Fastighets AB).

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Finally, we would love to express our profound gratitude to thank our parents and family members from the bottom of our hearts for providing us with unfailing support and continuous encouragement throughout the years of the study period and through the process of researching and writing this thesis. This accomplishment would not have been possible without them.

*Lund January 2024*

*Mohamed Soliman & Aleksandra Milkova*

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# Nomenclature

LKF - Lunds Kommuns Fastighets AB (the municipality that owns the building complex in district Linero in Lund.)

IVL – IVL Swedish environmental Research Institute

°C – degree Celsius

RH – Relative humidity

$RH_{crit}$ – Relative humidity critical

Million Programme- A housing programme were one million affordable dwellings were constructed in Sweden. It was implemented by the Swedish social democratic party year 1965-1974.

# 1 Introduction

Climate changes due to global warming are a demanding challenge for the society. There is need to reduce energy demands in the building sector of the global market, especially in the old building sector that were built from year 1960-1970. The building sector uses about 40% of the total global energy use (UNPE Environment, 2016). According to EUs energy efficient directive, the energy consumption in buildings needs to be reduced. Furthermore, the EU's directive about energy efficiency states that newly produced buildings should be nearly zero energy buildings by 2020. Members of EU should also take measures to encourage renovation of existing buildings according to the near-zero standard (Energimyndighetens, 2016). A significant energy saving can be reached to existing buildings because their performance level is commonly very far below current efficiency potentials (UNPE) Environment, 2016).

Housing and facilities stand for a large part of the energy use in Sweden. The Swedish parliament has decided that Sweden will reduce energy use in residential and commercial buildings by 20% by 2020 and by 50% by 2050 (Swedisol, 2016). There are 4.5 million residential buildings in Sweden where 2.5 millions of these are residential apartment buildings. Many of these buildings were built during the Million Programme in Sweden and three of four of these buildings will require extensive measures by 2050 to reduce energy use by the residential and commercial buildings (Energimyndigheten, 2015) .

One of the buildings in Sweden that needs to be renovated according to the EUs energy efficient directive is a multi-family building from the Million Programme in Linero. It is situated in a district created in 1969 in the eastern part of Lund. In the current situation, the housing in Linero has a poor façade construction as well as a high-energy consumption; therefore, it needs to be renovated for better energy performance and thermal comfort for its users. In this master's degree project, the ambition is to investigate the possibilities to improve the façade of this reference building in a moisture safe, thermally comfortable and energy efficient way in order meet the passive house criteria. This could be achieved by using prefabricated façade systems available on the European market. Therefore, innovative prefabricated façade elements were studied and compared to find the best solution for the reference building.

## 1.1 Background and problem motivation

To meet EUs energy efficient directives EU's Directive Commission decided to fund the project called Cityfied with the mission to develop demonstration projects at European level in the request of the FP7 SMART CITIES 2013, EeB.ENERGY.2013.8.8.1: "Demonstration of improved energy systems for high performance-energy districts" topic. In this context, three residential districts in different countries were chosen to be retrofitted at the city of Laguna de Duero (Valladolid, Spain), Soma (Turkey) and Lund (Sweden), (Cityfied, 2016).

The Cityfied Project aims to develop a replicable, systemic, and integrated strategy to adapt European cities and urban ecosystems into the smart city of the future, focusing on reducing the energy usage and Greenhouse gas (GHG) emissions as well as increasing the use of renewable energy source by developing and implementing innovative technologies and methodologies for building renovation, smart grid and district heating network and their interfaces with information and communication technologies (ICTs) and Mobility. (Cityfied, 2016).

It is challenging to achieve the directives from EU due to various climates present within the EU region and the economic difficulties. Sweden has a lot of existing buildings that need to have their facades renovated; however, to find innovative and energy efficient facades on the market that can achieve the directives from EU, work in different climates, be affordable and moisture safe and attachable to the Million Programme buildings is challenging. Therefore, EU decided to start the Cityfied project in three different countries, so knowledge and results could be shared between EU members.

Cityfied then collaborated with IVL (Swedish Environmental Research institute) and LKF (Lund Kommuns Fastighetsbolag) to determine how they were going to renovate the district called Linero in Lund. The focus of the retrofitting of Linero is to reach a higher energy standard and thermal comfort. One crucial part that needed to be renovated in this project was the poor facades that did not meet the EU directives. Therefore, the aim of this report is to compare different facades that will suit not only the reference building at Vikingavägen 26 but the whole Million Programme.

One part of such a building could be the façade and by finding the prefabricated facades system that are now on the European market made the authors search on the internet. Therefore, the search was pointed out that it should be most innovative, energy efficient and inspiring façade that are available in the European market.

The specific background is that the authors of this report searched on internet to find the most innovative, energy efficient and inspiring facades that were available on the European market. Therefore, 15 prefabricated facades matched the above stated criteria well and were therefore chosen to be compared and analysed. Therefore, a selection of the 3 most relevant prefabricated wall out of 15 were selected for the case study Linero and were further investigated. The main goal is to find the best suitable prefabricated façade that would help the reference building become an energy efficient building. Thereby providing a good example for future renovations regarding similar buildings of the Million Programme, which are going to contribute to decrease the Sweden's energy demand and meet the EU directives.

## 1.2 Research questions

In this study prefabricated façade systems available on the European market were evaluated. The main aim is to make an analysis of facades that are energy efficient and include aspects of the moisture safety, attachability, thermally performance for the renovation of the reference building. It should meet EUs directives by 2020. Consequently, fifteen of the prefabricated facades matched the criteria, and those fifteen prefabricated facades were compared and further analysed.

Another aim is also to analyse the prefabricated façade in the context of other Swedish Million Program apartment blocks. The best prefabricated façade on the European market that can be used in Sweden for future renovations of the Million Program.

Aside from the prefabricated façade meeting energy efficiency, moisture, and thermal performance, the prefabricated façade should also be easy to handle in the renovation process and to disturb the tenants as little as possible during the renovation.

Research sub-Questions that will aid in answering the investigation of this project:

- Are the chosen prefabricated facades able to be fixed onto the existing building?
- Is there a need to do a moisture analysis when using the chosen facades in this project in another project?
- Should the prefabricated facades have a vapour barrier between the existing façade and the prefabricated facade?
- Which of the chosen facades in this project have the best thermal performance?
- Does the thickness of the prefabricated façade element matter when looking at the U-value?
- How will the tenants be affected by the renovation?

## 1.3 Methodology and limitations

This study is based on a literature review with a qualitative evaluation. it analyses the attachability possibility, the moisture, and the thermal performance of the chosen prefabricated façade elements by using different simulation programs known as WUFI and HEAT2. Installations such as pipes, and ducts, etc. will be neglected in the Multi-active facades as the programs used are not complex enough to give full accurate results. Therefore, all the Multi-active facades are calculated without installations systems. The thermal comfort will also be calculated. The software's used in the analysis only resolve part of the reality, which means that careful analysis is needed in every possible or similar project to avoid risks. The U-value provided from the literature review was revised by means of hand calculations as well as the U-value provided in the simulation's software. The U-value calculation part can be found in appendix B.

There are a few limitations in this study that are important to highlight. This study does not have any detailed studies of Static loads and the different facades are only studied for the reference building in Linero. of note, the result may vary if the facades are applied to another facade with different existing materials than the reference building. The boundaries are that the balconies on the south side of the reference building are not studied. Only the south to the southwest part of the reference building is analysed, thus diverse parameters can be considered. For example, driven rain that only occurs on the southwest side in Lund. Another limitation is that the prices of the chosen facades will be stated but not analysed economically since the focus of this report is to find the best performing prefabricated façade that will meet the directives of EU.

# 2 Methods

Three different phases were taken to evaluate the project.

In phase I, much information was gathered by not only visiting the Linero district, but also by meeting with LKF, Cityfied (EU) and IVL. Herewith, a clear view of the current and desired state of Linero was attained. The authors of this study chose to only focus on the facade retrofit of the reference building. Consequently, this allowed the authors to make a list of requirements the new façade would need. There was a search done on the European market for new façade that would be retrofitted with the building characteristics.

Searching for innovative facades was difficult as information about innovative façade elements was limited. Comparing different insulation materials in the different façade elements made it easier to choose the facades for this project.

In phase II, the list made in phase I was extended and became a comparison table with properties in phase II. In this list the best prefabricated facade for the reference building were evaluated. The comparison table was created to make it easier to analyse and compare the different façades.

In phase III, three façades were selected from the list from phase II. These three facades meet the criteria of the comparison table and were further investigated. The final stage was to analyse and compare the three prefabricated façade elements by looking at the attachments, moisture analysis and thermal performance using different software’s such as AUTOCAD, WUFI and HEAT 2.

## 2.1 Linero

The housing area Linero in Lund with two blocks named Eddan and Havamal consists of 28 buildings with three level dwellings. The reference building is one of these identical 28 buildings that were built in 1970 and is therefore part of the Million Program. The blocks contain a total of 681 apartments with approximately 2000 tenants and are owned by the public housing company LKF (Cityfied, 2016). The geographic coordinates for the location of the Linero project is 55.694363N 13.239003W.

### 2.1.1 Architecture of the reference building

The building contains three stories of apartments as well as a basement floor. Each apartment contains a large balcony as well as a patio for the ground floor apartments. The buildings in the Linero project are the same in appearance and design. Figure 1 shows that the main entrances of the building are located on the northern façade and figure 2 shows the balconies are facing the southern façade. The mayor of Lund City gave the drawings of Linero from 1960 - 2017 to the authors. This is useful and important information for this research. For instance, these documents include several renovations that have taken place and can be seen in the document history over the years.

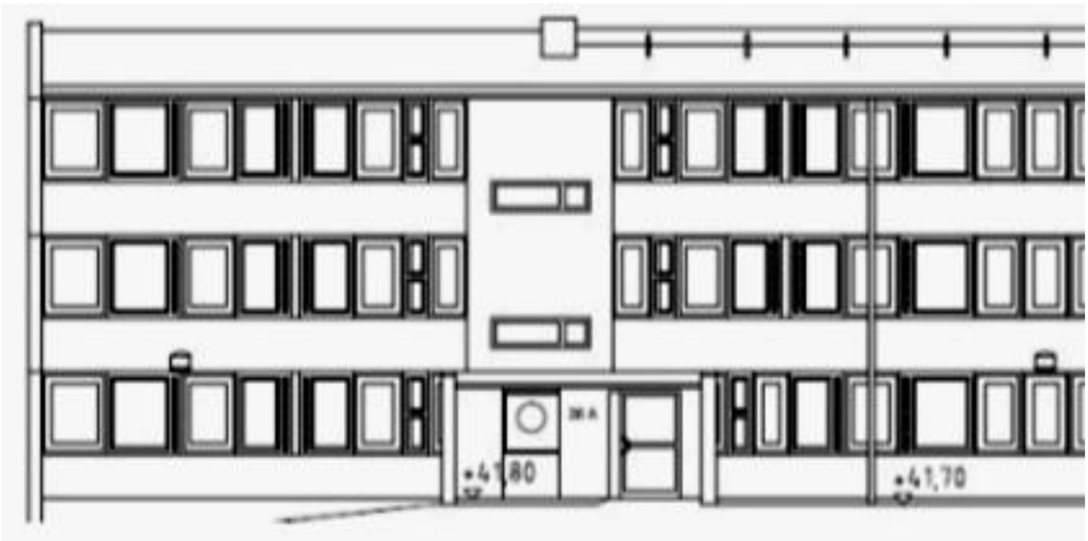



*Figure 1. Architectural drawing of the northern facade with the main entrance.*

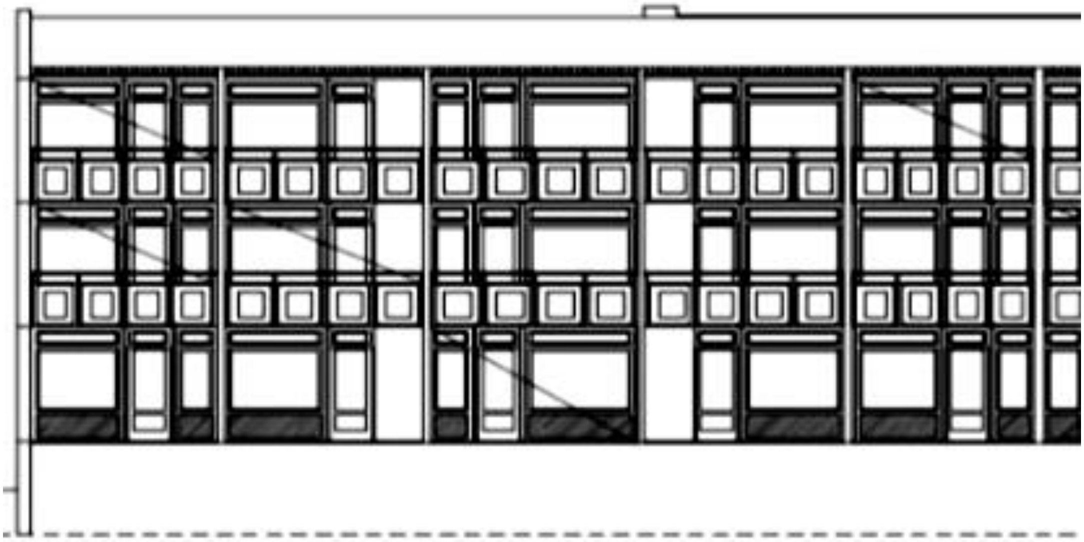


*Figure 2. Architectural drawing of the southern facade with balconies.*

Figure 3 shows the staircase with three apartments per floor. The apartments contain bathroom and bedrooms, which are located along the northern façade. While the balconies are connected with the living room and the kitchen facing the southern façade.

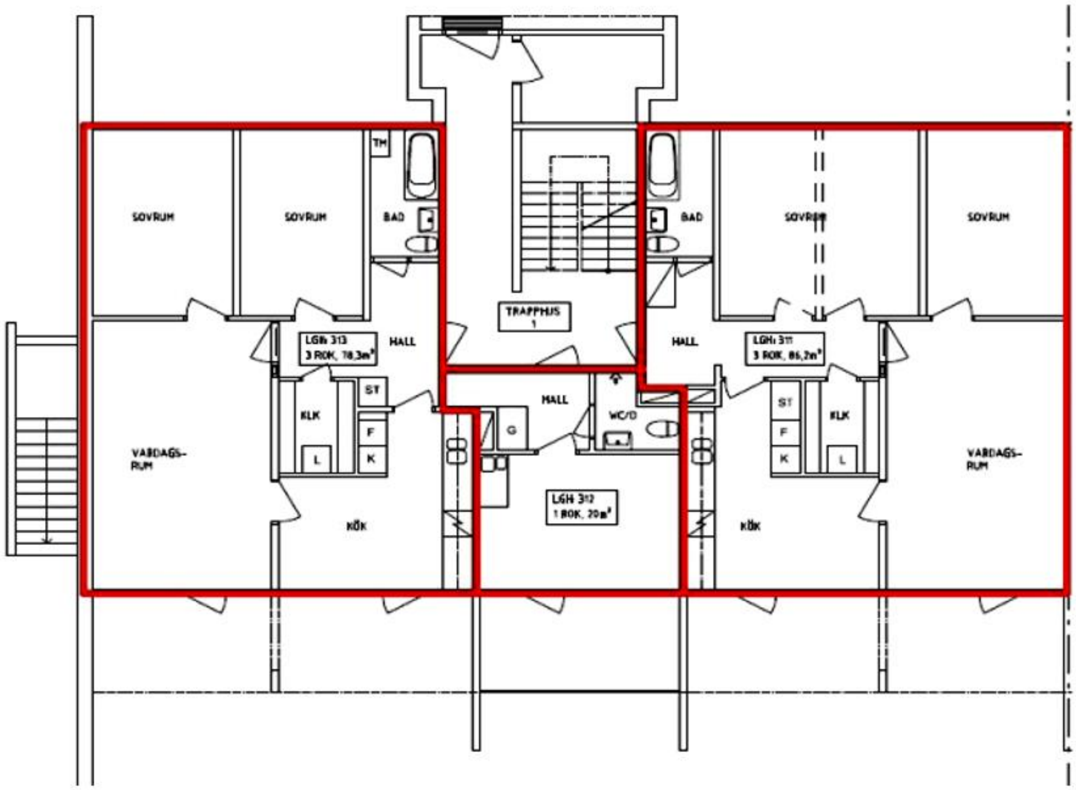



*Figure 3. Architectural typical floor plan.*

## 2.1.2 Existing building façade characteristics

The existing building façade consists of a concrete load-bearing structure system, which is also known as the sandwich facade system. The materials of which the facade is constructed are an outer layer of concrete, polystyrene in the middle and a final internal layer of concrete. According to the literature data from the Linero project given by the municipality to the authors by de mayor of Lund, the calculated U-value of the facade is 0.358 W/(m$^2$K). Figure 4 below illustrates the facade with the repeated floor of the existing building construction materials. The hand calculation can be found in section 2.3 below.

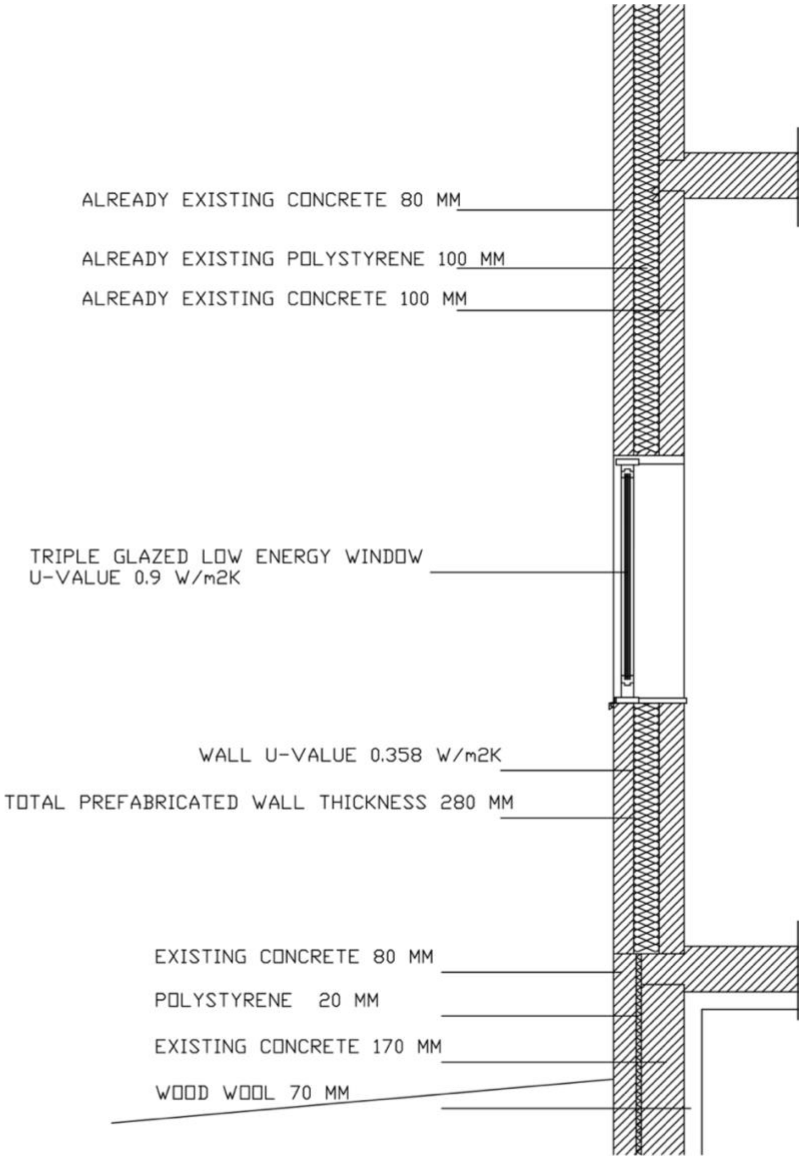



*Figure 4. The details of the materials and window of the existing building facade.*

The construction contains a longitudinal foundation, which is located below a load bearing concrete façade. Figure 5 below illustrates the basement floor-facade system and the part of the ground floor-facade. The drawing below shows the sandwich facade system, which was a load bearing construction system that was commonly used in the 1960s.

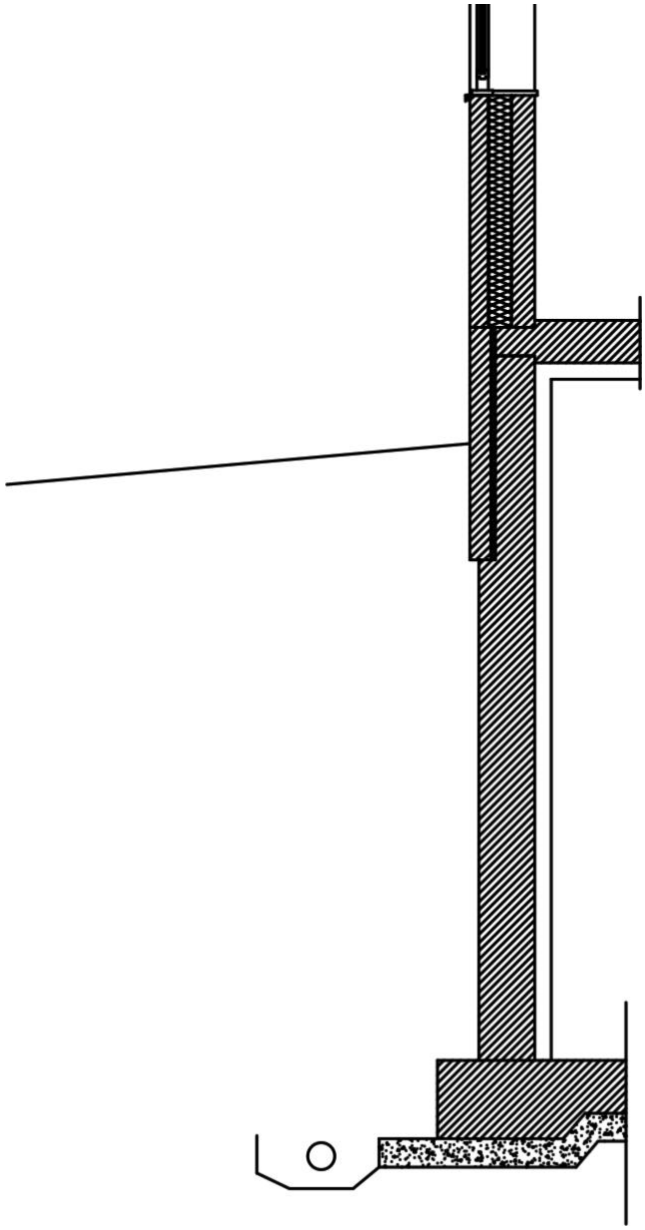


*Figure 5. The detail of the construction of the basement floor with the drainage pipe and the load bearing concrete facade.*

## 2.2 Calculation methods and formula

The method of calculating the U-value accurate with the evaluating the thermal transmittance of the façade. The U-value is expressed in $W/(m^2K)$. It corresponds to the amount of heat that is transferred through the façade structure with an area of $1m^2$ with a temperature difference of 1K between two boundaries, the indoor temperature and outdoor temperature. The lower the U-value the better the façade is insulated and the less thermal heat loss it will have.

Thermal Transmittance (U-value) the building envelope of the building:

Thermal Transmittance Calculation
The general formula for calculating the U-value is

U=1/Rt

Where:
- U= thermal transmittance ($W/(m^2. K)$)
- Rt= total thermal resistance of the element composed of layers ($m^2. K/W$), obtained according to:

**Rt=Rsi+R1+R2+R3+…+Rn+Rse**

Where:
- Rsi= interior surface thermal resistance (according to the norm by climatic zone)
- Rse= exterior surface thermal resistance (according to the norm by climatic zone)
- R1, R2, R3, Rn= thermal resistance of each layer, which is obtained according to:

R=D/λ

Where:
- D= material thickness (m)
- λ= thermal conductivity of the material (W/K. m) according to each material)

the thermal transmittance is inversely proportional to the thermal resistance therefore the greater the resistance of the materials that make up an envelope, the lower the amount of that is lost through it.

U= 1/R
R=1/U

## 2.3 U-value calculation of the existing façade

The material that the façade is constructed of will be evaluated by calculating the U-value. Below in the table of details structure are the provided materials that the façade is constructed of.

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| External | | | 0.06 |
| **Total resistance 4.32 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity

U-value=1/total thermal resistance
U-value=1/4.32
U-value=0.23 W/($m^2$K)

# 3 Literature review on prefabricated façades in Europe

## 3.1 Façade element search

The authors searched in the European market for prefabricated facades that were not only energy efficient, innovative and inspiring, but also to be well established and researched. The latter part was achieved by looking at types of facades that were a part of a report or study. This allowed the authors to retrieve data and information about the facades that have previously been tested, and this gave information such as the benefits and drawbacks. As a result, this was a good starting point when choosing for facades system.

The authors found and evaluated 15 prefabricated façade systems for the Linero case study. The 15 prefabricated façade systems were analysed upon the criteria to be energy efficient, meeting the passive house standards, to have a good airtightness to prevent thermal losses, should contain a low U-value window, and a low U-value façade system.

An energy efficient façade is a façade that meets the passive house standard by being airtight with a low window U-value and low facade U-value. To become energy efficient also means to have a high-performance insulation that is thin. This means that the total thickness of the existing facade and the added prefabricated façade do not take up too much space of the living area nor the outside area (Mir, 2011). Moreover, an energy efficient façade is constructed from materials that are organic and can be recycled but is moisture safe and fire protected (Cronhjort et al., 2009). An innovative façade is a façade that has low maintenance and that solves problems in an innovative way compared to that of a standard façade. For instance, the facade has a new technology, or it is made in a unique or innovative way. Another good and very important criterion in this thesis is that the façade should be attachable.

Table 1 below shows the 15 prefabricated facades that are available on the European market and that were chosen for this project to be further investigated. The 15 facades were chosen because they matched the authors criteria of a good facade. Table 2 below show the links to the literature review of the 15 prefabricated facades system used in the investigation for this study.

*Table 1. 15 The 15 European market prefabricated facade elements that meet the criteria for this study.*

| | |
|---|---|
| Facade 1 | TES facade |
| Facade 2 | Multi-active Large size prefabricated façade |
| Facade 3 | Alingsås facade |
| Facade 4 | Semi prefabricated standardised retrofit |
| Facade 5 | Large size prefabricated steel frame retrofit |
| Facade 6 | Prefabricated metal panel retrofit |
| Facade 7 | ECO sandwich facade |
| Facade 8 | Double skin facade |
| Facade 9 | Vacuum insulated prefabricated elements |
| Facade 10 | Green facades and building structures LWS |
| Facade 11 | Passive renovation De Kroeven 505 Roosendaal, NL |
| Facade 12 | Net zero energy renovation of a Swiss apartment building in Zurich |
| Facade 13 | The Innova Project - A New, Innovative Method for Carrying Out Energy Efficient Renovations |
| Facade 14 | Best Practice in Steel Construction |
| Facade 15 | Prefab external facade element with plastered facade |

*Table 2. Website links to the facades investigated in this thesis.*

| | Reference |
|---|---|
| **Wall 1** | http://tesenergyfacade.com |
| **Wall 2** | http://www.sci-nework.eu/fileadmin/templates/scinework/files/Resource_Centre/Innovative_Technologies/State_of_the_Art_Report_Multifunctional_Facade_Systems.pdf |
| **Wall 3** | http://www.iea-annex56.org/Groups/GroupItemID6/16.SE.pdf |
| **Wall 4** | http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_50_Retrofit_Strategies_Design_Guide.pdf |
| **Wall 5** | http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_50_Retrofit_Strategies_Design_Guide.pdf |
| **Wall 6** | http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_50_Retrofit_Strategies_Design_Guide.pdf |
| **Wall 7** | http://www.eco-sandwich.hr |
| **Wall 8** | http://www.gft.eng.cam.ac.uk/media/ff/the-route-to-an-ideal-adaptive-glazing-facade.pdf |
| **Wall 9** | http://www.bine.info/fileadmin/content/Publikationen/Englische_Infos/projekt_0907_engl_internetx.pdf |
| **Wall 10** | http://repository.tudelft.nl/islandora/object/uuid:f262c218-8801-4425-818f-08726dde5a6c?collection=education |
| **Wall 11** | http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_50_Documented_CaseStudies.pdf |
| **Wall 12** | http://www.iea-ebc.org/fileadmin/user_upload/docs/Annex/EBC_Annex_50_Documented_CaseStudies.pdf |
| **Wall 13** | http://www.paroc.com/campaigns/innova-project |
| **Wall 14** | http://sections.arcelormittal.com/fileadmin/redaction/4-Library/2-Steel_research_reports/4-Best_practice/Eurobuild/Residential_EN_Lowres.pdf |
| **Wall 15** | http://www.riko-hise.si/en/files/default/Riko-hise/brosure/Riko%20technical%20brochure.pdf |

### 3.1.1 Façade 1 TES façade

The TES Energy Façade was a WoodWisdom-Net project and the goal was to develop prefabricated wooden façade elements that would improve the energy efficiency of buildings. When used in façade renovations in Europe. The goal was to make a façade system with a low U-value that was not only innovative but also had good insulation and aesthetics (Cronhjort et al., 2009). Furthermore, it was created to develop, evaluate, and demonstrate a multifunctional cost-effective façade system. The vision was to transform the building sector from on-site building to an innovative, high-tech and energy-efficient industrial sector, working for an industrial building process. Moreover, the target of the TES method was primarily focused on the building's energy efficiency improvement and consequently in the reduction of greenhouse gas (GHG) emissions (Lattke, Larsen, Ott, et al., 2011).

The timber framed prefabricated TES façade modules combine a self-supporting structure with insulation infill and panelling and has a wide range of variety of exterior surfaces (Lattke, Larsen, Johannes Ott, et al., 2011). TES façade has a wide range of options and include rendered facades, panelled facades, glass facades, timber facades, metal sheet facades, stone or ceramic facades and plastic facades. High precision building components like windows are easy to integrate due to the modularity. Moreover, the TES façade can contain biogenic insulation materials and techniques, multiple glazing, solar active system and HVAC components (Lattke, Larsen, Ott, et al., 2011).

The TES façade projects are based on a systemized building method, which contributes to a customized building system for every new renovation project. The TES method is to measure, plan/build and apply. Modern methods such as Photogrammetry and 3D laser scanning are used to generate precise data of the target buildings or 3D-models, respectively (Lattke, Larsen, Johannes Ott, et al., 2011). This information is then placed in a CAD program to get the right measurements for the TES modules that are produced off-site. This shortens the application work on-site when replacing either certain layers of, or the existing building envelope in its entirety (Lattke, Larsen, Ott, et al., 2011).

The TES façade was applied to several buildings in Germany such as residential buildings and schools from 1950-1980 (Lattke, Larsen, Ott, et al., 2011). One of these buildings was in Augsburg, Grüntenstrasse and the aim was to transform the old building into an energy efficient contemporary piece of architecture with the TES façade modules. In this project the TES façade was cladded with rough sawn and white painted spruce boards. The existing balconies were converted into either living room extensions or wintergardens. This added either bigger interior space or bigger outdoor space. The tenants were very pleased with the project, as they could stay in their apartments during the renovation and additional value was created to the building with the new aesthetics (Lattke, Larsen, Ott, et al., 2011).

