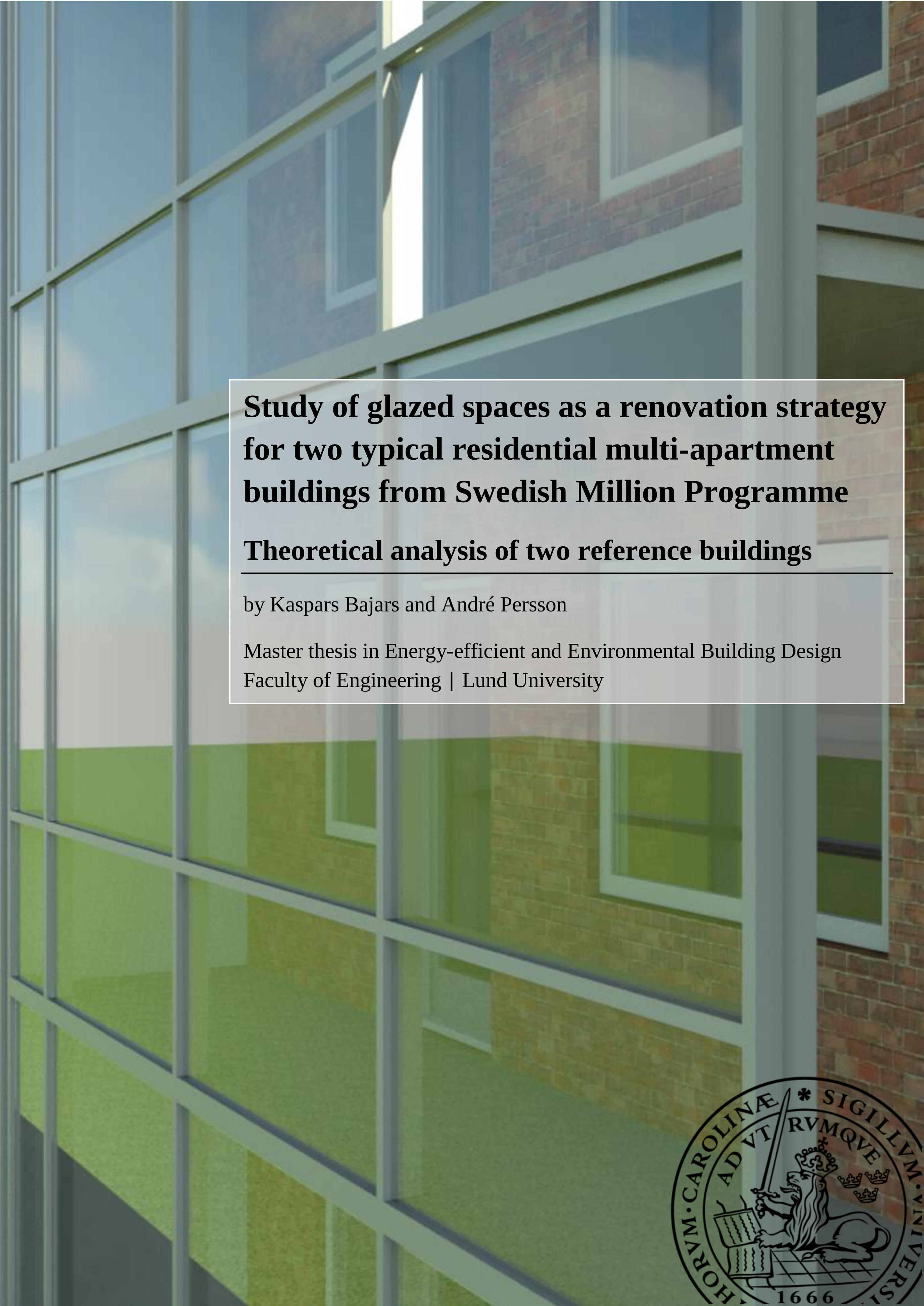

Study of glazed spaces as a renovation strategy for two typical residential multi-apartment buildings from Swedish Million Programme

Theoretical analysis of two reference buildings

by Kaspars Bajars and André Persson

Master thesis in Energy-efficient and Environmental Building Design
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 Malmoe and Helsingborg. 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 architectural and environmental aspects, tenant behavior and needs, their health and comfort as well as the overall economy.

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

Keywords: Energy renovation, Swedish Million Programme, glazed spaces, glazed balconies, double skin façade, energy efficient buildings, thermal comfort, economic feasibility, life cycle profit.

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Abstract

There were around one million apartments built in Sweden during 1965 to 1974 as part of the so called *Swedish Million Programme*, almost half of them concentrated in Stockholm, Gothenburg and Malmoe. These building are now considered unattractive. The need of renovation is urgent in many aspects - ventilation, windows, balconies, facades and sanitary pipe replacement. The total investment cost for the Million Programme has been estimated from 300 billion *SEK* to 500 billion *SEK* and is now one of the most discussed socio-economical and housing policy topics in Sweden. The aim of this study was to investigate the energy saving and thermal comfort potential of adding glazed spaces to existing building façades and determine if and to what extent the glazed alternatives could compete with a fully opaque solution that used traditional insulation instead.

Two different glazed alternatives were proposed and their impact on annual energy demand and thermal comfort in living spaces was tested on one low and one high-rise lamella building in Stockholm, Gothenburg and Malmoe. A sensitivity analysis on energy and thermal comfort was performed for both glazed alternatives. Note that the balcony doors were always closed in all the studied cases. Each solution's life cycle profit was analysed through various future scenarios where the price growth rate for energy and maintenance varied and was accounted with a real yield of 4 *%*. IDA-ICE was the only simulation tool used in this work.

It was found that by implementing glazing elements together with solely opaque elements can reduce the specific energy demand to the same extent as when using only opaque insulation elements. The specific energy use was reduced from 127 $kWh/(m^2 \cdot y)$ to 52 $kWh/(m^2 \cdot y)$ on the low-rise lamella building and from 118 $kWh/(m^2 \cdot y)$ to 56 $kWh/(m^2 \cdot y)$ on the high-rise lamella building, meaning that both buildings could achieve the limits of the Swedish building code. The glazed alternatives showed to contribute more to a better indoor thermal climate as the overheating hours could be decreased by up to 68 *%* compared to the opaque solution when implemented on the low-rise building, meaning that the FEBY 12 standards for thermal comfort could be met. However, when implementing the glazed solutions on the high-rise building, the FEBY 12 requirements could not be met even though the overheating was reduced compared to the opaque solution. The *g*-value of the glazing showed to have the highest impact on both the heating demand and the thermal comfort. The two glazed alternatives showed to not have the same profitability potential as the opaque renovation solution but it could however be solved in some cases by increasing the rent. The high-rise building was generally more prone for profitable investments.

It is suggested that housing companies would chose a fully opaque solution in order to expect a profit on the investment. However, it is also suggested that implementing glazed balconies together with opaque elements could be an option if the building is situated in communities with stronger household economies since the investment is in likely need of a rent increase to become profitable. Additional storage space, improved building appearance, weather resilience and balcony lifespan among many others were also considered as possible co-benefits that were introduced when implementing glazed spaces.

Preface

This work was the Degree Project and final part of the Energy-Efficient and Environmental Building Design Master programme at Lund University. It was conducted in collaboration with the Department of Architecture and Built Environment, the Department of Building Physics and NCC Building as a part of the international *Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building* research project.

Acknowledgments

The authors of this work would like to thank their supervisors Ricardo Bernardo and Petter Wallentén for their guidance and help throughout the entire work process. Rikard Nilsson from Division of Construction Management at Lund University for providing material costs and consulting with life cycle profit calculations; NCC Building for providing us with facilities and welcoming us to their office in Hyllie, Malmoe. Stephen Burke and Ludvig Andersson from NCC Building for administrating our stay at NCC and equipping us with the necessary literature and vital IDA-ICE tips, respectively. Stephan Palmgren from Balco for valuable comments on balcony design, added values and studied parameters. Anders Janson from Solfilmsgruppen for providing prices of coated glass. Last but not least the whole *Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building* research group for sharing their experiences and knowledge.

Malmoe, June 2017

Table of content

1 Introduction

This report was a part of the final stage in the *Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building* research project. Lund's technical university (LTH) and NCC are the main participants which in turns are a part of the international research project on multifunctional facades (IEA SHC Task 56 Building Integrated Solar Envelope Systems for HVAC and Lighting). The results of the respective project will be presented both in Sweden and internationally.

The authors of this report aim to contribute to the respective research project with results and conclusions on how to perform energy-efficient renovation of multi-family buildings from the Swedish Million Programme by application of glazed spaces and investigating the economic feasibility of the proposed solutions.

1.1 Background

There is a large housing stock share in Sweden, built in the period from the 1940's to 1970's, that is in need of renovation (Blomsterberg Å. , 2012). Multi-family buildings in Sweden built from 1961 to 1980 use 135 kWh/m^2 for heating and domestic hot water (DHW) on average (Energimyndigheten, 2015).

The European Union has agreed to reduce the greenhouse gas emissions by 20 *%*, from those documented in 1990, until 2020. The Swedish government is meanwhile targeting a reduction of 40 *%* by 2020 (Swedish Government, 2015). According to the European Commission (2016), the building stock in the EU accounts for 40 *%* of the energy consumption. Around 35 *%* of the EU's building stock is older than 50 years and there is a big total energy saving and CO_2 reduction potential in refurbishing the buildings energy efficiently (European Commission, 2016). Modern technology offers a huge energy-saving potential for these buildings.

The Swedish Million Programme is in need of urgent renovation in many aspects e.g. ventilation, windows, balconies, facades and sanitary pipe replacement. The basis and need varies between properties and are dependent on what has already been done on the property, its design and the owner's financial possibilities. The total investment cost for the Million Programme has been estimated from 300 billion *SEK* to 500 billion *SEK* and is now one of the most discussed socio-economical and housing policy topics. Apartments from the Million Programme are now being demolished in municipalities with a surplus of dwellings where one of the reasons is that they are hard to rent. Demolishing existing apartments could be the case in municipalities where there is a housing shortage if the housing companies decide to demolish and raise new buildings instead of renovating (Boverket, 2014).

It is argued that it is relatively easy to increase the thermal performance of a current building envelope with the help of adding more opaque insulation materials, while the challenge lies in using transparent elements instead. Performed studies shows that there is a large energy saving potential in using a transparent glass skin as a renovation measure as a substitute to the well-established opaque materials (Hamid et al., 2016) (Gosztonyi & Stefanowicz, 2016). It has been found in other studies that the energy efficiency of glazed spaces and their impact on thermal comfort is very sensitive towards orientation, their areal size, various glazing properties and space air-tightness values. However, the usage of glazed balconies and double skin facades as renovation measures is yet to be explored more broadly. The super insulated buildings require cooling, in many cases, to address the excessive summer overheating levels thus it is vital to design a living space that is not only energy-efficient, but also has comfortable indoor thermal conditions.

Using glass as a structural material is very often linked to a modern and contemporary architecture. Mies van der Rohe considered glass to be an expression of the current machine age as he believed that buildings should be a clear and true reflection of their time (Rawn, 2014). Le Corbusier suggested that using glass as one of the core materials improves clarity and sharpness. It significantly increases the potential of architectural combinations and embodies the characteristics of the industrial era. It brings purity based on contemporary aesthetics, which is one of the most superior assertions in architecture (Corbusier, 2012).

With this in mind, it is of high necessity to refurbish these buildings energy- and cost-efficiently (Blomsterberg Å. , 2012). Blomsterberg (2012) considers prefabricated modules to play an important part in today’s well needed innovative and cost-efficient concepts.

1.2 Aim and objectives

The aim of this Master Thesis was to determine how well a typical Swedish Million Programme building with a mix of glazed and opaque elements could perform compared to an identical building with fully opaque elements instead.

The objectives of the study were to:

- Investigate and propose one mixed solution of opaque and glazed materials on a typical high-rise lamella building from the Swedish Million Programme;
- Investigate and propose two mixed element solutions on a typical low-rise lamella building from the Swedish Million Programme;
- Design all solutions to meet the current Swedish Building Code in regards of energy and FEBY 12 thermal comfort performance;
- Perform a sensitivity analysis on both proposed renovation alternatives;
- Determine the economic feasibility for each proposed solution from a life cycle cost perspective;
- Discuss what other benefits than reducing energy demand and providing comfortable indoor climate the proposed design alternatives could potentially have.

1.3 Scope

Investigate how glazed spaces affect energy renovation of two reference multi-apartment building from the Swedish Million Programme by means of annual energy demand, thermal comfort and added values in the three largest Swedish cities. Also discuss how different glazed space properties can impact its thermal performance and impact the living spaces among other benefits.

A fully opaque solution was implemented on the low-rise lamella building and then combined with glazed elements resulting in two different alternatives. Single solution of mixed opaque and glazed elements was implemented on the high-rise lamella building and then compared to an already conducted study.

The comparison between the different cases was mainly based on quantitative method when it comes to energy use, thermal comfort and LCP analysis. The sensitivity analysis on energy use, thermal comfort by means of overheating in living spaces and LCP was tested on both alternatives.

The hypothesis is that although the glazed spaces will create thermal buffer zones adjacent to the existing building façade, they will not be able to outperform opaque elements with traditional thermal insulation in neither energy nor thermal comfort. However, it can be expected that the annual energy demand will remain within the limits of Swedish building code. By adding glazing to the building envelope, the energy renovation will become more appealing as it will increase the added values of living standards.

1.4 Limitations

This study was limited to two contrasting reference buildings and three locations (Gothenburg, Malmoe and Stockholm) that represented typical cases of multi-apartment buildings from the Swedish Million Programme.

Only one multi-active façade renovation solution was implemented on the high-rise lamella building due to the unfavourable building geometry.

Original structures below the ground level were kept and remained unchanged in all cases. Constructive aspects of the façade modules, glazed spaces and their fixing, moisture and fire safety were taken into account to disregard solutions that were clearly not feasible from the beginning and could be seen as a discussion topic. However, a deep analysis was not carried out. The thermal comfort in glazed balconies was not studied since, however, possible overheating was believed to be easily solvable.

The study was performed with closed windows and balcony doors, unless otherwise stated.

1.5 Approach of the study

This research project was carried out in a quantitative approach, starting with a state of art literature review to acquire an overview of existing studies on multifunctional facades and glazed spaces. The attention was emphasized on previous investigations within the current *Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building* research project led by LTH and NCC. The investigated design alternatives and the study of their material properties were decided by subjective evaluation of added value criteria. A qualitative analysis accounting for improved indoor comfort, modernization of the building envelope and others was also conducted. Thereafter, simulations of the energy saving potential of relevant strategies on two reference buildings were carried out using IDA-ICE indoor climate and energy simulation tool. Finally, the cost-efficiency of proposed design alternatives was investigated by means of life-cycle profit analysis and net present value method. The different measures and the work process can be seen in Figure 1.

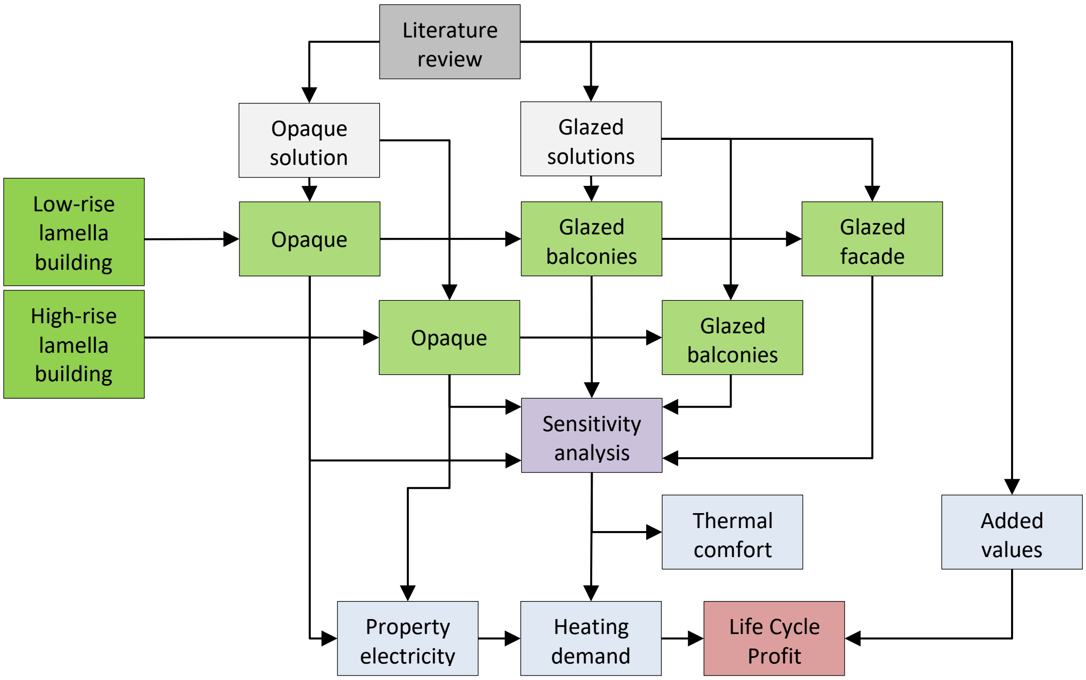


Figure 1: The approach of the study

1.6 Terminology

ACH – air change per hour; times of air exchange of a specific space during one hour.
AHU – air handling unit.
COP – coefficient of performance; ratio of useful heating or cooling provided for the energy that is required in return.
DSF – double skin façade; façade structure consisting of two skins place in the way that allows passage of air in the cavity between them.
Form factor – relation between the building envelope area and heated floor area.
GWR – glass to wall ratio, percentage value of total vertical glazed surface area divided by the total external wall area.
HR – heat recovery.
LCC – life cycle cost; cost calculation method that determines cost efficiency of a specific option which allows to compare it with other alternatives.
LCP – life cycle profit; analytical method that targets reaching the highest long-term profit of an investment.
NPV – net present value;
Shading coefficient – a number used to compare solar radiant heat admission properties of different glazing systems or geographical locations (Turner, 1977).
SHGC – solar heat gain coefficient; a fraction of incident solar radiation that gets transmitted through a glazed surface.
SFP – specific fan power; parameter that quantifies the energy efficiency of an air handling systems.
Time lag – delay of heat flow through an object based on its heat capacity (Lechner, 2015).

A – surface absorptivity; the amount of radiation that a surface can absorb compared to a black body.
ε – surface emissivity; the amount of heat that a surface can radiate compared to a black body.
U_m – mean U-value of building envelope.

1.7 Contributions

In general, the workload of the study was divided equally between the two authors. However, A. Persson was responsible of describing and calculating life-cycle costs while K. Bajars was responsible of performing and describing the IDA-ICE simulations.