Another TES façade renovation in Munchen of two residential buildings (owner GWG München, public housing company) from 1954 demonstrated similar results. The energy use before the renovation was 220 $kWh/m^2y$ and after renovation it was reduced to 20 $kWh/m^2y$. The TES façade renovation met the passive house standard and reached all the goals and visions stated from WoodWisdom-Net project (Lattke, Larsen, Ott, et al., 2011).

### 3.1.2 Façade 2 Multi-active façade

In south of Graz (Styria, Austria) there is a residential area called Dieselweg. The buildings were built in 1960 and their condition was poor and energy inefficient. The existing building structure had no insulation in the cellar ceiling, exterior facades, or the floor to the attic. The balconies caused significant thermal bridges due to cantilevering concrete slabs. Since there is no thermal separation, this mainly has a significant problem on thermal bridging. The apartments used single heating devices that used solid and fossil fuels or electric heating devices. Because of these mentioned poor structural conditions the buildings had a very bad energy performance, which led to high heating costs and poor thermal comfort and living quality. One of the most challenging circumstances of the renovation was to resettle the tenants during the renovation (Höfler et al., 2010).

The main goal for this project was to reach the passive house standard. This meant that for this specific project there should be a 93% reduction of the heat demand. To meet this big heat reduction, innovative Multi-active solar-active energy prefabricated façade modules were attached to the existing building.

These large scale Multi-active facades modules are made of a solar comb that is arranged on an OSB board covered by a glass panel that in this project is coloured in yellow. In between is a rear ventilated air space. When the sunlight falls through the glass the temperature increases in the airspace and solar comb. This lowers the temperature difference between outside and inside especially in winter and leads to reducing the heat losses and an improved effective U-value (than the static state) (Kobler et al., 2011).

Besides the solar active system, the Multi-active façade could also have diverse installations integrated into the façade. In this project the balconies were integrated into the new prefabricated façade, which not only eliminated the thermal bridges but also increased a living space for the occupants. Moreover, the Multi-active façade modules were equipped with further integrated components like ventilation ducts with heat recovery system, windows and shading appliances (Schwehr et al., 2011).

The results from this project were very good as the passive house standard was achieved. The heating costs was decreased by about 90%. The tenants were pleased as they did not have to move out of the building during the renovation as well as for the lower monthly charges. Moreover, the $CO_2$ emissions were reduced by renewable sources e.g., solar thermal energy. The indoor environment was improved, and an essential increase of the thermal and user comfort was achieved.

This project was supported by the Austrian system of public housing aid by the non-profit organisation “Wohnungsgemeinnützigkeit” of the GIWOG Corporation, additional research funds and by special support provided by the governor of environmental affairs of Styria. Together they found a way that allow an amortization of the investments within reasonable time and keeping the social rental fees low.

### 3.1.3 Façade 3 Alingsås façade – renovation using passive house technologies

An apartment complex called Brogården is situated in Alingsås Sweden. It consists of 300 apartments in three-four storey buildings that were built between 1971 and 1973 during the Million Program.

The building's structure was made of concrete with an infill facade. The facades consisted of gypsum boards on a non-loadbearing wooden stud with insulation and façade bricks. The basements cast-insitu facades were made of concrete and had no insulation. The roof slab was made of 300mm insulation and wooden rafters with props on roof slab. The windows had one single panel with an aluminium sash and one additional panel (Lattke, Larsen, Johannes Ott, et al., 2011).

The buildings in the complex and their domestic hot water were heated by district heating. Each apartment had radiators under their windows and were ventilated by mechanical exhaust ventilation without heat recovery.

The buildings in the complex needed a renovation due to wear and tear. For instance, the yellow façade of bricks was partly destroyed by moisture, which contributed to a poor indoor thermal climate. The balconies of the apartments contain thermal bridges. The apartments had bad indoor climate where it was moisture as well as the radiators were worn out. To solve this problem, Alingsåshem (which is a municipality-owned housing company owned by AB Alingsås town hall) and construction company Skanska started to cooperate on this demonstration project.

The main goal of the Brogården project was to combine the necessary renovation with passive house technologies to upgrade the buildings to a passive house standard. This by renovating the poor parts of the building, improve thermal comfort, create a variation in apartment size, improve the energy efficiency by at least 50 % and preserve the architectural impression of the façade.

Well insulated prefabricated façades modules were therefore, attached to the buildings. Thermal insulation was added to the roof, gables and base plate, which improved the airtightness from 2 l/sm² to 0.2 l/sm² at 50Pa. The old windows were replaced by triple panel windows. New balconies were built that was supported by columns to eliminate thermal bridges. This incorporated the balconies with the living rooms. An installation of decentralized balanced ventilation system with heat recovery exchange efficiency of 80% was installed. Because of this installation radiators were no longer needed and were replaced with heating coils in the supply air of the ventilation system. The fixed lighting of the building was changed to low energy lighting and individual metering of the household electricity and domestic hot water was installed(Höfler & Aschauer, 2010).

This project was very successful as the results demonstrate an overall energy use reduction by 60% while keeping a similar architectural appearance. The planning process was lengthy, and buildings were renovated with traditional Swedish building materials in standard sizes and common contractors. The energy savings were estimated to be paid back in 17 years. Although the project took a long period, the tenants were satisfied with the renovation.

This project revealed that when renovating to meet the passive house standards, comprehensive efficient project management is needed. All skills and competence must be involved from the very start of this project. In addition, the tenants should be informed from the very start of the renovation project.

### 3.1.4 Façade 4 Semi prefabricated standardized retrofit modules from Schweiz

The IEA project on "Prefabricated Systems for low Energy Renovation of Buildings" identified potential solutions to assist in the sustainable refurbishment of residential buildings.

In this report the façade and the roof construction were researched module it was undertaken in Switzerland in collaboration with Swiss industry partners. The focus of this report was on the large prefabricated units with integral ventilation ducts for external retrofitting and how they are applied to achieve a significant reduction in heating energy demand.

Moreover, the aim was to identify methods of refurbishing existing residential buildings to achieve levels of energy efficiency at least between 30 – 50 kWh/(m²·y). The participating research institutes were Lucerne University of Applied Sciences and Arts (HSLU), the Swiss Federal Laboratories for Materials Science and Research (Empa) in Zurich, University of Applied Sciences North-western Switzerland (FHNW, Swiss Federal Institute of Technology Zurich (ETH-Z), Swiss Federal Institute of Technology Lausanne (EPFL) and Paul Scherrer Institute (PSI) (Schwehr et al., 2011).

For this project a new largely standardized and prefabricated building envelope was laid around the existing building, improving the façades, to add room extensions or a new attic floor. The modules showed satisfactory results according to the report and acted as the quality of a newly built building because of the good insulation, excellent comfort and reducing sound properties. The mechanical ventilation system with heat recovery was integrated in the façade and roof modules. The project aimed and succeeded for optimized constructions, efficient construction processes, high quality standards and reliable budgeting. Ventilation ducts were placed within the prefabricated units, which meant that refurbishment of the building exterior was permissible. The façade and roof units were delivered to the site as far as possible in pre-assembled with components such as windows, ventilation ducts, blinds, thermal insulation, solar energy systems and possibly other utility services pre-installed in the modules.

### 3.1.5 Façade 5 Large size prefabricated steel frame retrofit in France

A French project has been implemented in the frame of IEA annex 50 Project Prefabricated Systems for Low Energy Renovation of Residential Buildings and was sponsored and financed by ADEME under the name of RECOLCI: Réhabilitation Énergétique des immeubles de logements Collectifs par Composants Intégrés. The aim was to set a solution for façade renovation of collective buildings by having an energy efficiency approach such as limiting the heating and cooling consumption plus domestic hot water to 50 to 60 kWhPE/($m^2 \cdot y$). This project also wanted to have a low intrusive solution for the occupants and noise protection.  Moreover, to create a prefabricated solution with reducing installation costs for a better safety, easy installation, low disturbance for occupants. The panels should also have a high diversity of cladding and exterior finishes (Zimmermann, 2011).

The elements were developed for buildings less than 7 stories. They had to be attached by 20cm steel cross-section profiles and were stacked vertically so the load is vertical divided. The façade module was made of a steel frame with integrated windows, insulation and air tightness prefabricated off site and all kinds of finishing cladding systems were installed on site. Ventilation ducts was embedded inside the façade module or installed apart due to availability of existing ducts in many French collective buildings. The most important part was to make the elements self-standing and able to support load bearings allowing addition of surfaces (one or two story's that could be rented or sold) to an existing building to close loggias and balconies (Hövels, 2008).

The module solution showed a performing insulation façade (U-value= 0.22W/($m^2 \cdot K$).) associated with a double flow centralized ventilation system and proper treatment of the whole building. This allowed the building to reach a level at 50 kWhPE/($m^2 \cdot y$) for energy consumption (heating and cooling, ECS, ventilation) (Kobler et al., 2011).

### 3.1.6 Façade 6 Prefabricated metal panel retrofit modules in Portugal

Within the scope of IEA ECBCS Annex 50 "Prefab Systems for Low Energy / High Comfort Building Renewal", a Portuguese Project was set up, funded by FCT – Fundação para a Ciência e Tecnologia (Portuguese Science and Technology Foundation Programme). The aim of this project was to develop prefabricated retrofit solutions for an efficient renovation regarding solar energy control, energy consumption, thermal comfort, thermal performance and acoustics and lighting behaviour. The developed modules were then applied onto the existing building façade. The prefabricated solutions integrated all the tubes and pipes related to the HVAC, domestic hot water, and high-quality solar systems, as well as all the necessary domestic cables, which allowed easy assembly (Schwehr et al., 2011).

The prefabricated facades were made to have a simple mounting system based on two steel U-profiles on each side of the modules with pins and holes to be fitted into a support structure that is then bolted on to the existing facade. The modules had an area of $1m^2$ and weighted $12kg/m^2$ to be easy for transportation. When creating the facades three aspects were considered: the technical value, the economic value of embodied energy when choosing the materials. The materials that were used for insulation had a 100% recyclable material called agglomerated black cork due to an industrial production without additives and it is very abundant in Portugal. The extruded polystyrene (XPS) (with or without moulded ducts or cavities for ducts and cables) because of the technical possibility of moulding or creating cavities to lodge ducts and due to its competitive price. In Portugal and in Europe it is one of the most applied insulation products (Volf et al., 2018).

The result of the project showed that the thermal resistance of the element was 4.35 $m^2 \cdot K/W$ and had a U-value= 0.23 $W/(m^2 \cdot K)$. A small thermal bridge occurred in the docking area section between modules, but no other thermal bridges occurred in any other sections. The module showed no risk of moisture build-up, and it was very easy to install. The application of this solution to a test building resulted in the reduction of the thermal transmission coefficient of the exterior opaque envelope from the U-value 1.9 to 0.2 $W/(m^2 \cdot K)$ contributing to a reduction of 69% of the total building needs.

### 3.1.7 Façade 7 Eco-sandwich

The reusable and fully recyclable facades are not a part of a project but were interesting to consider as they are highly durable but with a low operating cost. According to the website state these facades are to be economical and enable rapid construction with high aesthetic values. The U-value of this facade was according to the website < 0,20 W/m$^2$K and the reduction of energy use is 46 % lower during the 50-year lifecycle compared other current products on the market. Therefore, these panels could be used for a fast construction of low energy, passive house, nearly zero energy buildings on a large scale (ECO-SANDWICH, 2015).

In a controlled environment when producing these panels there is a low possibility for construction damage and the fire resistance for these facades were classified as class E190. The wool in these panels called Ecose® is made of abundant recycled and naturally occurring materials such as glass bottle, silica and internal waste etc. which provide environmental benefits and act as a very good thermal insulation material. Since there is no more information about the attachments of this facade it is not further investigated (ECO-SANDWICH, 2015). These facades can be used as load bearing panels in a new construction or as cladding facade panels for different kind of buildings. The authors belief that, the Eco-sandwich facade have a high chance of sustainably improve the energy performance of the building stock and creating a move to reach towards the EUs goals by 2020.

### 3.1.8 Façade 8 adaptive glazing façade

There is a lot of examples on the market on how to refurbish the existing façade to an adaptive glazing façade. It is a glass facade that is constructed Infront of the existing façade and surrounding the building.  But none really has the information for how they are attached and if they are fabricated or not. There is a study that looks closer to the benefits of having an adaptive façade to improve the energy efficiency of buildings. The study identifies the thermo-optical properties of an ideal adapting glazing façade by an inverse approach, which makes use of optimization on a building that has a south oriented office room located in London. The study showed that a glazing façade with monthly adaptiveness can significantly reduce the energy consumption in the case study. Since the information was interesting but not enough it is not further investigated (Luible et al., 2015).

### 3.1.9 Façade 9 VIP element

Buildings that are energy optimized usually require a thick thermal insulation too meet the passive house standards. But when using vacuum-insulated prefabricated elements the building can achieve a much greater insulation effect with the same thickness as that of conventional materials. The slim structured VIP elements with a good thermal insulation are made of porous, pressure resilient core, which is sealed in a diffusion tight-barrier plastic film in a vacuum chamber. VIP elements are therefore very useful for refurbishment projects where the outside space and indoor space are limited but a high energy performance is required (Simmler et al., 2005).

When planning to build with VIP panels there should be a close cooperation with the manufacturer. The panel sizes should be made to measure or be aligned with the grid. Large format VIP panels are the best option to optimize the insulation properties with uninterrupted surfaces with the part to be sealed with their edges, which is the weak point of VIP elements. This not only shortens the installation process, but it also lowers the labour costs.

The VIP panels were tested in a passive house demonstration building project in “Neumarkt in der Oberpfalz” in Germany in 2005. This project was sponsored by the Federal Ministry of Economics and Technology (BMWi). VIP was integrated in the exterior facade in the wood main structure. In the ground contact a pressurized exterior facade of concrete was used as well as in the foundation slab. In the flat roof and the gable roof a wood main structure was used.

According to the producer, this project demonstrates that it is possible to complete a whole building using VIP elements. The passive house standard could be met with only 4 cm thick VIP elements. After the first year of the operation, it was found that all VIP elements were intact, and no condensation problems were identified. Further VIP elements for interior insulation are sustainable because of its high insulation effect and its diffusion tightness.

### 3.1.10 Façade 10 Green façade

Prefabricated living facade systems was part of a thesis that aimed to see if there is an effect of vertical greenings systems on a façade regarding moisture transport and condensation compared to a bare facade. This thesis also evaluated the sustainability aspects of prefabricated living façade systems. The result of the thesis reveal that vertical greening systems had no negative impact neither on moisture transport nor on condensation through the façade compared to the façade. The living facades are pre-vegetated prefabricated modular panels with a short growing period (0 to 1 year). A lot of different plant species can be placed and the structuring panels in living facades were designed to allow the rainwater to flow internally from module to module with a drip pipe incorporated into the system (Mir, 2011).

The drip pipe was connected to a water pump that could add additional nutrients into the water system. The panels improved air quality and reducing the urban heat effect as well as working as a sound insulator. Furthermore, additional benefits of the prefabricated living façade systems include shading, which moderate the buildings internal temperature and created a microclimate as well as providing biodiversity and natural animals habitat and working as an insulator for both seasons summer and winter to protect the facades from graffiti. The disadvantage with these panels is that it could damage the façade if it is mounted directly onto the façade therefore it would be better is there is a gap between them Green façade and the existing façade.  Although it seems very sustainable and eco-friendly, the maintenance of these facades is a lot and the panels are very heavy especially when watered. This means that they are expensive to maintain and to buy. Therefore, further investigation is not made.

### 3.1.11 Façade 11 prefabricated timber façades and roofs

The elements that were used in this project from VDM (a company nearby) were prefabricated timber facades and roofs with triple glazed windows. They were used as a renovation project in De Kroeven 505 Roosendaal, Netherlands. The buildings that were identical single-family houses were from 1960 and had not been improved for over 40 years so the tenants were asking for an energy efficient renovation. The tenants were involved in the process together with the building company and decided to perform a low energy renovation. 256 buildings were going under a renovation process, which meant that the renovation process had to be as short as possible, so two different architect firms cooperated to come up with the fastest passive house renovation but at the same time ensure a variety in architectural and technical solutions (van Oorschot, 2017).

They tried two different prefabricated facades on two different pilot buildings in the area. One had 200 mm external EPS insulation with plaster rendering and windows integrated and prefabricated timber roof elements filled with 350 mm cellulose insulation. The other one contains the same plaster rendering and windows integrated; the difference was that it was 360 mm wide timber elements with cellulose fibber insulation with a U-value of 0.11W/($m^2$.K). Then a new cavity was formed between the inner leaf and the timber element to seal around the timber frames. Moreover, battens were mounted on site to allow natural slate tiles as a ventilated façade. The renovation process was short, and the tenants were satisfied, and the final energy savings were 72,3 % (Volf et al., 2018).

### 3.1.12 Façade 12 Large prefabricated light weight wooden elements

This façade element is a part of a demonstration project report from Zurich, Switzerland where they renovated a building built from 1954. The building had an external brick facade that was 32 cm thick and it was not insulated before renovation. The building suffered from insufficient insulation with a lot of thermal bridges, which reduced the thermal comfort. In this project the renovation strategy was to keep the building social, environmental and sustainable. The new renovation had to be carried out within three months and the new apartments had to reach the passive house standard (Miloni et al., 2011).

The prefabricated elements that were used in this project were made of large prefabricated wooden elements with integrated ventilation system and an aluminium cladding. The air distribution system and the electric conduits were placed before mounting the elements on to the building. The elements worked perfect for both roof and façade purposes. the prefabricated elements were light weighted, and this helped for static reason compared to the existing concrete slabs and brick facades. This also allowed the construction of facade element that are not in line with the facades of the existing building below. The buildings energy consumption reduced after the renovation with 80 percent, which meant that it met the passive house standard and was certified as a MINERGIE-P-Standard (Miloni et al., 2011).

### 3.1.13 Façade 13 Parco wooden prefabricated façades

The company Paroc, which makes TES prefabricated facades, decided to be part of a project called the "Innova project" and the project was invented to motivate housing cooperatives to carry out energy efficiency improvements. The Innova project was collaborating with ARA (the Housing Finance and Development Centre of Finland), Sitra (the Finnish Innovation Fund) and TEKES (the Finnish Funding Agency for Technology and Innovation), as well as several industrial partners including Enervent, Ensto, Lammin Ikkuna and Paroc (Parco, 2013).

The Innova project was focused on a typical multi-storey house of the 1970s that was renovated to meet the Finnish Passive House requirement. The four-storey-high building was in Peltosaari, Riihimäki. Laser scanning was conducted and modelled for the dimensioning of the elements. The outer concrete panel and the thermal insulation of the old exterior facades were replaced by vertical facade elements with wooden frame structure. The ventilation ducts, windows and the balcony doors were installed in the elements, as the first layer of the plaster rendering of the facades (Parco, 2013).

The new renovation method reduced the duration of the on-site construction work with half of the time compared to the respective renovations of similar multi-storey houses in the same area. Retrofitting was an opportunity for upgrading the architecture of the building. The aim of the project was to meet the requirements of the Finnish Passive House definition as suggested by the VTT researchers, i.e., the heating energy demand of the building should be max. 25 kWh/m² after the renovation. The simulation results showed that the target was met even without any additional thermal insulation in the floor structure (Parco, 2013).

The heating energy demand is reduced by 75 % and the results stated here was from the simulation program IDA ICE. It was also found in this project that when a part of the ventilation ductwork is installed in the facade elements, the new suspension needs for ceilings became significantly smaller, which did not reduce the room height compared to if whole ductwork would be built inside the building. Furthermore, this reduced the amount of construction work inside the apartments. The U-values before the building was renovated of the facades were 0,25 W/(m²K) and now it has a U-value of 1.0 W/(m²K) and for the loadbearing facade 0,27 and now a new U-value of 1.0 W/(m²K) as well.

The elements that were used in this project consisted of 69 elements with various widths. The element widths were selected so that plaster rendering of all the window and door recesses could be done in the element factory. The laser scanning of the exterior and the 3D- modelling of the building was conducted so the elements could be dimensioned right. The wood frame had panel layers on both sides of the frame and 9 mm of spruce plywood was fixed onto the frame by gluing and by screws. Then mineral wool with plaster rendering was glued onto the cement fibber board and the façade material behind the balconies was a wooden cladding with ventilation cavity behind it and all the work was carried out without scaffoldings.

## 3.1.14 Façade 14 steel prefabricated façade

Non-loadbearing infill facades are designed to resist wind forces and to support the weight of the cladding and to work as a support to the external envelope.  There are two types of infill facades:  Individual C sections (facade studs) that are installed on site and attached to the top of the slab and the underside of the beam of slab. And prefabricated storey high facade panels that are attached externally to the structure and are connected to the floors and columns (Döring, Vassart, et al., 2009).

Large prefabricated panels can be designed vertically between floors and horizontally between columns. Depending on the type of support the provision for relative minimum movements are considered reasonable for beams up to 5 m span: 10 mm – for steel-framed buildings or existing concrete buildings; 20 mm – for new concrete buildings. The top of the facade panel is restrained by a bracket and attached at maximum 600 mm centres to the inside face of the panel. Every bracket is designed to allow for relative vertical movement and to resist wind suction forces (Döring, Kuhnhenne, et al., 2009). Advantages with prefabricated steel frames are that they are light weight constructions with minimum material use and no waste on site. Large openings can be created easily, and facade panels can be prefabricated, or site installed and lastly the cladding can be pre-attached in prefabricated facade systems. Moreover, there is one or two layers of 12 mm thick fire resisting plasterboard that prevent passage of smoke and flame from floor to floor and has a fire resistance of 30-60min (Döring, Kuhnhenne, et al., 2009).

There were several case studies done with steel in the study but no detailed information about a specific steel prefabricated facade in the information was given by the reference. The study is more general and therefore no further investigation was done.

### 3.1.15 Façade 15 Riko timber façade

The founder of Riko Group is Janez Skrabec. The Riko houses that are made in this company can be custom designed with quality craftsmanship. They can be made for residential buildings and public buildings with a guarantee of 30 years. The houses are low energy houses, healthy and ecological and the facades and ceilings are made of wood and timber. The two basic building systems of this company are “SOLID TIMBER FACADE -LMS” and “TIMBER FRAME FACADE-ROS” (Riko Haus, n.d.).

The company is dedicated to developing and improve their products regularly, and this is achieved by cooperation with numerous scientific and educational institutions as (Faculty of Architecture - University of Ljubljana, Faculty of Civil Engineering and Geodesy, Biotechnical Faculty – University of Ljubljana, ZRMK Institute in Ljubljana, and Otto Graf Institute in Stuttgart). They have a lot of references on already built houses. The company has a lot of domestic and international certificates that confirm the quality of their products with European patent. They won a price “The best environmental product in Slovenia for 2002, Energy ID – ZRMK Institute”. Riko facades are recognized for their high-quality ecological construction (Riko Haus, n.d.).

The Riko Houses Company aims to increase the standard of living by encouraging new achievements in living-space design and to raise awareness of the importance of ecological materials, the value of healthy living and environmentally friendly construction. According to the company the Riko houses are healthy and economical homes. According to the producer, they are continuing the rich tradition of using wood as a building material. Wood fibre is a good insulator during the winter as well as during the summer, which decreases the heating and cooling costs. It also works as a good sound insulation and has a natural ability to receive and emit humidity from the air, which gives a positive impact on the indoors atmosphere with a comfortable indoor temperature (Riko Haus, n.d.).

It is stated that the company do large prefabricated facade units with built in doors and windows and prearranged facades, which makes it easy to move in fast as the construction period is short, but that’s all to say about it. There is no more information on how they are really constructed or how much they cost.

# 4 Results

In this part of the thesis the result of the Prefabricated façade system will be discussed. Furthermore, details as well as solutions for the Linero case will be discussed. In addition, potential improvements for the renovation of the Linero and presenting the prefabricated façade that could be suitable for the Linero case will be highlighted.

## 4.1 The attachment

This part of the thesis reveals how the attachment of a prefabricated façade could be done on an existing building. A literature review was executed in relation to the Linero project. As a result, a total of 4 different types of mounting were identified for prefabricated façade systems to attach onto existing building. Further analysis was conducted on the orientation of the element; specifically, being placed either horizontally or vertically onto the existing building. In addition, the connections of the elements were evaluated as well as the integration of the windows into the prefabricated facades.

This project commenced on how a prefabricated façade could be attached onto an existing building. After visiting the Linero site, the authors investigated the exterior of the building. Evaluating different angles of the building and comparing that data with the drawings that were provided to them by the mayor from the municipality of Lund revealed interesting key points.

### 4.1.1 Types of mounting

During the investigation, the prefabricated facades available on the market were examined including different methods of attachments. A total of four different attachments methods were identified. Lattke & Larsen mention the different types of mounting of prefabricated façade onto an existing building façade. The four different ways of mounting a prefabricated façade element can be seen in figure 6. The steps of attachment of a façade onto the existing building are as follows:

- The hanging type system. It hangs the prefabricated façade down from the main construction of the roof of the building. The load is distributed downward through the main load bearing structure system of the building.
- The story-mounted system. This is fixed between the two floors and constructed horizontally to the floor slabs of the building. This type is connected from the floor to the ceiling for each floor.
- The standing vertical façade system. This system can be mounted in different ways:
    - The load will be fixed into the current building construction.
    - Own separated foundation system that is constructed next to building façade.
- The prefabricated façade element fixed to the ceiling with an inclination inward into the building (this is only when the facades are non-load bearing facades) (Lattke, Larsen, Ott, et al., 2011).

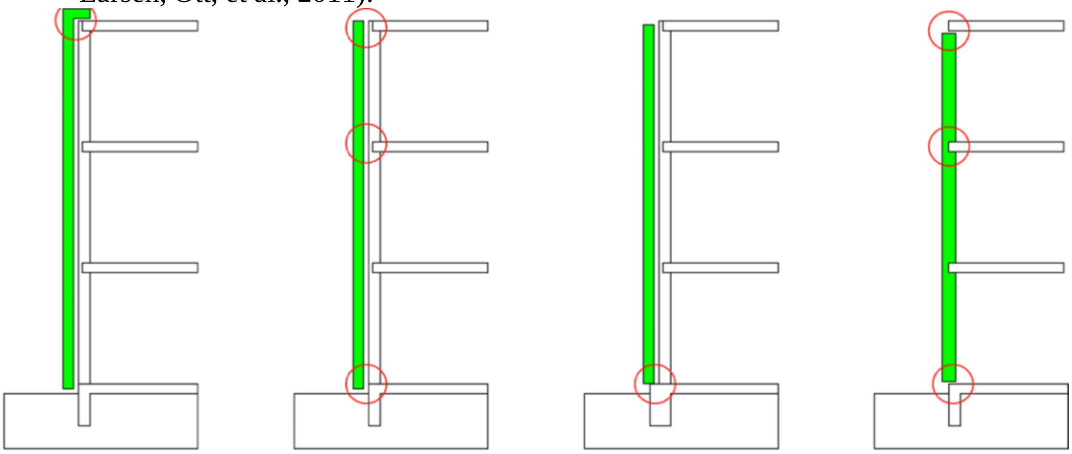


*Figure 6. Detail of attachment of the prefabricated façade elements onto the existing building structure and the location of attachment with screws.* (Lattke, Larsen, Ott, et al., 2011).

When at the Lineor site, advantages and disadvantages were revealed for the attachment of prefabricated onto the existing building. Looking at the drawings that were provided by the municipality of Lund and visiting the site several point to take into consideration were identified. Firstly, the building contains a sloped roof with an angle of 4 degrees, which should be taken into consideration for the typology of the mounting the new prefabricated façade element. Secondly, the building contains a basement that is located below ground level, which indicates that the foundation slab is deep underground. Thirdly, the main outer façade of the existing building are all load bearing walls, which indicates that it can't be removed from the existing building. If the facades are to be removed, the building will collapse.

When looking at the four different options from figure 6 above, which illustrates the four different types of mounting of prefabricated façade for the Linero Projects. Starting from the foundation in the Linero case the foundation slab is deep underground, and this is due to the presence of a basement in the building. This indicates that the prefabricated façade cannot be seated onto the extension of the foundation that will carry the load of the prefabricated facade. Therefore, option 3 and 4 are neglected from the prefabricated façade attachment onto the existing building. Furthermore, option 1 is not suitable because the prefabricated façade will hang from the roof of the building, but the roof of Linero case contains a sloped roof of a 4 degree angle. Therefore, option 1 is not suitable and will be neglected from the investigation for the prefabricated façade attachment onto the existing building.

There is no extension that goes out of the building that could carry the load of the prefabricated façade elements. The solution for the Linero project is to add steel L-bracket from below, which will carry the load of the prefabricated façade. As a result, the suitable option for the Linero case will be option 2 see in figure 7, as it contains a steel L-bracket that is fixed onto the existing building façade to carry the load of the prefabricated façade elements.

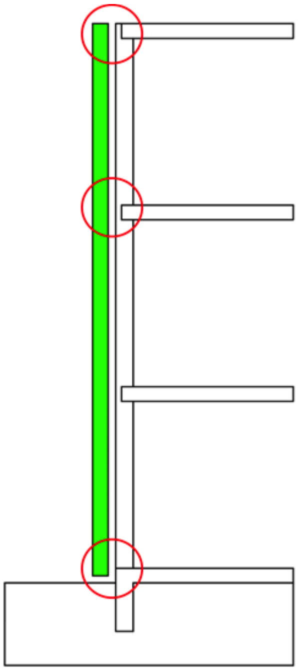


*Figure 7. The authors chosen attachment of the prefabricated facade onto the existing building façade.*

## 4.1.2 Orientation of the prefabricated façade element placement

After analysing the European market there are two main ways to place the prefabricated façades onto the existing building, which are horizontally or vertically. Figure 8 shows a comparison between the two options of how the prefabricated façade and how they could be suitably oriented onto the existing building façade.

1. **Horizontal**

The fixations are done from floor-to-floor level of the prefabricated façade elements with a horizontal application(Lattke, Larsen, Ott, et al., 2011).
Load supports floor wise or at base.

- Elements are delivered in the mounting direction.
- Load support at base contains a reduction of forces applied to existing structure system.

2. **Vertical**

The prefabricated façade element will fit from ground level to the building height (Lattke, Larsen, Ott, et al., 2011).
Load support at base

- Elements must be tilted from transport to be mounted.
- Load support at base, no additional forces applied to existing structure.

*Figure 8. illustrate the attachment of the prefabricated facade onto the existing building facade and indicating a better illustration of how the windows need to be inserted in the prefabricated façade.*

The two options to place the prefabricated façades onto the existing building were mentioned in the TES Energy façade document. The suitable fit for the Linero project was determined by looking at the façade of the building and comparing the two orientation options. This comparison clearly demonstrates that the same dimensions were used irrespective of the orientation of prefabricated façade element that would be placed onto the existing building facade.

The vertically placement of the prefabricated façade system will be difficult due to the openings caused by the windows that need to be integrated into the prefabricated façade. For instance, at least 300 mm of prefabricated façade should be around the windows to fix the prefabricated façade with each other. In addition, the vertical placement of the prefabricated façade has disadvantage with transport reaching the site such as the prefabricated façade needs to be lifted and rotated to be fitted into place onto the existing building façade.

The horizontally placement will be easier as the window opening are inside the prefabricated façade. Therefore, the prefabricated façade can be fixed between the two floor levels. In addition, the element will be in its horizontal position when arriving at the site. This suggests ease of placing and installing the prefabricated façade element onto the existing building because the prefabricated façade element will be directly lifted from transport and placed onto the existing building façade (Lattke, Larsen, Ott, et al., 2011).

### 4.1.3 Element connection

The element connections are illustrated below in figure 9. There are three types of joint systems that could be used for the prefabricated façade system, which are the following:

1. Flush joint
2. Rebate joint
3. Tongue in groove joint

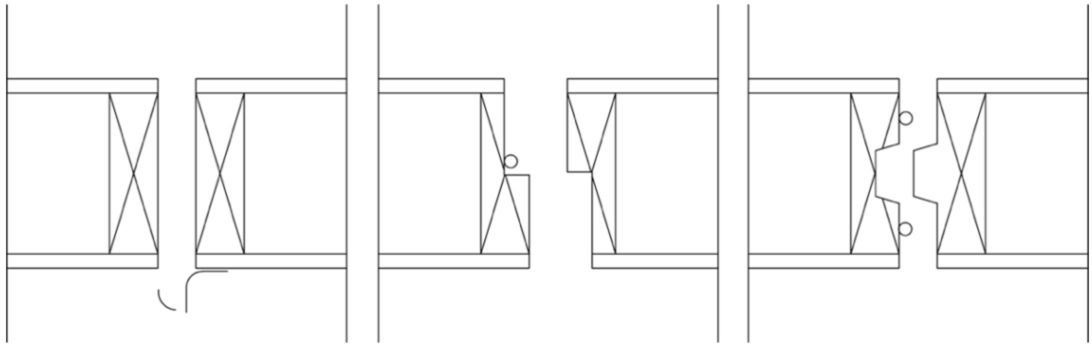


*Figure 9. The three options of connections between the prefabricated facade elements to reduce the thermal bridges and airtightness known as the flush joint, rebate joint and the tongue in groove joint concept form* (Lattke, Larsen, Ott, et al., 2011).

The drawings displayed in figure 9 illustrate the connection of two prefabricated façade elements to each other. There is always a need to add an elastic sealing around junctions between the prefabricated façade element to make it airtight, sound and fire protected. An additional solution is to fill the gaps with a strip of bendy mineral wool insulation. The gaps are located at the panels side of the wood (near the screws). The exterior layer of the façade panels is sealed; thus, it can protect it from wind and driven rain entering between the panels (Lattke, Larsen, Ott, et al., 2011).

### 4.1.4 Window integration

Adding the window into the prefabricated façade could be done within the process of its manufacturing. were this implemented, then it should take into consideration the surveying, construction, and assembly process. The new windows are integrated within the prefabricated façade element and will replace the old window of the existing building. The space between the façade and existing building envelope will be filled with mineral wool or cellulose fibre insulation material. This will be added around the window frame for more protection against thermal bridges (Lattke, Larsen, Ott, et al., 2011).

## 4.2 Façade element search

The façade element search revealed 15 refabricated façade available on the European market. Consequently, a comparison table was made to further investigation and to compare them with each other. Secondly, an analysis revealed the façade performance after being explored with different properties that were chosen to meet the EU directives and regulations.

*Table 3. 15 prefabricated facade elements with names, from the European market.*

| | |
|---|---|
| Facade 1 | TES facade |
| Facade 2 | Multi-active Large size prefabricated façade |
| Facade 3 | Alingsås facade |
| Facade 4 | Semi prefabricated standardised retrofit |
| Facade 5 | Large size prefabricated steel frame retrofit |
| Facade 6 | Prefabricated metal panel retrofit |
| Facade 7 | ECO sandwich facade |
| Facade 8 | Double skin facade |
| Facade 9 | Vacuum insulated prefabricated elements |
| Facade 10 | Green facades and building structures LWS |
| Facade 11 | Passive renovation De Kroeven 505 Roosendaal, NL |
| Facade 12 | Net zero energy renovation of a Swiss apartment building in Zurich |
| Facade 13 | The Innova Project - A New, Innovative Method for Carrying Out Energy Efficient Renovations |
| Facade 14 | Best Practice in Steel Construction |
| Facade 15 | Prefab external facade element with plastered facade |

## 4.3 15 prefabricated façade attachment and structure selection

Let's investigate the 15 prefabricated façade with the attachment and structure system as well as with the information that is provided in the literature review. The authors came across two main structure systems, steel or wood. The prefabricated façades were then investigated based on their attachment capability and structure selection.

Façades 1, 2 and 3 contain a steel L-brackets that the prefabricated façade can be fixed on. As a result, facades 1, 2, and 3 were well illustrated and provided sufficient information that could be used for this thesis, and these facades also contained detailed drawings of the attachment (For further details and calculations on drawings, attachment and connections see Appendix A).

The other 12 prefabricated façade weren't suitable for various reasons and is explained below in further details. Facades 8, 14 and 15 were disregards in this research because they contain inadequate information about the materials, conductivity value (for hand calculation) and input value (for WUFI simulation software). Facades 7, 9, 10, 11, 12 and 13 were disregards in this research because they contain inadequate information about the attachment and structure system. Façades 4 and 5 were neglected from the investigation because the detail drawing lacked information on the L-bracket and attachment method. Facade 6 was neglected as the structure of its panels were not clearly illustrated. It had $1m^2$ large panels with a 0.5 cm gap between each panel, causing thermal bridges.

## 4.4 Façade performance

A reduced U-value for a façade helps in the reduction of energy usage of a building. Therefore, the U-value of 15 prefabricated façade systems were investigated to evaluate how the building could be improved by the various 15 facades. Table 4 demonstrates the U-value of the prefabricated façade system on its own as well as how the U-value changes when the prefabricated façade is attached onto the existing building façade.

The U-values analysed for the 15 prefabricated façade include the U-value provided from literature, WUFI simulation, and hand calculations. Therefore, the main aim was to determine which façade will perform best based on the given U-value in relation to the different properties used and that could meet the EU directives and regulations.

### 4.4.1 Façade U-value

The 15 prefabricated façade systems were constructed into the WUFI simulation. The prefabricated facades were constructed in the WUFI simulation with the same materials that they were constructed of. There was a difference in the U-value provided from literature compared to the U-value obtained from the WUFI simulation.

Therefore, a hand calculation was performed to see if there was any difference amongst the U-value of different simulation methods. This was done and added in the table 4 for further analysis. The U-values were compared amongst each other.

This analysis is focused solely on the prefabricated façade when they are not attached onto the existing façade. Now let's observe how the prefabricated façade will perform based on the U-value when it is attached onto the existing building façade and how it will improve the case study for the Linero project.

The Prefabricated facades were then attached onto the existing building façade in the simulations software. This provided a U-value was added into the table 4 to observe the improvement of the U-value for the Linero case. Furthermore, a hand calculation was made to observe the difference between the WUFI simulation and hand calculation. For further detailed information about the U-value calculations see Appendix B.

*Table 4. The table illustrate the different U-value for the different facades on the European market.*

| | **Facade U-value (W/(m$^2$K))** | | | | |
|---|---|---|---|---|---|
| | Prefabricated façade from the European market | | | Prefabricated façade attached onto existing facade | |
| | Report | WUFI | Hand calc. | WUFI | Hand calc. |
| Facade 1 | <0.15 | 0.126 | 0.138 | 0.095 | 0.088 |
| Facade 2 | <0.15 | 0.238 | 0.191 | 0.147 | 0.106 |
| Facade 3 | <0.15 | 0.099 | 0.109 | 0.079 | 0.075 |
| Facade 4 | <0.15 | 0.107 | 0.109 | 0.084 | 0.075 |
| Facade 5 | <0.15 | 0.119 | 0.157 | 0.091 | 0.095 |
| Facade 6 | 0.23 | 0.177 | 0.176 | 0.121 | 0.102 |
| Facade 7 | 0.20 | 0.149 | 0.182 | 0.108 | 0.104 |
| Facade 8 | 0.12 | No info | No info | No info | No info |
| Facade 9 | 0.10 | 0.098 | 0.079 | 0.078 | 0.059 |
| Facade 10 | 0.11 | 0.151 | 0.559 | 0.306 | 0.177 |
| Facade 11 | <0.15 | 0.115 | 0.106 | 0.089 | 0.074 |
| Facade 12 | 0.16 | 0.165 | 0.153 | 0.115 | 0.094 |
| Facade 13 | 0.10 | 0.107 | 0.103 | 0.083 | 0.072 |
| Facade 14 | <0.15 | No info | No info | No info | No info |
| Facade 15 | 0.16 | No info | No info | No info | No info |

A boundary was put for the data in table 4. The boundary for the U-value was set at the passive house standards, which contains a U-value 0.15W/m$^2$K. The passive house standard requires the U-value to be <0.15W/m$^2$; as a result, any facade systems that are higher than this U-value will be rejected for further analysis.

### 4.4.2 Window U-value

Passive house standards for the window U-value are suggested a U-value of 0.80 W/($m^2$K) or less in most cold climate temperature. The frame from the window must be well insulated and fitted with a low e-glazing filled with Argon or Krypton gas to prevent it from heat transfer. Table 5 below contains the windows that are integrated in some of the prefabricated façade. There are some of the prefabricated façades that do not contain a window; therefore, those prefabricated façade system are mentioned as 'no window'. The windows that are mentioned in the table 5 contain a U-value of 0.80 W/($m^2$K).

*Table 5. Window U-value for the different facades with integrated windows.*

| | **Window U-value (W/($m^2$K))** |
|---|---|
| | Prefabricated façade with windows |
| Façade 1 | 0.8 |
| Facade 2 | 0.8 |
| Facade 3 | 0.8 |
| Facade 4 | 0.7 |
| Facade 5 | 0.8 |
| Facade 6 | 0.8 |
| Facade 7 | No window |
| Facade 8 | 0.8 |
| Facade 9 | No window |
| Facade 10 | 0.7 |
| Facade 11 | 0.8 |
| Facade 12 | 0.8 |
| Facade 13 | 0.8 |
| Facade 14 | 0.8 |
| Facade 15 | No window |

### 4.4.3 Façade thickness

The 15 prefabricated façades differ in thickness from each other. The provided thickness that was found in the literature review were all put in figure 10 below. The thickness of a prefabricated façade ought to be taken into consideration when looking at the renovation of the Lineor case because there are various consequences linked to it. For instance, the outdoor surrounding of the building includes a pedestrian path as well as garden area around the building. Therefore, the author's set a limit of 0,4 m for the prefabricated façade thickness, indicated with the green line in figure 10. Any prefabricated façade that exceeds this line will be neglected out of the study as it crosses the limit.

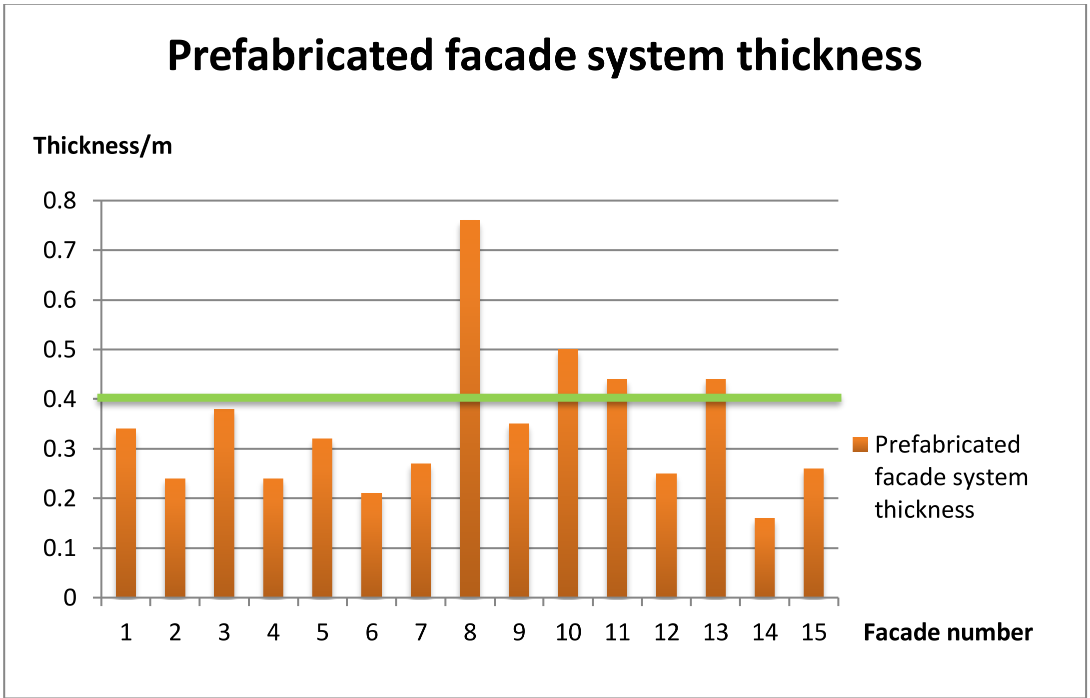



*Figure 10. Shows thickness of the 15 chosen prefabricated facades.*

### 4.4.4 Results of the comparison table

Table 6 a comparison table of the façades for the Linero case. It is an illustration of the findings and the results of the 15 prefabricated façades from the literature review, WUFI calculation and hand calculation.

*Table 6. 15 prefabricated facade comparison table.*

| | **Passive house standards** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Façade U-value <0.15 (W/(m²K))** | | | **Window U-value <0.8 (W/(m²K))** | | | | | |
| | **Facade U-value (W/(m²K))** | | | **Window U-value (W/(m²K))** | **Façade Thickness/m** | **Main structure system** | **Attachable** | **Tested** | **Case study** |
| | **Report** | **WUFI calc.** | **Hand calc.** | | | | | | |
| Facade 1 | <0.15 | 0.095 | 0.088 | 0.8 | 0.34 | Wood | Yes | Yes | Yes |
| Facade 2 | <0.15 | 0.147 | 0.106 | 0.8 | 0.24 | Wood | Yes | Yes | Yes |
| Facade 3 | <0.15 | 0.079 | 0.075 | 0.8 | 0.38 | Wood | Yes | Yes | Yes |
| Facade 4 | <0.15 | 0.084 | 0.075 | 0.7 | 0.24 | Wood | Yes | No | No |
| Facade 5 | <0.15 | 0.091 | 0.095 | 0.8 | 0.32 | Steel | Yes | Yes | Yes |
| Facade 6 | 0.23 | 0.121 | 0.102 | 0.8 | 0.21 | Steel | Yes | Yes | Yes |
| Facade 7 | 0.20 | 0.108 | 0.104 | No window | 0.27 | Steel | No | Yes | Yes |
| Facade 8 | 0.12 | No info | No info | 0.8 | 0.76 | Steel | No | No | Yes |
| Facade 9 | 0.10 | 0.078 | 0.059 | No window | 0.35 | Wood | Yes | Yes | No |
| Facade 10 | 0.11 | 0.306 | 0.177 | 0.7 | 0.5 | Wood | No | Yes | Yes |
| Facade 11 | <0.15 | 0.089 | 0.074 | 0.8 | 0.44 | Wood | No | Yes | Yes |
| Facade 12 | 0.16 | 0.115 | 0.094 | 0.8 | 0.25 | Wood | No | Yes | Yes |
| Facade 13 | 0.10 | 0.083 | 0.072 | 0.8 | 0.44 | Wood | No | Yes | Yes |
| Facade 14 | <0.15 | No info | No info | 0.8 | 0.16 | Wood | No | No | No |
| Facade 15 | 0.16 | No info | No info | No window | 0.26 | Wood | No | No | No |

Table 6 demonstrates which of the prefabricated facades is suitable to meet the specification of the Linero project. Those specifications include the set boundaries based on literature data. The authors rejected prefabricated facades that did not pass to meet the specification and conditions of the Linero project, which are:

- The prefabricated façade should have passive house standard therefore, the façade U-value <0.15 (W/($m^2$K))
- The prefabricated façade should have passive house standard therefore, the window U-value <0.80 (W/($m^2$K))
- The Prefabricated façade should not be more then 0,4 m in thickness that is due to the surrounding of the building such as pedestrian area and gardens around the building
- The main structure system of the prefabricated façade is wood or Steel
- The prefabricated system can be attached onto the Linero case
- Previous data such as case studies of prefabricated facades available

By meeting the criteria mentioned above, the prefabricated façade can be successful for the Linero case.

The façade U-value provided in the literature review was written down for each prefabricated façade that was founded in the European market. Therefore, the authors have set a boundary, which is that the prefabricated façade should have a U-value that is below the passive house standards. The passive house standards contain a U-value that is <0.15 (W/($m^2$K)). That means that any façade containing a U-value above this 0.15 (W/($m^2$K)) will be neglected out of the investigation of the prefabricated façade study such as façades 6, 7, 12 and 15.

The WUFI and hand calculation were studied when the prefabricated façade is attached onto the existing façade. Therefore, the façade U-value was studied and needed to be <0.15 (W/($m^2$K)) to reach the passive house standards. Studying this the results shows that there were prefabricated facades system that showed different result from the literature review such as façade 8 and 14 not to forget is that façade 10 show the U-value above the passive houses standards therefore this three façade are neglected out of the study.

The window U-value are all having the passive house standards and some are even below the passive house standards were the window U-value <0.8 (W/($m^2$K)). There are some prefabricated façades with no windows will be neglected out of the study. As the windows are integrated in the prefabricated façade it is going to reduce the thermal bridges. Therefore, the façades 7, 9 and 15 are neglected out of the study.

The set boundaries for the façade thickness in this part is due to the surrounding of the building. Therefore, the authors have measured at the Linero the measurement of the pedestrian area surrounding the building as well as the gardens around the building. The boundary that was set to 0,4 m to have a clear surrounding and not to make obstacle for the pedestrian area as well as the gardens around. Therefore, façades 8, 10, 11 and 13 are neglected out of the study.

According to the European market wood or steel are the most suitable structure system for the prefabricated façade. For instance, wood, as the main structure system, has low thermal bridges. On the other hand, steel prefabricated façade system has thermal bridges occurring in the prefabricated façade. Therefore, steel wouldn't be suitable for the Linero case. Therefore, the facades 5, 6, 7 and 8 with the steel main structure system are neglected out of the study.

The attachment capability of the prefabricated facades onto the existing façade is an important element to consider and evaluate. After studying each of the 15 prefabricated façades system in detail for their attachment capability, it showed that serval façades are not attachable onto the existing facade. Therefore, façades 7, 8, 10, 11, 12, 13, 14 and 15 are neglected out of the study.

In addition, to guarantee the literature data available is valid, as a result, proven data using case studies for each prefabricated façade. Data on the 15 prefabricated façade was investigated. Some of the prefabricated façade contains case studies, which indicates that the prefabricated façade has been tested. In addition, showing that there is prove of the prefabricated façade been attached onto an existing building façade indicating the building performance as well as the building improvement on thermal comfort. As a result, the façades that lacked information whether they were tested, were neglected from this study, such as façade 4, 8, 9, 14 and 15.

Finally, after comparing all the prefabricated façade based on the calculation and requirement only 3 of the prefabricated façade qualify to meet the requirements for Linero case in Lund. These are façade 1, 2 and 3, as they satisfy all the specification conditions such as the set boundaries applied in table 6.

Façades 1, 2, and 3 meet a good façade U-value with integration of windows with a good performance of the U-value. The façade thickness doesn’t exceed 0,4 m. Its main structure system is wood. It is attachable onto the Linero existing building façade.  facades 1, 2, and 3 were further analysed with more in-depth information in computer simulations and in details drawings of the attachment.

## 4.5 Computer results

The software's below were used for the detail drawings as well as for the simulations of the prefabricated façade system attached onto the existing building façade of the Linero.

Therefore, three softwares were used in the investigation. AutoCAD was used for drawing out the details drawing of the prefabricated façade attached onto the existing building façade. WUFI was used for simulating the moisture diffusion in the multilayer building components, which are exposed to the natural weather conditions. HEAT2 was used for simulating the thermal bridge analysis.

AutoCAD is a computer-aided drawing software used for drawing various construction details. In this case AutoCAD (AUTODESK, 2017) was used for drawing the various parts of the building envelope and the junction between them as well as the site plans. This to illustrate a clear understanding of how the components are connected to each other.

WUFI is a computer software, which allows calculation of the moisture diffusion in multi-layer building components exposed to natural weather. The moisture calculations in WUFI are one-dimensional (Fraunhofer IBP, 2017). In this project WUFI was used to calculate the RH in the exterior facade.

HEAT2 is a thermal analysis software that enables rapid creation of a two-dimensional construction model (Blocon, 2017). In this project HEAT2 was used for calculating the thermal performance of the various parts of the building envelope as well as calculating the thermal bridges.

### 4.5.1 Façade detail drawing analysis with AutoCAD

The drawings below will illustrate the attachment of the 3 prefabricated façades onto the existing building façade that have passed the comparison table, table 6.

In AutoCAD drawings, the existing building façade is marked with a black colour while the blue colour represents the prefabricated façade. The red colour represents the details illustrating the attachment/fixture and structure system. the green colour represents the details illustrating the steel L-brackets that are placed below the prefabricated façade elements.

The detail drawings clarify the insulation material that each prefabricated façade consists of as well as the type of window that has been used in the prefabricated elements. Moreover, the drawing illustrates clear details of the attachment of the prefabricated façade onto the existing façade, which is the load bearing structure system of the building.

#### 4.5.1.1 TES attachment drawings

The TES prefabricated façade is represented below in figure 11 indicating all the materials and thicknesses as well as the U-value of the façade and Window and the attachment onto the existing building façade. The TES prefabricated façade has a total thickness of 340mm that doesn't include the existing façade, which has a total thickness of 280mm. The U-value of the prefabricated façade attached onto the existing building façade has a U-value of 0.094W/m$^2$K. The prefabricated façade contains the fixation, main studs and beams, integration of the windows and its location in the façade elements. The window from the prefabricated façade fits onto the opening of the existing building façade. The glass used in the TES prefabricated façade contains a triple glass window with a 36mm krypton gas fill, which provides a U-value of 0.5W/m$^2$K. The exterior cladding layer of the TES prefabricated façade consists of exterior plaster of 4 layers.

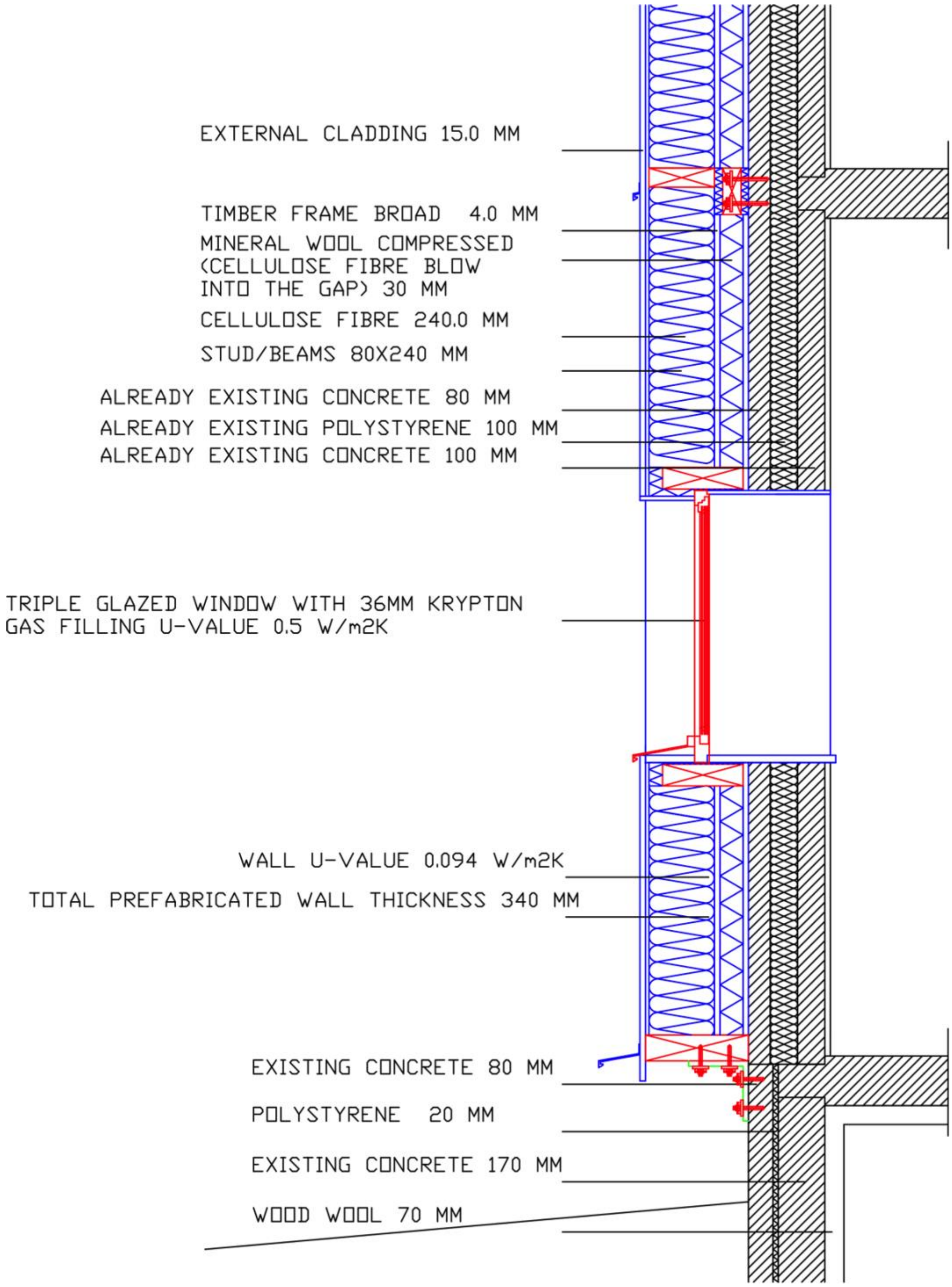



*Figure 11. Detail drawing of the TES prefabricated facade attached onto the existing building facade with the materials labelling and the U-value of the window and facade.*

#### *4.5.1.1.1 Attachment or fixation*

The attachment of the TES façade onto the existing façade contains the steel brackets that are located at the bottom of the prefabricated façade. The steel L-bracket, which is illustrated in (green) colour in figure 12. The (red) colour illustrates screws that are fixed at the bottom of the prefabricated façade and into the existing building façade.

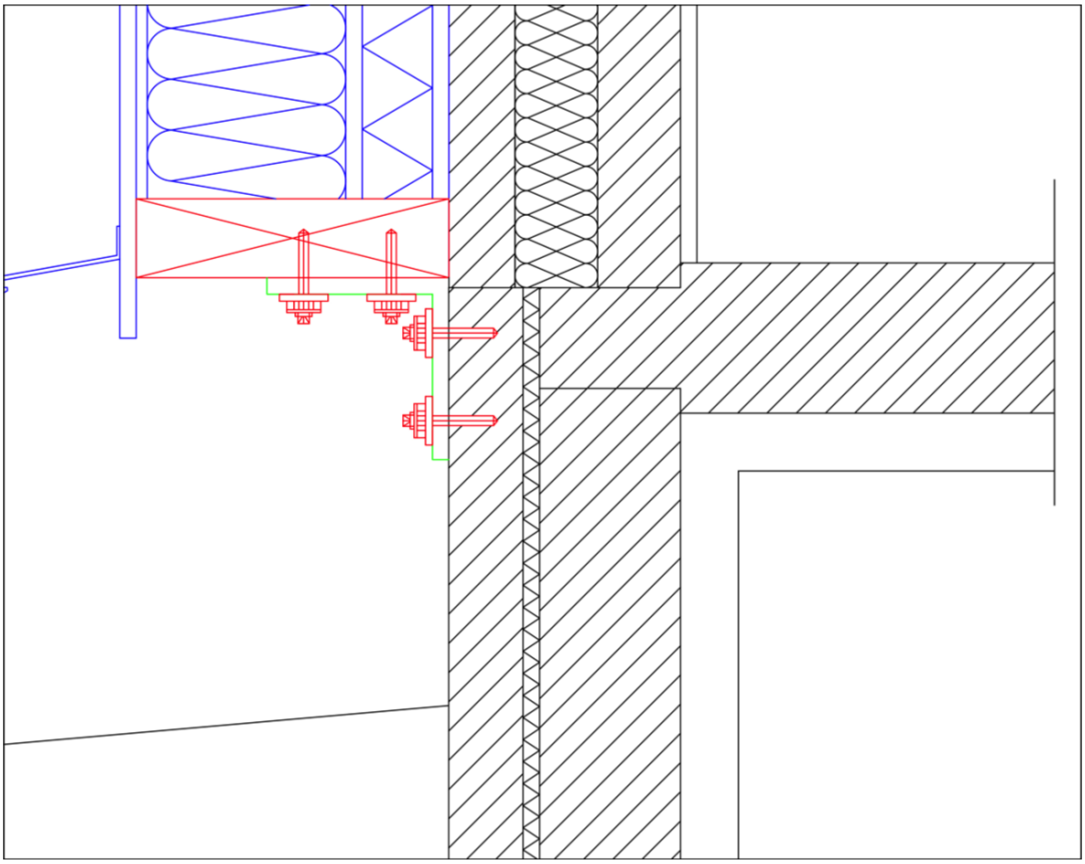


*Figure 12. L-bracketing at lower part of the prefabricated facade that is fixed onto the existing building facade and carrying the TES prefabricated facade element.*

### *4.5.1.1.2 Window integration*

The windows are integrated in the prefabricated façade and are fixed during the manufacturing process. The areas around the windows are sealed against thermal bridges. The windows are mainly located in between the studs and fixed to the main structure system of the prefabricated façade. This is illustrated in figure 13 where a detail drawing shows the location of studs and beams in (red) colour.

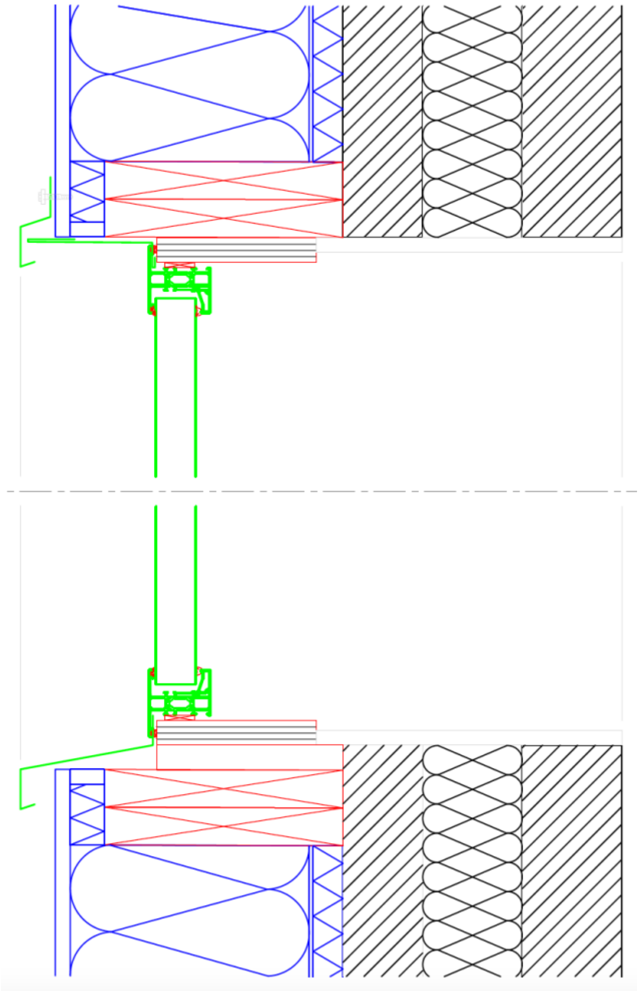


*Figure 13. Detail drawing of the window location in the prefabricated TES facade element.*

#### 4.5.1.1.3 Fixation at the slab

The fixations at the slabs are the areas where the two panels are joined tighter with each other and are laying on top of each other, which can be seen in figure 14. The fixation for the prefabricated façade panels are fixed onto the slab. The wood studs are fixed and then the surrounding area around it is filled with cellulose or mineral wool insulation material to prevent it from thermal bridges. After that is done the second panel is placed on top of the other prefabricated façade element.