2 Literature review

This chapter represents all the obtained theoretical knowledge during a state of art literature review that was required in order to complete this Master Thesis.

2.1 The Swedish Million Programme

In 1965, a parliamentary decision was made that one million apartments would be built during 1965-1974, this is now known as *The Swedish Million Programme* (Formas, 2012). Due to the socio-economic growth in Sweden during the post-war period, more people requested for larger house-holds and better living-standards. The economic boom lead to a population resettlement and labour immigration which made the building industry heavily strained and forced to develop new industrially standardized construction methods. The new standardized construction methods reduced the architectural impact (Industrifakta, 2008) which resulted in today's view of the Million Programme as "monotone buildings" and "concrete boxes" (Formas, 2012). These buildings are generally considered as non-attractive as a result of this construction method. Although most of the residential areas are well performing communities, there is a few which are characterized as excluded from the society. Those are areas with a lower household income, higher unemployment and a higher share of people on welfare from the state. Moreover, buildings in these areas are also more worn-down than their counterparts located elsewhere (SABO, 2009).

The apartments from the Million Programme were built all over Sweden but almost half of them were concentrated within the regions of the three largest cities; Stockholm, Gothenburg and Malmoe (Industrifakta, 2008). These cities have a strong housing market and good economy (SABO, 2009). Lamella buildings were the most commonly built, with a share of 85 % from the million-program building period. Low-rise lamella buildings hold 65 % of the total share and high-rise lamella buildings 20 % (Formas, 2012). Three storey low-rise lamella buildings were the most commonly built and represented around 45 % of the total built apartments during the period. The most commonly used construction material was on-situ concrete and represented 80 % of the built apartments. While bricks represent the largest share of façade materials (33 %) followed by a combination of brick, façade panels, sheet metal and other materials (17 %) and concrete (15 %) (Industrifakta, 2008). These buildings typically have either inset balconies that usually have three enclosed sides by the building envelope and one with guard balustrades or projecting balconies with guarded walk-on platforms that were installed onto the main structure with a direct or post fix or independently supported by columns. Projecting balconies added extra floor space and offered an instant outdoor access, a vital factor in urban multi-storey apartment buildings, without compromising the indoor space (Sapphire Balustrades, 2015). Around 80 % to 93 % of the building stock from the Million Programme era is connected to district heating according to Industrifakta (2008) and Boverket (2010).

The Swedish Association of Public Housing Companies (SABO) had in 2009 around 300 000 apartments that were in need of refurbishments. According to SABO (2009), it would take 30 years to renovate all of them, which means that there is an urgent need of speeding up the refurbishment process. With that being said, it is also necessary to raise the demands that these projects will be implemented in an economically viable way. The costs of the most important refurbishment measures are at least 50 billion *SEK* for SABO and if the refurbishment is even more comprehensive the total cost will increase substantially (SABO, 2009).

2.2 Building regulations and standards in Sweden

There are four different climate zones in Sweden where climate zone 1 is the northern-most zone and climate zone 4 represent the southern-most zone. All buildings should be designed accordingly to the requirements in Table 1 (Boverket, 2016).

Table 1: Climate zone based annual energy demand and average heat transfer coefficient requirements in Sweden.

Climate zone	**1**	**2**	**3**	**4**
Specific energy use (non-electrically heated) / (*kWh / (m²·y)*)	115	100	80	75
Average heat transfer coefficient (U_m) / (*W / (m²·K)*)	0.4	0.4	0.4	0.4

If it is not possible to fulfil the requirements of the specific energy use listed above, the *U*-values in Table 2 should be pursued (Boverket, 2016).

Table 2: Building construction *U*-value requirements.

Construction part	**Roof**	**Wall**	**Floor**	**Window**	**Door**
Heat transfer coefficient / (*W / (m²·K)*)	0.13	0.18	0.15	1.2	1.2

If only a part of façade is being renovated, it could be permitted to target for a higher *U*-value.

Specific fan power (SFP) values from Table 3 should be targeted when replacing the existing ventilation system (Boverket, 2016).

Table 3: Specific fan power requirements for ventilation system replacement.

Ventilation system type	Supply- and exhaust-air with HR	Supply- and exhaust-air without HR	Exhaust air with HR	Exhaust air
SFP / (*kW/(m³/s)*)	2.0	1.5	1.0	0.6

The requirements for thermal comfort are referred to rooms where people are frequently present. The thermal comfort is required to be within the level of a directed operative temperature of 18 °*C* as lowest and a temperature difference of 5 *K* as highest. Furthermore, the floor surface temperature cannot be lower than 16 °*C* and reach higher than 26 °*C*. Additionally, the air velocity within the room should not exceed 0.15 *m/s* during the heating season and 0.25 *m/s* throughout the rest of the year (Boverket, 2016).

When designing a passive house, the Swedish Centre for Zero Energy-buildings (2012) require a calculation and presentation of the indoor temperature for the room or part of building which has the most hours of overheating. The temperature should not exceed 26 °*C* for more than 10 *%* of the period from April to September.

2.3 Previously made energy-efficient renovations

A report on extensive energy efficient refurbishments on buildings from the Million Programme have been carried out by Byman and Jernelius (2012) where it was studied how to halve the energy demand and determine the profitability of such renovation strategies. The study was performed on lamella- and tower block-buildings located in Stockholm and Gothenburg. In Table 4, the taken measures and project outcomes of the respective lamella-buildings are presented.

Table 4: Characteristics and findings of previously refurbished Million Program buildings.

Real estate company and project	Svenska bostäder, Nystad 7	Svenska bostäder, Trondheim 4	Alingsåshem, Brogården	Gårdestensbostäder, Gårdsten
Additional insulation to façade / *mm*	80	50	430-480*	150
Additional insulation to roof / *mm*	300	200	500	150
Additional insulation to basement wall or slab / *mm*	Basement, 80	Basement, 150	Slab, 100	Basement, 200
Specific energy use, before / (*kWh / m²*)	164	214	177	263
Specific energy use, after / (*kWh / m²*)	78	94	58	145
Improved energy efficiency / *%*	52	56	67	47
Rent increase / %	17	24	40	7
Total renovation cost / (*SEK / m²*)	12 000	14 600	19 800	5 615
Energy renovation cost / (*SEK / m²*)	2 140	3 490	5 600	1 070
Yield	Interest rate, 5 %	Interest rate, 5 %	Dividend yield, 5,5 %	Payback period, 20 years
Profitable investment	No	No	Yes	Yes
Measures to make the project profitable	Large rent increase	Large rent increase	Considered to be profitable after 18 years	Considered to be profitable after 20 years

** = The façade itself was replaced, thus the insulation was not additionally added* **(Alingsåshem, 2009)**.

In addition to the measures stated in Table 4, air tightness of building envelope was improved, FTX-ventilation system installed, thermal bridges reduced and indoor standard increased by renovating kitchen, bathroom and other rooms. There was a big difference in how real estate companies estimated the future price-growth rate, which in turn would affect the profitability of these projects (Byman & Jernelius, 2012).

The total and energy-efficient measures cost differed between the projects. The Gårdsten project proved to be the most cost efficient, with a cost of 8 *SEK* per saved *kWh*. Brogården, on the other hand, had the highest investment cost for energy efficient measures and also the largest improvement in specific energy use after the renovation; however, it was the least cost efficient project with a cost of 47 *SEK* per saved *kWh*. When the projects were recalculated using the same interest rate and price growth rate, 5 *%* and 0 *%* respectively, all projects were considered to be profitable within 25 years except for Brogården. However, if the interest rate was decreased to 4.5 *%* (i.e. lower demands on profitability) and the price growth rate increased to 4 *%*, the projects were profitable sooner and Brogården was considered to be profitable within 50 years (Byman & Jernelius, 2012).

Byman and Jernelius (2012) concluded that it was possible to halve the specific energy use in all retrofit projects. It was however not obvious that the measures would be profitable over time. The cost could be minimized by only executing the most cost-effective measures, dependent on the condition of any specific building. It is often less costly to reduce the energy demand in buildings with high energy consumption. The revenues could be increased by increasing the rental area and implementing measures that would increase the attractiveness of the building or built area. It was vital to combine important renovations with energy efficient measures (Byman & Jernelius, 2012).

2.3.1 Tenant perspective on an energy-efficient renovation

A report made by Blomsterberg and Pedersen (2015) assessed how multi-family house tenants perceived renovations that were mainly aimed at energy demand reduction. The common opinion was that numeral renovation measures have improved the living conditions. The most discussed topics in the interviews were measures that impacted the social environment, e.g. new windows, safety doors, improved ventilation system. Not many interviewees mentioned energy savings during in the questionnaire unless they were directly asked. Some tenants experienced coldness and draught from ventilation system and referred to it as a way for the housing company to save money, instead of an environmental friendly measure (Blomsterberg & Pedersen, 2015).

There seemed to be a disparity between what was informed to be an energy-efficient renovation before the work took place and what the tenants could physically see and experience, which subsequently lead to mistrusting the housing company (Blomsterberg & Pedersen, 2015).

At the beginning, many tenants were worried about how the renovation would affect the apartment rent. After the renovation, some of the tenants experienced the rental increase as unfair, indicating that their income was too low to afford it (Blomsterberg & Pedersen, 2015).

2.4 Prefabricated construction

Prefabricated construction is a method of constructing various components of a structure at a production site that are later brought to the construction site where they are assembled as a unit (Constructionworld, 2016). This method is considered to be beneficial from different aspects, the website Constructionworld (2016) presents several benefits; they are as followed:

- Eco-Friendly: Traditional construction methods could lead to a waste of material which could lead to an increased waste. Since prefabricated constructions are assembled in a factory, waste materials could be internally re-cycled. Prefabricated construction method is also considered to be more precise than the conventional on-site method. It can increase the energy-efficiency and eco-friendliness of the component as result of reduced air infiltration and tighter joints.
- Financial Savings: Constructionworld considers this aspect to be one of the most advantageous assets of prefab construction. The production cost of prefabricated modules is often lower since manufacturers usually get volume discounts from material suppliers which are reflected in the cost of production.
- Consistent Quality: These modules are usually built by experienced crew under controlled manufacturing environment. The method avoids possible flaws from construction-built structures like varying craftsmanship skills and schedules from independent contractors.
- Reduced Site Disruption: Since many of the model components are completed at the production site, there are fewer obstructions on the building site. This leads to a more efficient approach with less interference with equipment and material suppliers etc.
- Shorter construction time: Prefabricated modules can be transported and assembled on site which, in most cases, could reduce the construction time by half.

2.5 Passive solar heat gains through glazed spaces

Absorption of all solar radiation, both heat and light, is a function of building size, shape and location, its glazing properties and solar radiation intensity. When incident solar radiation falls on glass, some parts of radiation are reflected back in space, some are absorbed by the glass itself and the rest is transmitted through to the space behind the glass. This proportion is dependent on the properties of a particular glazing type (Turner, 1977). Lechner (2015) suggested that every building with a heating system should take advantage of passive solar heat gain potential if there is an access to the winter sun.

There are two types of admitted solar heat – primary and secondary transmitted as shown in Figure 2. Primary transmitted heat is a result of an incident solar radiation that is transmitted through a glazed surface and is further absorbed and stored in an indoor object, raising its temperature (Turner, 1977). The rising temperature of these objects, increase their emissivity in the electromagnetic spectrum’s long-wave part. However, the opaqueness of glass in the long-wave range traps the passing energy which raises the indoor temperature (Lechner, 2015). Room heat radiation has a wavelength longer than 4000 *nm* which cannot be transmitted by an ordinary glass. This means that the heat radiation within a glazed room is not being transmitted through the glass, but instead reflected and absorbed. The absorbed heat will then be released through low temperature radiation, convection and conduction. That is considered to be the greenhouse effect which causes overheating in glazed spaces (Carlson, 2005). Once glass has reached a thermal equilibrium, all excess heat is re-radiated to indoor and outdoor spaces as secondary transmittance (Turner, 1977).

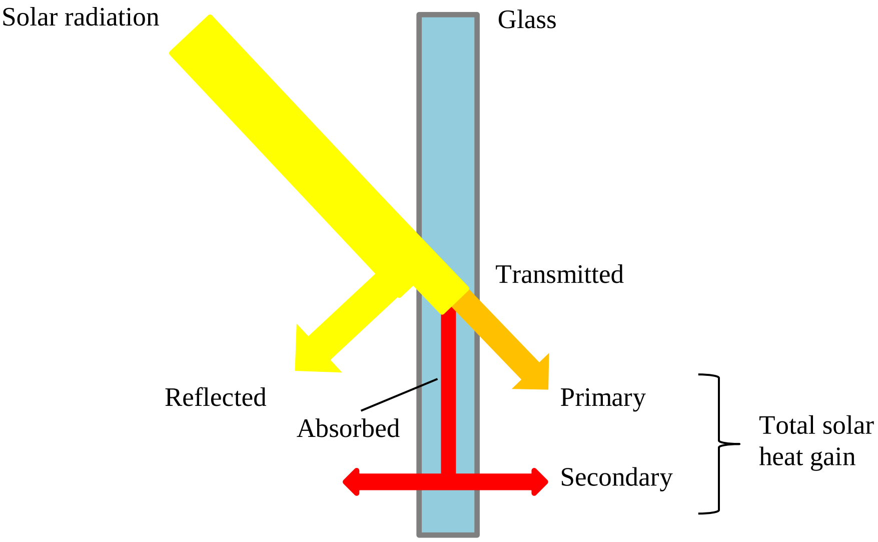
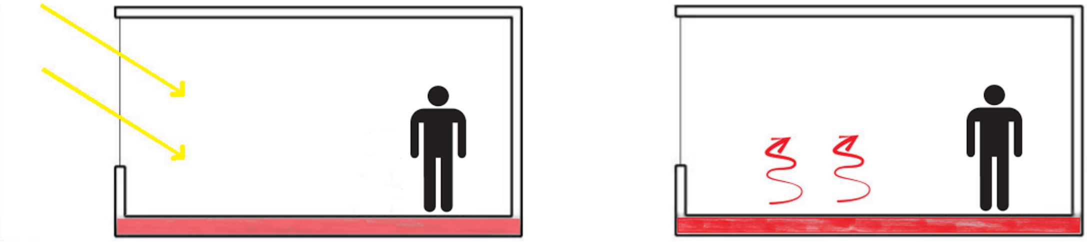


Figure 2: Illustration of solar transmission gains and thermal losses through a glazed surface (Greenspec, 2009).

Solar heat gains can be divided in three major groups – direct, indirect and isolated gains (see Figure 3). The major difference lies in the way the absorbed heat is distributed as the indoor space temperature decreases. Direct gain means that the thermal mass absorbs the radiant solar heat within the glazed space during the day and releases it during night as the indoor temperature decreases. Indirect gains work as direct gains but the space is not heated directly from solar radiation but through convection from the heated thermal mass. Isolated gains use both principles as the glazed space is directly heated from solar radiation which in turn indirectly heats the adjacent room. (Energy Efficiency and Renewable Energy Clearinghouse, 2000).

Direct gain



Day: Thermal mass inside the space absorbs the radiant solar heat
Night: As the space temperature decreases, the thermal mass warms it with radiant heat

Indirect gain

Day: Thermal mass in the DSF absorbs radiant solar heat
Night: Thermal mass warms space with radiant heat outer skin of DSF reduces convection losses

Isolated gain (glazed balcony)

Day: Thermal mass inside the glazed balcony absorbs radiant solar heat
Night: Thermal mass warms space with radiant heat; sun space warms room through convection. External thermal mass allows sustaining warm balcony air temperature for longer

Figure 3: Illustration of direct, indirect and isolated passive solar heat gain concepts.

Allowing a free seasonal passage of solar radiation through glazing can positively contribute to the energy consumption of a building if wisely used (North Carolina Solar Center, 1998). Burberry (1978) proposed that an unobstructed south facing window can have a positive heat balance during the heating season, October – April, in London, where the daily average solar irradiance on the respective surface during the respective period is 1.75 *kWh/m²/day* (Solar Electricity Handbook, 2009). Furthermore, it suggests that vertical south facing glazed surfaces in Sweden could potentially have even more positive heat balance since the daily average solar irradiance during heating season is 1.86 *kWh/m²/day* in Gothenburg, 1.88 *kWh/m²* in Stockholm and 2.22 *kWh/m²* in Malmoe (Solar Electricity Handbook, 2009). It was concluded by North Carolina Solar Center (1998) that south-facing window in northern latitudes receives the peak solar radiation during heating season.

Bolcomb (1988) stated that the orientation is 80 *%* of the solar passive design. True south is the perfect orientation, however, 30 degrees towards east or west will result in similar energy performance (Energy Efficiency and Renewable Energy Clearinghouse, 2000). They also stated in their report that sun space with vertical south facing glazing and no overhead glazing is the simplest and most reliable isolated solar gain system.

Masonry structures are most effective in 10 *cm* to 15 *cm* thickness with surface absorbance of no less than 70 *%* when exposed to direct solar radiation (North Carolina Solar Center, 1998). Holloway (2010) and Lechner (2015) came to similar conclusion, stating that the 10 *cm* in masonry have the highest heat storing efficiency and that any thickness beyond 15 *cm* is pointless, while for wood the most effective heat storing occurs in the first 2.5 *cm*. Windows facing south should have as high solar heat gain coefficient as possible to increase the solar heat gains during heating season if summer overheating can be avoided (Lechner, 2015).

Lechner (2015) suggested sealing the sunspace from main building body during the nights of heating season to avoid heat draining away from indoor spaces.

Mazria (1979) recommended that double skin façades in cold climates, with the average winter outside air temperature between -7 *°C* to -1 *°C*, could be designed according to rule of thumb; 0.43 to 1 m^2 of south facing double skin should be installed for every m^2 of space floor area, although Lechner (2015) suggested using 1:1 ratio instead, which can be achieved by altering the ceiling height of a living area.

There are various types of glazed spaces and façades, among many Carlson (2005) mentions double skin facades (DSF) and fully glazed façades. DSF consists of two skins with a high proportion of glass. Solar protection, mechanical ventilation and openable units can be placed within the cavity of the two skin layers in order to protect it from weather. Openings can be placed in the outer skin to enable natural ventilation; they can be placed at the top or bottom of the façade, or even in each element if it has been divided into sections. The cavity between the layers varies but is often of the size which makes it possible to fit walkways for maintenance purposes. Larger distance between the two skins makes it possible for internal windows to be openable. The DSF is often constructed with one pane glazing in front of the inner skin. Carlsson (2005) presents the following benefits of DSFs:

- Improves the indoor climate;
- Decreases the transmission- and ventilation losses during the heating season;
- The climate control system size can be reduced;
- An integrated solar control system can reduce the solar gains and overheating;
- Reduces outside noise;
- Improves building security;
- Allows implementing a photovoltaic system.