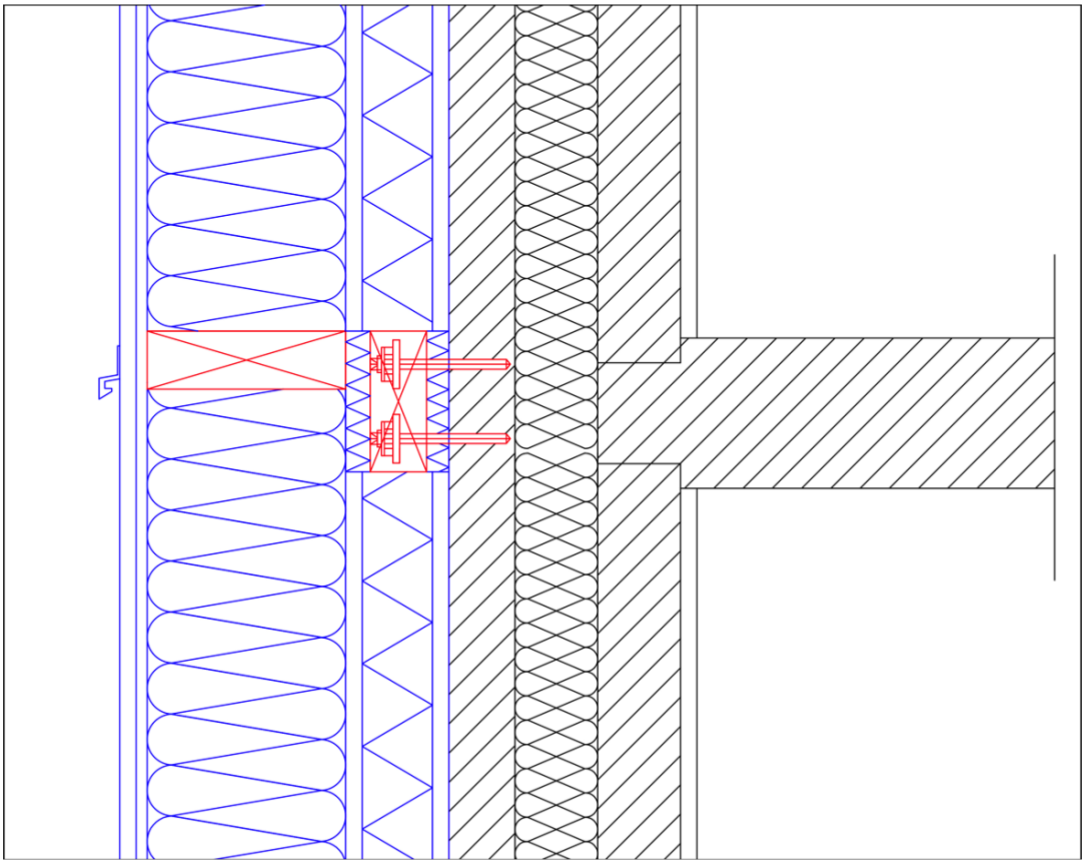


*Figure 14. Detail drawing of attachment at the floor slab were the prefabricated facade is attached onto the existing building facade.*

### 4.5.1.2 Multi-active attachment drawings

The Multi-active prefabricated façade is represented below in figure 15 indicating all the materials and thicknesses as well as the U-value of the façade and Window and the attachment onto the existing building façade. The Multi-active prefabricated façade has a total thickness of 240mm and that does not include the existing façade, which has a total thickness of 280mm. The U-value of the prefabricated façade attached onto the existing building façade has a U-value of 0.139 W/($m^2$K). The prefabricated façade contains the fixation, main studs and beams, integration of the windows and its location in the façade elements. The window from the prefabricated façade fits onto the opening of the existing building façade. The glass used in the Multi-active prefabricated façade contains triple glazed with krypton gas filling, which provides a U-value of 0.85 W/($m^2$K). The exterior layer of Multi-Active prefabricated façade consists of a toughened safety glass is with a thickness of 6mm.

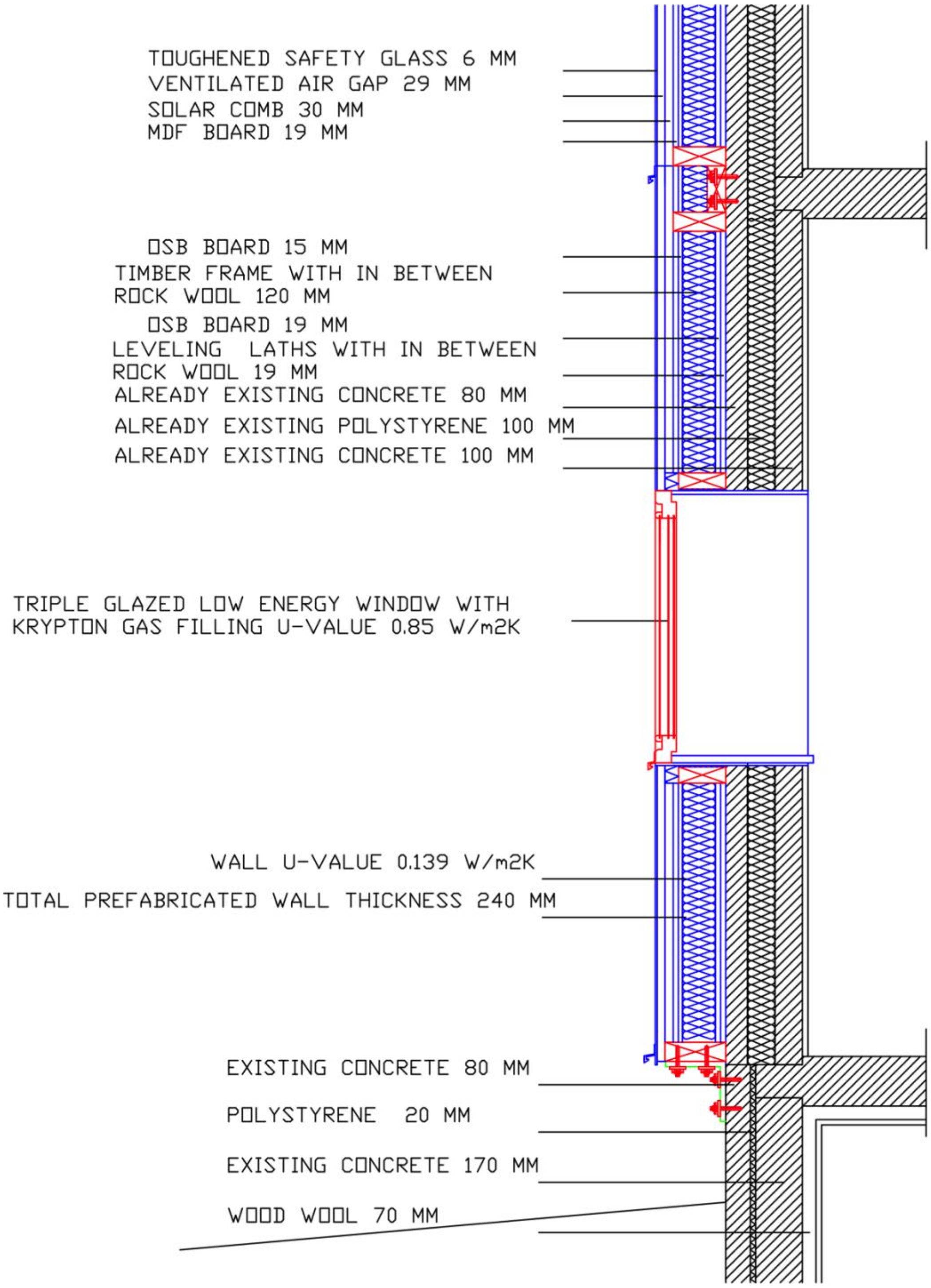



*Figure 15. Detail drawing of the Multi-active Prefabricated facade attached onto the existing building facade with the materials labelling and the U-value of the window and facade.*

#### *4.5.1.2.1 Attachment or fixation*

The attachment of the Multi-active façade onto the existing façade are made by the steel L-brackets that are located at the bottom of the prefabricated façade. The steel L-bracket has a (green) colour been illustrated in figure 16. The (red) colour illustrates the screws that are fixed at the bottom of the prefabricated façade and into the existing façade.

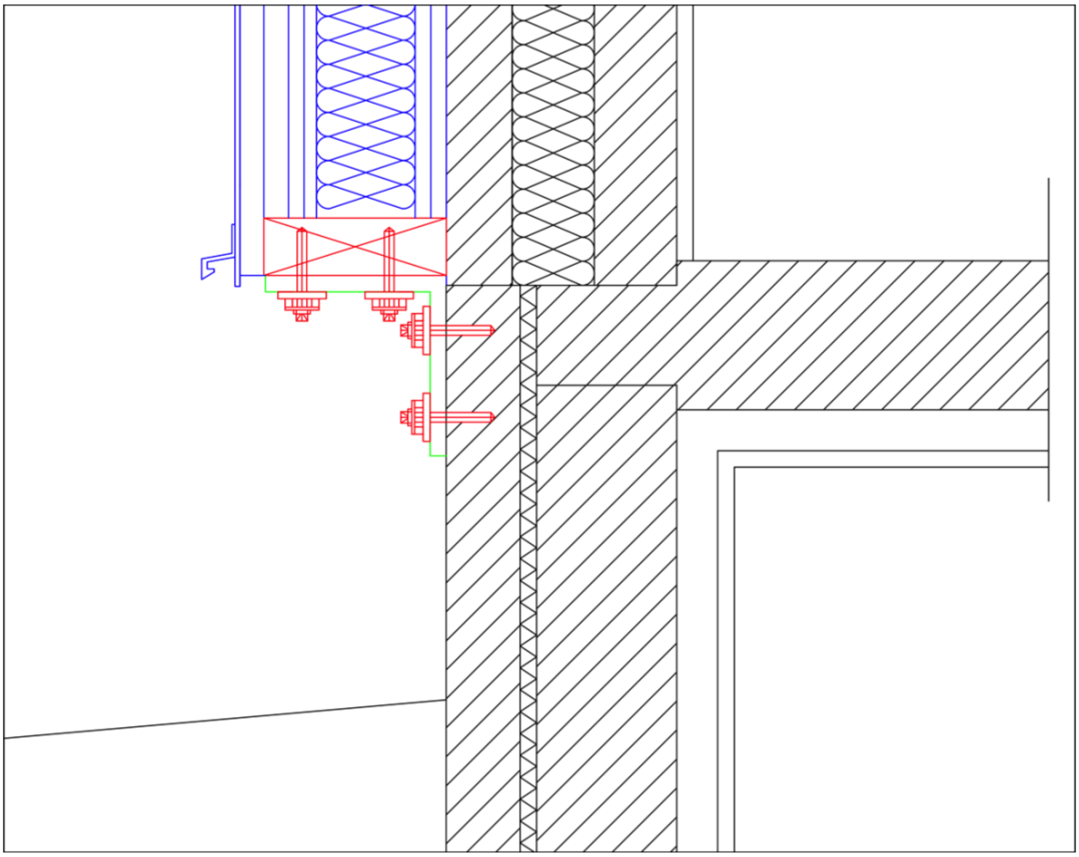


*Figure 16. L-brackets are placed at the lower part of the prefabricated faced that is fixed onto the existing building facade and are carrying the Multi-active prefabricated facade element.*

#### 4.5.1.2.2 *Window integration*

The windows are integrated in the prefabricated façade and are fixed during the manufacturing process. The areas around the windows are well-sealed against thermal bridges. The windows are mainly located in the external layer of the façade where they are fixed into the façade with the aluminium frame. This is well sealed and airtight will protect the façade from thermal bridges. This is illustrated in figure 17 for further detail in the detail drawing.

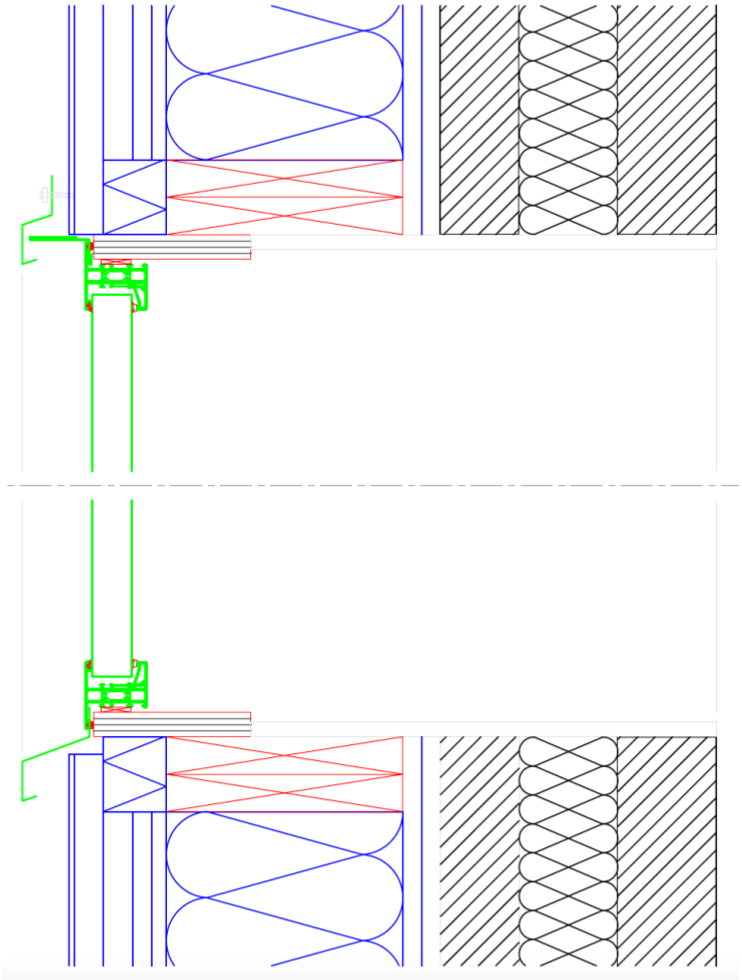


*Figure 17. Detail drawing of the window location in the prefabricated Multi-active facade element.*

#### *4.5.1.2.3 Fixation at the slab*

This prefabricated façade panel is fixed directly onto the slab see in figure 18 below in the detail drawing. The wood studs are placed first and then the surrounding area are filled with cellulose or mineral wool insulation material to prevent it from thermal bridges. Secondly, the second panel is placed on top of the other prefabricated façade element.

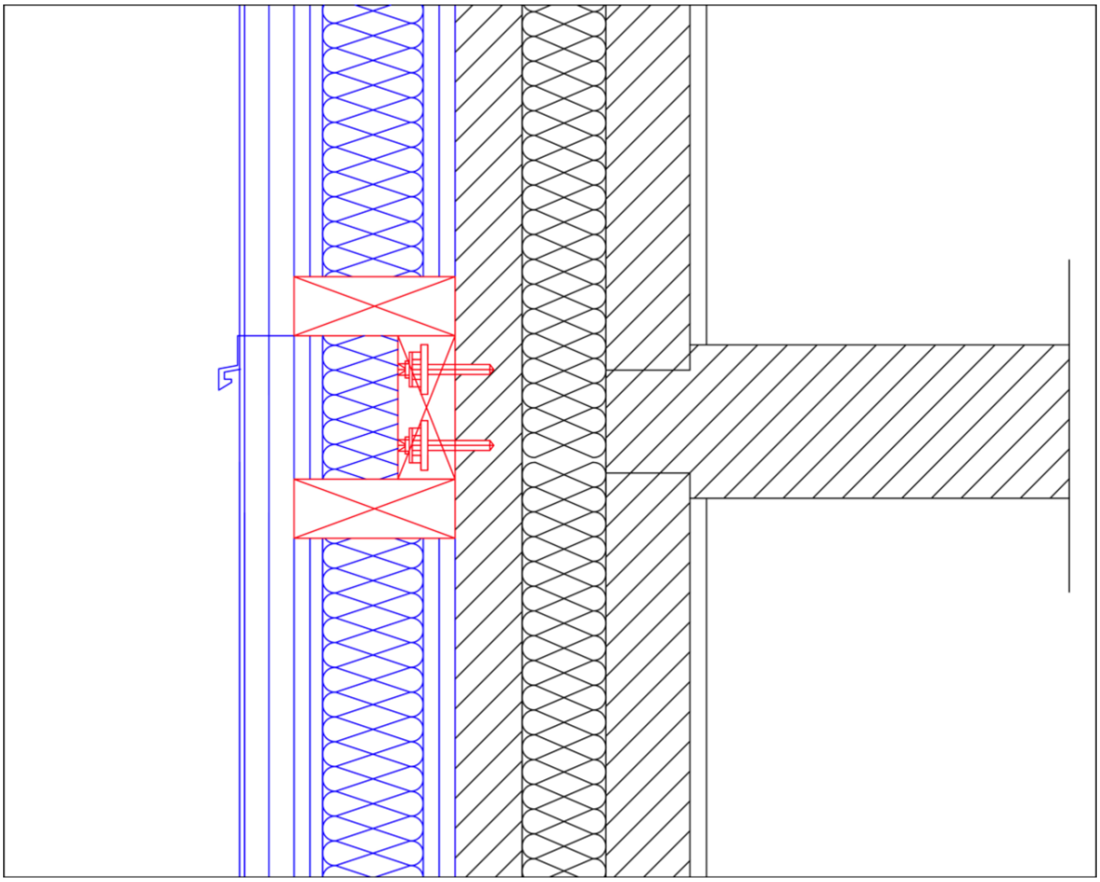


*Figure 18. Detail drawing of attachment at the floor slab where the prefabricated facade is attached onto the existing building facade.*

### 4.5.1.3 Alingsås attachment drawings

The Alingsås prefabricated façade is represented below in figure 15 indicating all the materials and thickness as well as the U-value of the façade and Window and the attachment onto the existing building façade. The Alingsås prefabricate façade has a total thickness of 375mm. The 375mm does not include the existing façade, which has a total thickness of 280mm. The U-value of the prefabricated façade attached onto the existing building façade has a U-value of 0.091 W/(m$^2$K). The prefabricated façade contains the fixation, main studs and beams, integration of the windows and its location in the façade elements. The window from the prefabricated façade fits onto the opening of the existing building façade. The prefabricated façade has a triple glazed window that contains krypton gas, which provides a U-value of 0.85 W/(m$^2$K). The exterior cladding layer of the Alingsås consists of a brick cladding with a thickness 20mm.

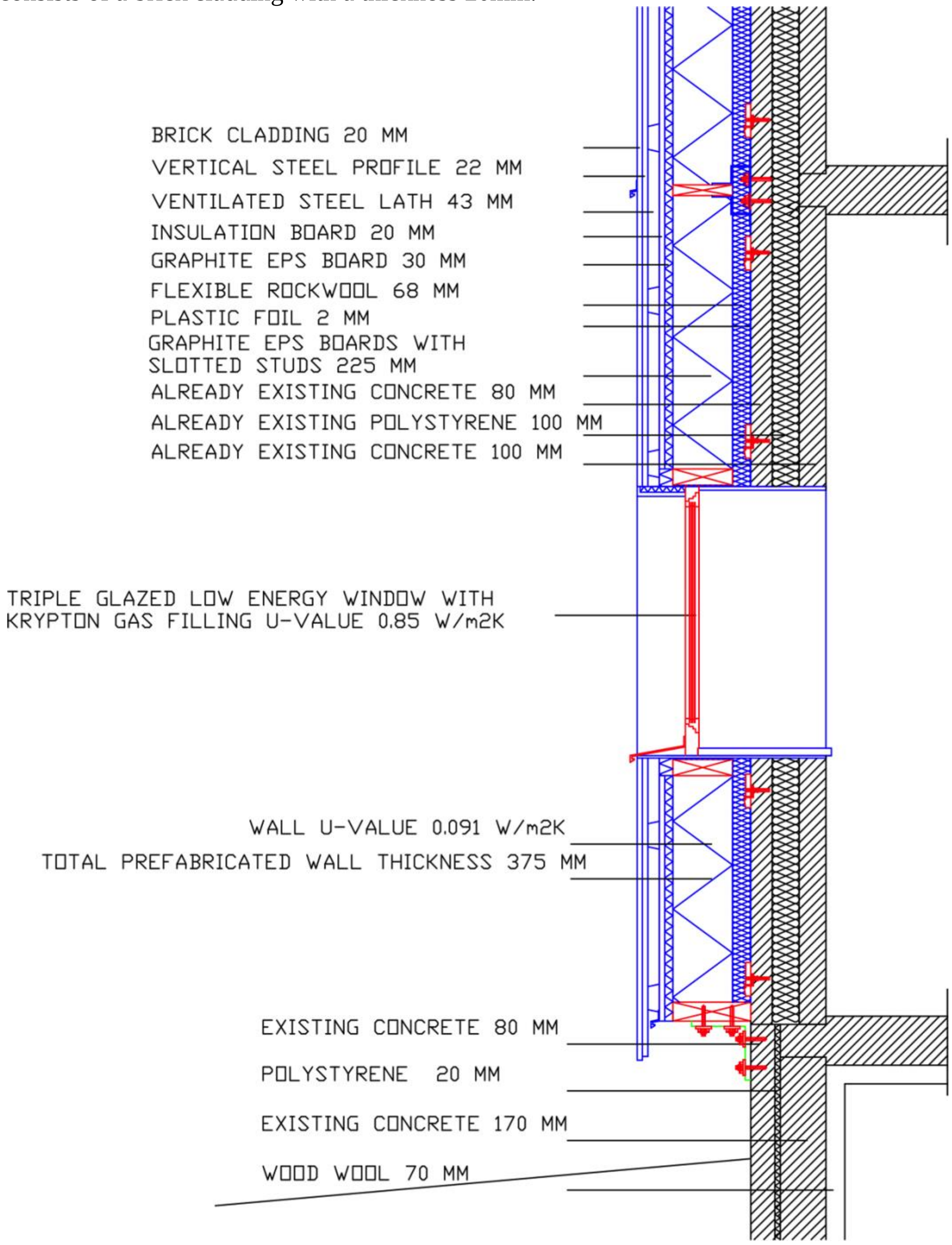



*Figure 19. Detail drawing of the Alingsås prefabricated facade attached onto the existing building facade with the materials labelling and the U-value of the window and facade.*

### *4.5.1.3.1 Attachment or fixation*

To be able to attach the Alingsås façade onto the existing façade, a steel L-bracket located at the bottom of the prefabricated façade was crucial. The steel L-bracket has a (green) colour is illustrated in figure 20. The (red) colour illustrates the screws that are fixed at the bottom of the prefabricated façade and into the existing façade.

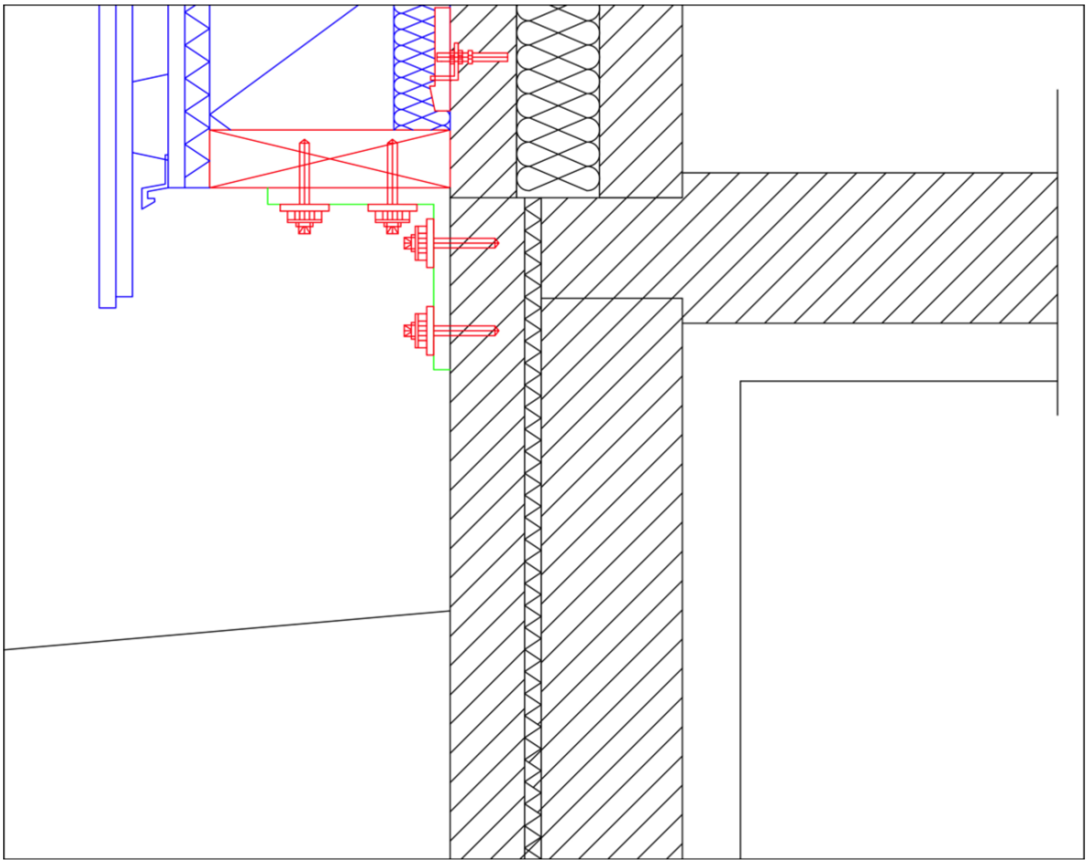


*Figure 20. L-bracketing at lower part of the prefabricated facade that is fixed onto the existing building facade and carrying the Alingsås prefabricated facade element.*

#### *4.5.1.3.2 Window integration*

The windows are integrated in the prefabricated façade and are fixed during the manufacturing process. The areas around the windows are well-sealed against thermal bridges. The windows are located in the middle of the prefabricated façade. The window is fixed to the studs, which are the main structure system of the prefabricated façade. This is illustrated in figure 21 for further detail below in the detail drawing.

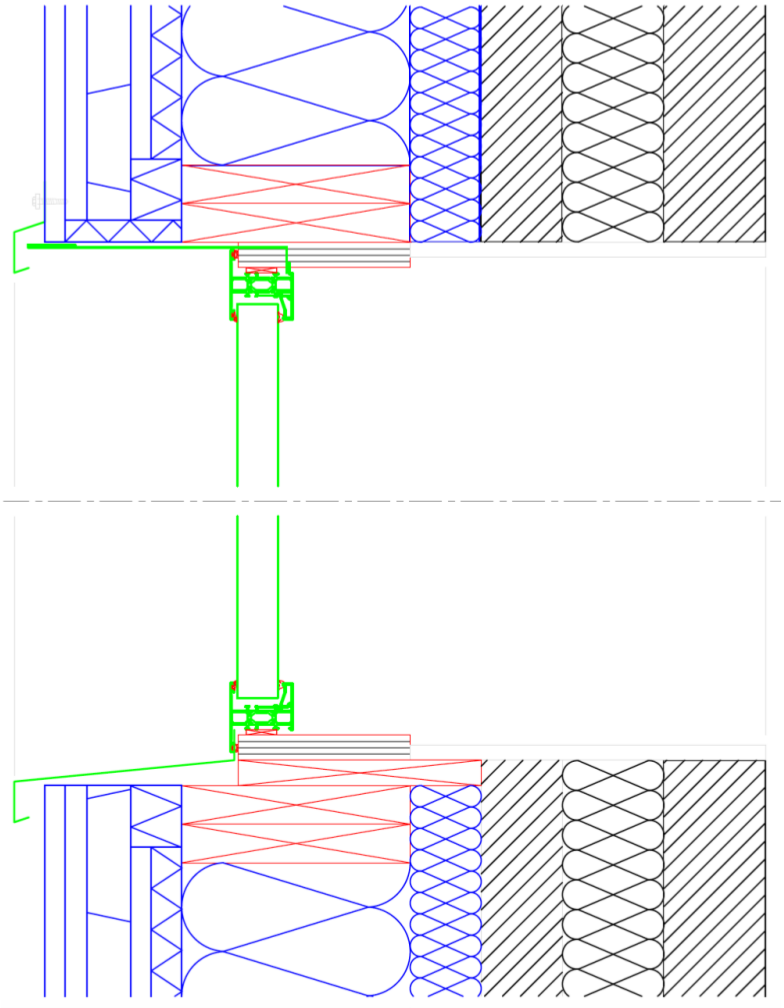


*Figure 21. Detail drawing of the window location in the prefabricated Alingsås facade element.*

### *4.5.1.3.3 Fixation at the slab*

This prefabricated façade panel is fixed directly onto the slab see in figure 22 below in the detail drawing. The prefabricated façade is fixed onto the façade with a steel plate, which is connected to the prefabricated facade. The surrounding area is then filled with cellulose insulation material or mineral wool to prevent it from thermal bridges. Secondly, the second panel is placed on top of the other prefabricated façade element.

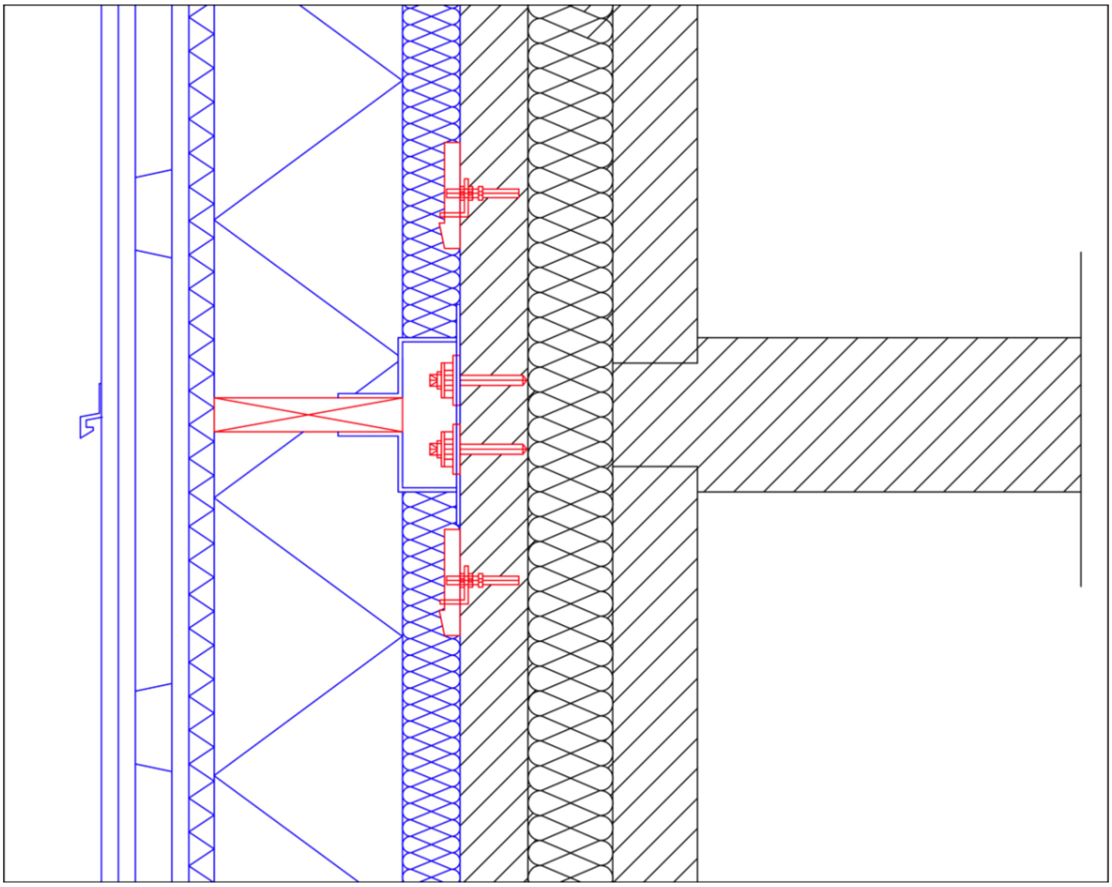


*Figure 22. Detail drawing of attachment at the floor slab where the prefabricated facade is attached onto the existing building facade.*

### 4.5.2 WUFI input

#### 4.5.2.1 Outdoor climate conditions

The weather simulation data file used in the program was set at the climate of Lund, file EN15026. The simulation period was carried out for a ten-year period, the date of the simulation took place from the 1st of January 2017 to the 1st of January 2027 and the time step was set for every hour. The initial RH was assumed to be 60% and the initial temperature was 20 °C.

Figure 23 below explains the temperature and the RH of the Lund location according to the weather file data. The temperature variation is shown by the red line in the first graph. The blue line in the second graph explains the RH. The highest temperature reached in Lund in the WUFI program is around 30 °C; the coldest attainable temperature is around -10 °C. Higher temperatures give a lower RH and vice-versa. The graph clarifies the relationship between the RH and temperature. The average RH is high even though the temperatures were never extremely cold.

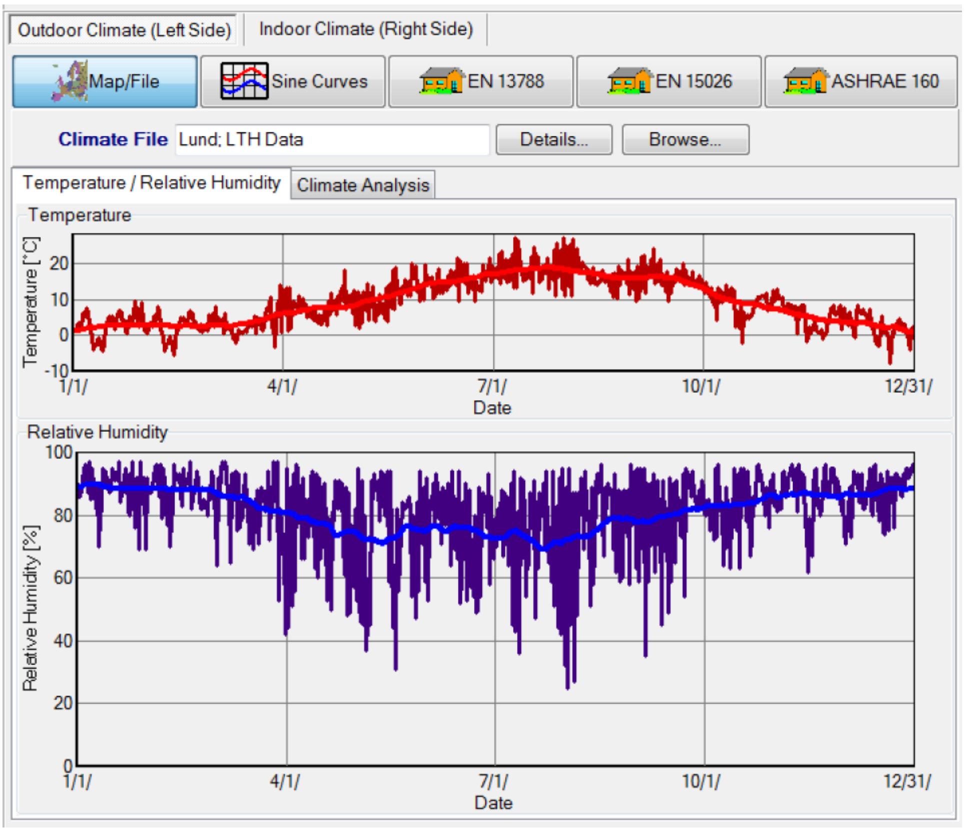



*Figure 23. The image illustrates the yearly temperature and RH for the outdoor climate condition. (Source: WUFI input data).*

### 4.5.2.2 Indoor climate conditions

Figure 24 shows the indoor climate data. The file used in the program was set at the climate of Lund, EN 15026. Figure 24 below illustrates the temperature of the indoor environment as well as the RH ranges from 30% to 60 %. The indoor temperature ranges from 20 °C to 25 °C. These settings were used for all the prefabricated façade systems that were analysed in WUFI.

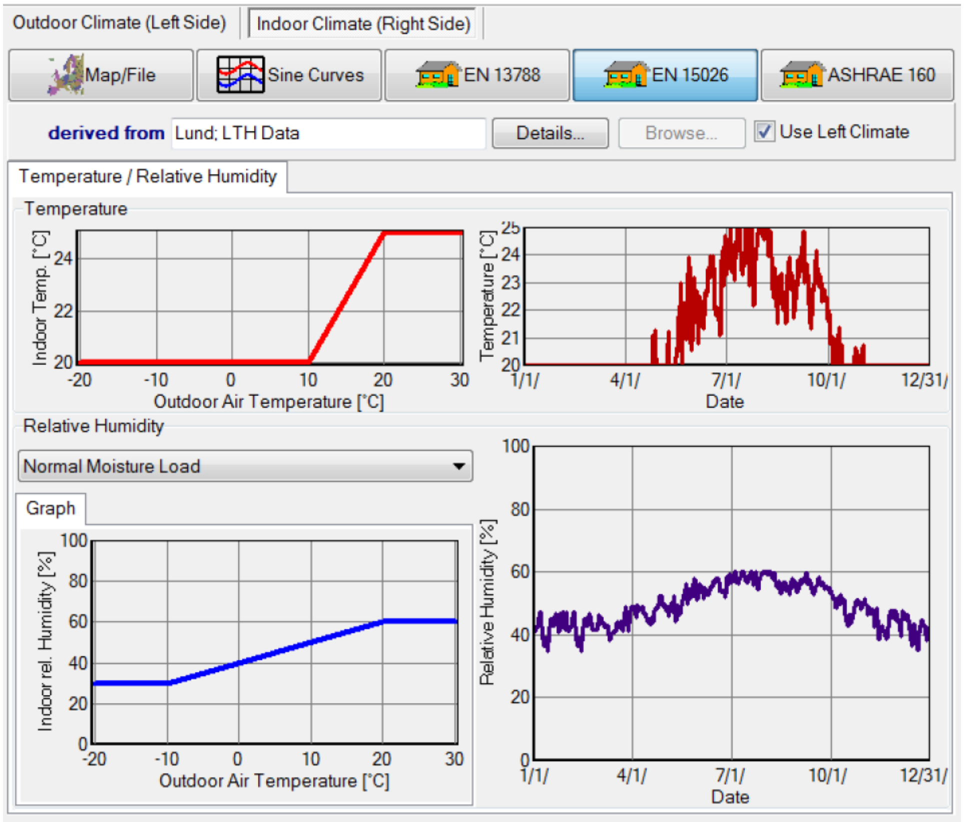



*Figure 24. The images illustrate the temperature and RH for the indoor climate conditions. (Source: WUFI input data).*

#### 4.5.2.3 Orientation and surrounding conditions

The orientation of the building was set to southwest because that is the orientation for the wind driven rain; known as the worst-case scenario for Lund, Sweden.

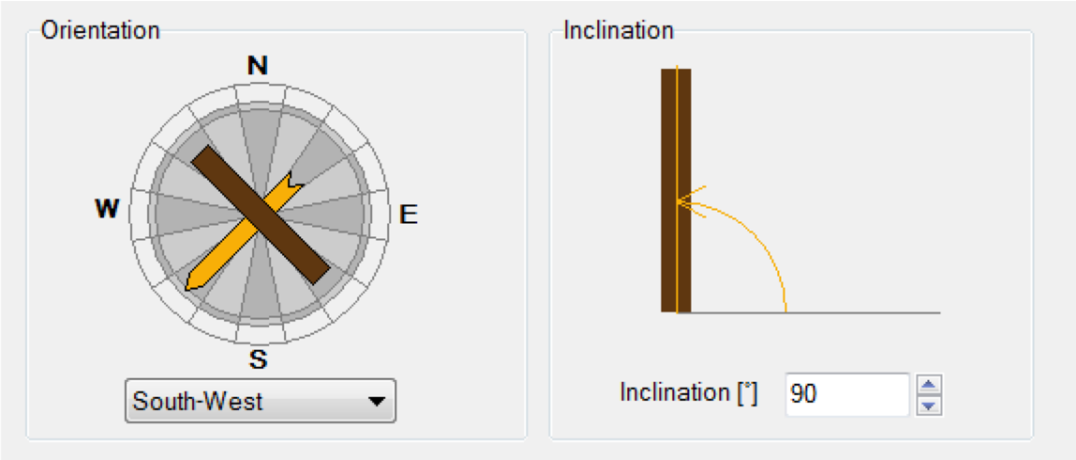



*Figure 25. The images illustrate the orientation for the worst case with wind-driven rain, which has orientation southwest and the inclination of the facade that has an angle of 90 degrees. (Source: WUFI input data).*

#### 4.5.2.4 WUFI Output

The WUFI simulations were carried out and data was received from where the monitors were located for measuring the temperature and the RH. Of note, the monitoring points lie within the insulation and not at the wooden studs. These monitors were placed at different material locations and different depths inside the prefabricated façade envelope to observe and understand what is happening inside the prefabricated façades envelope; specifically, how the temperature and RH passes through the materials inside the prefabricated façade as well as the existing building facade. Below are some tools that were used to get the final moisture results for each façade.

**Analysis tools**

The analysing tool that validates the prefabricated façade is used with the help of the WUFI simulation software. WUFI showed the investigation of how climate can affect the prefabricated façade and causes the risk of mould to growth (Olof Mundt-Petersen, 2015).

**WUFI model limitations**

It is a calculation tool that takes into consideration the measurements of the numerical and a physical model that is designed in the program. Therefore, errors were not taken into consideration, but the WUFI software may have created some of the errors in the calculation of the physical model (Olof Mundt-Petersen, 2015)

**WUFI calculation models**

The calculations in the WUFI software were focused on Moisture and mould growth. In the WUFI calculation model, the studs and beams are ignored in the one-dimensional calculation process. The one-dimensional calculation also yields the impact of the initial construction moisture (Olof Mundt-Petersen, 2015).

**Materials parameters used in the WUFI calculations**

The material database provided in the WUFI software has most of the materials with material properties. The material database limit is the hydrothermal calculation part in the software. The hydrothermal calculation deals with different materials properties throughout the calculation process, such as using one sorption curve for each material (Fraunhofer IBP, 2017); (Olof Mundt-Petersen, 2013).

**Climate and initial and boundary conditions used in the WUFI calculations**

The software provides a climatic database; for instance, there are different types of climate data files such as the European standards or the USA standards. For this study the European standards data file was used to represent the Lund weather climate. This was used in the simulation of the three prefabricated façades. The climate database takes into consideration the two types of climate data, which are the indoor and outdoor climate data.

**Important factors affecting the risk of moisture**

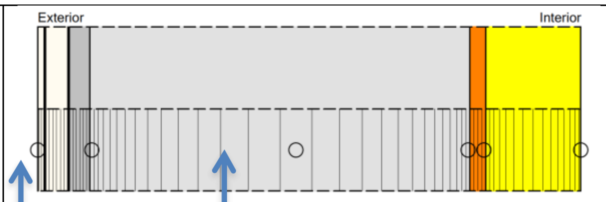
These parts show the further illustration of locations were monitors of WUFI simulations were placed in the prefabricated façade to observe the moisture risk. The results of this study illustrate the monitor position in relation to temperature and relative humidity. The graphs show the explanation of how temperature and RH act with each other on a vice versa relation.

### 4.5.2.5 Façade WUFI analysis

The advantages of doing a WUFI simulation is to estimate the factors affecting the moisture safety and the risk of moisture or linked damage that might occur inside the prefabricated façade. Therefore, calculations were done to measure the one-dimensional transient heat and moisture. The software contains a material and climate database where the boundary conditions are retrieved from the calculation tool.

The locations that were investigated, where monitors were placed, in the simulation program are at the insulation layer and not at the wooden studs and beams of the prefabricated façade element. All the WUFI simulations were executed. The results of the TES, Multi-active and Alingsås prefabricated facades for the Linero project were obtained from the WUFI analysis and subsequently compared with each other. Of note, the WUFI analysis was executed where the prefabricated facades were attached onto the existing building façade.

### 4.5.2.6 TES façade




| Risk of moisture at the following monitors |
| --- |
| Exterior monitor |
| Monitor 1 |
| Monitor 2 |
| |

The picture above shows the TES façade. The different colours mark each material layer in the façade. The small circles represent the monitors' location for investigating the temperature and RH in the insulation materials. Monitor 1 is located at the beginning of the cellulose insulation material. Monitor 2 is located at the centre of the cellulose insulation material. The circles located at the outermost layer of both exterior and interior side of the prefabricated wall are placed by default in the program and are therefore neglected.

**Monitor 1**

The results of monitor 1 in TES prefabricated façade are displayed in figure 26. Below are the graphs of the monitor position in relation to temperature and relative humidity.

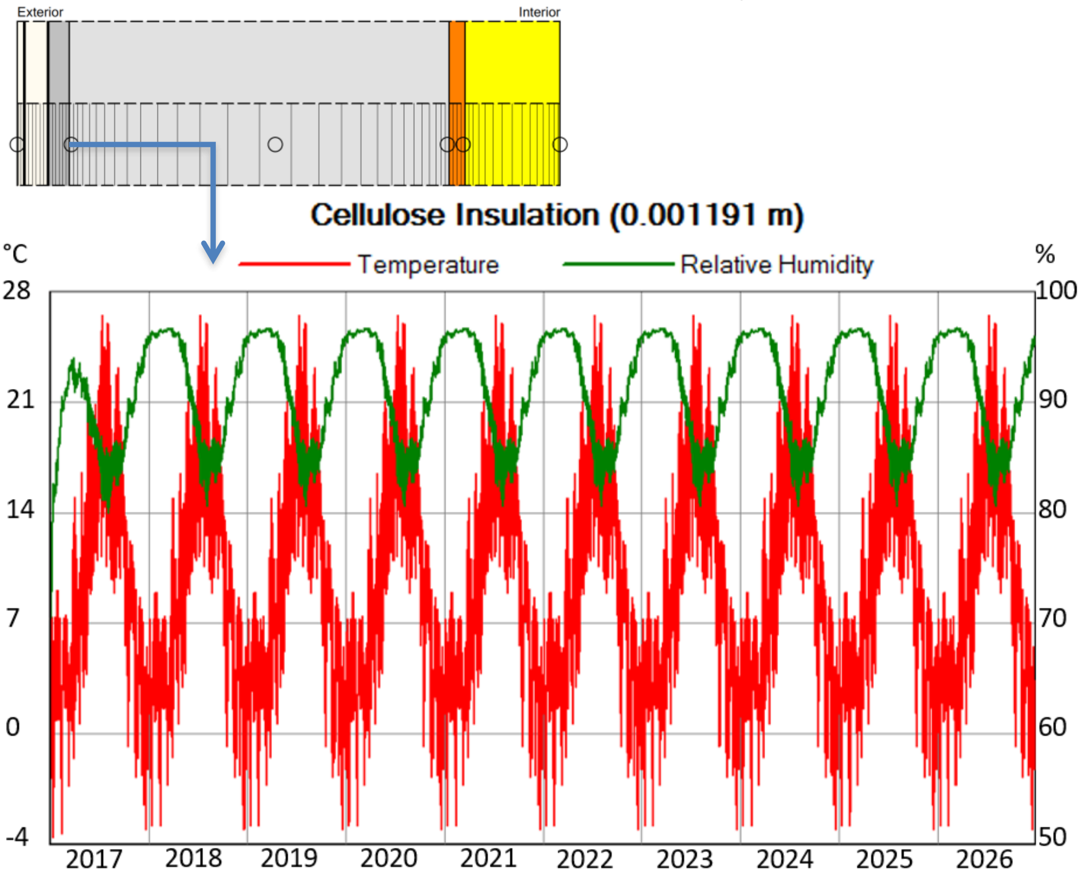



*Figure 26. The graph above shows that the RH is above 95% when the temperature is ranging from -4 till 26 °C.*

The graph in figure 26 for monitor 1 illustrates RH, which is the green line, and it is above 90%. This indicates that the water content in the insulation material is high at this point. The specific location of monitor 1 is interesting because it is situated near the outer surface of the prefabricated façade. This can give information on the rain penetration performace. Meanwhile, the exterior side of the TES prefabricated façade has been treated with plastered exterior cladding. The porosity and water absorption rates of the common plaster are 18% and 9.4%, thus the absorption of water from the exterior layer of the TES prefabricated façade is within accepted range (GÖRHAN & KÜRKLÜ, 2018).

The cold and warm weather could affect the RH. In winter periods the RH is at 95% and at the RH during summer periods is at 85%. When spring and summer seasons commence, the temperature rise above 20°C and the water content in the outdoor climate is reduced; as a result, the RH reaches around 80% to 85%. This RH is high and it indicates that the location of monitor 1 in the prefabricated façade might have a risk for mould growth. This indicates that the moisture in the insulation layer might be a problem. In addition, the high RH causes a higher leakage and therfore it results in a low insulation resistance value.

**Monitor 2**

The results of monitor 2 in TES prefabricated façade are displayed in figure 27. Below are the graphs with the monitor position in relation to temperature and relative humidity.

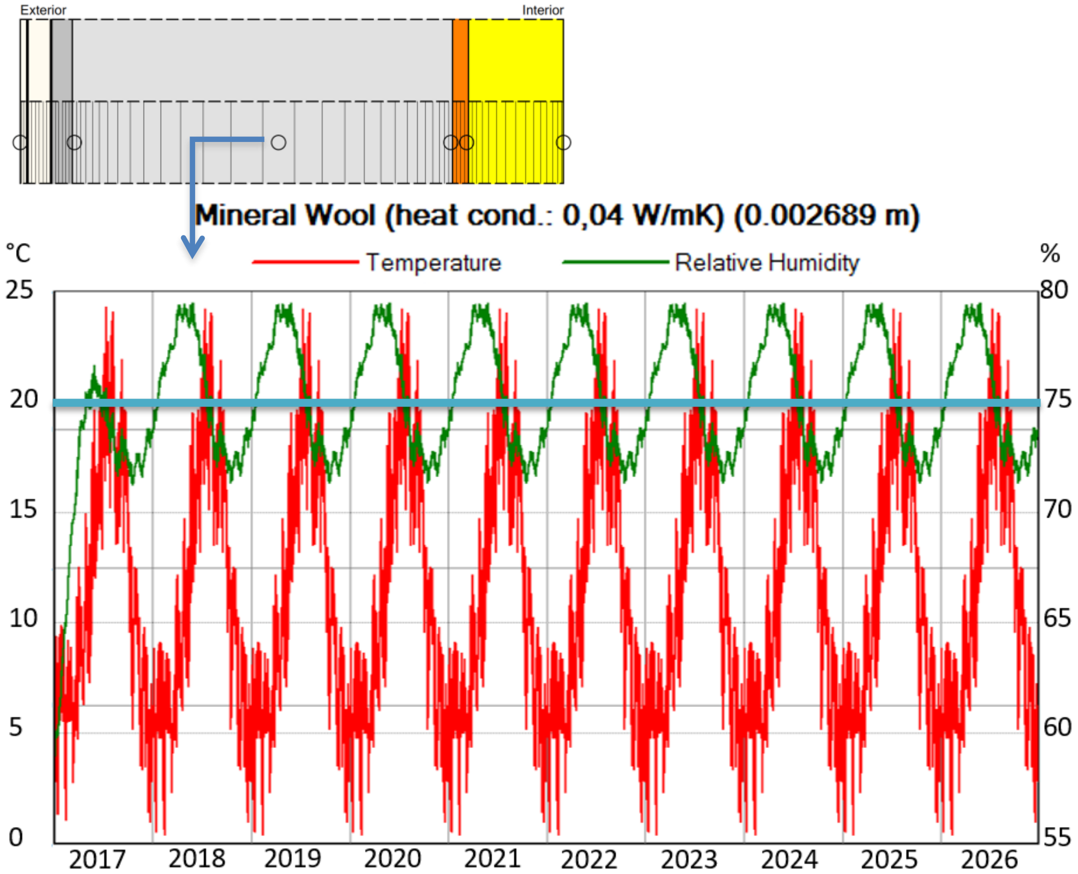



*Figure 27. The RH percentage dropped at the centre of the cellulose insulation material and is now below 80%.*

The graph in figure 27 for monitor 2 illustrates a blue line to represent the RH at 75%. The RH reaches above the 75% during the winter period but it does not reach 80% RH, thus this shows that there is no risk for mould growth. The specific location of monitor 2 is interesting because it is situated at the center of the insulation material in the prefabricated façade This can give information on the RH performance and whether it improves compared to the performance at monitor 1 location. On the other hand, spring and summer seasons have a RH that reaches around 72% to 74%. This means that there is no risk for mould growth happening in the insulation material at the location of monitor 2. When the RH is below the 80%, it will have a lower the risk for mould to occur. Therefore, the RH is a critical factor for an ideal condition of the prefabricated façade and its performance during not only winter seasons but also spring and summer seasons. Furthermore, the RH depends on temperature; therefore, conditions with a high temperature will yield a low value for RH and vice versa.

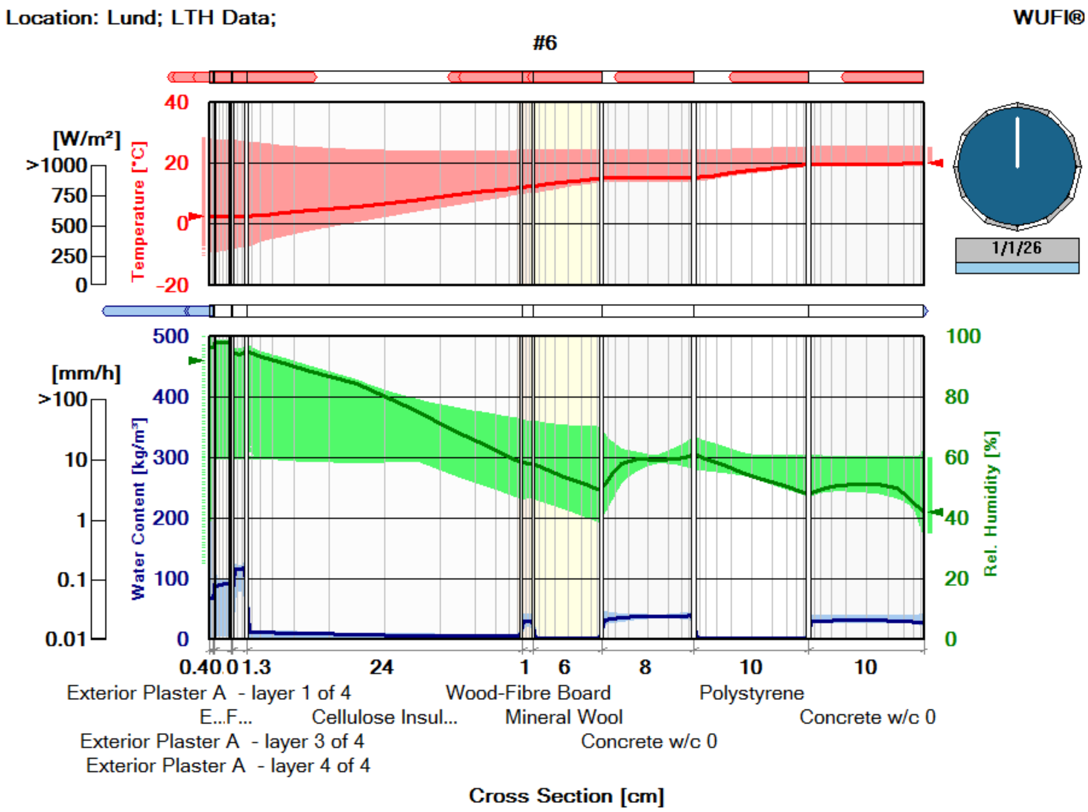
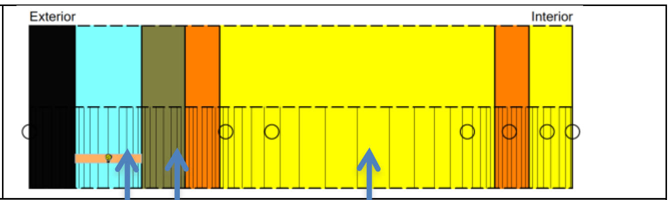



*Figure 28. WUFI analysis animation illustrate the hourly simulation for the Temperature, RH and water content through different material layers over time for the TES façade.*

The graph in figure 28 illustrates the calculations for moisture and heat flow, which is an hour-by-hour calculation. The graph at the top, with red colour, illustrates the temperature performance throughout the prefabricated façade as well as the existing façade. The temperature performance is different between the outdoor on the left side of the graph and the indoor represented on the right side of the graph. The red line that passes through is the temperature at a particular hour of the simulation. The spread of temperature on the y-axis represents the extreme conditions of both winter and summer seasons.

The simulation software indicates high RH. This occurs at monitor 1 when the RH is above the 80%, and this is located at the cellulose insulation material. The moisture decreases when moving towards the interior side of the prefabricated facade. Monitor 2 supports this notion, as it shows an improvement on the RH performance that is decreased compared to the data of monitor 1. Therefore, the risk of mould growth decreases in the prefabricated façade from the exterior side towards the interior side.

### 4.5.2.7 Multi-active façade




| Risk of moisture at the following monitors |
|---|
| Exterior monitor |
| Monitor 1 |
| Monitor 2 |
| Monitor 3 |
| |

The picture above shows the Multi-active façade. The different colours mark each material layer in the façade. The small circles represent the monitors' location to investigate the temperature and RH in the insulation materials. In addition, the picture shows an orange horizontal line in the second material layer with a turquoise colour. This line represents the sun source that is added in the program for the solar comb material (Gönülol, 2016).

The simulation software indicates that there might be a risk for high RH that occurs only at monitor 1at the mineral wool insulation layer. Monitors 2 and 3 have a RH below 75%; as a result, there is no risk for moisture problem and for mould growth. This is due to solar comb material that heats up the material of the prefabricated façade, thus it reduces the moisture content in the prefabricated façade system.

The locations that were investigated in the simulation programme are at insulation material of the prefabricated façade element. The circles located at the outermost layer of both exterior and interior side of the prefabricated wall are placed by default in the program and are therefore neglected.

**Monitor 1**

The results of monitor 1 in Multi-Active prefabricated façade are displayed in figure 29. Below are the graphs with the monitor position in relation to temperature and relative humidity.

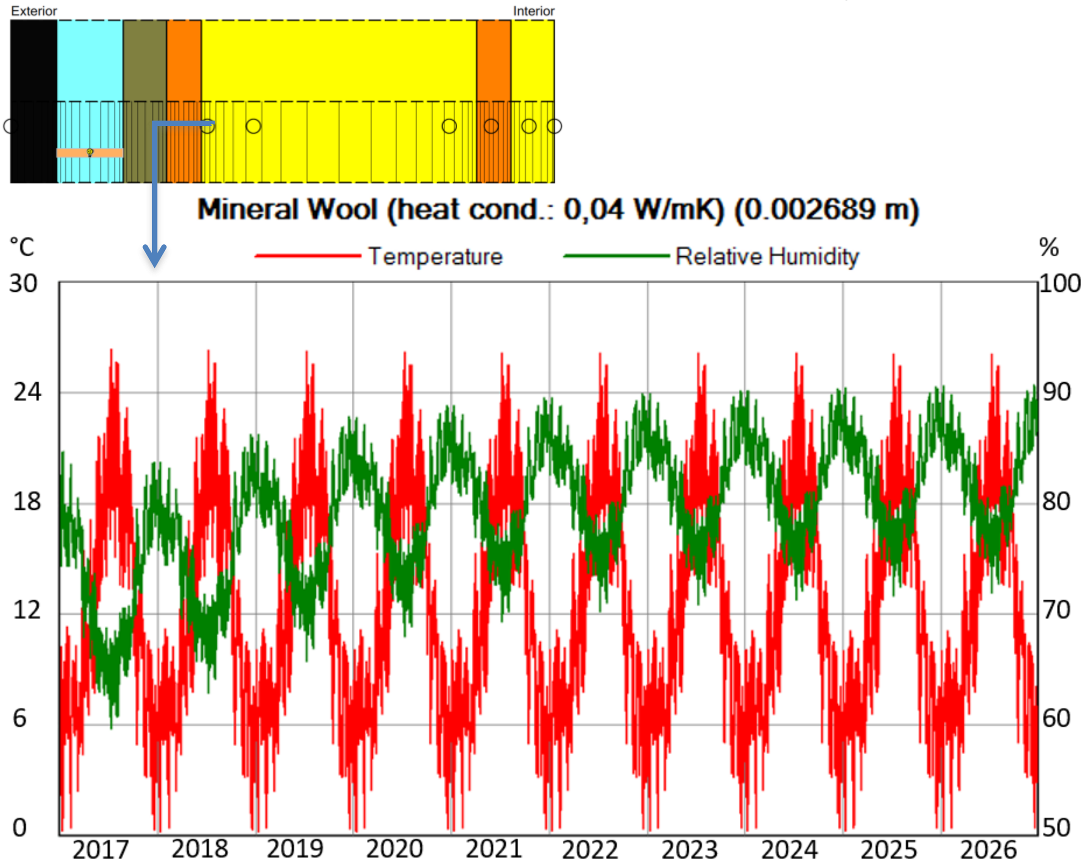



*Figure 29. The location of the monitor is placed at the beginning of the mineral wool insulation material. RH increases slightly over the years but only at the beginning of the layer. The RH can vary as the special comb layer only works when the sun is present.*

The graph in figure 29 monitor 1 illustrates RH, which is the green line, and it reaches between 75% to 90%. This indicates that there might be a risk for moisture problems. The specific location of monitor 1 is interesting because it is situated near the outer surface of the prefabricated façade. This can give information on the rain penetration performace. Meanwhile, the exterior side of the Mutli-active prefabricated façade has been treated with toughened safety glass exterior cladding. The porosity and water absorption rates of the common toughened safety glass are waterproof, thus the absorption of water from the exterior layer of the Multi-active prefabricated façade is zero (Wiederhorn et al., 2011).