DSF is considered to be a cold façade, meaning that the outer skin is separated from the inner skin (the warm construction) by a ventilated air cavity. The outer skin consists of a sill plate made of one or two units of security glass which is a part of the design and performs as a weather protection for the inner skin. The inner skin has the insulating properties and supports the outer skin structurally. Occurring moisture and excess heat within the cavity is being extracted from the top by means of the stack effect or mechanical ventilation (Carlson, 2005).

2.5.1 Air change rate in unconditioned spaces

Swedish Building Regulations (Boverket, 2016) do not require nor suggest any specific air change rate in unconditioned spaces. However, it has a direct impact on the annual energy demand according to Hilliaho et al. (2015) who performed a sensitivity analysis of intentional and unintentional ventilation rates in glazed spaces. Heusler and Sinnesbichler (2008) stated that air change rate in a double skin façade depends on the external glazing type, distance between the building skins, ventilation opening surfaces and their respective flow coefficients. They investigated the distance-dependent air change coefficient and found that adding a second pane to the external glazing decreased air change coefficient and made the respective space more air-tight. However, the impact of second pane decreased as the distance between the skins was increased. It was suggested by Åke Blomsterberg et al. (2007) that an unconditioned space with localized open joints or permanent ventilation openings would result in 3 *ACH*, however, a well-sealed space with small ventilation openings in 1 *ACH*. Furthermore, 1 *ACH* was also the measured air change rate in glazed access balconies of the Brandaris renovation project in Netherlands (ArchiMEDES, 2003), where single paned sliding windows were used and the glazed façade had a 1000 cm^2 gable opening. Hilliaho et al. (2015) studied a typical 1970s built block apartment building in Finland, which had a similar geometry to low and high-rise lamella buildings from the Swedish Million Programme, and used 2 – 4 *ACH* in the glazed balconies of their base case model. An 80 years old brick hospital building with added glazed façade in Malmoe, Sweden, studied by Elfborg et al. (2013) had an air change rate of 90 *l/s*.

2.5.2 Recorded findings of glazed spaces

Glazed balconies

A comprehensive Finish climate based study with 156 cases, carried out by Hilliaho et al. (2015), has shown that glazed balconies in buildings from the 1960’s to 1970’s can lower the heating need of an apartment by up to 30 *%*. It was shown that the energy saving potential was even slightly higher if the building was placed in or near the three largest cities of Sweden; Stockholm, Gothenburg and Copenhagen (near Malmoe). The structure, i.e. *U*-value, between the glazed space and the apartment played a big role as it was shown that insulating the façade, changing the window or balcony door resulted in a higher insulation level which reduced the benefits from the solar heated balcony space. A recessed balcony had a higher energy saving potential than a protruding balcony due to the higher ratio between glazing towards outside and façade adjacent to indoor spaces. However, by extending the width of the protruding balcony, the energy saving potential increased together with the increment of the thermal buffer zone between indoors and outdoors. The type of glazing, i.e. *U*-value, showed no significance to the energy saving potential unless the air-tightness of the glazing was simultaneously improved. Furthermore, the combination of air-tightness and thermal insulation had a stronger impact in the case of recessed balconies, compared to protruding balconies. It was also proven that the *SHGC* of the glazing was of more importance than the thermal insulation level (Hilliaho, Lahdensivu, & Mäkitalo, 2015).

The energy saving potential from a pre-study made on a low-rise lamella building by Gosztonyi & Stefanowicz (2016) showed that the heating demand for an apartment on the top floor and a middle apartment on the second floor had a reduced heating demand of 18 *%* and 30 *%* respectively. When changing the balcony glazing *U*-value from 5.8 $W/(m^2{\cdot}K)$ to 0.8 $W/(m^2{\cdot}K)$, the heating demand could be reduced by 27 *%* and 44 *%* respectively. It was also shown that using natural ventilation, to reflect tenant habits of ventilating, a heated balcony, had no significant effect on the annual heating need in living spaces. The authors also concluded that larger distances between the building skins result in higher annual energy savings.

B. Jörgensen and J. Hendriksen (2000) concluded that it is possible to design economically feasible and architecturally appealing glazed balconies that can reduce the energy demand up to 40 *%* and protect the building envelope from degradation. The study was made on balconies connected to a brick façade with a *U*-value of 1.45 $W/(m^2{\cdot}K)$. It was found that the balcony glazing area did not influence the energy savings noticeably and the largest saving was obtained using low-e double pane glazing filled with gas. They proposed two principal designs according to balcony type. Recessed balconies should be designed air tight and with insulating glazing while protruding balconies should be designed less air tight or “open” as the authors expressed it. However, it was also mentioned that the protruding balconies would also benefit from the highly-insulated principle. The authors concluded that balconies improved indoor climate during heating season while the expected balcony overheating during cooling season could easily be solved by opening balcony glazing. The report also underlined the positive tenant reactions regarding thermal comfort (B. Jörgensen & J. Hendriksen, 2000).

Glazed facades

Abdul Hamid et al. (2016) studied the energy saving potential and changes in indoor climate when adding outer glass skin to existing brick walls of a building (*U*-value 1.35 $W / (m^2{\cdot}K)$) in Malmoe, Sweden. The east, south and west façades had additional glass skins and around one third of all parameters were studied in a combination with a new ventilation system that had 82 *%* heat recovery efficiency. They conducted that the energy savings increased as a result of an increased glazed façade area and ranged from 5.6 *%* to 25.3 *%*. The energy savings was found to be directly linked to *U*-value and *SHGC* of glazing, the amount of glazing and any combination of these parameters.

Furthermore, the yearly mean temperatures within the cavity decreased as glazing was added to more facades. As a result of an increased temperature within the airspace between the glass skin and the existing brick facade, the indoor temperature increased. This study revealed the necessity of an increased ventilation rate in the building to ensure a comfortable thermal comfort. It was found that the most efficient active cooling measure included mechanical ventilation linked to the cavity between the two building skins by ground integrated ducts. The respective strategy increased the mean indoor air temperature in July by only 0.7 *°C* compared to non-renovated building. Heat extraction from the air cavity was also studied by means of opening two windows (around 0.6 m^2 each) at the upper part of the south façade. However, the effect was moderate. The effect of adding blinds, externally or internally, was considered to be a persuasive passive measure in order to reach a good indoor climate in living spaces. External venetian blinds outperformed internal ones as it improved both – indoor thermal comfort and reduced excess heat accumulation within the airspace, while internal blinds only had a pleasing effect on indoor temperatures (Abdul Hamid, Hilliaho, Lahdensivu, Nordquist, & Wallentén, 2016).

2.6 Passive cooling measures

Solar control system is a potential energy saving measure that should be designed so that it takes advantage of available solar heat during the heating season and avoids adding excess heat during the cooling season. However, if these spaces are poorly designed a conditioning unit is required for cooling premises, which normally increases the maintenance and investment costs by a quarter for new buildings and even more for renovation projects (Turner, 1977).

Solar control systems can be fixed or movable. Movable devices can be subdivided into manually or mechanically operable. Mechanical systems can increase the thermal comfort due to their active response to changing surrounding conditions.

Shading devices are one of the most commonly used solar control systems. They can be manual, mechanical, active or passive. Roof and balcony overhangs above a window are fixed passive structures that reduce the amount of solar irradiation reaching a glazed surface (National Renewable Energy Laboratory, 2001). Blinds, screens and awnings serve the same purpose; however, they can be both movable and fixed. Window openings, vents and partially glazed sunspaces with fixed openings can limit heat flow entering the space and improve excess heat extraction. (Energy Efficiency and Renewable Energy Clearinghouse, 2000).

Mavrogianni et al. (2014) and Rijal et al. (2008) investigated human habits to control indoor climate by opening windows when indoor and/or outdoor temperature increases and concluded that it is an effective method to extract excess heat from living spaces. The concept of opening glazed spaces is shown in Figure 4.

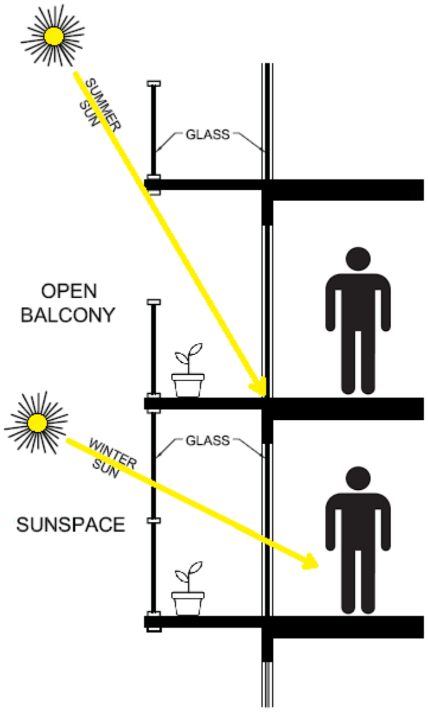


Figure 4: Sunspace opening as a passive cooling measure (Lechner, 2015).

Low-E glass (Figure 5) is a specially coated glazing that has a significantly lower emissivity than the conventional glazing types thus reducing the thermal transmission from indoors to outdoors by reflecting most of the indoor heat back in the room (Pilkington, 2011). It can be considered as a possible passive cooling measure to reduce the overheating levels without significantly reducing the indoor daylight conditions as oppose to shading devices. However, it is a static cooling measure that cannot be turned on and off.

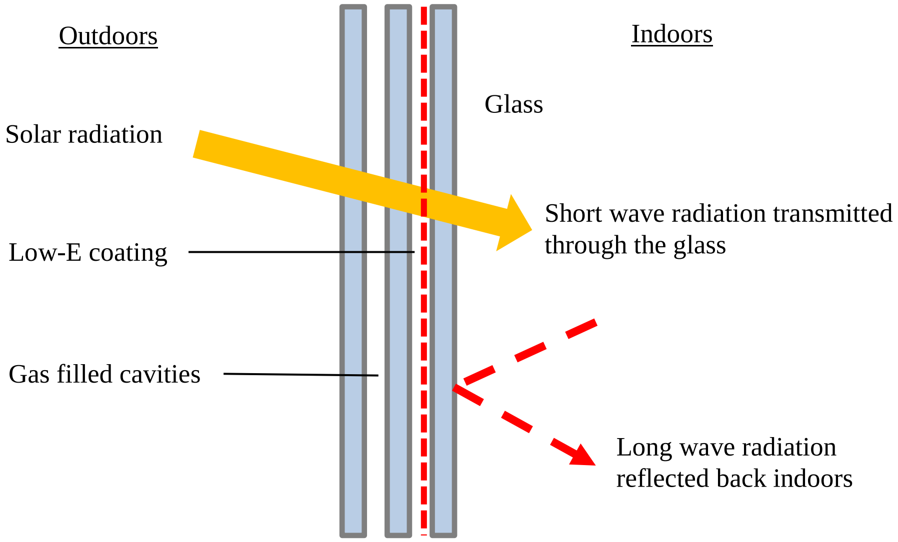


Figure 5: Characteristics of Low-E glazing (Greenspec, 2009).

2.7 Added values of glazed spaces

Glass has always been one of the most fascinating and versatile materials ever produced. It was considered to be a luxurious building material, mainly used in churches and by rich. The start of industrial revolution introduced machinery to the glass industry, which allowed to increase the quality of glass, while decreasing its price making it more affordable to general public (Understand Construction, 2014). It can be argued that glazed spaces and balconies add value to building when correctly designed. They can improve building appearance, indoor environment, energy performance, building m^2 price and other aspects. Many world-famous architects have discussed the importance of glazed spaces in modern architecture and its effect on building design.

The reinvented float glass method, used in modern window production, by Sir Pilkington in 1958, improved and optimized the production process and allowed to commercialize glass (King Fisher Windows, 2012). The development of energy-efficient windows has increased significantly since then, going from leaky single pane to coated air-tight triple glazed windows, increasing the applicability of glass in buildings (Jones, 2015).

Kahn discussed the importance of sun in building design and how its presence could be utilized to its maximum potential by increasing the glazed areas. He said “The sun never knew how great it was until it hit the side of a building” (Hatherley, 2013). The idea of using solar heat for all building types in cold climates started developing in 1920’s, when multiple housing projects that took advantage of solar irradiation were developed by Walter Gropius from the Bauhaus design school (Lechner, 2015). Needless to say, solar heat has become a vital part of the modern architecture since then.

According to North Carolina Solar Center (1998) sun space has three added values – auxiliary heat source, space for plant growing and additional habitable area when the thermal conditions in the space are comfortable enough. A fully glazed sunspace provides full enclosure, increased weather resilience and also improves transparency, unity and fluidity of the added space, the fundamental factors of architecture according to Mies van der Rohe, who is considered to be a pioneer of an extensive glass use in building design (Rawn, 2014). Lechner (2015) suggested that possibly the greatest advantage of glazed spaces is that they improve the indoor environment.

North Carolina Solar Center (1998) claimed that people whose living area is equipped with a sun space consider it to be the most enjoyable part of their estate property. Also, Lechner (2015) underlined the attractiveness of sunspaces in the eyes of their owners. It was also concluded by NCSC (1998) that an increased size of solar space is the common desire for those who already own one. Results of six-step grading system, graded from poor to excellent, follow up tenant survey by Malm et al. (2014) from different energy renovation projects involved in the *E2ReBuild* research group showed that improved balconies are one of the main desires of tenants. The added values of adding extra balcony space and/or converting them into glazed spaces were verified by surveying tenants from 55 apartments located in Augsburg, Munich (both Germany), Oulu (Finland) and Voiron (France), whose balconies where changed as a part of the energy renovation. The overall response was very positive, resulting in 75 – 100 % satisfaction rate. However, residents of Halmstad (Sweden) renovation project, whose balcony remained unchanged, reflected their opinion in an 80 *%* dissatisfaction rate.

According to Balco Balcony Systems LTD (2013) glazing a balcony extends its life expectancy by up to 50 years, improves safety and apartments’ value while increasing the building appearance and reducing the energy costs by approximately 20 *%*. It also reduces draughts, outside noise and possibility of frost damages on the façade where a glazed balcony is installed.

If identical depths are used for both - balconies and DSF, they allow creating a uniform facade surface pattern which also improves the architectural quality of the building according to Mies van der Rohe (Rawn, 2014).

2.8 Opaque solution

A previously made study of a nine-storey high-rise lamella building, built in 1963 and characteristic of a typical Swedish Million Programme multi-apartment building (same high-rise lamella building as investigated in this study) consisting of 105 apartments, was energy renovated. Conditioned area of the existing building was 9235 m^2. The existing building was characterized by poor building envelope with the U_m value of 1.18 $W/(m^2 \cdot K)$, mechanical exhaust air ventilation system, that exhausted air through ducts located in kitchens and bathrooms and had no heat recovery. Heating was performed by a district connected centrally controlled two-pipe hydronic radiator network. The specific annual energy demand of the existing building was measured at 141 kWh/m^2 including the domestic hot water use and property electricity. Domestic hot water used was assumed to be 20 $kWh/(m^2 \cdot y)$ instead of 25 $kWh/(m^2 \cdot y)$ suggested by SVEBY (2009). Annual electricity use was measured in the existing building and recorded at 8.7 kWh/m^2 and was further split for lighting, air handling unit and pump operation. Site-measured annual energy use was than compared to a calibrated IDA-ICE model to match the measured and simulated buildings. The difference in annual energy used in the measured and simulated buildings was neglectable thus the IDA-ICE building model was concluded to be precise enough to simulate the energy saving measures. Their proposed energy saving measures included improving the thermal properties of building envelope, installing a centralized air handling unit (AHU). Improving the building envelope consisted of changing the existing windows and balcony doors with a U-value of 2.4 to 0.8 $W/(m^2 \cdot K)$ for windows and 1.2 $W/(m^2 \cdot K)$ for balcony doors. Reducing the U-value of existing roof structure from 0.48 to 0.1 $W/(m^2 \cdot K)$ and façade structure from 0.47 to 0.13 $W/(m^2 \cdot K)$. The efficiency of the heat recovery was set at 80 *%* and due to limited amount of shaft space, the supply-air ducts were placed within the new façade modules. The obtained energy simulation results showed that space heating could be reduced from 67.5 $kWh/(m^2 \cdot y)$ to 29.7 $kWh/(m^2 \cdot y)$. Furthermore, the specific fan power (SFP) of ventilation system also met the Swedish building code regulations and the respective strategy was considered successful. Photovoltaic solar panels were added for local electricity production to reduce the electricity bought from the grid (Hadzimuratovic & Swedmark, 2016).

The Opaque solution has not been thoroughly studied nor applied on the low-rise lamella building which was investigated in this study. However, R. Bernardo (2017) suggested applying the exact same ventilation method used in high-rise lamella building to the low-riser resulted in lower air velocities and subsequently lower pressure drops which meant that the duct system was designed in a conservative manner. In his simplified calculation, he concluded that each apartment (area of 81.5 m^2) with a minimum air flow requirement of 28.5 *l/s* per apartment. Two separate ductworks with dimensions of 110 *mm* x 80 *mm* were used for each apartment, one on each façade. From the high-rise building, each ductwork was designed to transport 19 *l/s* without surpassing the considered pressure drop limit of 1 *Pa/m*. In the case of low-rise building each of the two air supply ducts would transport 14.3 *l/s* instead, which means that pressure drops would be lower than the considered 1 *Pa/m* limit and also lower than those calculated for the high-rise building. In addition, the critical path of low-rise building ventilation systems was shorter than in the high-rise due to fewer floors that the air had to travel to.

2.9 Life cycle cost

There are a variety of tools to use when calculating the life cycle cost (LCC) which allows monitoring and estimating costs and schedules. Economic analysis is an important, simple yet effective design making strategy to analyse different design alternatives and their respective investment costs (V. Farr, 2011).

The total concept method is a procedure which aims to look at actions that are combined together from different energy saving solutions in order to not only implement the most profitable measures, but also include measures that contribute to energy savings which they otherwise could not achieve on their own. In this way, energy saving measures that are not profitable on their own, can then as a package among other profitable measures satisfy the required investment's profitability (BELOK, 2015).

2.9.1 Calculation method

There are three methods to calculate profitability. The pay-off (also called pay-back) method is a concept which calculates the repayment period i.e. the period where the surplus of income exceeds the initial investment cost. It is considered to be a simple method which does not include any interest rates or depreciations. The pay-off method does not consider any capital costs. An investment is considered to be profitable if its actual payback time is shorter than a predetermined payback time. This method is considered to favour short-term investments and may not be suitable for all LCC analysis (SABO, 2011) (Byman & Jernelius, 2012).