The cold and warm weather could affect the RH. In winter periods the RH is 90% and the RH during summer periods is at 72% to 77%. The summer period has no risk for mold growth due to the low RH and high temperature. On the other hand, a high RH could indicate that the location of monitor 1 in the prefabricated façade might have a risk for mould growth. This indicates that the moisture in the insulation layer might be a problem. In addition, the high RH causes a higher leakage and therfore it results in a low insulation resistance value.

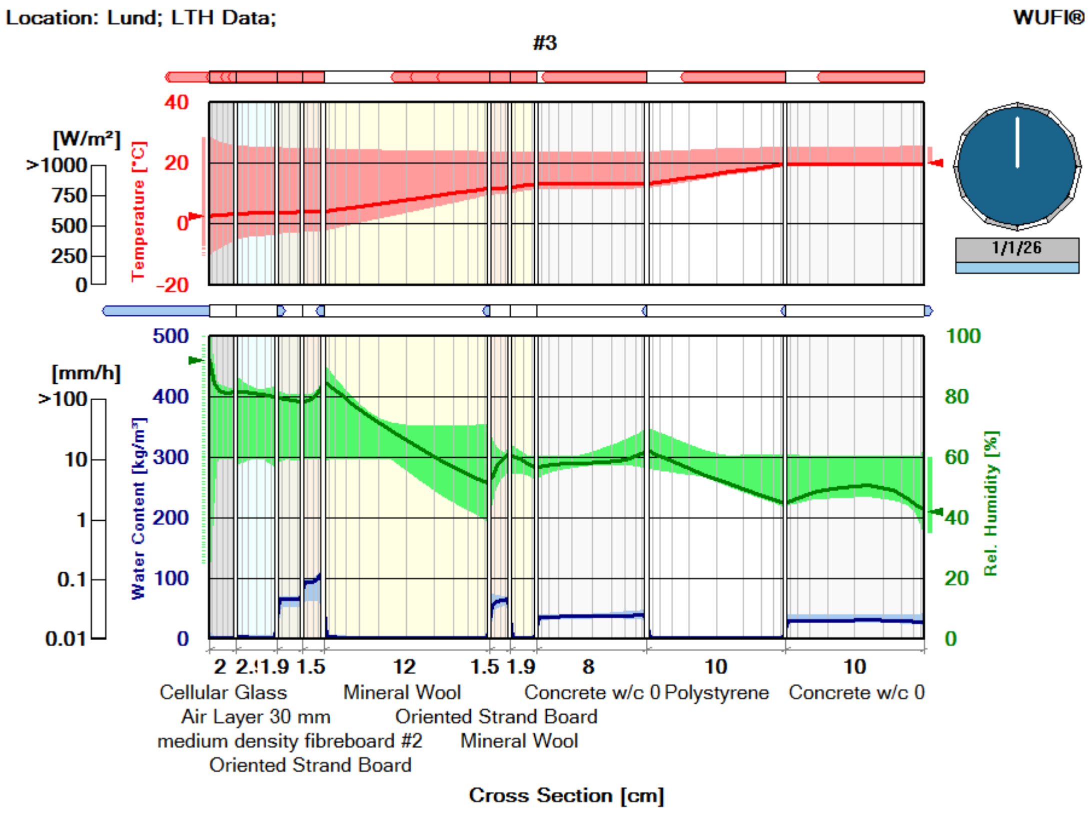


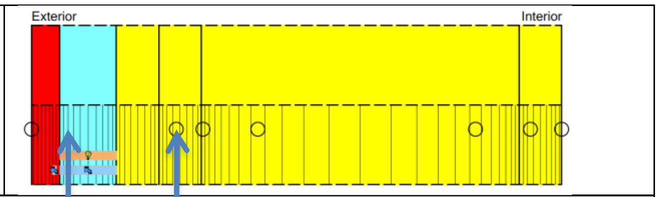

*Figure 30. Temperature, RH and water content through different material layers of the Multi-active façade*.

The graph in figure 30 illustrates the calculations for moisture and heat flow, which is an hour-by-hour calculation. The graph at the top with the red colour illustrates the temperature performance throughout the prefabricated façade as well as the existing façade. The temperature performance is different from the outdoor on the left side of the graph compared to that of the indoor on the right side of the graph. The red line that passes through is the temperature at a particular hour of the simulation. The spread of temperature on the y-axis represents extreme conditions of both winter and summer seasons.

The simulation software indicates high RH. This occurs at monitor 1 when the RH is above the 80%, and this is located at the mineral wool insulation material. The moisture decreases when moving towards the interior side of the prefabricated facade. Monitor 2 supports this notion, as it shows an improvement on the RH performance that decreases and is below 70%. Therefore, the risk of mould growth decreases in the prefabricated façade from the exterior side towards the interior side, having no risk for mould growth at the interior side where monitor 2 is placed.

However, the Multi-active WUFI results varies because of the special solar comb layer that reduces the moisture content, specifically when it is activated by the sun. In addition, the investigations at monitor 2, and 3 reveal a decreased RH value that is below 75%. This indicates that there is no risk of moisture problems or mould growth in the insulation materials at the locations of these monitors.

#### 4.5.2.8 Alingsås façade




| |
|---|
| **Risk of moisture at the following monitors** |
| Exterior monitor |
| Monitor 1 |
| Monitor 2 |
| |

The picture above shows the Alingsås façade. The different colours mark each material layer in the façade. The small circles represent the monitors' location to investigate the temperature and RH in the insulation materials.

This RH is high and it indicates that the location of monitor 1 in the prefabricated façade might have a risk for mould growth. This indicates that the moisture in the insulation layer might be a problem. The risk of moisture decreases in the prefabricated façade from the exterior side towards the interior side where the risk of moisture decreases below 80% of RH at monitor 2. As a result, there is no risk for moisture problem and for subsequent mould growth.

The location that was investigated in the simulation program is at the insulation material of the prefabricated façade element. The circles located at the outermost layer of both exterior and interior side of the prefabricated wall are placed by default in the program and are therefore neglected.

**Monitor 1**

The results of monitor 1 in Alingsås prefabricated façade are displayed in figure 31. Below are the graphs with the monitor position in relation to temperature and relative humidity.

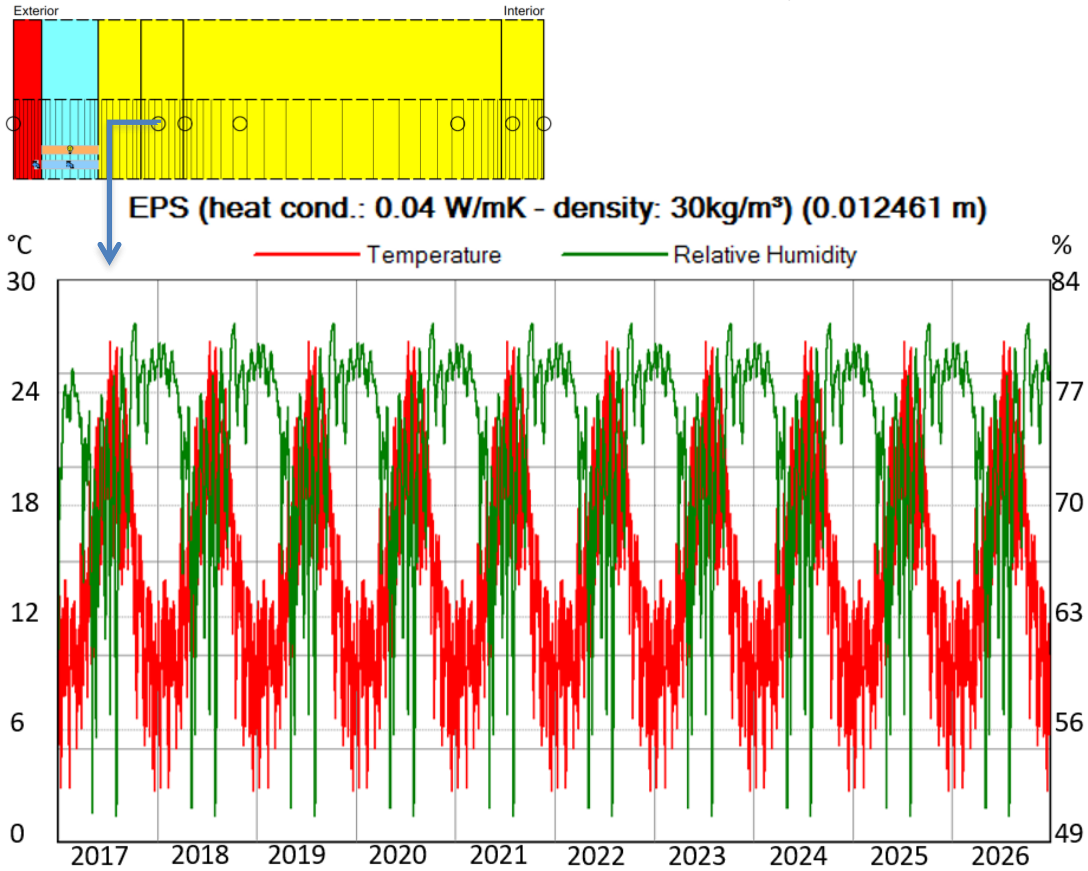



*Figure 31. The graph above shows that RH varies a lot during the years and illustrating to be having a RH at 80%.*

The graph in figure 31 monitor 1 illustrates RH, which is the green line, and it reaches between 50% to 80%. Although the chances for mould growth could happen at a high RH  it is undetermined because the temperature is low and mould typically doesn't grow at low temperatures. The specific location of monitor 1 is interesting because it is situated near the outer surface of the prefabricated façade. This can give information on the rain penetration performace. Meanwhile, the exterior side of the Alingsås prefabricated façade has been treated with Brick exterior cladding. The porosity and water absorption rates of the common brick are 12% and 20%, thus the absorption of water from the exterior layer of the Alingsås prefabricated façade is within the accepted range (Kahangi Shahreza et al., 2021).

The cold and warm weather could affect the RH. In winter periods the RH is 80% and the RH during summer periods is between 50% to 70%. When spring and summer seasons commence, the temperature rise above 20°C and the water content in the outdoor climate is reduced; as a result,  the RH reaches around 50% to 70%. The summer period has no risk for mold growth due to the low RH and high temperature. On the other hand, the RH is high during winter and it indicates that the location of monitor 1 in the prefabricated façade has a risk for mould growth. This suggests that the moisture in the insulation layer is a problem. In addition, the high RH causes a higher leakage and therfore it results in a low insulation resistance value.

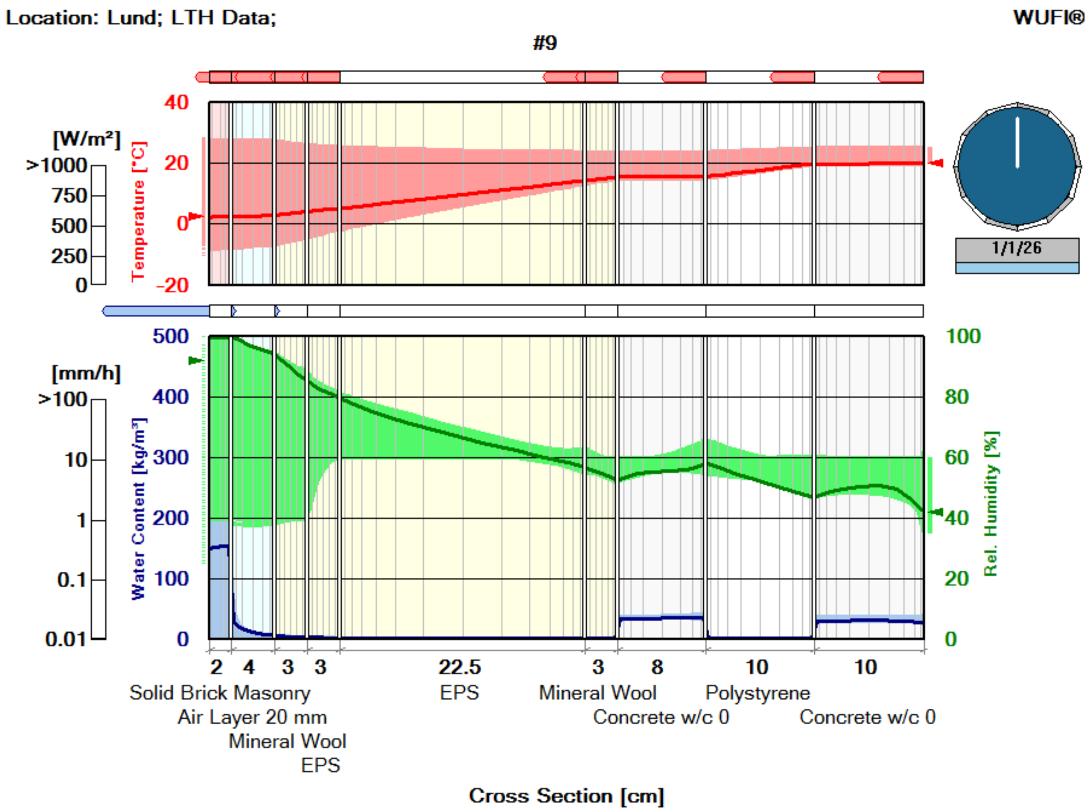



*Figure 32. Temperature, RH and water content through different material layers of the Alingsås façade.*

The graph in figure 32 illustrates the calculations for moisture and heat flow, which is an hour-by-hour calculation. The graph at the top with the red colour illustrates the temperature performance throughout the prefabricated façade as well as the existing façade. The temperature performance is different from the outdoor, which is on the left side of the graph compared to the data of the indoor represented on the right side of the graph. The red line that passes through is the temperature at a particular hour of the simulation. The spread of temperature on the y-axis represents extreme conditions of both winter and summer seasons.

The simulation software indicates high RH. This occurs at monitor 1 when the RH is at 80%, and this is located at the Graphite EPS Board insulation material. The moisture decreases when moving towards the interior side of the prefabricated facade. Monitor 2 supports this notion, as it shows an improvement on the RH performance that decreases. Therefore, the risk of mould growth decreases in the prefabricated façade from the exterior side towards the interior side.

Because of the moisture problems that occurred in the software at monitor 1, the authors decided to investigate the matter further. A vapour barrier was added as a layer between the existing building façade and the three prefabricated façades in the WUFI simulation. This was done to see if RH could be reduced. The results showed an improvement for all three prefabricated façade elements attached onto the existing façade of the Linero project; specifically, it yielded a 5% improvement in lowering RH.  The result was only visible in numbers as it was too small value to show up on the charts/graphs.

### 4.5.3 HEAT2

HEAT2 is a PC-program that is validated against the standard of EN ISO 10211 and EN ISO 10077-2. It is a program for two-dimensional transient and steady-state heat transfer.

In this thesis three facades (TES, Multi-active and Alingsås façade) were investigated in HEAT2. The HEAT2 software measures resistance-change factor per degree Celsius of temperature change and this is called the temperature coefficient of resistance. The aim was to see how these three facades performed when the prefabricated facades are attached onto the existing façade. The facades were drawn in the program with a scale of 1:1 containing the different materials that the prefabricated façade is constructed of and were added onto the existing material library in the program. If a material was absent in the software, a new material was created in the software by the authors with the right properties and information mentioned in the literature review. The properties for all the facades including conductivity U-value and resistance value that were used in WUFI and HEAT2 are in Appendix B.

#### 4.5.3.1 HEAT2 inputs

Input for the outdoor temperature was set to -5 °C and the indoor temperature to 23 °C. The three prefabricated facades had at -5 °C a thermal resistance value (R-value) of 0,06 $m^2\ K\ W^{-1}$ and at 23 °C a thermal resistance value of 0,12 $m^2\ K\ W^{-1}$. Simulating the modelled of the prefabricated façade a colour scheme shows up with a colour gradient representing the different temperatures at -5 °C has a deep purple colour and at 23 °C it is hot pink.

**Analysing points**

The analysis for the façade results in HEAT2 are based on these points:

- Thermal bridges
- Thermal comfort
- Temperature variations
- Estimation of surface temperatures (condensation risk)
- Analysis of junction, fastenings and window frames
- Heat flow output of the whole facade

#### 4.5.3.2 Façade HEAT2 analysis

During HEAT2 software analysis, the process starts by drawing each of the prefabricated façade with each material layer and properties that is given in the literature review. To setup the correct boundary conditions, the indoor and outdoor temperature need to be assigned. This will reflect to the indoor environment and geographical position. After running the simulation of the steady-state calculation, it is possible to examine the temperature variation in the prefabricated construction using the post-processor. Consequently, it is a suitable method for validating the boundary-conditions. To calculate the thermal bridges, the EN ISO 10211-2 standards were followed.

The result for the three prefabricated facades simulated in HEAT2 reveal the analysis of several junctions such as facade-soil junction, facade-window junction, intermediate floor-facade junction, and the roof junction.

#### 4.5.3.3 TES façade

The HEAT2 simulation of the TES prefabricated façade is displayed in figure 33. It repsents the linero with a TES prefabricated façade attached onto the existing building. The HEAT2 simulation analaysis is performed at the insulation materials of the prefabricated façade and the existing building façade.

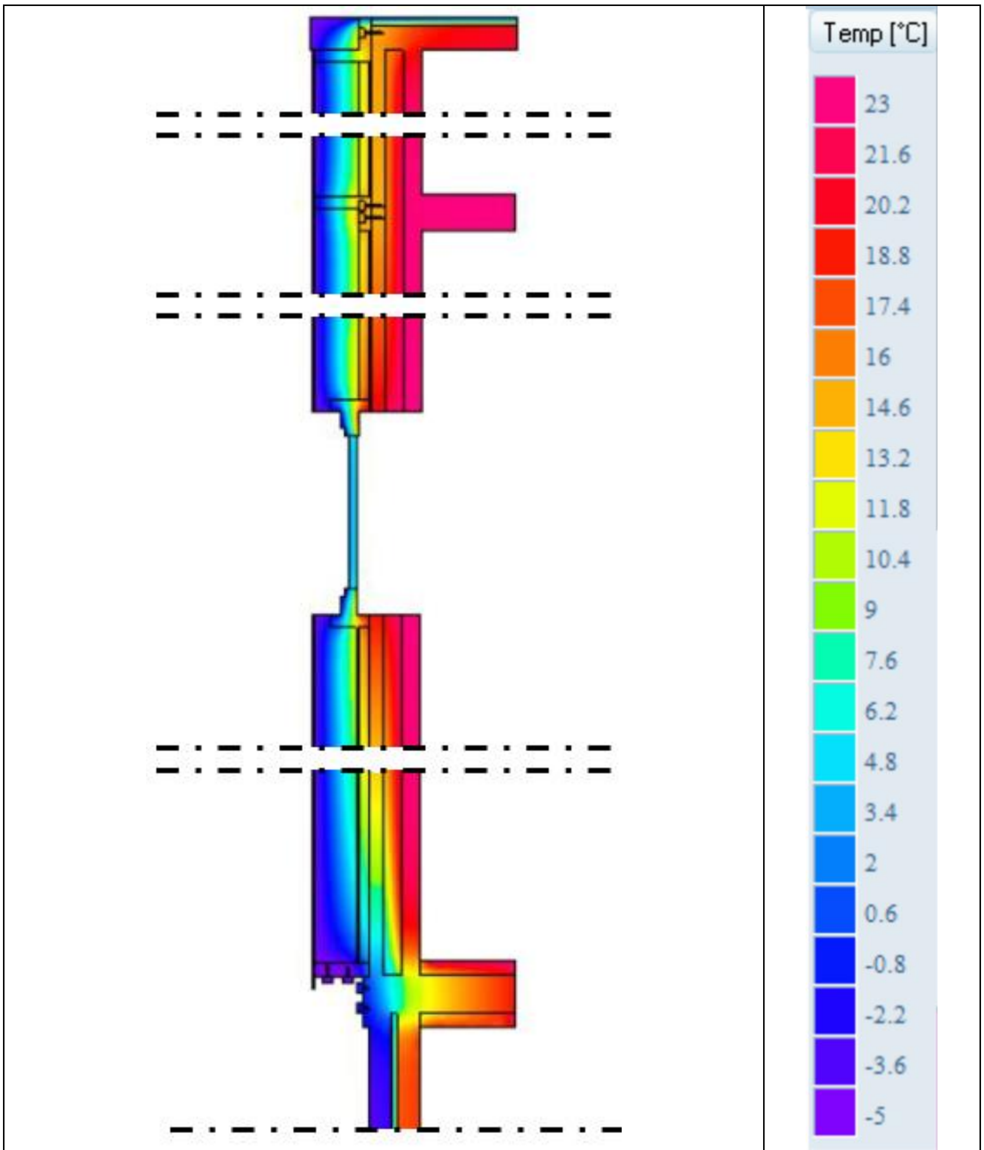



*Figure 33 TES prefabricated facade taken at the different junctions for the thermal bridge analysis to calculate the temperature and the heat flow.*

Results of the simulations in HEAT2 for the thermal bridges of the TES prefabricated facade onto the existing facade are given in a temperature profile divided into different junction. The heat flow output from HEAT2 was 161.92 W/m$^2$.

### 4.5.3.4 Multi-active façade

The HEAT2 simulation of the Multi-active prefabricated façade is displayed in figure 34. It repsents the linero with a Multi-active prefabricated façade attached onto the existing building. The HEAT2 simulation analaysis is performed at the insulation materials of the prefabricated façade and the existing building façade.

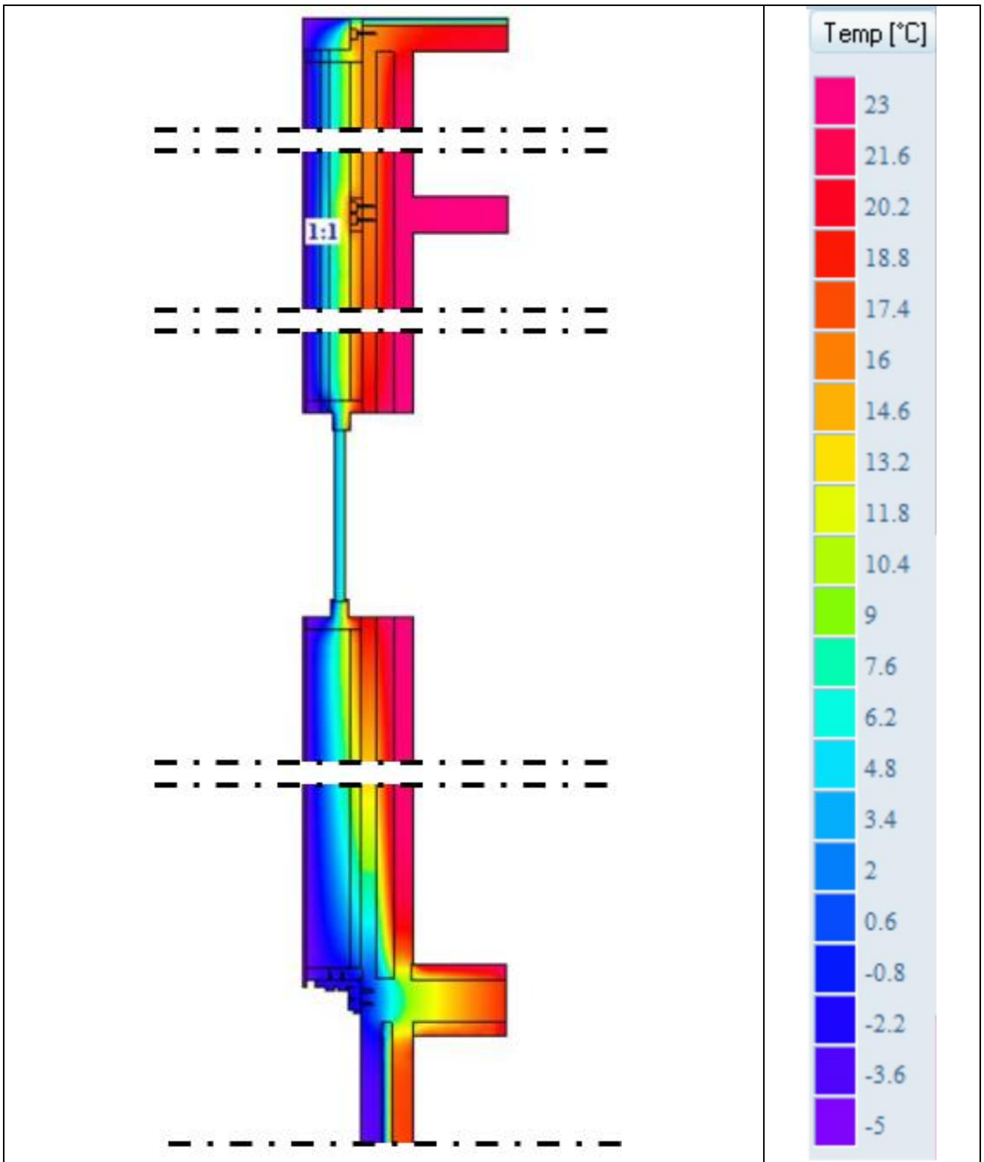



*Figure 34 Multi-active prefabricated facade taken at the different junctions for the thermal bridge analysis to calculate the temperature and the heat flow.*

Results of the simulations in HEAT2 for the thermal bridges of the Multi-active solar comb prefabricated facade on the existing façade is given in a temperature profile divided into different junction. The 1:1 symbol mark the solar comb layer that absorbs heat from the solar faced. The heat flow output from HEAT2 was 173.07 W/m$^2$.

### 4.5.3.5 Alingsås façade

The HEAT2 simulation of the Alingsås prefabricated façade is displayed in figure 35. It repsents the linero with a Alingsås prefabricated façade attached onto the existing building. The HEAT2 simulation analaysis is performed at the insulation materials of the prefabricated façade and the existing building façade.

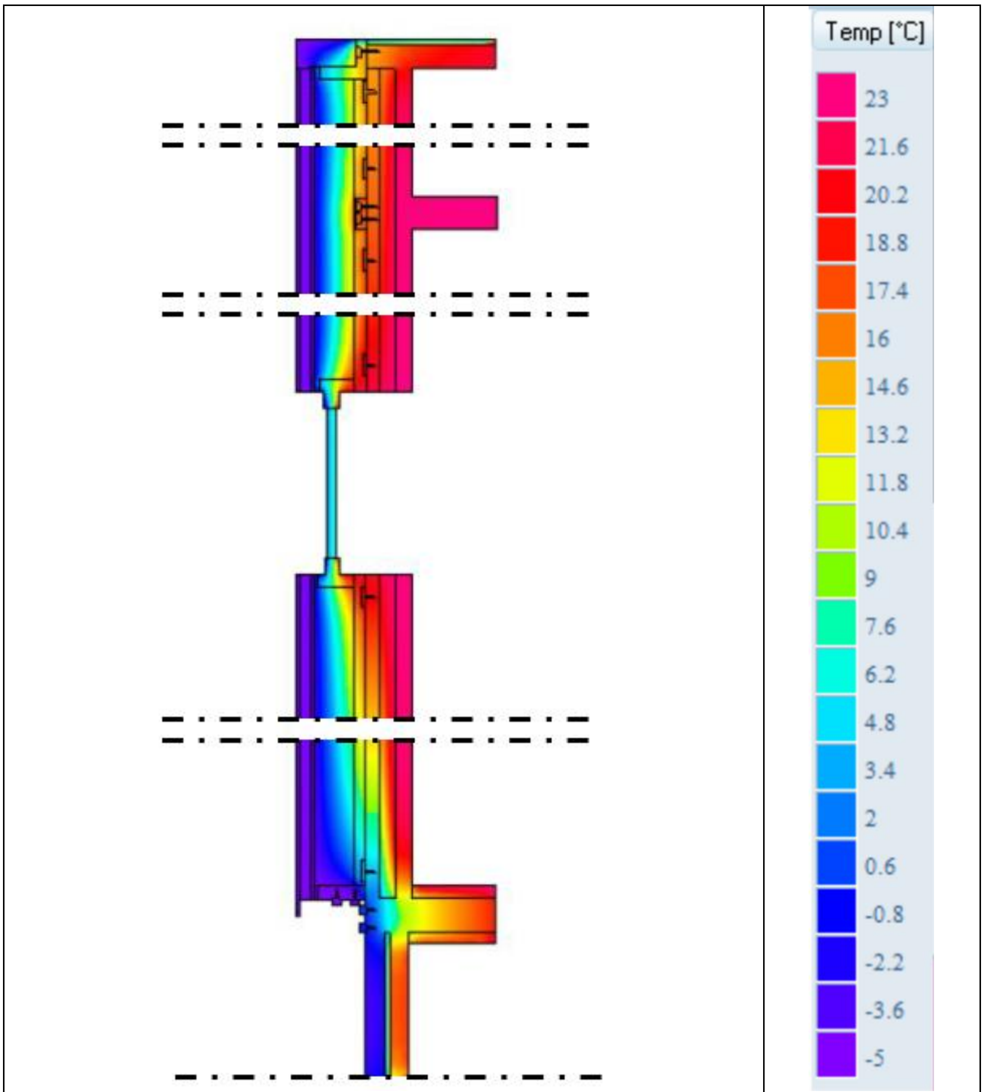



*Figure 35 Alingsås prefabricated facade taken at the different junctions for the thermal bridge analysis to calculate the temperature and the heat flow.*

Results of the simulations in HEAT2 for thermal brides of the Alingsås prefabricated facade on to the existing facade is given in a temperature profile divided into different junctions. The heat flow output from HEAT2 was 179.84 W/m$^2$.

# 5 Discussion and conclusions

The aim of this thesis is to search on the European market for a suitable prefabricated façade that would be used in the renovation of the reference building in Linero, located in Lund. The main goal is to make the building more energy efficient. Fifteen prefabricated façades from the European market were selected, analysed, and compared in this project. To set an example for further similar renovations of the Million Program buildings. The aim was to not only find façades that had the potential to be a good solution for our reference building but also to set an example for future similar renovations of the Million Program buildings. This was achieved by a literature review based on qualitative evaluations of the prefabricated façade elements.

From the 15 prefabricated facades, 3 prefabricated façade elements were suitable to meet the criteria of this thesis: the Case 1 facade (from Germany), the Case 2 (from Austria) and the Case 3 (from Sweden). The other 13 prefabricated facades were disregarded as they either did not meet the project's quality standards, the comparison table in section 4.4.4

Not meeting the project's quality standards was often the result of diverse climates for which the 15 prefabricated facades were made, as the 15 prefabricated facades were made in different countries across Europe. Therefore, it was important to investigate if they were energy efficient and meet the Swedish climate. According to the computer programs HEAT2 and WUFI, the 3 selected prefabricated façade elements demonstrated good results in relation to attachability, moisture risks and thermal performance. Of note, the computer programs can never give a 100 percent true result because of diverse errors in inputs and outputs. Because simulations have limitations extra measurements and hand calculations were done as well. When investigating the different countries climate file for the 3 selected prefabricated façade elements, the climates are not so different, and the results were trustworthy. With that said it is still necessary and highly recommended to do a moisture analysis for every new project before using the prefabricated façade elements that were analysed in this project.