The present value method estimates all expected present and future costs during its life time as total cost in today's cash value. Thus, one can compare the initial investment with the excess of payment caused by the investment. An investment is considered profitable if the present value is positive. The present value method is favourable since it includes all quantified effects, however it is harder to apply than other methods (SABO, 2011) (Byman & Jernelius, 2012).

Life cycle cost analysis (LCCA) is essentially a form of yield based calculation method that compares the future energy and maintenance costs for alternative energy-efficient investments. Cash flow differences in alternate solutions, caused by various investments, should also be considered in the calculation model. The calculation period reaches over the whole economic life span. The investment with the total lowest life cycle cost is the most profitable. The method is favourable since it considers the investments total life span. Byman and Jernelius (2012) argue that the total life cycle cost of a solution alone is not enough to determine the profitability of an investment. Thus, an LCC of one measure needs to be put in perspective to an LCC of alternative solutions (Byman & Jernelius, 2012).

It is also important to consider the relation between development of the results, cash flow and assets. A project can seem profitable by definition but if the above ratio is not in favour of a company's economic conditions it will in reality become unprofitable. SABO (2011) argues that measures which result in higher borrowing leads to higher interest costs, which means that the cash flow is highly influenced by the achieved energy savings.

2.10 Validation of IDA-ICE simulation tool

IDA-ICE is a dynamic multi-zone and whole year simulation tool for energy consumption and indoor climate studies. It allows to have a holistic approach on the building energy models, including building envelope, installation and control systems as well as the plant. The program is designed mainly for HVAC designers and sustainability engineers (EQUA, 2017).

IDA-ICE building simulation tool has been validated and described in detail by Kropf and Zweifel (2007) and Moosberger (2007). Crawley et al. (2008) investigated and concluded that IDA-ICE is accurate and suitable for analytical studies of glazed spaces; Hilliaho et al. (2015) came to the same conclusion.

IDA-ICE allows to design the windows as standard, with constant thermal conductivity, transmittance and emissivity properties, or detailed (Detwind) ISO 15099 (2003) based model, with dynamic properties. Therefore, it was vital to review the findings of previously performed studies on static and dynamic calculation model differences to receive accurate simulation results for a precise evaluation of the proposed glazed balcony solution. Thalfeldt et al. (2016) noted that solar transmittance and absorbance of standard window glazing was calculated by a fixed angle dependency curve method, while detailed window used physical formulas and also took the mutual pane interaction into account.

The significant effect of indoor and outdoor temperature difference on window thermal transmittance has been addressed by Kurnitski et al. (2004), also Petersen (2014) reflected on this matter calculating the heating energy demand of a building located in cold Nordic climate zone with static and dynamic hourly window *U*-value. It was concluded that dynamic value gives higher accuracy and minimizes the possible underestimation of annual heating demand, therefore making it the preferred calculation method. Arici et al. (2015) stated in their numerical study that the energy balance of glazing materials is dependent on changing outdoor conditions.

The comparison between site-measured and IDA-ICE simulated air temperatures in glazed balconies was performed by Hilliaho et al. (2015) and it was concluded that detailed window had higher accuracy than standard window compared to the measured data. The sensitivity analysis comparing standard and detailed window models in IDA-ICE 4.6 modelling tool performed by Thalfeldt et al. (2016) showed that using standard window resulted in lower annual heating demand and more overheating hours than when using detailed window. It was found that a higher temperature difference than the 20 *K* used in ISO 15099 (2003) between indoors and outdoors result in higher window thermal conductivity, which ultimately decreases window *U*-value. In addition, fewer panes in window resulted in larger thermal conductivity differences between the two models. Eventually, two-paned detailed window model transmitted 5.5 *%* lesser solar radiation annually than identical standard window.

3 Methodology

The proposed solutions and the sensitivity analysis were defined through numerous simulations where different settings, found during literature reviewing, were evaluated. Figure 6 shows the process where discontented settings were changed until a satisfying parameter was found and to be considered worth investigating further by the authors.

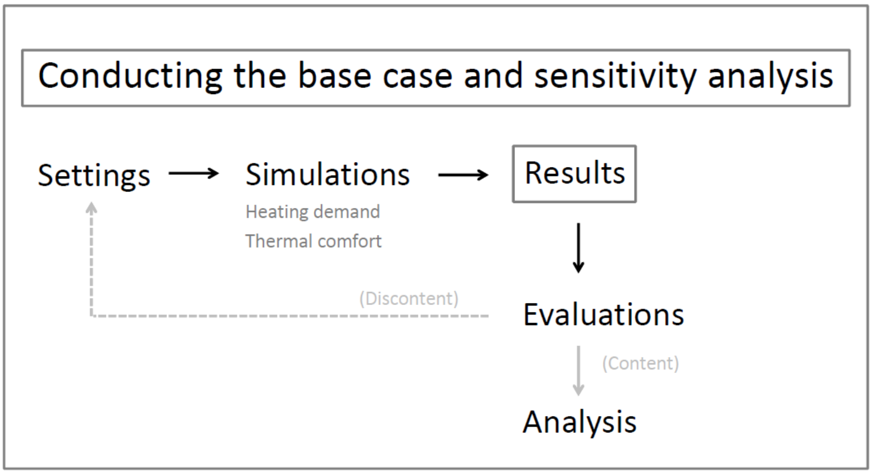


Figure 6: Graphical illustration of energy simulations and parametric study approach.

3.1 Original buildings and Opaque solution

Both IDA-ICE building models have been provided by NCC Sweden. The original high-rise lamella building and its characteristics have already been discussed by Hadzimuratovic and Swedmark (2016) and thus was not addressed any further in this work. However, different input values for the original low-rise lamella building can be seen in Appendix A. In addition to Appendix A, the specific thermal properties of different construction parts of low-rise lamella building are shown in Appendix D.

A detailed study of the fully opaque solution, the design and energy calculations of FTX ventilation system for high-rise building has already been conducted by Hadzimuratovic and Swedmark (2016). They investigated the theoretical energy saving potential and cost-effectiveness of facade module integrated active technologies that could be applied on the Swedish Million Programme buildings. In order to make both low and high-rise lamella buildings more comparable, changes to IDA-ICE model input values were made to the finalized high-rise lamella solution proposed by Hadzimuratovic and Swedmark (2016). They consisted of changing the COP of fuel carrier to 0.90, heating coil efficiency in AHU changed to 1.0, the AHU heat exchanger was shut off from June to August, new thermal bridges (0.0827 $W/(m^2 \cdot K)$), window *SHGC* was changed to 0.56 and the heating setback was set to 20 $°C$ in apartments and utility rooms and 16 $°C$ in staircases.

The fully opaque solution has not been studied on the low-rise lamella building. In order to improve the replicability of the findings from high-rise building, same constructions, installations and ventilation strategy was used for the low-riser. Since every apartment in low-rise building had two longitudinal façades, the ducting was divided in two for each apartment. The size of the ductwork was kept the same as in the high-rise lamella building for simplicity of implementation and high replicability. Some minor adjustments were carried out to the Opaque building model; removed cooling units, recalculated thermal bridges (0.0698 $W/(m^2{\cdot}K)$), new window and balcony door U-value (0.8 $W/(m^2{\cdot}K)$), the AHU heat exchanger was shut off from June to August. These changes were made to improve the model accuracy, allow studying indoor thermal comfort and passive cooling measures as a part of sensitivity analysis.

The form factor of low-rise lamella buildings was 1.03, while it was 0.79 in case of high-rise. Low and high-rise lamella buildings had 0.39 and 0.48 *GWR*s, respectively.

3.2 Alternative 1

3.2.1 Low-rise lamella

First alternative for the low-rise lamella building was built based on opaque renovation alternative model with only altering the south-west façade with balconies. The existing protruding balconies were demolished and new, longer ones were installed and glazed. They were designed to cover the whole south-west external wall adjacent to apartments.

Balconies were constructed as additional building bodies, which were set adjacent to main building body. Every balcony was created as a separate zone to increase the accuracy of the heating demand and overheating hours in spaces behind glazed balconies and also have a better control options over balcony sensitivity to different studied parameters. All neighbouring balconies were made adjacent to one another and manually connected to spaces behind them. Balcony glazing was made without specifying exact frame or fixing location but using a frame fraction of 0.1 instead. Therefore, balcony glazing frames shown in Figure 6 have only an illustrative purpose.

Green and white surfaces in Figure 7 represent components from Opaque solution and original building, respectively. White areas remained untouched and would only have a cosmetic renovation. These were not the actual colours used in the simulation building model, but only to illustrate the different building component types.

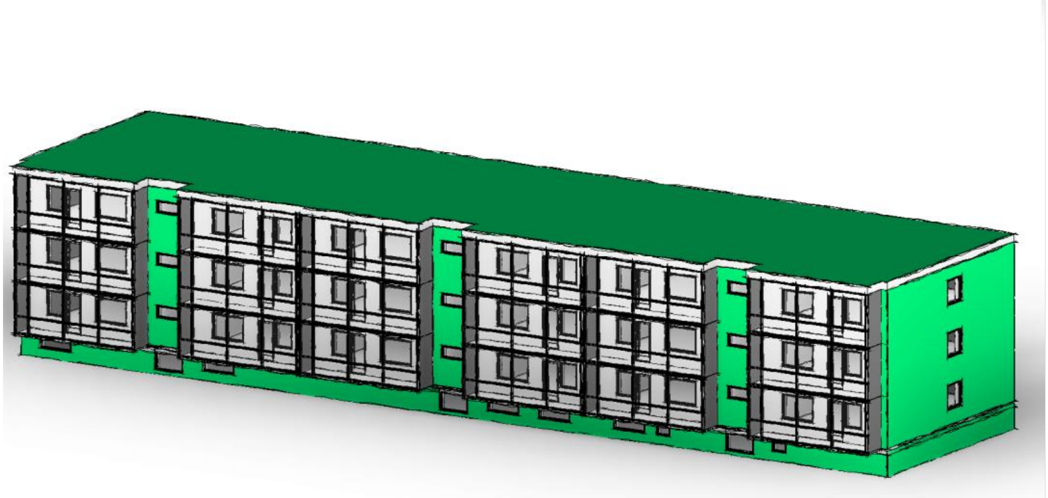


Figure 7: Graphical representation of low-rise lamella building ALT 1.

All input data for base case of low-rise lamella building Alternative 1 is shown in Table 5 Specific transmission loss values can be seen in Appendix D.

Table 5: Base case input data of low-rise lamella building ALT 1.

Parameter	**Value**
Location	Gothenburg (57.7089 ° N, 11.9746 ° E), Sweden
Weather file	Gothenburg-Säve (ASHRAE 2011)
Orientation	South-west (230 °)
Wind profile	Suburban (ASHRAE 1993)
Building geometry	48.44 x 11.08 x 10.8 *m* (L x W x H)
Heated floor area	2148 m^2
Number of apartments	18
Apartment size	82 m^2
Insulated, existing wall *U*-value	U=0.15, U=0.31 $W/(m^2 \cdot K)$
Roof, floor *U*-value	U=0.08, U=0.39 $W/(m^2 \cdot K)$
Surface properties	A=0.5, ε=0.9
Window, door properties	U=0.8 $W/(m^2 \cdot K)$, $SHGC$=0.26
Windows and doors behind balcony*	U=0.8 $W/(m^2 \cdot K)$, $SHGC$=0.52
Building air leakage	0.01777 $l/(s \cdot m^2)$, building envelope
Thermal bridges	0.073 $W/(m^2 \cdot K)$, building envelope
Heating set point	20 °*C* apartments, 16 °*C* utility rooms
Heating system	Ideal heater, COP=0.9
Supply air rate	0.35 $l/(s \cdot m^2)$
Supply air temperature	19 °*C*
Heat recovery system	FTX=80 % temperature efficiency
Internal gains	4 W/m^2 apartments, 0.83 W/m^2 utility rooms
Openness of glazed surfaces	Always fully closed
Shading of glazed surfaces	No shading installed
Balcony geometry	6.9 x 1.55 x 2.6 *m* (L x D x H)
Balcony type	Protruding with glazed front
Balcony structure properties	U=1.195 $W/(m^2 \cdot K)$, ρ=500 kg/m^3, c=1050 $J/(kg \cdot K)$
Balcony glazing properties	U=5.4 $W/(m^2 \cdot K)$, $SHGC$=0.44
Balcony air leakage	2 *ACH*

** Different SHGC than windows and doors not facing balconies.*

3.2.2 High-rise lamella

Similar to low-rise lamella building, also the proposed glazing alternative for the high-rise lamella building was built on the base of opaque building model, where the existing inset balconies were closed by installing glazing on the open side. The existing façade walls facing balcony space remained not renovated, keeping the same structure and appearance as in the original, existing building. Other parts of the building were designed according to Opaque solution.

Balconies were designed as additional building bodies in IDA-ICE and set adjacent to main building body. Every balcony contained a separate zone to improve their controllability in IDA-ICE simulation tool. Balcony spaces were adjacent to two or one other balcony space, located below and/or above them. Exact location of balcony glazing frames and fixing points was not specified but frame fraction of 0.1 was used instead, which meant that balcony glazing frames shown in Figure had only an illustrative purpose.

Green and grey surfaces in Figure 8 represent components from Opaque solution and original building, respectively. Grey areas are ones that remained untouched and would only have a cosmetic renovation. These were not the actual colours used in the simulation building model, but only to illustrate the different building component types.

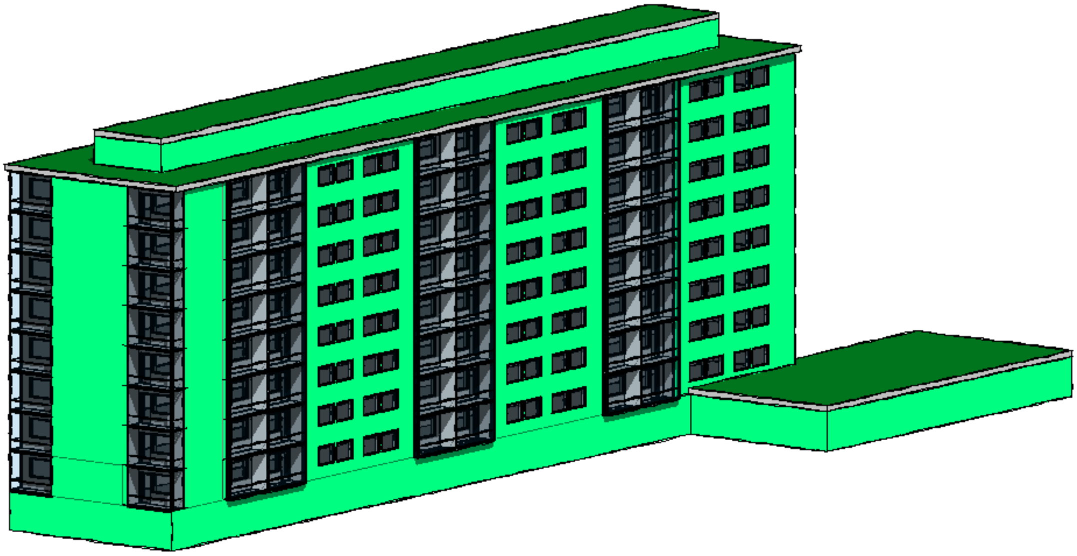


Figure 8: Graphical representation of high-rise lamella building ALT 1.

All input date for base case of high-rise lamella building Alternative 1 is shown in Table 6. Specific transmission loss values can be seen in Appendix D.

Table 6: Base case input data of high-rise lamella building ALT 1.

Parameter	Value
Location	Gothenburg (57.7089 ° N, 11.9746 ° E), Sweden
Weather file	Gothenburg-Säve (ASHRAE 2011)
Orientation	South-east (127 °)
Wind profile	Suburban (ASHRAE 1993)
Building geometry	69.4 x 13.6 x 24.39 *m* (L x W x H)
Heated floor area	9235 m^2
Number of apartments	105
Apartment size	67 m^2
Insulated, existing wall U-value	U=0.128, U=0.460 $W/(m^2\cdot K)$
Roof, floor U-value	U=0.096, U=3.476 $W/(m^2\cdot K)$
Surface properties	A=0.5, ε=0.9
Window, door properties	U=0.8 $W/(m^2\cdot K)$, $SHGC$=0.26
Windows, doors behind balcony	U=0.8 $W/(m^2\cdot K)$, $SHGC$=0.52
Building air leakage	0.03 l/(s·m²), building envelope
Thermal bridges	0.091 $W/(m^2\cdot K)$, building envelope
Heating set point	20 °*C* apartments, 16 °*C* utility rooms
Heating system	Ideal heater, *COP*=0.9

Supply air rate	0.35 $l/(s\cdot m^2)$
Supply air temperature	19 $°C$
Heat recovery system	FTX=80 % temperature efficiency
Internal gains	4 W/m^2 apartments, 0.83 W/m^2 utility rooms
Openness of glazed surfaces	Always fully closed
Shading of glazed surfaces	No shading installed
Balcony geometry	8.4 x 1 x 2.6 *m* and 1.38 x 3.8 x 2.6 *m* (L x D x H)
Balcony type	Recessed with glazed front
Balcony slab	U=1.195 $W/(m^2\cdot K)$, ρ=500 kg/m^3, c=1050 $J/(kg\cdot K)$
Balcony glazing properties	U=5.4 $W/(m^2\cdot K)$, $SHGC$=0.44
Balcony air leakage	2 *ACH*

3.3 Alternative 2

Second alternative was only proposed for the low-rise lamella building only since the building geometry of high-rise lamella building was not considered favourable for installation of a double skin façade from an architectural perspective due to recessed balcony type. The building model of Alternative 2 was based on the model of Alternative 1 (ALT 1). In addition to extended balconies, a glazed building skin was installed in front of south-west façade in places where it is adjacent to utility rooms, staircases and basement. The depth of the DSF was identical to the depth of the balconies to create a smooth façade surface.

The simplified model of double skin façade was designed by connecting four additional building bodies, consisting of single zone each, to the main building body and the glazed balconies. Double skin volume consisted of four zones, whereas one was installed along the whole ground floor on south-west façade and the other three in front of the existing staircases, also facing south-west. All four zones were mutually joined by openings and manually connected to the adjacent zones from main building body and glazed balconies. Frame fraction of 0.1 was used for the glazed façade, therefore, DSF frames and fixing points shown in Figure had only an illustrative purpose.

Green and white surfaces in Figure 9 represent components from the Opaque solution and original building, respectively. White areas are ones that remained untouched and would only have a cosmetic renovation. These were not the actual colours used in the simulation building model, but only to illustrate the different building component types.

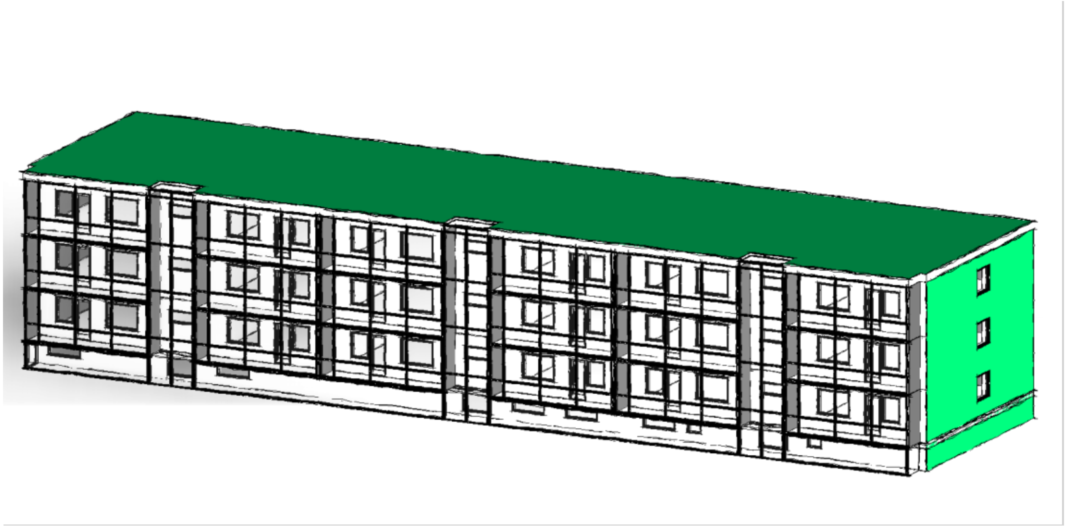


Figure 9: Graphical representation of low-rise lamella building ALT 2.

Since Alternative 2 was based on Alternative 1, all additional parameters for the base case of low-rise lamella building are presented in Table 7. Specific transmission loss values can be seen in Appendix D.

Table 7: Base case input data of low-rise lamella building ALT 2.

Parameter	Value
Double skin façade type	Column
DSF glazing properties	U=5.4 $W/(m^2 \cdot K)$, $SHGC$=0.44
DSF air leakage	2 ACH

3.4 Sensitivity analysis

Sensitivity analysis of both glazed design alternatives was conducted in order to assess their replicability and sensitivity of different parametric values that were considered to have medium to large effect on their energy and thermal comfort performance. The effect of tenant behaviour was not included in the sensitivity analysis thus additional 4 $kWh/(m^2 \cdot y)$ for airing, suggested by SVEBY (2009) can be added to the estimated annual heating demand results.

3.4.1 IDA-ICE accuracy assessment

The significance of this project required to perform large series of detailed and accurate energy and thermal comfort simulations, which are very time demanding. However, the time available for the authors of this work suggested not increasing the simulation time of sensitivity analysis, therefore it was decided to perform an accuracy assessment, on ALT 1 of low-rise lamella building located in Gothenburg, with a mix of different tolerance and time step values, where their impact on the energy results, overheating hours and simulation time was assessed and compared to one another.

IDA-ICE has default integrated simulation parameter values, 0.02 tolerance and 1.5 *h* time step, which can be found under the Simulation Data object sub-tab Advanced. An acceptable simulation speed was reached when using these default values. The available information under help tab stated that tolerance value determines the accuracy of equation solving, therefore suggesting that a number closer to zero, would result in higher accuracy. On the other hand, reducing the tolerance value results in a shorter simulation time, while compromising the accuracy of obtained results. Same applies for maximal time step value, decreasing the value reduces the time period between measurements. It is suggested that increasing the time steps might result in lack of stability in results. Different tested values using cross simulation method for the ALT 1 of low-rise lamella building are presented in Figure 10.

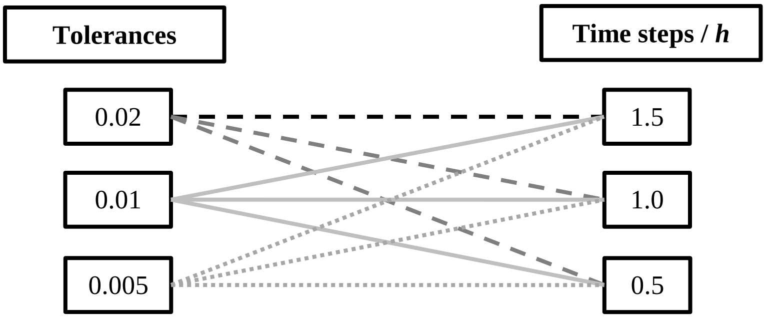


Figure 10: Cross simulation of different studied tolerance and time step values on ALT 1 of low-rise building located in Gothenburg. Black dashed line represents the base case combination.

The results of the accuracy assessment are presented in Appendix B.

3.4.2 Window and balcony glazing shading factor

The Million Programme buildings are located in different locations that have various shading conditions from the surrounding environment. The neighbourhoods where these building are located often have a different plot layout, therefore precise shading conditions cannot be replicated for all cases. Shading factor, however, is a simplified numerical value that represents possible shading objects in a near distance and has a high applicability. Since replicability of proposed renovation strategy was of high importance, it was decided to use shading factor instead of designing the specific plot conditions in IDA-ICE model.

Shading factor is dependent on shading objects in the surrounding environment and distance to them from the shaded object. Urban, suburban and rural areas intend to have different shading factors. SVEBY (2009) design guidelines suggest to use 0.5 shading factor for external windows which also includes shading by own building geometry and obstacles in the near distance. The respective value is then used to reduce the manufacturer given transmittance properties of a window by half. However, the shading factor of large glazed spaces was not addressed in any literature or standards that were reviewed in the early stages of this work. Thus, the authors of this work interpreted that the shading factor stated by SVEBY (2009) should be applied on the outermost glazed components that are exposed to the solar radiation first. However, the innermost component, window, should have no shading factor, meaning that it performs at its full transmittance potential given by producer. In order to address the effect of this simplification, a sensitivity analysis was performed where the mutual relation of different shading factors used for outermost and innermost glazed building components were studied.

There were two different scenarios for the window shading factor, the proposed simplification method with no shading factor or the SVEBY (2009) suggested value of 0.5, shown in Figure 11. It was also decided that the shading factor used on the balcony glazing should be no more than that of the SVEBY (2009) suggested value for windows due to the favourable building geometry, which does not self-shade the balcony glazing by neither the balcony structure above nor any other own building structure. Balcony shading factor was reduced by increments of 0.2 until 'no shading' was reached.

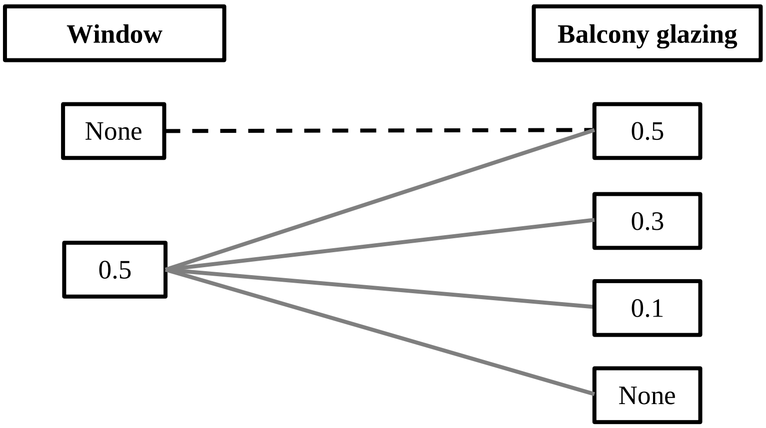


Figure 1: Cross simulation of different studied window and balcony glazing shading factors on ALT 1 of low-rise building in Gothenburg. Black dashed line represents the base case combination.

3.4.3 Location

The Opaque solution was simulated for the three largest cities in Sweden; Gothenburg, Malmoe and Stockholm in order to increase the applicability of proposed design alternatives on the Million Programme buildings. Table 17 in Appendix C shows some of the weather parameters according to location, where location 1, 2 and 3 represent Gothenburg, Malmoe and Stockholm respectively. The weather files were accessed from ASHRAE International Weather for Energy Calculations (IWEC) 2 database through the IDA-ICE software.

3.4.4 Orientation

Low-rise lamella building

The performance of a glazed façade is highly dependent on its orientation. The façade with balconies of low-rise lamella building was originally oriented towards south-west; however, four more orientations, shown in Table 8 were studied to investigate the directional sensitivity of glazed balconies.

Table 8: Building orientation of ALT 1, low-rise lamella building in Gothenburg. North is defined by IDA-ICE as 0 degrees.

Orientation	South-west	East	South-east	South	West
Degrees / °	230	90	130	180	270

High-rise lamella building

The original orientation of high-rise lamella building was that longitudinal facades were facing southeast and northwest and since recessed balconies were located in both of these facades, three additional cardinal directions were investigated to cover the whole 270-degree range. The longitudinal façade with main entrance was facing either of the directions shown in Table 9, while the other longitudinal façade faced opposite direction.

Table 9: Building orientation of ALT 1, high-rise lamella building in Gothenburg.

Orientation	South-east	East	South	South-west
Degrees / °	143	90	180	233

3.4.5 Air change rates in unconditioned spaces

Renovation which includes adding additional external spaces to the existing building envelope allows reaching any specific air change rate in these respective spaces. Specific air change rates can be achieved by strategically placed and sized fixed or operable ventilation openings. It was decided to investigate the extent of variations in heating demand and overheating hours, compared to base case, to suggest the most efficient air change rate for the specific building geometries. In order to simplify the energy model, the air change rates in the unconditioned spaces were forced by increasing the infiltration through building envelope without specifying the opening size or location. These infiltration rates were based on values found in other research projects:

- 2 - 4 *ACH* (Hilliaho, Lahdensivu, & Mäkitalo, 2015)
- 3 *ACH* (Blomsterberg, o.a., 2007)
- 1 *ACH* (ArchiMEDES, 2003)
- 90 *l/s* (Elfborg, Nordquist, Stein, Vrbanjac, & Wallentén, 2013)

Air change rates were manually converted to infiltration ($l/s/m^2$) by external envelope surface and then used as IDA-ICE input value for added balconies and double skin façades. The hand calculated air changes were then compared to the simulated yearly average rates. Constant annual air change rates of 1, 2 and 4 *ACH* were used when studying various glazing types in ALT 1 and ALT 2. The sensitivity of these numeric values was investigated to determine the air change impact on double skin façade of ALT 2.

3.4.6 Balcony design

Swedish Building Regulations requires window *U*-value to be 1.2 or lower. However, selecting windows with such thermal properties did not meet the 0.4 U_m value demand for the building envelope that was required by BBR (Boverket, 2014) at the time when *Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building* research project started, which this Master thesis was also a part of. Therefore, passive windows, corresponding to *U*-value of 0.8 were chosen for the base case. Although review on the new version of BBR by Burke (2017) suggested that meeting a specific U_m value was no longer required unless the building was thoroughly renovated, which meant keeping only the load bearing structures and changing the rest. Therefore, building owners are allowed to select any windows who meet the minimum *U*-value requirements of current BBR. In addition to windows with 0.8 and 1.2 *U*-value, it was decided to also consider 1.0 *U*-value as an option to widen the range of possible combinations. Only windows facing balcony space were assessed in this parametric study while windows facing outdoors had 0.8 *U*-value.

There were no specific thermal or transmittance requirements for balcony glazing found in the reviewed literature and standards, which allowed limiting the study to single and double paned balcony windows. The increased thermal resilience of the balcony space and its effect on annual energy demand and overheating hours in the living spaces was assessed by studying the impact of adding a secondary pane to the single-paned clear balcony glazing. Furthermore, two-paned glazing with low-e coating was considered as a passive solar control system to reduce the transmitted solar radiation to the balcony space and thus the overheating in both balconies and apartments.

Table 10: Input data for cross simulations between different window U-values and balcony glazing types of ALT 1.

Window type	***U-value [W/(m²·K)]***	***ACH* in balcony**	***SHGC***
Triple pane clear	0.8		0.52
Triple pane clear	1.0		0.52
Triple pane clear	1.2		0.52
Balcony glazing type			
Single pane clear, leaky	5.44	4	0.44
Single pane clear, typical	5.44	2	0.44
Single pane clear, tight	5.44	1	0.44
Double pane clear, typical	2.64	2	0.4
Double pane clear, tight	2.64	1	0.4
Double pane coated, tight	2.64	1	0.18

This study was only conducted for ALT 1 in Gothenburg, which is the reference location of both buildings, and Stockholm, for which the preliminary study of weather data suggested to have the highest annual energy demand and potential for overheating.

In order to address the mutual relation of windows and balcony space, 18 sets of simulations with multiple variables were conducted, presented in Figure 12. Three types of windows with different *U*-values were paired with 6 different combinations of balcony glazing types and balcony air-tightness values. They were cross simulated with one another.

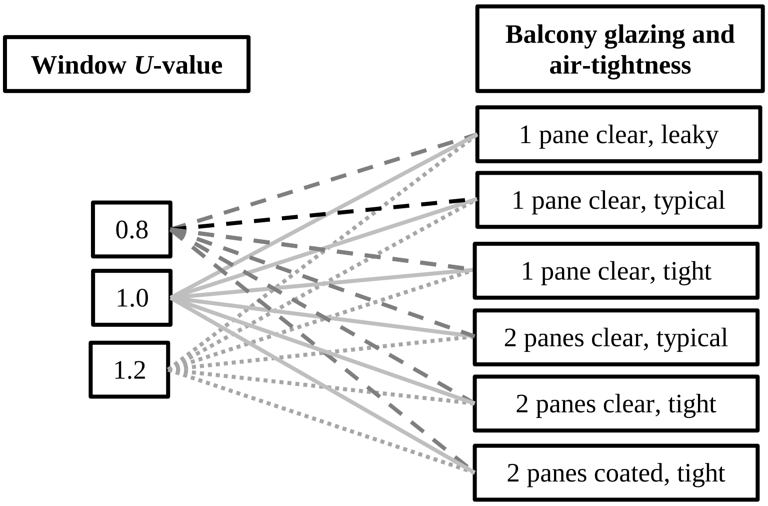


Figure 2: Cross simulations of different window U-values, balcony glazing types and balcony air-tightness on ALT 1, low-rise lamella building in Gothenburg. Black dashed line represents the base case combination.

3.4.6.1 Low-rise lamella building

Gothenburg

All 18 simulation sets, see Figure 12, were tested on low-rise lamella building located in Gothenburg only to determine which factors had the highest impact. Such strategy would allow limiting the amount of simulations for other locations of both low and high-rise buildings. Thus, only the better performing parameters and combinations would be investigated further in other locations.

Stockholm

It was assumed that the trend of variations between the different combinations would be similar to those noted in Gothenburg. Therefore, it was decided to only conduct a selection of cross simulations in Stockholm, which would first address the mutual relation between base case windows, *U*-value of 0.8, in combination with different glazing types. Second, base case conditions of balcony space with single pane clear glazing and typical, 2 *ACH*, balcony air-tightness, in combination with different window U-values, see Figure 12. This was done to evaluate the impact of window thermal properties on overheating hours in living spaces and determine which, window or balcony glazing has a higher impact on the indoor comfort.

Number of glazed surfaces

Exchanging one 4 m^2 large external lightweight concrete wall with a glazed surface in every balcony of low-rise lamella building was considered as a possible design alternative for the proposed balcony type. The parametric study was performed for a combination of clear single pane balcony glazing, typical (*2 ACH*) balcony air-tightness, 0.8 *U*-value windows. Also, the additional glazed surface was of clear single pane. Only annual heating demand and overheating in the apartments were obtained from IDA-ICE model and studied further.

3.4.6.2 High-rise lamella

The preliminary study performed on low-rise lamella building suggested performing a parametric study only in Stockholm with windows having *U*-values of only 0.8 and 1.2. Whereas the window with highest thermal resilience was combined with 6 different balcony glazing types and different balcony air-tightness values. Thermally poorest window, *U*-value 1.2, was only combined with both two-paned balcony glazing and tight balcony air space, refer to Figure 12.

3.4.7 Passive cooling measures

Window opening was used to minimize heat accumulation within the glazed balcony during the cooling season (June to August) that could further lead to overheating in indoor living spaces adjacent to the balcony. However, since it was very difficult to make an accurate estimation of tenant behaviour, opened balcony glazing percentages investigated in this study covered a range of fully closed to 80 *%* open with 20 *%* increments. The option *PI* schedule in IDA-ICE replicates an automatic glazing opening system. It was assessed as a possible passive cooling strategy and set to open apartment windows towards balcony space and balcony glazing when temperatures in these respective spaces exceeded 26 *°C*. Moreover, coated balcony glazing was added as an additional cooling measure to compare its performance against the cooling by opening balcony glazing. The criteria of window *U*-value selection in the cross simulations between window *U*-values and opened balcony glazing area was identical to that already explained in chapter 3.4.6.

Figure 12 shows different tested combinations that were on both lamella buildings and different locations. However, note, that the sets of various combinations differed according to building or its location.

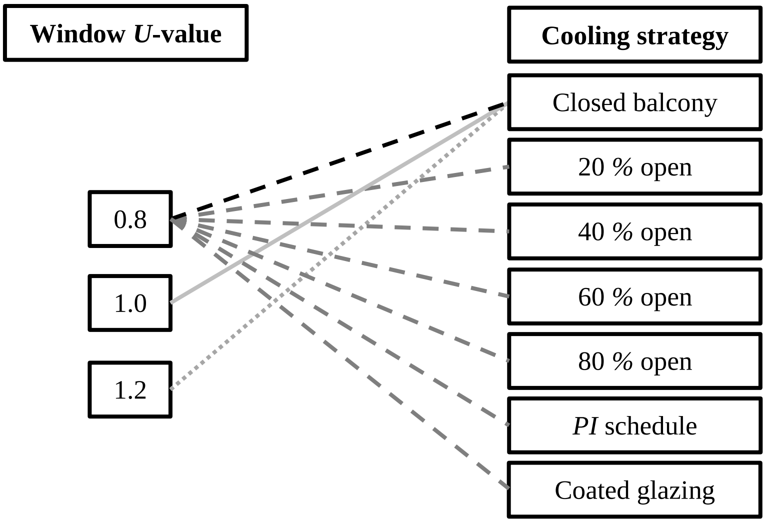


Figure 3: Cross simulation study between different window U-values and cooling strategies. Black dashed line represents the base case combination.