Four different methods of attachment were proposed based on the examination of the mounting of the prefabricated façade elements onto the existing building. After thorough evaluation, only one method for attachment was the best option, thus option 2 of the four methods was the preferred one, which is installing the prefabricated façade with a L-bracket onto the loadbearing existing facade that would carry the façade element. Option 1 requires the prefabricated façade to be placed at a pitched roof, yet this was not possible as the façade element was too heavy. Option 3 requires the prefabricated façade to lean onto the extension of the foundation. As a result, option 3 did not work for the reference building because the extension of the foundation lies underground beneath the basement level, and the basement could not be extended because of the basement windows present. Option 4 requires the whole façade to be removed from the existing building, yet this was not feasible as the existing building had a loadbearing structure system. If the loadbearing structure system be removed, the whole building will collapse.

The 3 selected prefabricated façades had two attachment and fixation options: horizontally or vertically. As the existing façade had windows attached horizontally in a row, the most cost-effective and natural selection is to choose to place the façade elements horizontally, so they mimic the aesthetic look of the building. Also, because the instalment process would be easier as the prefabricated facades came with incorporated windows and could therefore be fixed right into the already existing openings of the building façade. To place them vertically or diagonally would not only be economical inefficient, but also time consuming and it would interfere with the aesthetics of the building.

The 3-types of element connections that were suitable for the façade elements in this study were the flush joint, rebate joint and the tongue in groove joint. Since the facades are prefabricated, it did not take a long time to put them onto the existing building and it did not affect the tenants at all. As a result, the tenants need not move out for this project and during this period. Subsequently, it is more cost-effective. When looking at the different facades the Case 3 façade was the cheapest one, which cost 125 Euro/m$^2$, compared to Case1 façade 140 Euro/m$^2$ and the most expensive is the Case 2 façade 350 Euro/m$^2$.

To evaluate if any changes were made to the building since construction and before the start of this investigation, LKF (Lund Kommuns Fastighetsbolag) was appointed. LKF informed the authors that the only renovation on the existing facades were the windows. These windows were replaced with double panel windows, and this took place in 2006. Although these windows need to be replaced again to meet the current EU regulations, the prefabricated element facades would be a more suitable and convenient option because the windows are integrated within the prefabricated façade element reaching the passive house standards. This is desired, as the prefabricated façade could be installed with very high performing windows in one mounting. The prefabricated facade that had the best window U-value was Case1 façade with a U-value of 0.5 $W/m^2K$; nonetheless, the other two façades had also very good U-value of 0.85 $W/m^2K$.

The Case 1 and the Case 2 façade could have installations in the prefabricated facade elements. However, it also means that the facade would be a bit thicker than a normal Swedish facade of today. Therefore, depending on what prefabricated facade one chooses there is a large variation in the total thickness of the facade. In most cases you will need to take the facade thickness into consideration due to a buildings' surroundings. In this project the thickness of all the 3-façade elements would not interfere with the surroundings, as there is a lot of space between the buildings and the pedestrian area.

The authors of this study were also curious to see if a thicker facade had a better U-value and in this case that was true. The thickest facade was the Case 3 façade with an astonishing 375mm together with the existing building comparing to the Case 1 façade that was 340mm and Case 2 façade 240mm. Case 3 façade had the lowest facade U-value of 0.091 $W/m^2K$ comparing to Case1 façade 0.094 $W/m^2K$ and Case 2 façade 0.139 $W/m^2K$. When comparing the Case 1 and the Case 3 façade there was only a difference of 0.003 $W/m^2K$ in the U-value but 35mm difference in thickness. Further the thickness of the Case 2 facade was 137mm less than the Case 3 facade. In conclusion, the most suitable facade regarding thickness and U-value was that all were suitable for this reference building as the thickness does not interfere with surroundings and they all meet the passive house standard as they are below 0.15$W/m^2K$.

The WUFI simulation software has monitors that can be placed anywhere in the façade to observe penetration of moisture. All 3 facades that were analysed in WUFI, the monitors were placed in the insulation material of the prefabricated façade elements. The monitors revealed information about the RH and temperature and if there is a risk of moisture problems or mould growth. As long as the monitors revealed RH results below 80%, the prefabricated facade system had reduced risk for moisture problems. The different facades showed differences when evaluated individually, yet when the facades were attached on to the existing building, they yielded similar results to each other.

The main conclusion of the WUFI analysis study is that for this specific project the authors would renovate the reference building with the Case 1 façade. The Case 1 façade had the best U-value and the best thermal performance. Case 1 facade was innovative because it had special materials that would reduce the moisture from the façade. This was however hard to calculate in the WUFI software, as this material did not exist as an input, giving Case 1 a WUFI result with an error. In conclusion, the authors find the facade moisture for the 3 prefabricated façade elements safe.

The HEAT2 program illustrated the temperature variation in the attachment of the prefabricated façade system onto the existing building. It was focused on thermal bridges and thermal comfort. The temperature flow that penetrates through the prefabricated façade and the existing façade was set at a comfort temperature of 23 °C. the results from this analysis revealed that the thermal comfort was good for all the 3 facades.

The facades showed temperature variation, heat flow and thermal bridges very clearly. The façade with the L-bracket fastening had temperature difference and therefore the biggest thermal bridge was observed there for the 3 prefabricated elements. Finally, when comparing the whole facades from the roof till the basement, the integrated windows as well as L-brackets fastenings demonstrated to have the most thermal bridges. However, when comparing the 3 prefabricated facades with each other, the Case 1 façade is the most suitable façade. On the other hand, the least suitable facade is the Case 3 façade. In conclusion, the Case 1 prefabricated façade is the best façade with the least amount of heat leakage due to the least thermal bridges. The Case 2 façade comes second place, while the Case 3 façade comes third place. To guarantee this observation is valid, a hand calculation was performed by the authors for a heat flow calculation in the HEAT2 software. These results demonstrate that it was indeed correct. Thus, according to the heat transfer, the Case 1façade had a value of 175$W/m^2$ and Case 2 façade had a value of 213$W/m^2$ and Case 3 façade a value of 261$W/m^2$. Consequently, Case 1 façade had the lowest heat flow and was 33% better than the Case 2 façade and 18% better than the Case 3 façade.

As a final conclusion, based on the findings in this report all 3 the prefabricated facades would suit the reference building of the Linero case as well as contribute to decrease the energy demand and meet the EU regulations and directives. They would thereby all set a good example for the renovation of houses within the Million Program.

# 6 Future perspective

It might be interesting to make more detailed analysis of the moisture performance of the different facades taking into account different materials used for the studs. Another interesting future study would be to put the monitor systems at a different location such as the studs and beams of prefabricated façade elements. Furthermore, it would be interesting to see the energy performance of the new renovation and see how much it will be reduced. For instance, it would be interesting to delve into analysing the prefabricated façade with or without different types of vapour barriers. Another thing to investigate could be a risk analysis and LCC as well as LCA. Lastly investigating a façade element that is placed diagonally could have added value for future projects.

# 7 References


AUTODESK. (2017). *AUTODESK*. https://www.autodesk.com

Blocon. (2017). *HEAT2*. https://buildingphysics.com/heat2-3/

Cityfied. (2016). *A smarter way to delivering sustainable urban renovations at district level*. http://www.cityfied.eu/

Cronhjort, Y., Piironen, J., Hirsi, H., Nuikka, M., Lylykangas, K., Huttunen, E., Hietaniemi, J., & Kaila, A. (2009). *TES Energy Facade Timberbased element systems for improving the energy efficiency of the building envelope*. https://www.researchgate.net/publication/294521160_TES_Energy_Facade_Timberbased_element_systems_for_improving_the_energy_efficiency_of_the_building_envelope

Döring, B., Kuhnhenne, M., Vassart, O., Harper, C., Beguin, P., Herbin, S., Seppänen, A., Lawson, M., Yandzio, E., Scheublin, F., & Bakens, W. (2009). *Integrated pre-fabricated steel technologies for the multi-storey sector*. https://doi.org/10.2777/41420

Döring, B., Vassart, O., Harper, C., Beguin, P., Herbin, S., Seppänen, A., Lawson, M., Yandzio, E., Scheublin, F., & Bakens, W. (2009). *Integrated pre-fabricated steel technologies for the multi-storey sector*. Off. for Official Publ. of the European Communities. https://doi.org/10.2777/41420

ECO-SANDWICH. (2015). *ECO-SANDWICH*. https://www.eco-sandwich.hr/eco-sandwich-2/

Energimyndigheten. (2015). *Energimyndigheten*. https://www.energimyndigheten.se/en/

Energimyndighetens. (2016). *Energimyndighetens årsredovisning 2015*. www.energimyndigheten.se

Fraunhofer IBP. (2017). *WUFI*. https://wufi.de/en/

Gönülol, O. (2016). *Examination of Solar Comb Integrated Multifunctional Façade Systems*.

GÖRHAN, G., & KÜRKLÜ, G. (2018). The Investigation of Heat Performance and Thermal Conductivity of Different Wall Materials at High Temperatures. *Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü Dergisi*, *22*, 10. https://doi.org/10.19113/sdufbed.99438

Höfler, K., & Aschauer, J. (2010). *IEA: ECBCS-ANNEX 50 1 AEE-Institute for Sustainable Technologies PREFAB SYSTEMS FOR LOW ENERGY/ HIGH COMFORT BUILDING RENEWAL*. https://nachhaltigwirtschaften.at/resources/iea_pdf/iea_ecbcs_annex_50_anhang6b-moduldokumentation.pdf

Höfler, K., Geier, D., & Aschauer, J. (2010). *Residential area Dieselweg, Graz*. http://www.iee-square.eu/informationpublications/Brochures/SQUARE_Short_info_Pilot_project_Austria_EN.pdf

Hövels, J. (2008). *The Open Modular Façade Concept*.

Johansson, P. (2012). *Vacuum Insulation Panels in Buildings Literature review Report in Building Physics*. https://www.researchgate.net/publication/275209501_Vacuum_Insulation_Panels_in_Buildings_Literature_Review

Kahangi Shahreza, S., Niklewski, J., & Molnár, M. (2021). Experimental investigation of water absorption and penetration in clay brick masonry under simulated uniform water spray exposure. *Journal of Building Engineering*, *43*. https://doi.org/10.1016/j.jobe.2021.102583

Kobler, R. L., Binz, A., Steinke, G., Höfler, K., Geier, S., Aschauer, J., Boulanger, X., Silva, F. P., & Almeida, M. (2011). *IEA ECBCS Annex 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings Retrofit Module Design Guide*. Empa, Building Science and Technology Lab CH-8600 Duebendorf Switzerland. http://www.ecbcs.org

Lattke, F., Larsen, K., Johannes Ott, S., & Cronhjort, Y. (2011). *TES EnergyFaçade-prefabricated timber based building system for improving the energy efficiency of the building envelope*. https://www.researchgate.net/publication/294085946_TES_Energy_Facade_-_prefabricated_timber_based_building_system_for_improving_the_energy_efficiency_of_the_building_envelope_funded_by_Woodwisdom_Net_Research_project_from_2008-2009

Lattke, F., Larsen, K., Ott, S., & Cronhjort, Y. (2011). *TES Energy Facade – prefabricated timber based building system for improving the energy efficiency of the building envelope, funded by: Woodwisdom Net, Research project from 2008-2009.*

https://www.researchgate.net/publication/294085946_TES_Energy_Facade_-_prefabricated_timber_based_building_system_for_improving_the_energy_efficiency_of_the_building_envelope_funded_by_Woodwisdom_Net_Research_project_from_2008-2009

Luible, A., Overend, M., Aelenei, L., Knaack, U., Perino, M., & Wellershoff, F. (2015). *Adaptive facade network-Europe*. https://tu1403.eu/?page_id=209

Miloni, R., Partner, M. &, Grischott, W. N., Für Architektur, K., Zimmermann, Z. M., Switzerland, D., Geier, S., Höfler, K., & Venus, D. (2011). *IEA ECBCS Annex 50-Prefab Retrofit of Buildings Building Renovation Case Studies IEA ECBCS Annex 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings Building Renovation Case Studies*. Empa, Building Science and Technology Lab CH-8600 Duebendorf Switzerland. http://www.ecbcs.org

Mir, M. A. (2011). *Green façades and building structures* [TU Delft]. https://repository.tudelft.nl/islandora/object/uuid%3Af262c218-8801-4425-818f-08726dde5a6c

Olof Mundt-Petersen, S. (2013). Wood in carbon efficient construction: Tools, methods and applications. *Important Factors the Affecting Moisture Safety in Wooden Buildings*, 104–105. https://www.researchgate.net/publication/285975185_Wood_in_carbon_efficient_construction_Tools_methods_and_applications

Olof Mundt-Petersen, S. (2015). *S. Olof Mundt-Petersen Moisture Safety in Wood Frame Buildings Blind evaluation of the hygrothermal calculation tool WUFI using field measurements and determination of factors affecting the moisture safety*. https://lucris.lub.lu.se/ws/portalfiles/portal/3853018/4937649.pdf

Parco. (2013, April). *Ventilated facade*. Ventilated Facade. https://pdf.archiexpo.com/pdf/paroc/ventilated-facades/9579-238113.html

Riko Haus. (n.d.). *Riko Technical brochure*. Retrieved April 23, 2022, from https://pdf.archiexpo.com/pdf/riko-hise/riko-haus-technical-brochure/60433-119153.html

Schwehr, P., Fischer, R., & Geier, S. (2011). *IEA ECBCS Annex 50 Prefabricated Systems for Low Energy Renovation of Residential Buildings Retrofit Strategies Design Guide*. Empa, Building Science and Technology Lab CH-8600 Duebendorf Switzerland. http://www.ecbcs.org

Simmler, H., Brunner, S., Heinemann, U., Schwab, H., Kumaran, K., Mukhopadhyaya, P., Quénard, D., Sallée, H., Noller, K., Kücükpinar-Niarchos, E., Stramm, C., Tenpierik, M., Cauberg, H., & Erb, M. (2005). *Vacuum Insulation Panel Properties Energy Conservation in Buildings and Community Systems Programme*. https://www.iea-ebc.org/Data/publications/EBC_Annex_39_Report_Subtask-A.pdf

swedisol. (2016). *swedisol*. https://swedisol.se

UNPE Environment. (2016). *UN Environment Annual Report 2016*. https://www.unep.org/annualreport/2016/index.php

Van Oorschot, J. A. W. H. (2017). *STATE-OF-THE-ART DEEP RENOVATION CONCEPT WITH MODULAR PREFABRICATED FAÇADE AND ROOF PANELS: EXPERIENCES FROM THE NETHERLANDS*. https://www.more-connect.eu/wp-content/uploads/2018/10/STATE-OF-THE-ART-DEEP-RENOVATION-CONCEPT-D3.2.pdf

Volf, M., Hejtmánek, P., Lupíšek, A., Kalamees, T., Christensen, F., Olesen, S., van Oorschot, J. A. W. H., Mørck, O. C., Borodinecs, A., & Šenfeldr, P. (2018). *Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions D2.2 A set of basic modular facade and roof elements including renewable energy production and integration of HP insulation*. https://www.more-connect.eu/wp-content/uploads/2019/07/MORE-CONNECT_WP2_D2.2-I-Set-of-modular-facade-elements-II-Integration-of-RES-III-Super-Insulation.pdf

Wiederhorn, S., Fett, T., Rizzi, G., Fünfschilling, S., Hoffmann, M., & Guin, J. (2011). Water Penetration-Its Effect on the Strength and Toughness of Silica Glass. *Journal of the American Ceramic Society*, *94,* s196–s203. https://doi.org/10.1111/j.1551-2916.2011.04530.x

Zimmermann, M. (2011). *Prefabricated Systems for Low Energy Renovation of Residential Buildings Energy Conservation in Buildings and Community Systems Programme*. https://www.iea-ebc.org/Data/publications/EBC_PSR_Annex50.pdf

# 8 Appendix A

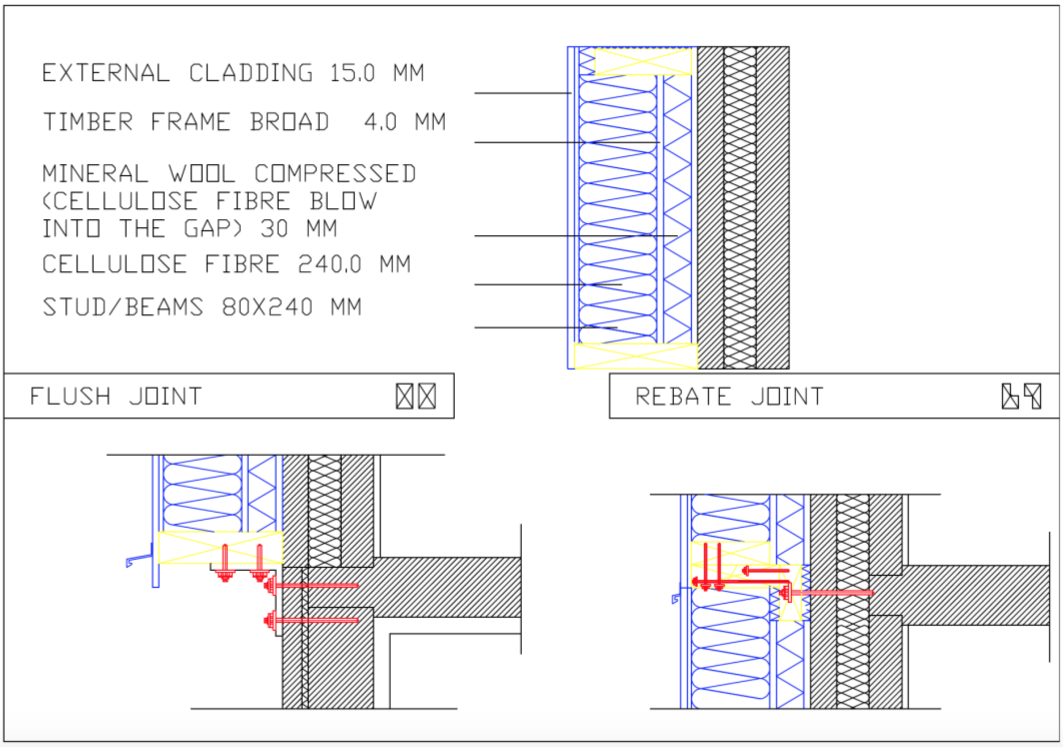
## 8.1 13 prefabricated façade detail drawings

Detailed colourful drawings were made to analyse the 13 facades from the European market when attached to the existing building. The authors of this thesis made an own façade that is also illustrated below. The prefabricated façades are drawn in a blue colour and the existing building façade in a black colour. The screws for the attachment are red and studs and beams yellow.

The U-values that are provided in the table below for each facade drawing is done at four different points:

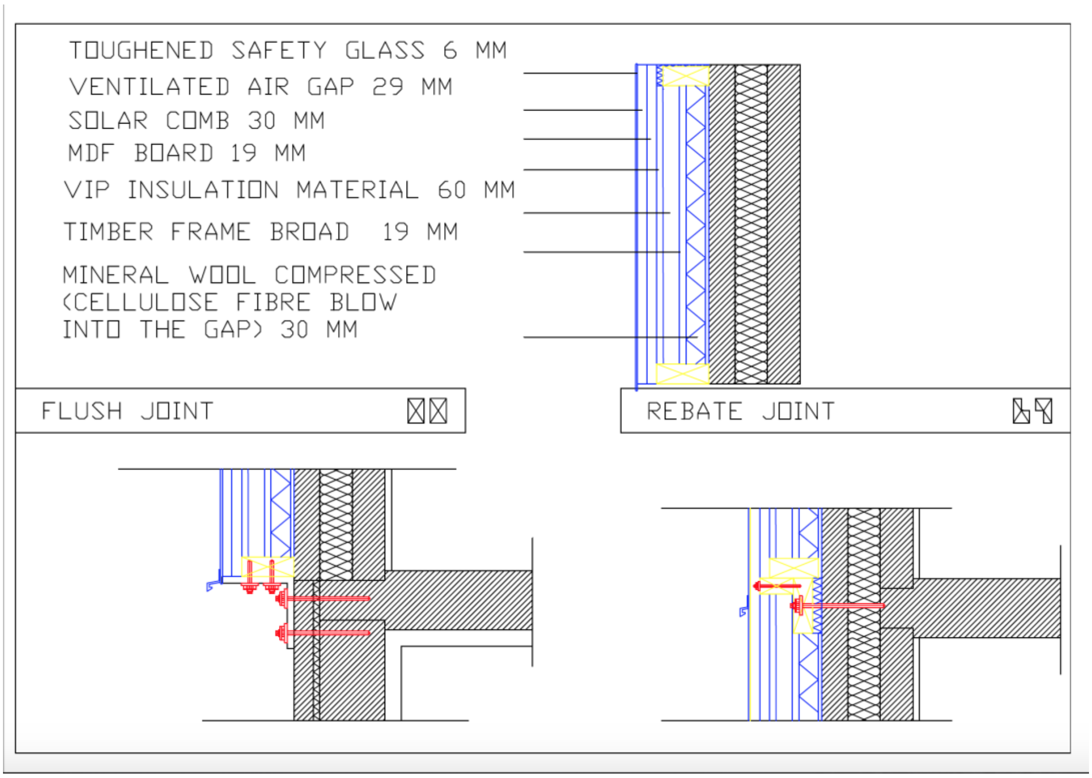
- Report provided U-value; U-value stated by the documents about the prefabricated façade.
- Only the prefabricated façade calculated in the WUFI software with the same materials that are shown in the drawings.
- The prefabricated façade attached onto the existing building façade.
- Hand calculation of the U-value.

### 8.1.1 Façade 1 TES



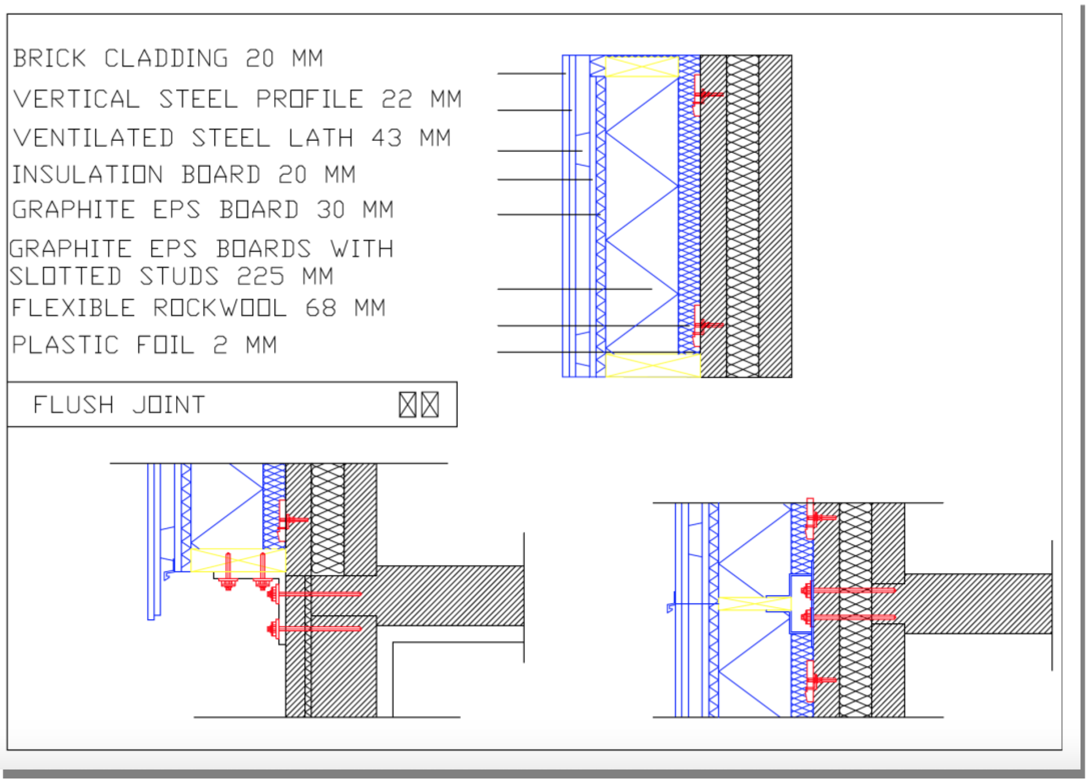

| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached onto the existing façade u-value | Hand calculated u-value |
| <0.15 W/m$^2$K | 0.126 W/m$^2$K | 0.138 W/m$^2$K | 0.095 W/m$^2$K | 0.088 W/m$^2$K |

### 8.1.2 Façade 2 Multi-active



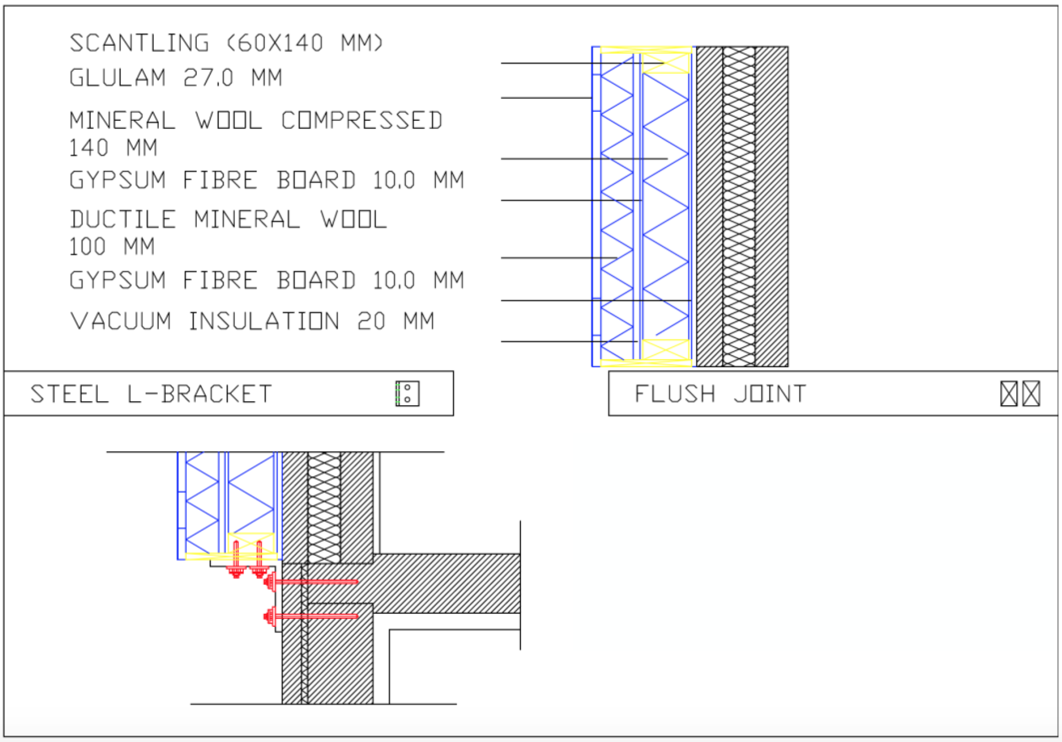

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| <0.15 W/m²K | 0.238 W/m²K | 0.191 W/m²K | 0.147 W/m²K | 0.106 W/m²K |

### 8.1.3 Façade 3 Alingsås



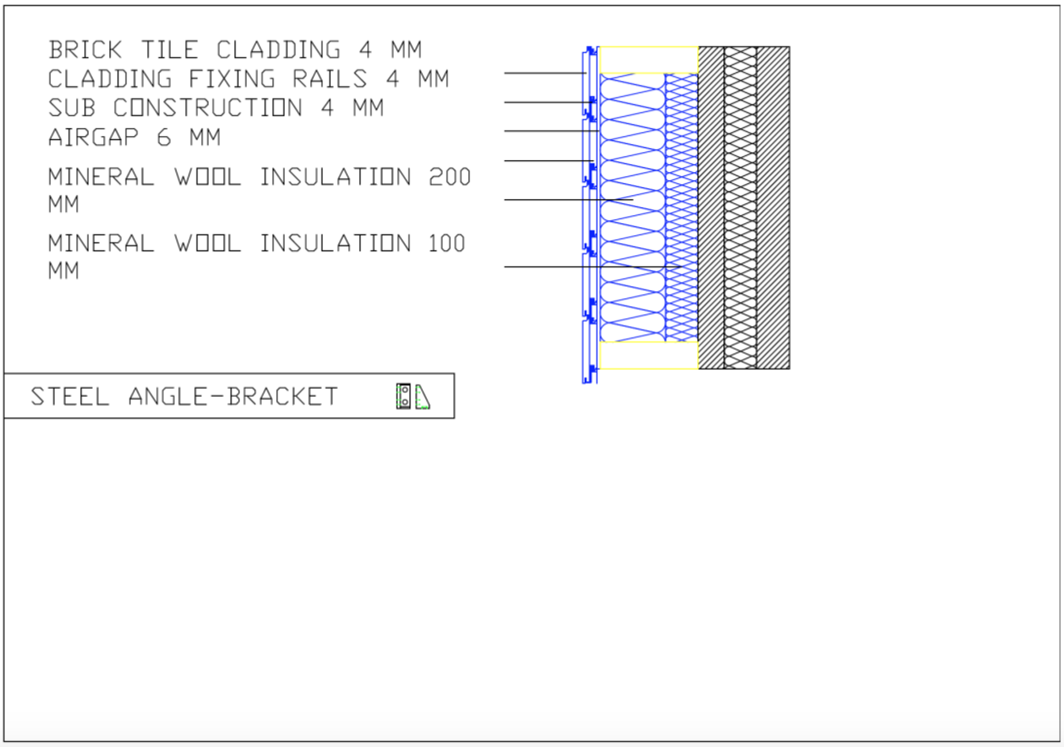

| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| <0.15 W/m$^2$K | 0.099 W/m$^2$K | 0.109 W/m$^2$K | 0.079 W/m$^2$K | 0.075 W/m$^2$K |