3.4.7.1 Low-rise lamella

Gothenburg

Preliminary analysis of building geometry, proposed changes and their sensitivity to Gothenburg weather data file suggested that overheating is unlikely for the building ALT 1 in this respective location. Therefore, it was only the most opened balcony glazing option, 80 %, respectively, that was coupled with different window *U*-value alternatives (Figure 13) and further investigated to address its impact on annual heating demand where it was expected to have the highest value of all the proposed opening areas.

Stockholm

Higher solar radiation and smaller solar incidence angle on a vertical surface was considered to potentially cause overheating for buildings located in Stockholm, therefore suggesting to investigate larger range of balcony opening percentages, ranging between 0 to 80 % opening, to find a balcony opening area that would reduce the apartment overheating to comfortable levels. The *PI* schedule suggested for Stockholm responds to the dynamic changes in the environment and replicates an automatic system or perfect tenant behaviour. It was set to have maximum possible opening areas of 80 % for the balcony glazing and 100 % for apartment windows. Coated glazing was studied as an additional measure; however, it was expected to increase the annual heating demand compared to other solutions since it would decrease the amount of solar radiation absorbed during all months and not just the cooling season. Eventually all 9 combinations, shown in Figure 13, were simulated for the low-rise lamella building located in Stockholm.

3.4.7.2 High-rise lamella

The study of cooling measures was performed for the reference location, Gothenburg, and Stockholm, which was expected to have the highest potential overheating due to same reasons already explained in chapter 3.4.7.1. Only one window type with a *U*-value of 0.8 was studied as it was guesstimated that other window types, with 1.0 and 1.2 *U*-values would have similar trends to those already noted in the sensitivity analysis of low-rise lamella building. Window with a *U*-value of 0.8 was then coupled with 7 different cooling strategies, see Figure 13.

3.4.8 Double skin façade

There were no specific air change rates, thermal nor transmittance requirements for DSF found in the reviewed literature and standards, therefore only single and double paned glazing types were studied. Two-paned coated glazing was considered as a passive solar control system to avoid installing large quantities of shading devices. Design approach of DSF and specific constant air change rates were according to chapters 3.3 and 3.4.5, respectively. Windows adjacent to DSF had a *U*-value of 0.8.

The effect of ALT 2 was studied in all three major locations - Gothenburg, Malmoe and Stockholm. However, a deeper study analysing various glazing types was only conducted for Gothenburg where both reference buildings were originally from.

Table 11: Input data for parametric study of double skin façade glazing types and air-tightness for ALT 2 of low-rise lamella building located in Gothenburg.

DSF glazing type	***U-value [W/(m²·K)]***	***ACH* in DSF**	***SHGC***
Single pane clear, leaky	5.44	4	0.44
Single pane clear, typical	5.44	2	0.44
Single pane clear, tight	5.44	1	0.44
Double pane clear, typical	2.64	2	0.4
Double pane clear, tight	2.64	1	0.4
Double pane coated, tight	2.64	1	0.18

3.5 Life Cycle Profit

LCP was carried out to assess the economic feasibility of proposed design alternatives and point out the most advantageous case. These calculations determined the total net present value (NPV) in today’s cash value. The LCC of different design alternatives solutions were put in perspective to an already performed renovation solution (Mini renovation) within ‘*Feasibility study of prefabricated multi-active façade elements for energy renovation of multi-family building’* research project. The Mini renovation aimed to prolong building life-span but did not include any energy reducing measures. Results of the LCP were considered profitable if the LCC of Mini renovation was higher than the solutions proposed in this study and unprofitable if it was lower than the solutions in this study. Total cost of the building’s life span consists of investment cost, energy (i.e. heating and electricity) cost, maintenance cost and a predetermined yield. The life span of the buildings was determined to be 60 years for all solutions.

Table 12 shows the cost of district heating (DH) and electricity according to Wall (2016) and Bjärnhag (2016).

Table 12: Monthly costs of district heating and electricity.

Month	**DH / *(SEK / kWh)***	**Electricity / *(SEK / kWh)***
December, January, February, March	0.675	0.800
April, May, October, November	0.330	0.800
June, July, August, September	0.220	0.800

The LCPs considered the real yield (y_r) of 4 %. The real cost increase (g_r) for energy and maintenance was studied from 0 % to 4 %, with increments of 1 %. The most likely future scenario was considered to correspond to the information presented in Table 13. They were calculated as the mean g_r over the last 18 and 12 years for energy and maintenance for renovations respectively (Statistiska centralbyrån, 2014).

Table 13: Real cost increase of district heating, electricity and maintenance.

Expense	**g_r / %**
District heating	1.385
Electricity price	1.682
Maintenance	2.616

Total areas of each solution together with their choice of material/construction and their respective investment and maintenance costs can be seen in Appendix E.

The LCP was obtained by using Eq. 1 for analysing the NPV for energy and maintenance.

$$P = F(1 + g_r)^N \qquad [SEK] \qquad (1)$$

In Eq. 2, P represents the present worth in *SEK*, g_r represents the real cost increase in *%* and N represents the amount of years and F is the future value in *SEK*.

The difference in annual energy demand between the calculated case and the already performed solution was considered to present the energy cost savings. The annual maintenance costs were subtracted from the annual energy cost savings and if the difference was positive, the annual result (i.e. the net effect) was considered profitable.

The NPV of the net effect for each year was calculated by Eq. 2 and added together.

$$NPV_{NE} = \frac{N_E}{(1+y_r)^N} \qquad [SEK] \qquad (2)$$

In Eq. 2 NPV_{NE} represents the net present worth of the net effect in *SEK*, N_E represents the net effect in *SEK*, y_r represents the real yield in *%* and N represents the amount of years.

The NPV_{NE} of each year was summed and the investment costs were deducted and the final LCP was determined. As all considered costs were accounted without value added taxes (VAT), 25 *%* VAT of the total costs were added on.

If Alternative 1 and Alternative 2 showed to be unprofitable, the lowest possible rent increase was found in order to make the renovations profitable. It was studied with a yearly rent increase of 1 *%* and under the most likely future scenario.

4 Results and analysis

4.1 Specific annual energy demand

The specific annual energy demand of original building was compared to all proposed design alternatives for both – low and high-rise lamella buildings and is shown in Figures 14 and 15. Different design alternatives compared to the original building are shown on horizontal axis and their respective annual energy demand is shown on vertical axis. Total annual energy demand is a sum of heating, domestic hot water and property electricity consumption. Black dashed line represents the maximum allowed annual energy demand for non-electrically heated buildings in Gothenburg (zone 4) – 75 *kWh/(m²·y)*.

Low-rise lamella

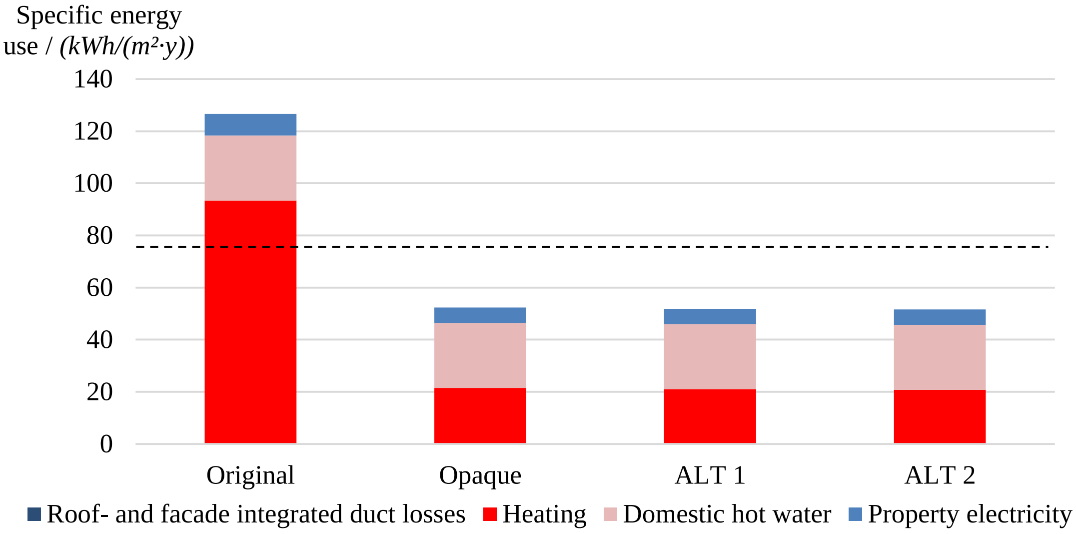


Figure 14: Total annual energy demand of different design alternatives in comparison to the original unrenovated low-rise lamella building in Gothenburg.

Thermal improvements of building envelope significantly reduced space heating from 93.4 *kWh/(m²·y)* in original non-renovated building to 21.3, 20.8 and 20.5 *kWh/(m²·y)* in the Opaque solution, ALT 1 and ALT 2. Domestic hot water accounted for 25 *kWh/(m²·y)*. Property electricity included electricity used by lighting, air handling unit and hydronic pumps required annual energy input of 8.2 *kWh/(m²·y)* in the original building and was reduced to 5.9 *kWh/(m²·y)* in the three renovation alternatives.

High-rise lamella

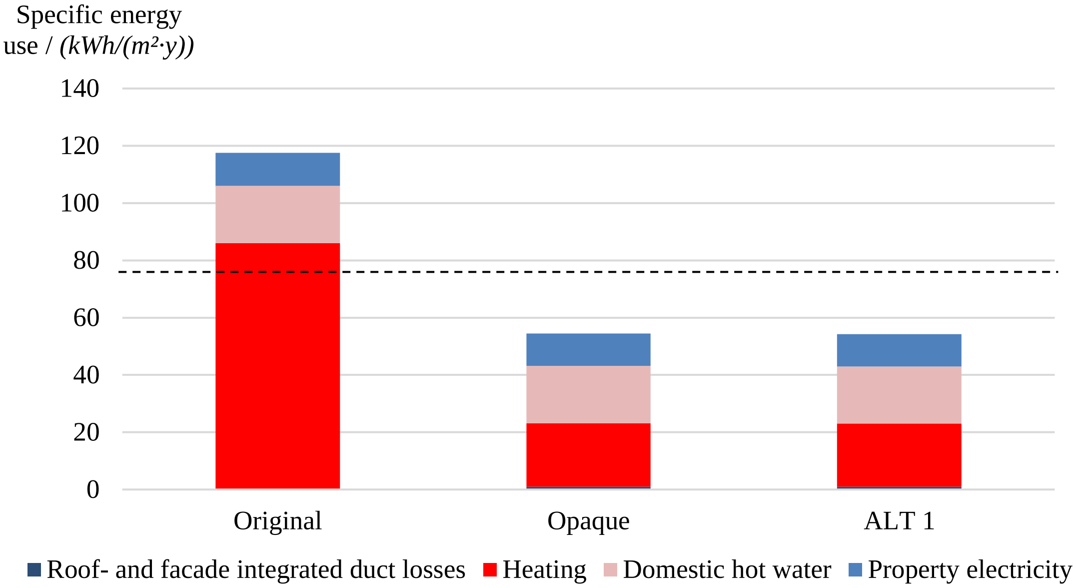


Figure 15: Total annual energy demand of both design alternatives in comparison to the original unrenovated high-rise lamella building in Gothenburg.

Annual heating demand and DHW were the major energy consumers. Although, DHW consumption remained to its originals levels (20 *kWh/(m²·y)*) since water saving measures were not considered in this work, heating demand was reduced significantly from 86 *kWh/(m²·y)* in the original building to 22.2 and 22 *kWh/(m²·y)* in the Opaque solution and ALT 1, respectively. Property electricity was also slightly reduced from 11.5 *kWh/(m²·y)* in original building to 11.3 *kWh/(m²·y)* in proposed renovation strategies. The significantly reduced annual energy demand allowed both design alternatives to reach the targeted BBR standards for non-electrically heated buildings.

4.2 Shading factor

It was assumed that using a 0.5 shading factor on balcony glazing instead of windows, as suggested by SVEBY (2009), would result in higher annual heating demand and apartment overheating since the ambient temperature in the balcony spaces would be lower with higher shading factors.

Horizontal axis in Figure 16 represents different balcony glazing and window shading factors. No and 0.5 window shading factors are presented in diagonal and cross-hatchings, respectively. Annual heating demand is presented on the primary vertical axis with bars. The scale of the axis is adjusted to start from 15 *kWh/(m²·y)* since the numerical differences between the various cases were not significant. Overheating hours in apartments are presented on secondary vertical axis with markers.

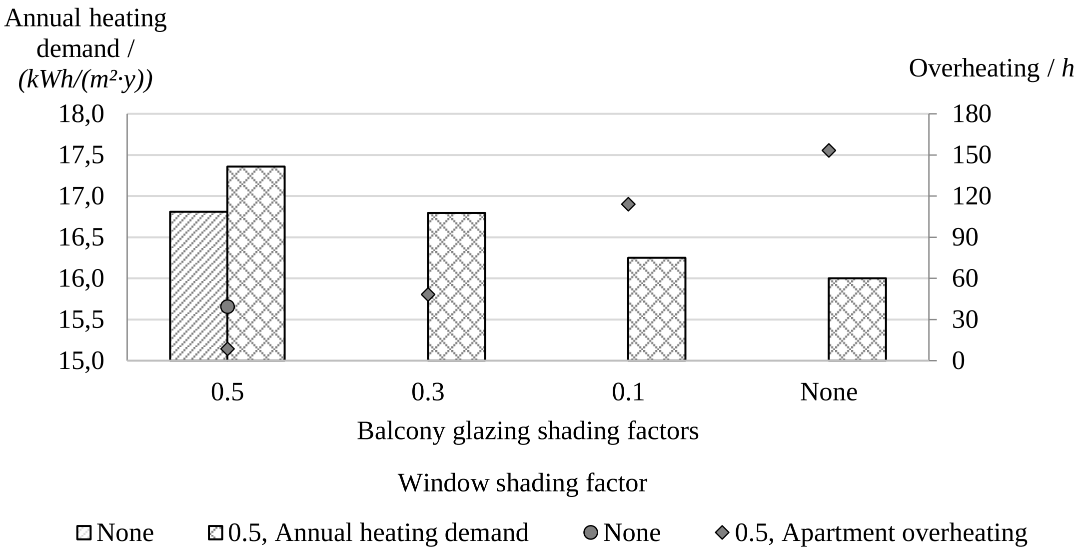


Figure 16: Study of balcony glazing and window shading factors on ALT 1, low-rise building in Gothenburg.

The difference between highest and lowest shading factor values, 0.5 and none, respectively, was higher for balcony glazing than for windows. Reduction of shading factors decreased annual heating demand. However, it increased apartment overheating hours significantly. Both variations had an exponential trend. It can be seen that the combination of 0.5 balcony glazing and 0.5 window shading factor had the highest annual heating demand and lowest apartment overheating, while a combination with 0 shading factor on balcony glazing and 0.5 on windows had the opposite results, lowest annual heating demand and highest overheating hours.

4.3 Location

Low-rise lamella

It was expected that all alternatives in Stockholm would have higher annual heating demand than in Malmoe or Gothenburg due to colder outside air temperature during the heating season.

Horizontal axis in Figure 17 represents annual heating demand and is formatted to start from 15 *kWh/(m²·y)*. Vertical axis shows number of apartment overheating hours that were above 26 *°C*. The dashed black line is a reference for FEBY (2012) thermal comfort standard. Every alternative and their respective locations are presented with markers. White filled markers represent Gothenburg; grey – Malmoe, black – Stockholm.

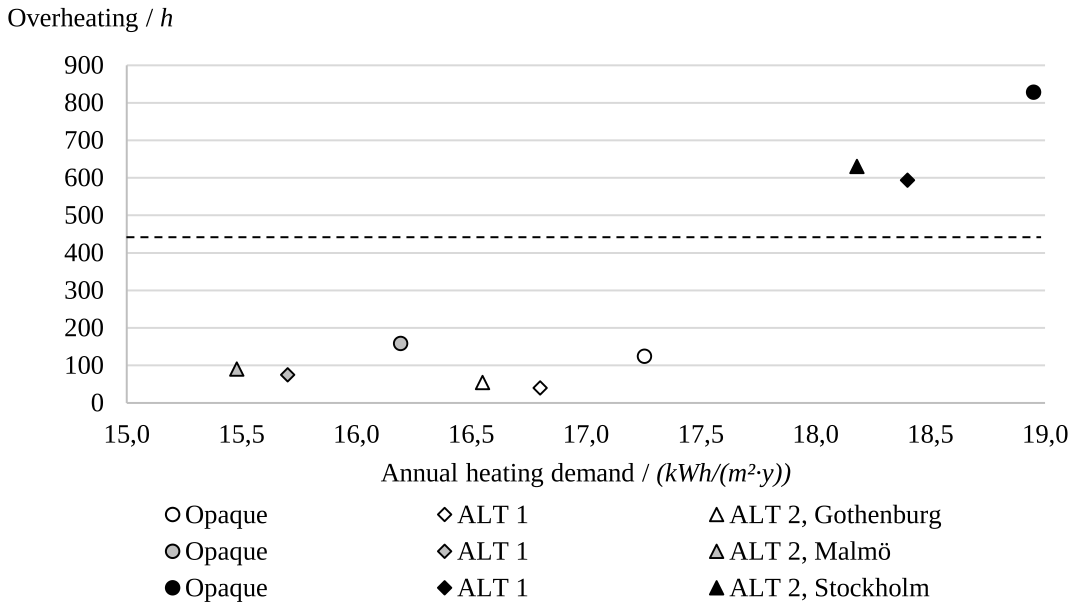


Figure 17: Location study of all proposed solutions on low-rise lamella building.

The difference in annual heating demand results is very little in different locations since the building has been super insulated and has a very good thermal resilience against the outdoor conditions. Opaque solution had the highest annual heating demand and highest number of overheating hours of all alternatives, while ALT 1 and ALT 2 had the lowest overheating hours and annual heating demand, respectively. The location study also showed that thermal comfort in Gothenburg and Malmoe met the FEBY (2012) limit of 436.8 overheating hours, measured during April – September. None of the proposed solutions in Stockholm met the same standard.

High-rise lamella

The geometry of high-rise building suggested that lower annual heating demand and more overheating hours compared to low-rise building should be expected. The difference between Opaque solution and ALT 1 in various locations was expected to follow the trend already noted in the study of low-rise building.

Annual heating demand in Figure 18 is represented on horizontal axis, scaled to start from 16.5 *kWh/(m²·y)*, and number of overheating hours above 26 *°C* in living areas on vertical axis. The dashed black line is a reference for FEBY (2012) thermal comfort standard. Every alternative and their respective locations are presented with markers. White filled markers represent Gothenburg, grey – Malmoe, black – Stockholm.

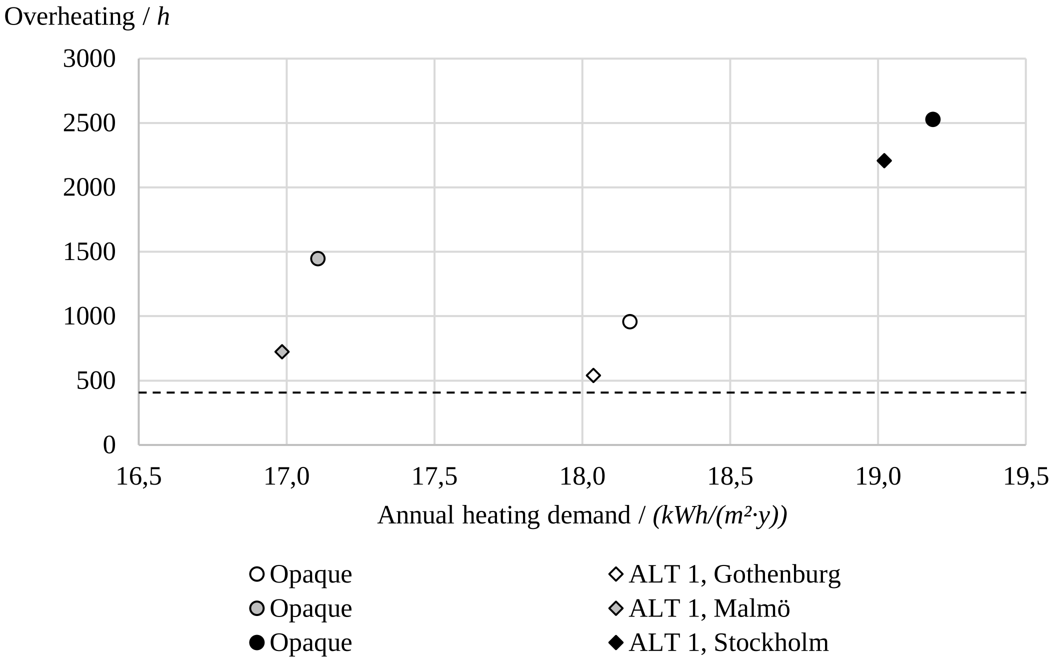


Figure 18: Location study of Opaque solution and ALT 1 on high-rise lamella building.

ALT 1 had both lower annual heating demand and fewer overheating hours in living spaces than the Opaque solution in all three studied locations. Although the overheating decreased significantly – by 14, 44 and 50 *%*, in Stockholm, Gothenburg and Malmoe, respectively. Annual heating demand reduction was minimal, below 1 *%*. Building located in Malmoe had the lowest annual heating, while it had the fewest overheating hours in Gothenburg. Once located in Stockholm, the high-rise lamella building had the worst performance in both annual heating demand and number of apartment overheating hours. Both alternatives did not meet the targeted FEBY (2012) thermal comfort standard in any of the studied location.

4.4 Orientation

Low-rise lamella

Annual heating demand in Figure 19 is presented on horizontal axis, starting from 16.4 *kWh/(m²·y)*, and number of overheating hours in living spaces above 26 *°C* on vertical axis. Five different orientations ranging from east to west were investigated on low-rise lamella building located in Gothenburg.

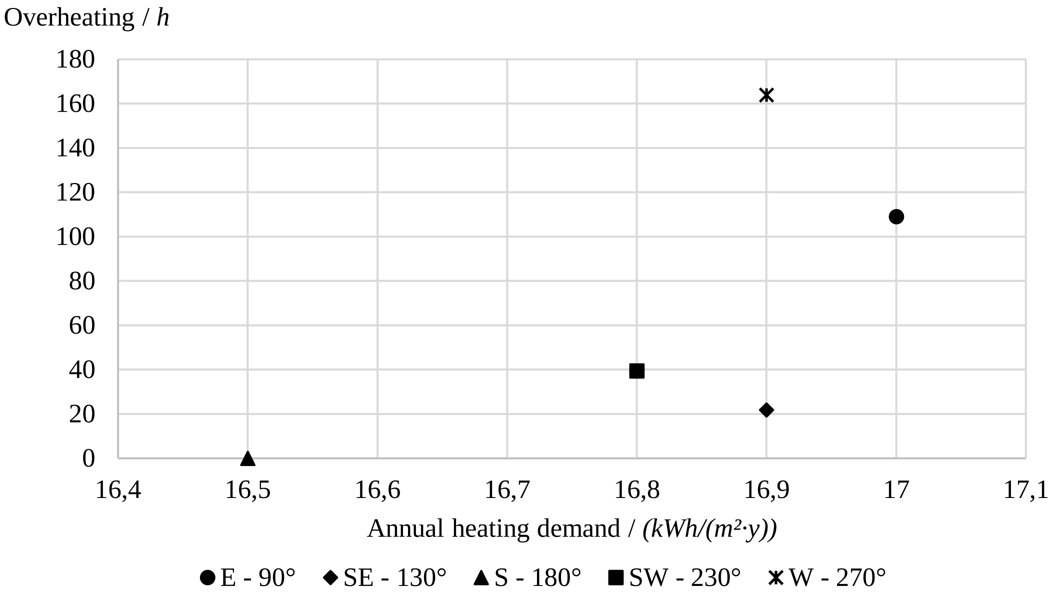


Figure 19: Annual heating demand and apartment overheating according to the orientation of glazed balconies from ALT 1, low-rise lamella building in Gothenburg.

It was found that south orientation is the most favourable for application of glazed balconies. It had the lowest annual heating demand, which was reduced by 2 *%* from the original southwest orientation, and fewest overheating hours in apartments, decreased from 39.5 to 0. The original southwest orientation was the second most favourable in annual heating demand and third in apartment overheating, being slightly worse than southeast. East orientation had the highest annual heating demand, while most overheating was accumulated when the glazed balconies were facing west.

High-rise lamella

Annual heating demand in Figure 20 is presented on horizontal axis, starting from 18.1 *kWh/(m²·y)*, and number of overheating hours in living spaces above 26 *°C* on vertical axis. Four different orientations ranging from east to west were investigated on high-rise lamella building located in Gothenburg. The black dashed line is a reference for FEBY (2012) thermal comfort standard.

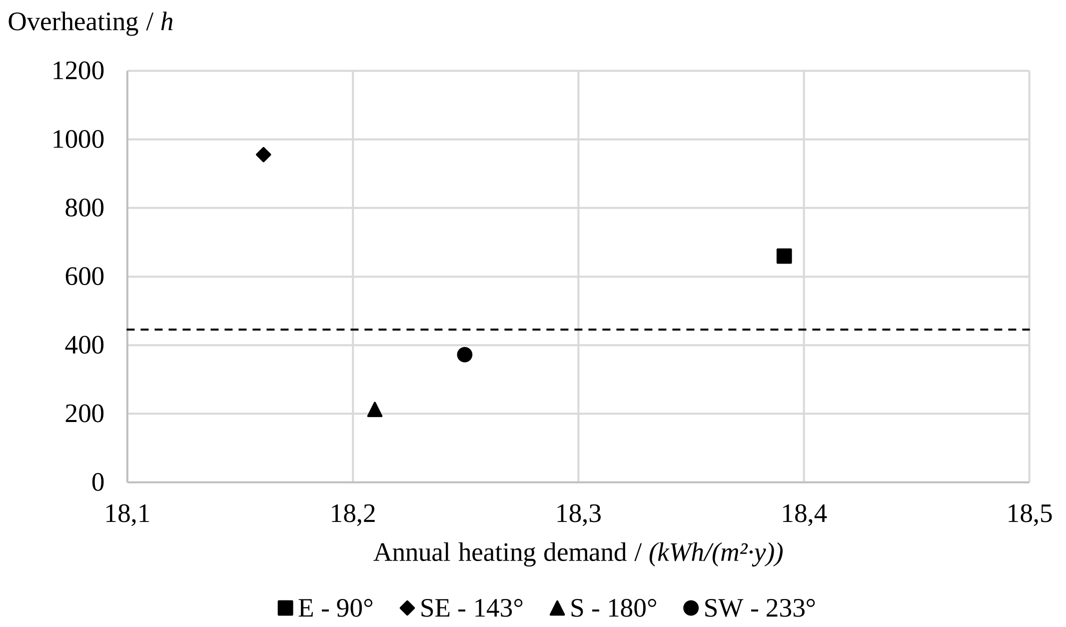


Figure 20: Annual heating demand and apartment overheating according to the orientation of façade with main entrance from ALT 1, high-rise lamella building in Gothenburg.

The original orientation whereas one longitudinal facade was facing southeast and the other northwest had the lowest annual heating demand. When these facades were facing south and north, lowest apartment overheating was received. East orientation had the highest annual heating demand, while most overheating was accumulated in the original southeast orientation.

4.5 Balcony design

4.5.1 Low-rise lamella

Gothenburg

Six different balcony glazing solutions, single and double paned windows, with constant annual balcony air-tightness ranging from leaky to typical to tight, in a combination with various window types, ranging from 0.8 to 1.2 in *U*-value, are shown on horizontal axis of Figure 21. Annual heating demand is presented on the primary vertical axis with bars. The scale of the axis is adjusted to start from 15.5 $kWh/(m^2 \cdot y)$ since the difference between the various cases is relatively little. Overheating hours in apartments are presented on secondary vertical axis with markers.

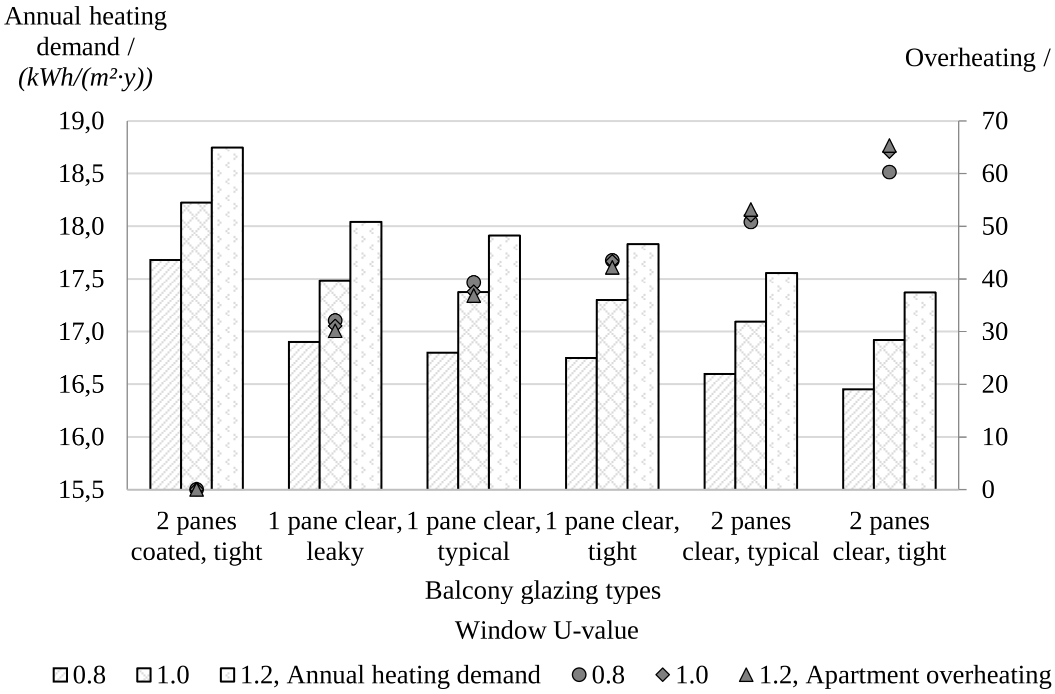


Figure 21: Annual heating demand and apartment overheating according to balcony glazing type and window *U*-value mutual relation in ALT 1, low-rise lamella building located in Gothenburg.

Making the balcony space more air-tight decreased the annual heating demand, but increased the number of overheating hours. Same phenomenon occurred when window *U*-value was reduced or second glazed pane was added to the balcony glazing. When coating was added to the two-paned balcony glazing the annual heating increased compared to other cases, however, the overheating hours disappeared completely. A combination of clear two-paned balcony glazing and window with *U*-value of 0.8 performed best in annual heating demand and worst in overheating. The difference between best and worst cases was 2.3 *kWh/(m²·y)* in annual heating demand and 66 overheating hours.

Stockholm

Since the window *U*-value had a very slight effect on deviations in overheating hours and a window with 0.8 *U*-value always performed better than windows with higher *U*-values in annual heating demand in Gothenburg case study, it was decided to eliminate windows with higher *U*-values than 0.8 and only investigate different balcony glazing types in Stockholm. Vertical axis of Figure 22 is scaled and starts from 16 *kWh/(m²·y)*. The black dashed line represents FEBY (2012) thermal comfort standard.

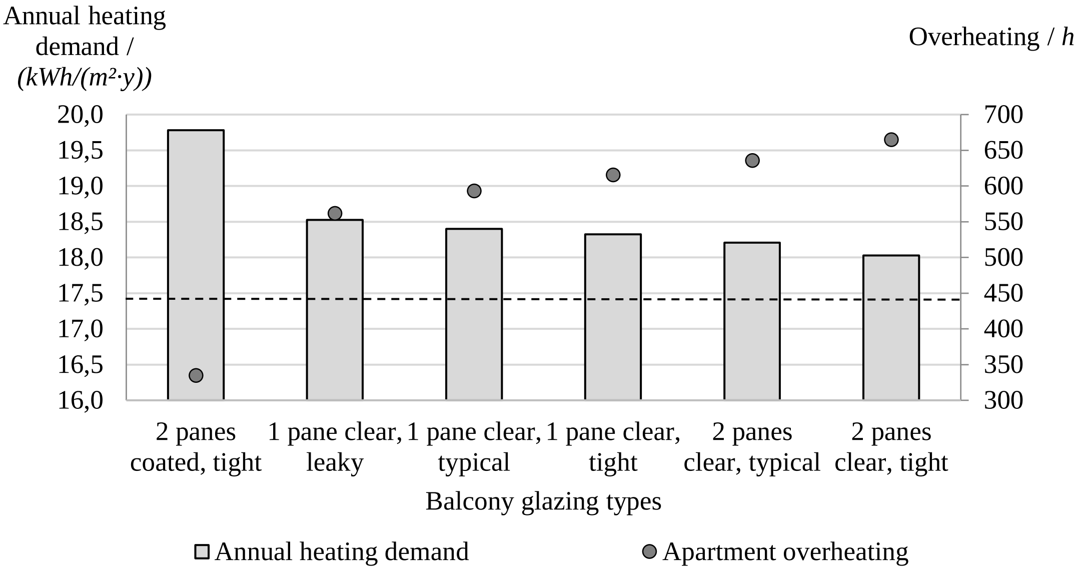


Figure 22: Annual heating demand and apartment overheating for different balcony glazing types in ALT 1 of low-rise lamella building located in Stockholm.

The trend in annual heating demand and overheating hours in Stockholm was similar to that already noted in Gothenburg, where more air-tight balcony space or windows with lower *U*-value reduced heating demand but increased the overheating hours in apartments. Nevertheless, it was only coated balcony glazing that managed not to exceed the FEBY (2012) overheating limit, resulting in 335 overheating hours. This finding is connected to the latitude of Stockholm, where summer solar altitude is lower than for the two other cities. As a result, balconies lose their solar shading abilities and cannot shade the apartment windows on the floor below as effectively, thus more solar gains are introduced to the apartments which leads to the higher overheating. However, coated balcony glazing had the highest annual heating demand, more than 7 *%* higher than the base case, with single pane clear window and typical air-tightness, and almost 10 *%* higher than the two-paned clear balcony glazing with best air-tightness.

Number of glazed surfaces

The differences in annual heating demand and overheating caused by installing an additional glazed surface on the side of the balcony that was previously made in lightweight concrete are shown in Figure 23. Horizontal axis represents annual heating demand and is formatted to start from 16.5 *kWh/(m²·y)*. Vertical axis shows number of apartment overheating hours that are above 26 *°C*. The black dashed line is a reference for FEBY (2012) thermal comfort standard. White filled markers represent Gothenburg and dark grey – Stockholm.

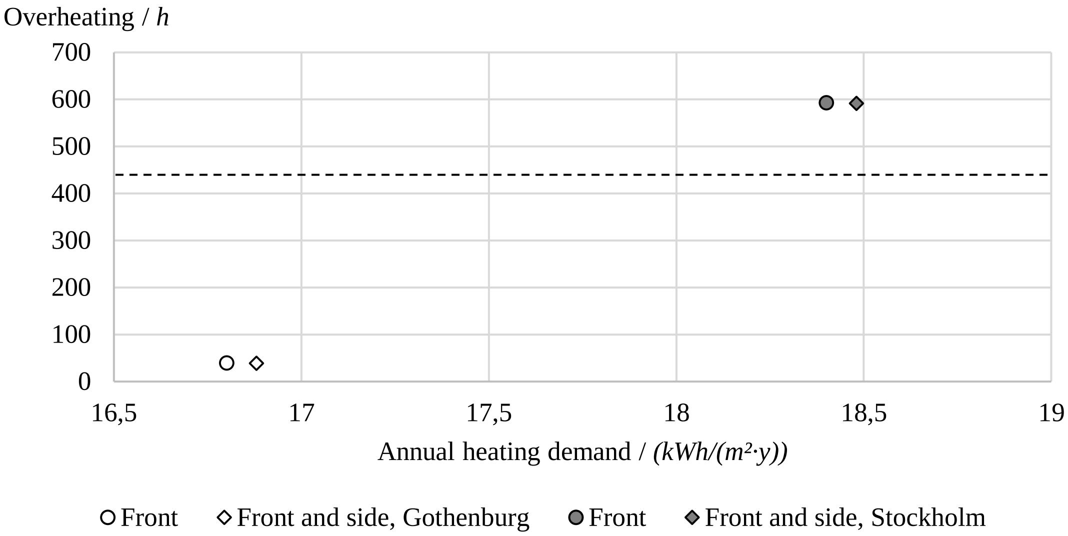


Figure 23: Annual heating demand and apartment overheating according to number of glazed vertical balcony surfaces performed on ALT 1, low-rise lamella building located in Gothenburg and Stockholm.

Exchanging the external lightweight concrete balcony wall with a glazed surface decreased the annual heating demand by 0.5 % and reduced the overheating in apartments by approximately one hour.

4.5.2 High-rise lamella

From the results obtained in the parametric study of low-rise lamella building it was expected that windows with a *U*-value of 0.8 would perform the best in annual heating demand but windows with a *U*-value of 1.2 paired with two-pane coated or two-pane clear balcony glazing would result in highest annual heating demand and most apartment overheating hours, respectively. Therefore, it was decided to only perform 8 simulations, six combinations of windows with a *U*-value of 0.8 and two combinations of windows with a *U*-value of 1.2, instead of 18 as in the case of low-rise building.