### 8.1.4 Façade 4 Semi prefabricated standardised retrofit



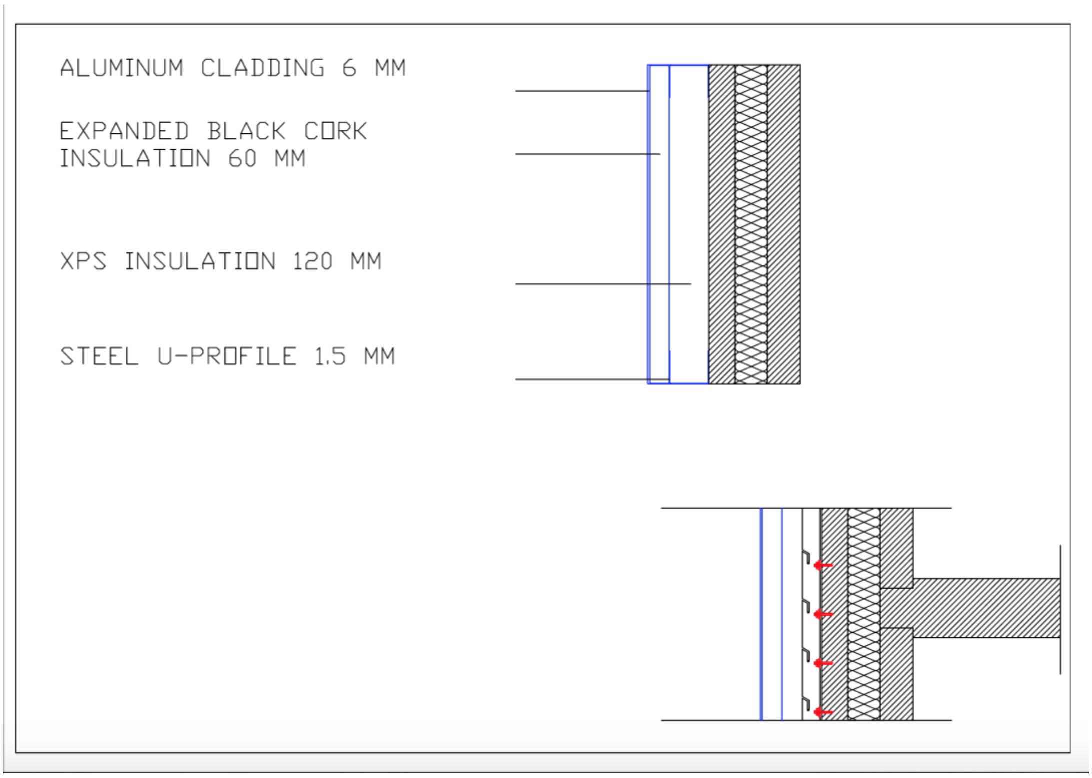

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| <0.15 W/m$^2$K | 0.107 W/m$^2$K | 0.109 W/m$^2$K | 0.084 W/m$^2$K | 0.075 W/m$^2$K |

### 8.1.5 Façade 5 Large size prefabricated steel frame retrofit



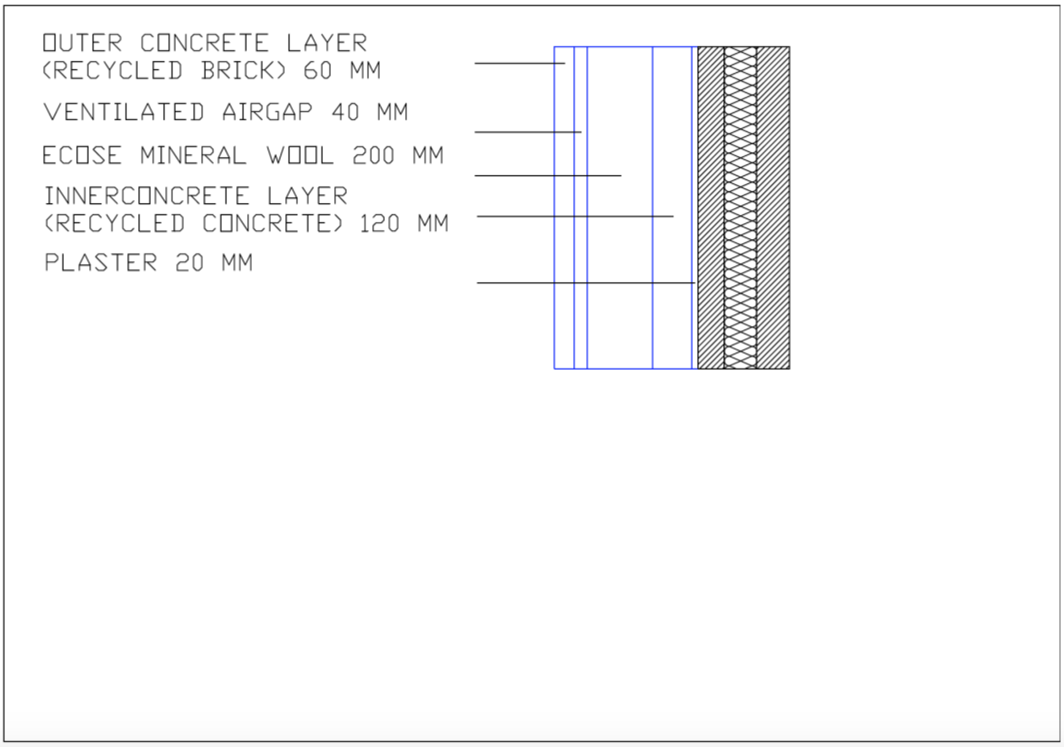

| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| <0.15 W/m$^2$K | 0.119 W/m$^2$K | 0.157 W/m$^2$K | 0.091 W/m$^2$K | 0.095 W/m$^2$K |

### 8.1.6 Façade 6 Prefabricated metal panel retrofit



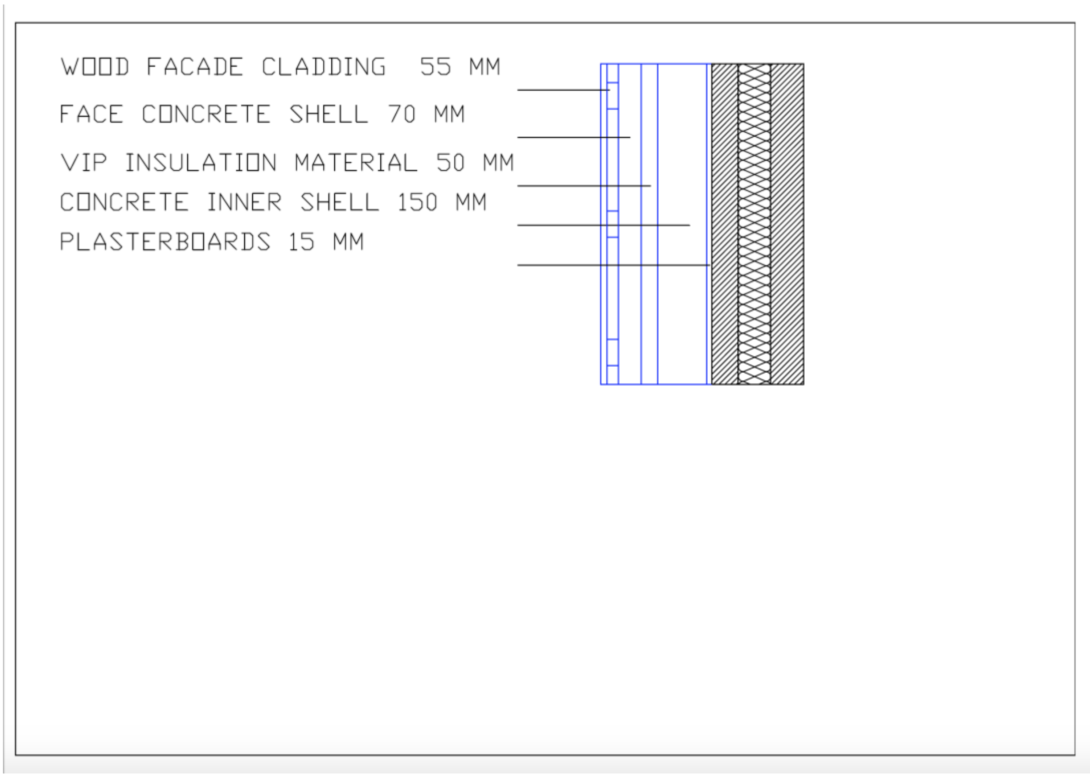

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.23 W/m²K | 0.177 W/m²K | 0.176 W/m²K | 0.121 W/m²K | 0.102 W/m²K |

### 8.1.7 Façade 7 ECO sandwich



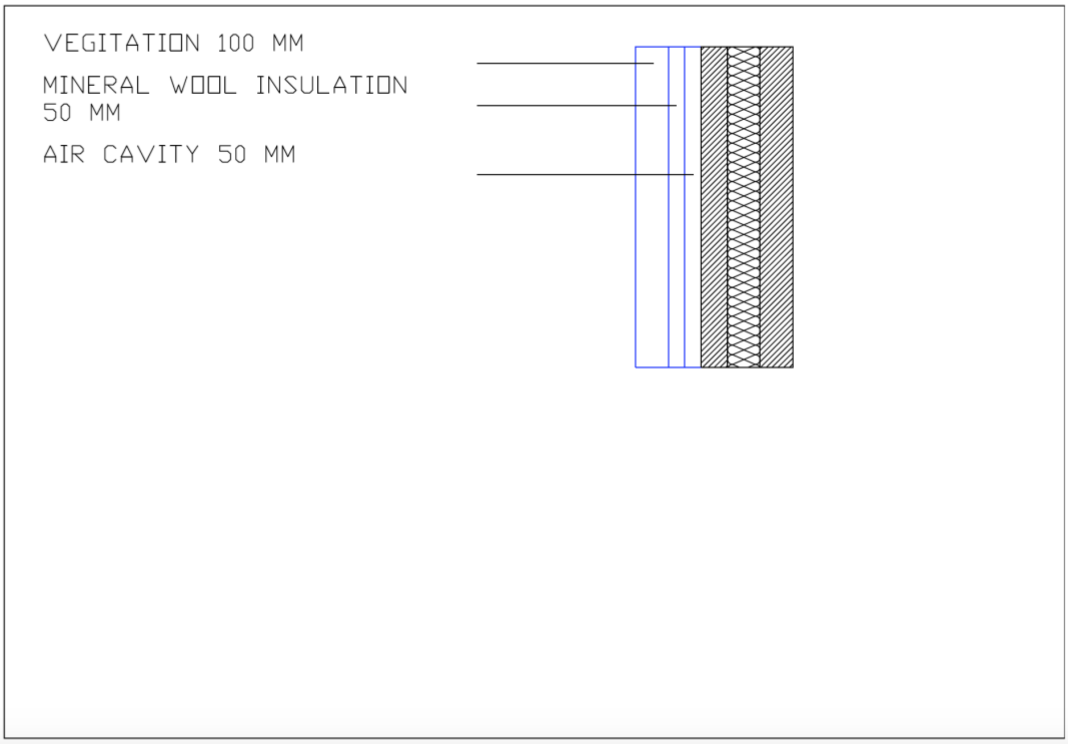

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.2 W/m²K | 0.149 W/m²K | 0.182 W/m²K | 0.108 W/m²K | 0.104 W/m²K |

### 8.1.8 Façade 9 Vacuum insulated prefabricated elements



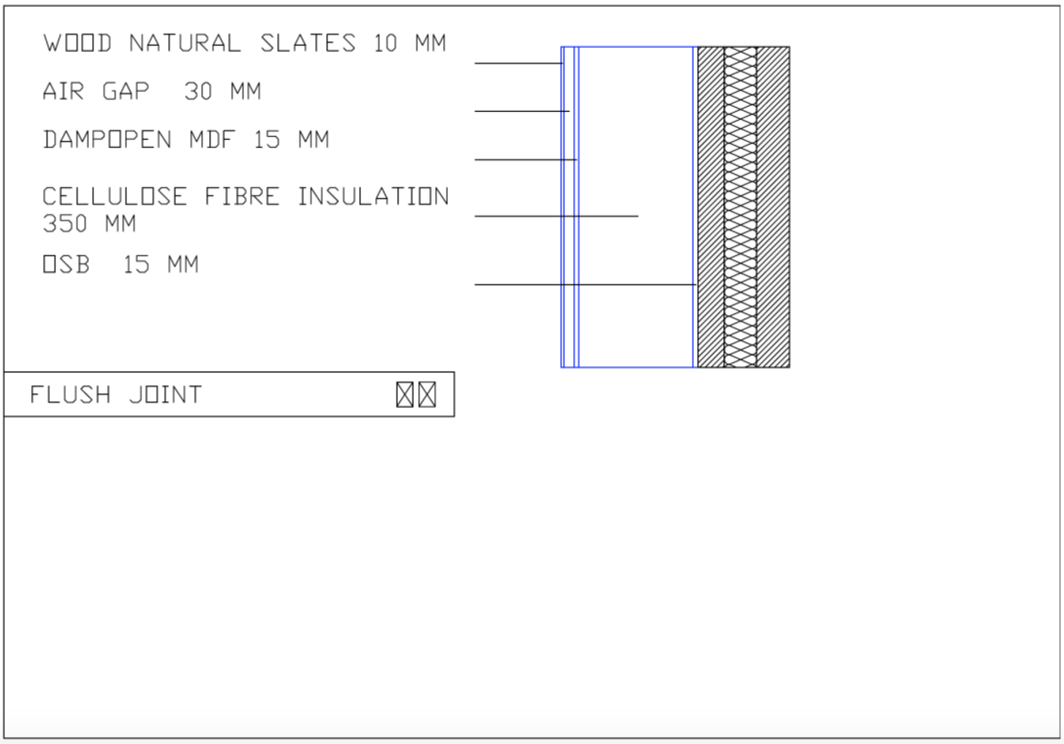

| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.09-0.11 W/m²K | 0.098 W/m²K | 0.079 W/m²K | 0.078 W/m²K | 0.059 W/m²K |

### 8.1.9 Façade 10 Green façades and building structures LWS



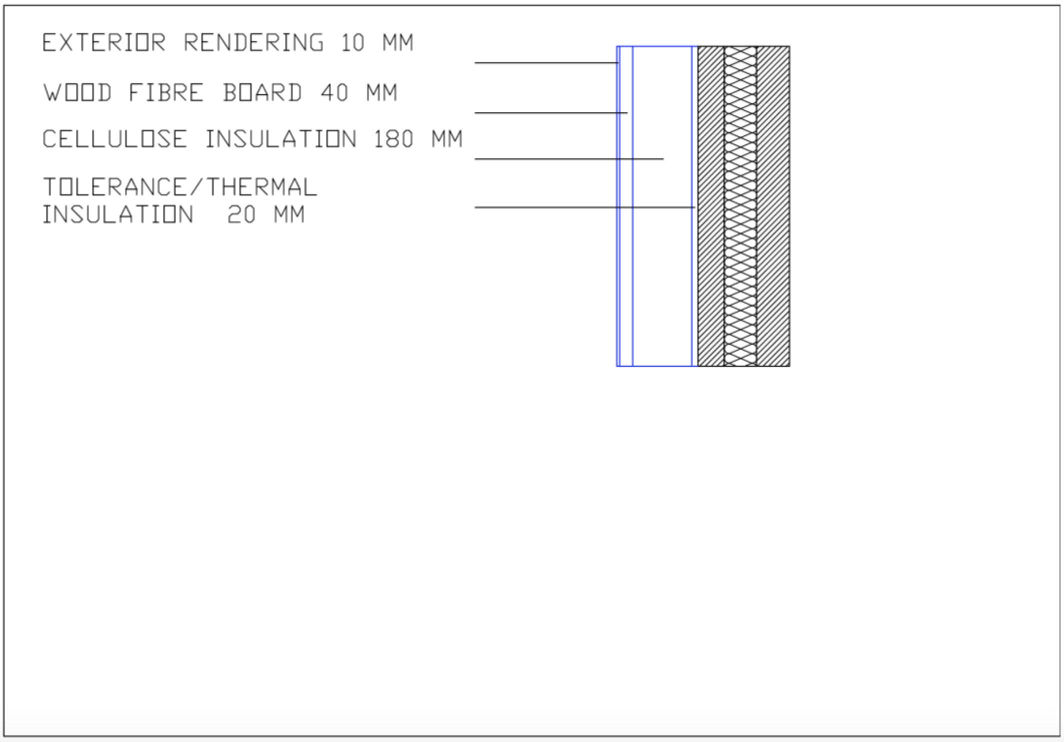

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.11 W/m$^2$K | 0.151 W/m$^2$K | 0.599 W/m$^2$K | 0.306 W/m$^2$K | 0.177 W/m$^2$K |

### 8.1.10 Façade 11 Passive renovation De Kroeven 505 Roosendaal, NL



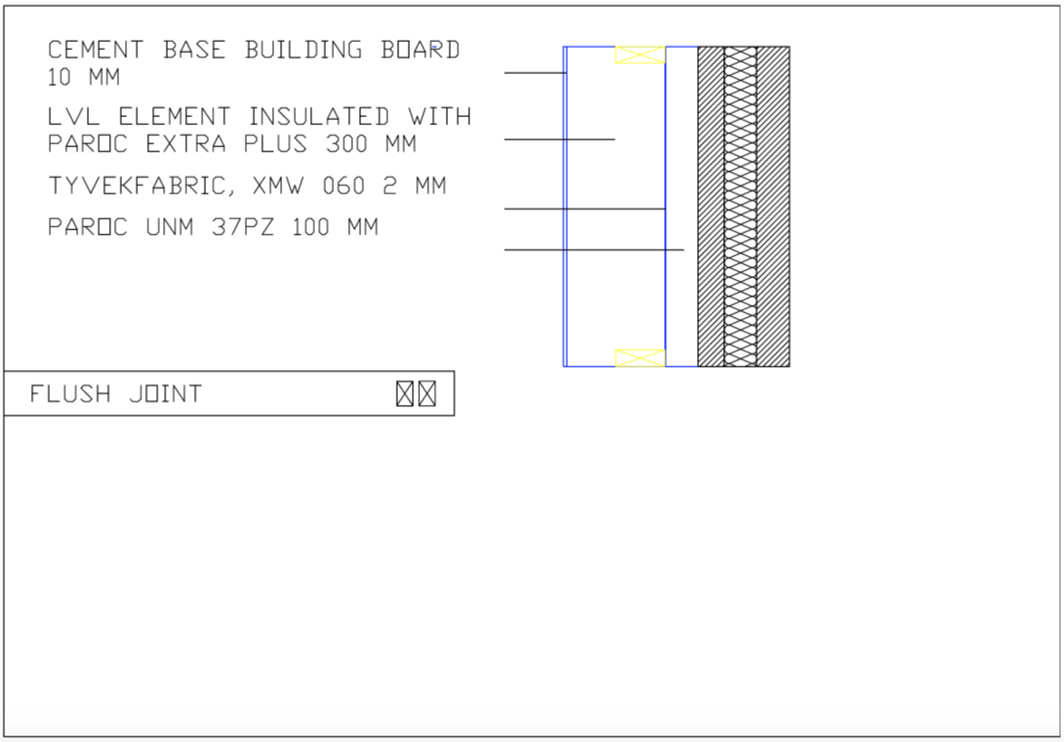

| | Prefabricated façade only | | Prefabricated façade onto existing building facade | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| <0.15 W/m²K | 0.115 W/m²K | 0.106 W/m²K | 0.089 W/m²K | 0.074 W/m²K |

### 8.1.11 Façade 12 Net zero energy renovation of a Swiss apartment building in Zurich




| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.16 W/m²K | 0.165 W/m²K | 0.153 W/m²K | 0.115 W/m²K | 0.094 W/m²K |

### 8.1.12 Façade 13 Innova project - a new, innovative method for carrying out energy efficient renovations




| | **Prefabricated façade only** | | **Prefabricated façade onto existing building facade** | |
|---|---|---|---|---|
| Report u-value | WUFI prefabricated u-value | Hand calculated u-value | Attached u-value | Hand calculated u-value |
| 0.1 W/m$^2$K | 0.107 W/m$^2$K | 0.103 W/m$^2$K | 0.083 W/m$^2$K | 0.072 W/m$^2$K |

# 9 Appendix B

## 9.1 U-value of the prefabricated façade onto the existing façade

### 9.1.1 Façade 1 TES

Details of structure

| Layer | Thickness (mm) | Conductivity (W/mK) | Resistance ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Mineral wool | 30 | 0.040 | 6.00 |
| Cellulose fibre | 240 | 0.040 | 0.75 |
| Timber board frame | 4 | 0.130 | 0.31 |
| External cladding | 15 | 0.730 | 0.02 |
| External | | | 0.06 |
| **Total resistance 11.39 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/11.39
U-value=0.088 $W/m^2K$

| Layer | Thickness (mm) | Conductivity (W/mK) | Resistance ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Mineral wool | 30 | 0.040 | 6.00 |
| Cellulose fibre | 240 | 0.040 | 0.75 |
| Timber board frame | 4 | 0.130 | 0.31 |
| External cladding | 15 | 0.730 | 0.02 |
| External | | | 0.06 |
| **Total resistance 7.26 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/7.26
U-value=0.138 $W/m^2K$

### 9.1.2 Façade 2 Multi-active

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Rockwool | 19 | 0.040 | 0.48 |
| OSB Boards | 19 | 0.13 | 0.14 |
| Rockwool | 120 | 0.040 | 3.00 |
| OSB Boards | 15 | 0.13 | 0.11 |
| MDF Board | 19 | 0.17 | 0.11 |
| Solar Comb | 30 | 0.03 | 1.00 |
| Ventilated Air Gap | 29 | 0.18 | 0.16 |
| Toughened Safety Glass | 6 | 0.2 | 0.03 |
| External | | | 0.06 |
| **Total resistance 9.35 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.35
U-value=0.106 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Rockwool | 19 | 0.040 | 0.48 |
| OSB Boards | 19 | 0.13 | 0.14 |
| Rockwool | 120 | 0.040 | 3.00 |
| OSB Boards | 15 | 0.13 | 0.11 |
| MDF Board | 19 | 0.17 | 0.11 |
| Solar Comb | 30 | 0.03 | 1.00 |
| Ventilated Air Gap | 29 | 0.18 | 0.16 |
| Toughened Safety Glass | 6 | 0.2 | 0.03 |
| External | | | 0.06 |
| **Total resistance 5.21 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/5.21
U-value=0.191 $W/m^2K$

### 9.1.3 Façade 3 Alingsås

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Plastic foil | 2 | 0.160 | 0.01 |
| Flexible Rockwool | 68 | 0.040 | 1.70 |
| EPS Boards | 225 | 0.037 | 6.08 |
| Graphite EPS board | 30 | 0.037 | 0.81 |
| Insulation boards | 20 | 0.130 | 0.15 |
| Ventilated gap | 43 | 0.18 | 0.23 |
| Vertical steel | 22 | 50.00 | 0.00 |
| Brick cladding | 20 | 0.840 | 0.02 |
| External | | | 0.06 |
| **Total resistance 13.32 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/13.32
U-value=0.075 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Plastic foil | 2 | 0.160 | 0.01 |
| Flexible Rockwool | 68 | 0.040 | 1.70 |
| EPS Boards | 225 | 0.037 | 6.08 |
| Graphite EPS board | 30 | 0.037 | 0.81 |
| Insulation boards | 20 | 0.130 | 0.15 |
| Ventilated gap | 43 | 0.18 | 0.23 |
| Vertical steel | 22 | 50.00 | 0.00 |
| Brick cladding | 20 | 0.840 | 0.02 |
| External | | | 0.06 |
| **Total resistance 9.18 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.18
U-value=0.109 $W/m^2K$

### 9.1.4 Façade 4 Semi prefabricated standardised retrofit

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Gypsum fibre board | 10 | 0.32 | 0.03 |
| Mineral wool compressed | 140 | 0.04 | 3.5 |
| Gypsum fibre board | 10 | 0.32 | 0.03 |
| Vacuum insulation | 20 | 0.007 | 2.85 |
| Mineral wool | 100 | 0.04 | 2.5 |
| Glulam | 3 | 0.048 | 0.06 |
| External | | | 0.06 |
| **Total resistance 13.29 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/13.29
U-value=0.075 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Gypsum fibre board | 10 | 0.32 | 0.03 |
| Mineral wool compressed | 140 | 0.04 | 3.5 |
| Gypsum fibre board | 10 | 0.32 | 0.03 |
| Vacuum insulation | 20 | 0.007 | 2.85 |
| Mineral wool | 100 | 0.04 | 2.5 |
| Glulam | 3 | 0.048 | 0.06 |
| External | | | 0.06 |
| **Total resistance 9.15 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.15
U-value=0.109 $W/m^2K$

### 9.1.5 Façade 5 Large size prefabricated steel frame retrofit

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Mineral wool | 100 | 0.04 | 3.5 |
| Mineral wool | 200 | 0.04 | 0.03 |
| MDF Board | 19 | 0.17 | 0.11 |
| Air gap | 30 | 0.18 | 2.5 |
| Brick tile cladding | 40 | 0.695 | 0.06 |
| External | | | 0.06 |
| **Total resistance 10.52 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity

U-value=1/total thermal resistance

U-value=1/10.52

U-value=0.095 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Mineral wool | 100 | 0.04 | 3.5 |
| Mineral wool | 200 | 0.04 | 0.03 |
| MDF Board | 19 | 0.17 | 0.11 |
| Air gap | 30 | 0.18 | 2.5 |
| Brick tile cladding | 40 | 0.695 | 0.06 |
| External | | | 0.06 |
| **Total resistance 6.35 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity

U-value=1/total thermal resistance

U-value=1/6.35

U-value=0.157 $W/m^2K$

### 9.1.6 Façade 6 Prefabricated metal panel retrofit

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| XPS insulation | 120 | 0.03 | 4 |
| Expanded black cork insulation | 60 | 0.04 | 1.5 |
| Aluminium cladding | 6 | 46 | 0.0001 |
| External | | | 0.06 |
| **Total resistance 9.82 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.82
U-value=0.102 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| XPS insulation | 120 | 0.03 | 4 |
| Expanded black cork insulation | 60 | 0.04 | 1.5 |
| Aluminium cladding | 6 | 46 | 0.0001 |
| External | | | 0.06 |
| **Total resistance 5.68 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/5.68
U-value=0.176 $W/m^2K$

### 9.1.7 Façade 7 ECO sandwich

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| XPS insulation | 200 | 0.04 | 5 |
| Expanded black cork insulation | 40 | 0.23 | 0.17 |
| Aluminium cladding | 60 | 0.3929 | 0.15 |
| External | | | 0.06 |
| **Total resistance 9.64 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.64
U-value=0.104 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| XPS insulation | 200 | 0.04 | 5 |
| Expanded black cork insulation | 40 | 0.23 | 0.17 |
| Aluminium cladding | 60 | 0.3929 | 0.15 |
| External | | | 0.06 |
| **Total resistance 5.5 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/5.5
U-value=0.182 $W/m^2K$

### 9.1.8 Façade 9 Vacuum insulated prefabricated elements

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| plasterboards | 15 | 0.13 | 0.11 |
| Concrete inner shell | 150 | 0.0372 | 4.03 |
| VIP insulation material | 50 | 0.007 | 7.14 |
| Face concrete shell | 70 | 0.072 | 0.97 |
| Wood façade cladding | 55 | 0.21 | 0.26 |
| External | | | 0.06 |
| **Total resistance 16.83 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/16.83
U-value=0.059 W/$m^2$K

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Plasterboards | 15 | 0.13 | 0.11 |
| Concrete inner shell | 150 | 0.0372 | 4.03 |
| VIP insulation material | 50 | 0.007 | 7.14 |
| Face concrete shell | 70 | 0.072 | 0.97 |
| Wood façade cladding | 55 | 0.21 | 0.26 |
| External | | | 0.06 |
| **Total resistance 12.69 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/12.69
U-value=0.079 W/$m^2$K

### 9.1.9 Façade 10 Green façades and building structures LWS

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Air gap | 50 | 0.035 | 1.14 |
| Mineral wool | 50 | 0.4 | 0.13 |
| Vegetation | 100 | 0.2 | 0.05 |
| External | | | 0.06 |
| **Total resistance 5.64 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity

U-value=1/total thermal resistance

U-value=1/5.64

U-value=0.177 W/$m^2$K

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Air gap | 50 | 0.035 | 1.14 |
| Mineral wool | 50 | 0.4 | 0.13 |
| Vegetation | 100 | 0.2 | 0.05 |
| External | | | 0.06 |
| **Total resistance 5.81 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity

U-value=1/total thermal resistance

U-value=1/1.67

U-value=0.599 W/$m^2$K

### 9.1.10 Façade 11 Passive renovation De Kroeven 505 Roosendaal, NL

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| OSB | 15 | 0.1049 | 0.14 |
| Cellulose fibre insulation | 350 | 0.04 | 8.75 |
| Dampopen MDF | 15 | 0.1 | 0.15 |
| Air gap | 30 | 0.18 | 0.16 |
| Wood natural slates | 10 | 0.21 | 0.04 |
| External | | | 0.06 |
| **Total resistance 13.56 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/13.56
U-value=0.074 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| OSB | 15 | 0.1049 | 0.14 |
| Cellulose fibre insulation | 350 | 0.04 | 8.75 |
| Dampopen MDF | 15 | 0.1 | 0.15 |
| Air gap | 30 | 0.18 | 0.16 |
| Wood natural slates | 10 | 0.21 | 0.04 |
| External | | | 0.06 |
| **Total resistance 9.42 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.42
U-value=0.106 $W/m^2K$

### 9.1.11 Façade 12 Net zero energy renovation of a Swiss apartment building in Zurich

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Tolerance/thermal insulation | 20 | 0.036 | 0.55 |
| Cellulose insulation | 180 | 0.0357 | 5.04 |
| Wood fibre board | 40 | 0.053 | 0.75 |
| Exterior render 4 | 1 | 0.25 | 0.004 |
| Exterior render 3 | 4 | 0.25 | 0.016 |
| Exterior render 2 | 1 | 0.87 | 0.001 |
| Exterior render 1 | 4 | 0.87 | 0.004 |
| External | | | 0.06 |
| **Total resistance 10.68 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/10.68
U-value=0.094 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Tolerance/thermal insulation | 20 | 0.036 | 0.55 |
| Cellulose insulation | 180 | 0.0357 | 5.04 |
| Wood fibre board | 40 | 0.053 | 0.75 |
| Exterior render4 | 1 | 0.25 | 0.004 |
| Exterior render 3 | 4 | 0.25 | 0.016 |
| Exterior render 2 | 1 | 0.87 | 0.001 |
| Exterior render 1 | 4 | 0.87 | 0.004 |
| External | | | 0.06 |
| **Total resistance 6.54 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/6.54
U-value=0.153 $W/m^2K$

### 9.1.12 Façade 13 The Innova Project – A new, innovative method for carrying out energy efficient renovations

Details of structure

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Existing Concrete | 100 | 1.280 | 0.08 |
| Polystyrene | 100 | 0.025 | 4.00 |
| Existing concrete | 80 | 1.400 | 0.06 |
| Paroc unm 37pz | 100 | 0.04 | 2.5 |
| Tyvekfabric xmw 060 | 2 | 2.3 | 0.0008 |
| LVL element insulated with Paroc extra plus 300 | 300 | 0.043 | 6.97 |
| Cement base building board | 10 | 0.459 | 0.021 |
| External | | | 0.06 |
| **Total resistance 13.81 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/13.81
U-value=0.072 $W/m^2K$

| Layer | Thickness / (mm) | Conductivity / (W/mK) | Resistance / ($m^2K/W$) |
|---|---|---|---|
| Internal | | | 0.12 |
| Paroc unm 37pz | 100 | 0.04 | 2.5 |
| Tyvek fabric xmw 060 | 2 | 2.3 | 0.0008 |
| LVL element insulated with Paroc extra plus 300 | 300 | 0.043 | 6.97 |
| Cement base building board | 10 | 0.459 | 0.021 |
| External | | | 0.06 |
| **Total resistance 9.67 $m^2K/W$** | | | |

Resistance=thickness/1000/conductivity
U-value=1/total thermal resistance
U-value=1/9.67
U-value=0.103 $W/m^2K$

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