Six different balcony glazing solutions were combined with windows that had *U*-values of 0.8 and 1.2. These combinations are presented on horizontal axis of Figure 24. Annual heating demand is shown on the primary vertical axis with bars. The scale of the axis is adjusted to start from 17 *kWh/(m²·y)* since the difference between the various cases is relatively little. Overheating hours in apartments are presented on secondary vertical axis with markers. The black dashed line represents FEBY (2012) thermal comfort standard.

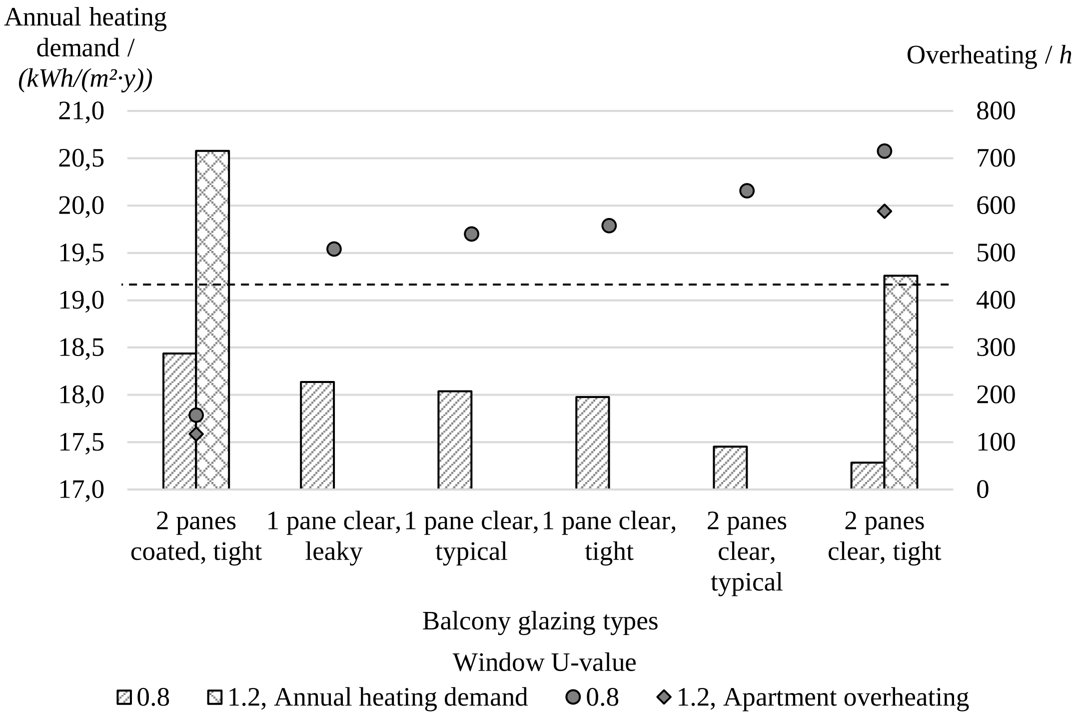


Figure 24: Annual heating demand and apartment overheating according to balcony glazing type and window *U*-value mutual relation in ALT 1, high-rise lamella building located in Gothenburg.

Windows with 0.8 *U*-value resulted in around 2 *kWh/(m²·y)* lower annual heating demand than those of 1.2 *U*-value. Same phenomenon can be noted for balcony glazing, where addition of second pane reduced annual heating demand by about 0.6 *kWh/(m²·y)*. However, lower thermal conductivity also accounted for an increase in apartments overheating hours by 14 – 22 *%* depending on the balcony air-tightness.

Making the balcony space more air-tight reduced annual heating demand but raised the overheating in living spaces, although the difference between various air-tightness values was less significant than different window and balcony glazing thermal conductivity values.

Applying coating to a two-paned balcony glazing was the only of proposed solutions that met FEBY (2012) thermal comfort standard. Once compared to the same type of balcony glazing without coating, the coated solution resulted in 1.1 and 1.3 *kWh/(m²·y)* increase in annual heating demand when combined with 0.8 or 1.2 *U*-value windows, respectively. Moreover, pairing two-paned clear balcony glazing with 0.8 *U*-value windows resulted in more overheating hours than when paired with 1.2 *U*-value window, which is opposite to the trend noted in the case of low-rise lamella building.

4.6 Passive cooling

4.6.1 Low-rise lamella

Gothenburg

Horizontal axis in Figure 25 represents opened balcony glazing area during June to August in a combination with windows of different *U*-values. Annual heating demand is presented on the primary vertical axis with bars. Overheating hours in apartments are presented on secondary vertical axis with markers.

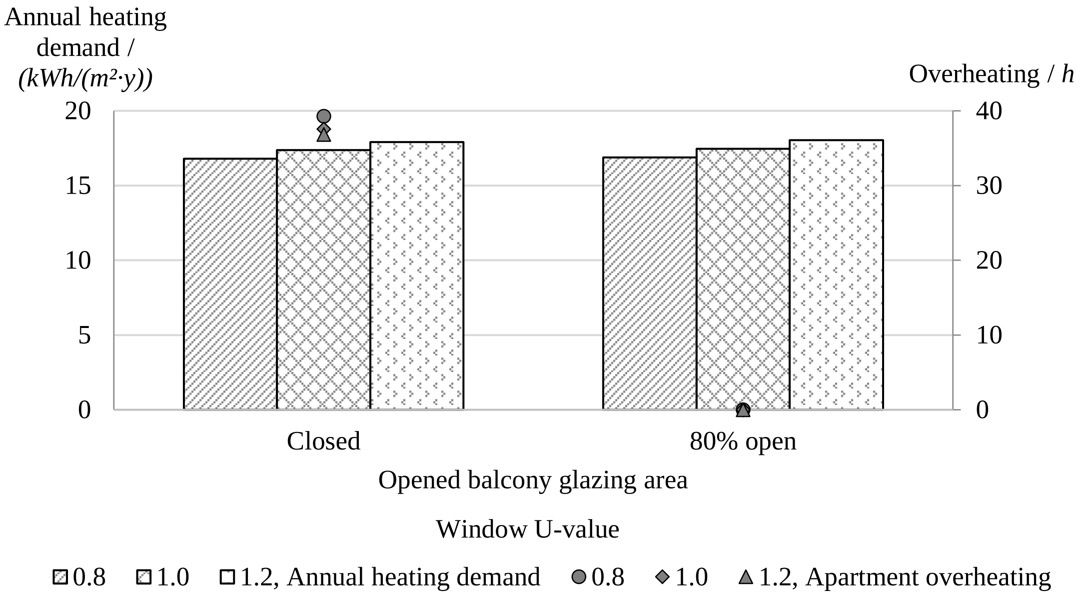


Figure 25: Comparison of closed and 80 % opened balcony glazing combined with different window *U*-values window in ALT 1 of low-rise lamella building in Gothenburg.

With an 80 % open balcony glazing area during June to August, it was possible to avoid any overheating with only 0.6 % increase in annual heating demand. The results of apartment overheating hours suggested that overheating occurs only between June and August.

Stockholm

Horizontal axis in Figure 26 represents different passive cooling measures by opened balcony glazing area, balcony glazing opening according to *PI* schedule or applying coating to balcony glazing. Moreover, the dashed line represents 436.8 overheating hour FEBY (2012) thermal comfort standard for living spaces for location Stockholm.

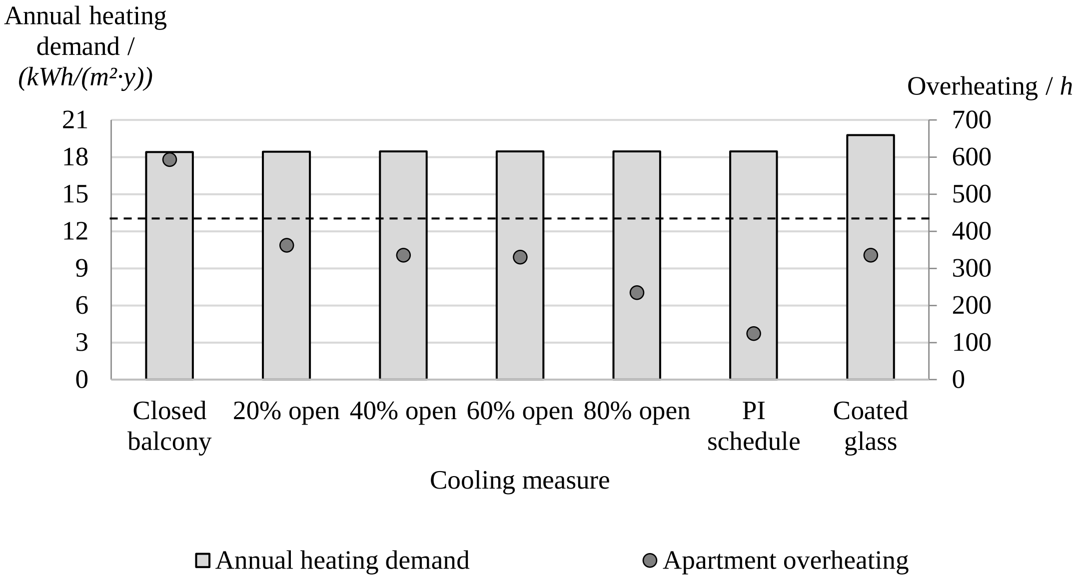


Figure 26: Different cooling measure impact on annual heating demand and apartment overheating in ALT 1 of low-rise lamella building in Stockholm.

The number of overheating hours in Stockholm varied significantly between fully closed and 80 *%* opened balcony glazing. 20 *%* opened balcony glazing already met the FEBY (2012) thermal comfort standards. The deviations in annual heating demand were very little between the different cooling measures, except for coated glazing which was a permanent measure and thus also reduced the transmitted solar heat gains all year around. The application of *PI* schedule resulted in fewest apartment overheating hours.

4.6.2 High-rise lamella

The pre-study of high-rise lamella building suggested that overheating could exceed FEBY (2012) thermal comfort standard in all locations, although apartment overheating could reach extreme levels in Stockholm. Overheating hours tend to be higher with lower window *U*-values as it was already found in chapter 4.5.2. Therefore, different cooling measures were only proposed to the base case of ALT 1 and its reference location, Gothenburg, and location with potentially most extreme overheating conditions - Stockholm.

Gothenburg

Various passive cooling measures, opened balcony glazing area during June to August or according to *PI* schedule and coated balcony glazing, are presented on horizontal axis of Figure 27. Annual heating demand is presented on the primary vertical axis with bars and overheating hours in apartments are on secondary vertical axis with markers. Black dashed line was used as a reference for FEBY (2012) thermal comfort standard, corresponding to 436.8 overheating hours above 26 *°C* in living spaces.

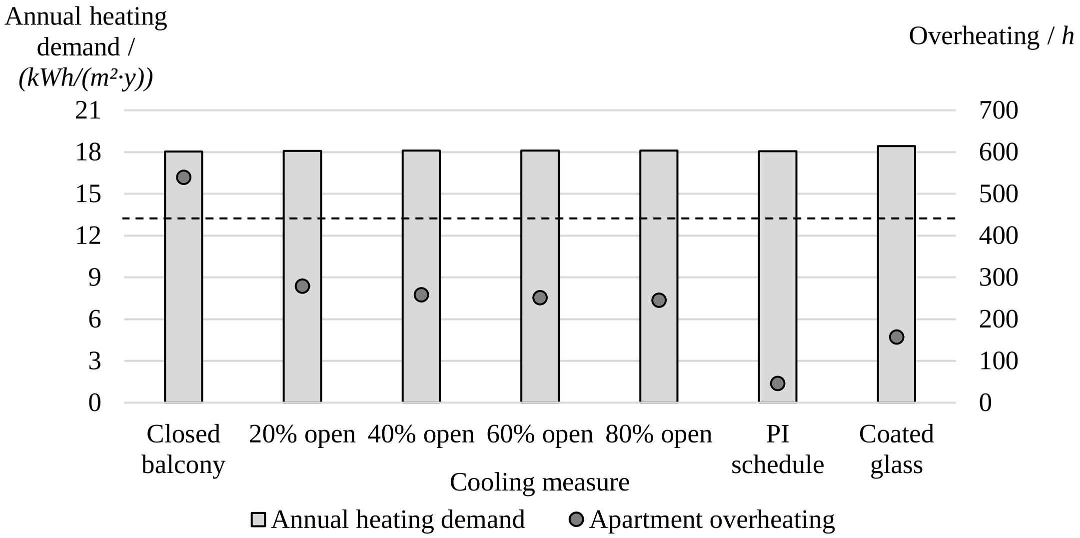


Figure 27: Different cooling measure impact on annual heating demand and apartment overheating of ALT 1, high-rise lamella building in Gothenburg.

Once the balcony glazing was 20 % opened, apartment overheating hours were almost halved. Increase of opened balcony glazing area decreased the overheating hours only slightly. *PI* schedule reduced the overheating hours in living spaces by 92 %. Although, coated balcony glazing was the second most effective cooling measure, reducing the overheating hours by 71 %, it resulted in largest annual heating demand increase - 2.2 %.

Stockholm

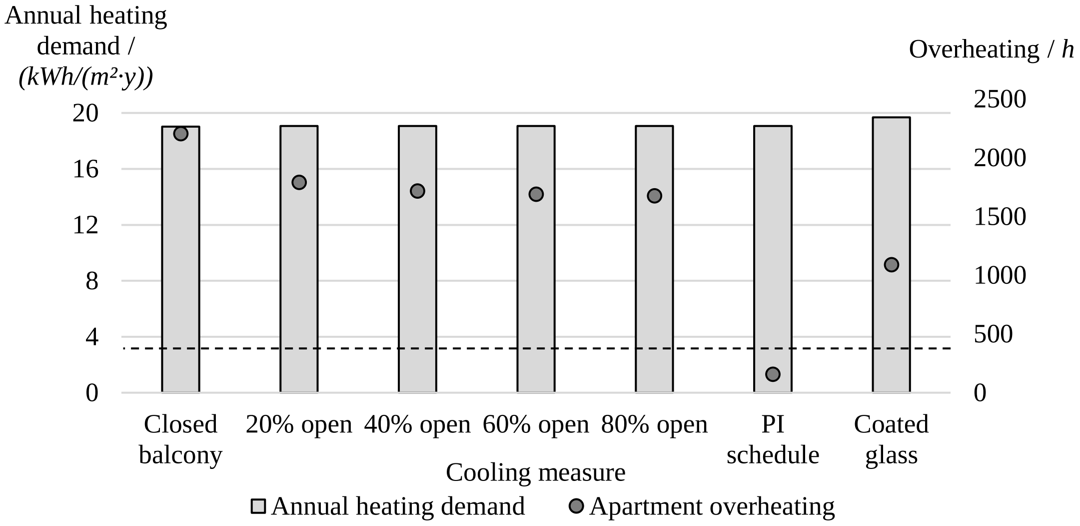


Figure 28: Different cooling measure impact on annual heating demand and apartment overheating on ALT 1 of high-rise lamella building in Stockholm.

As shown in Figure 28, only *PI* schedule met the targeted FEBY (2012) comfort standard for high-rise lamella building in Stockholm, where 157 overheating hours were reached, reducing the initial 2206 overheating hours by impressive 93 *%*.

4.7 Double skin facades

Air change rates in DSF

Five different constant air change rates in the DSF are shown on horizontal axis of Figure 29. Annual heating demand is presented on the primary vertical axis with bars. Overheating hours in apartments and DSF are presented on secondary vertical axis with markers.

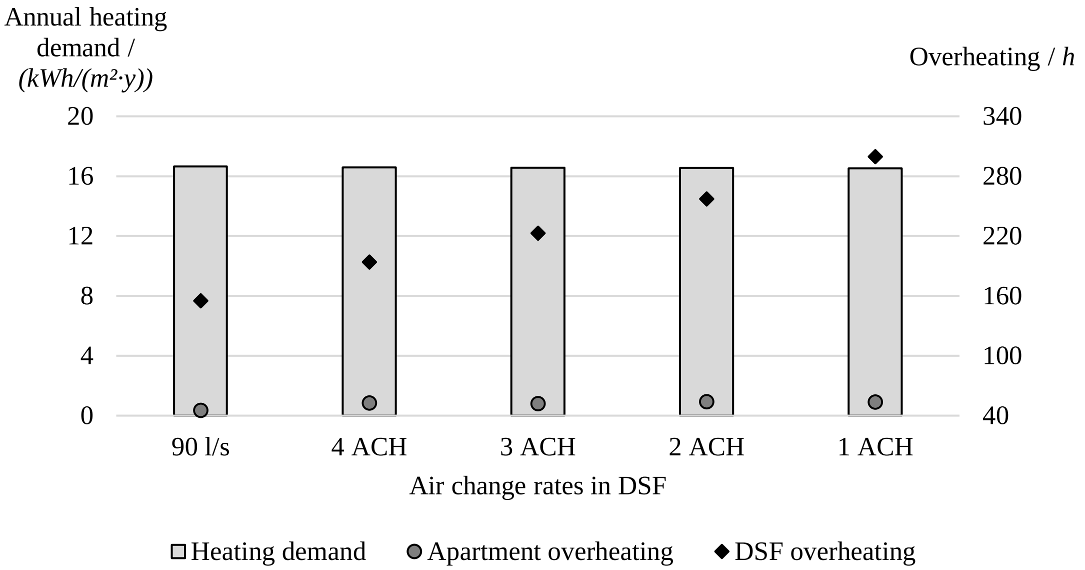


Figure 29: The effect of different DSF air change rates on annual heating demand, apartment and DSF overheating on ALT 2, low-rise lamella building in Gothenburg.

Annual heating demand and overheating in apartments deviated very little with different cases even despite significantly higher air change rates. Lower air change rates resulted in slightly lower annual heating demand and slightly higher overheating hours in apartments. The differences in DSF overheating were more significant and almost doubled between the highest and lowest rates, 90 *l/s* and 1 *ACH*. The apartment overheating and annual heating demand was not significantly affected mainly due to small DSF volume and surface area, compared to the total building envelope.

DSF glazing types

Single and double-paned DSF glazing types with air change rates ranging from leaky to tight are presented and compared to ALT 1 in Figure 30. Annual heating demand and number of overheating hours above 26 *°C* in apartments are presented on horizontal and vertical axis, respectively. Horizontal axis is scaled to start from 16.3 *kWh/(m²·y)*. Both axes are adjusted to reflect the small variations between the different glazing types.

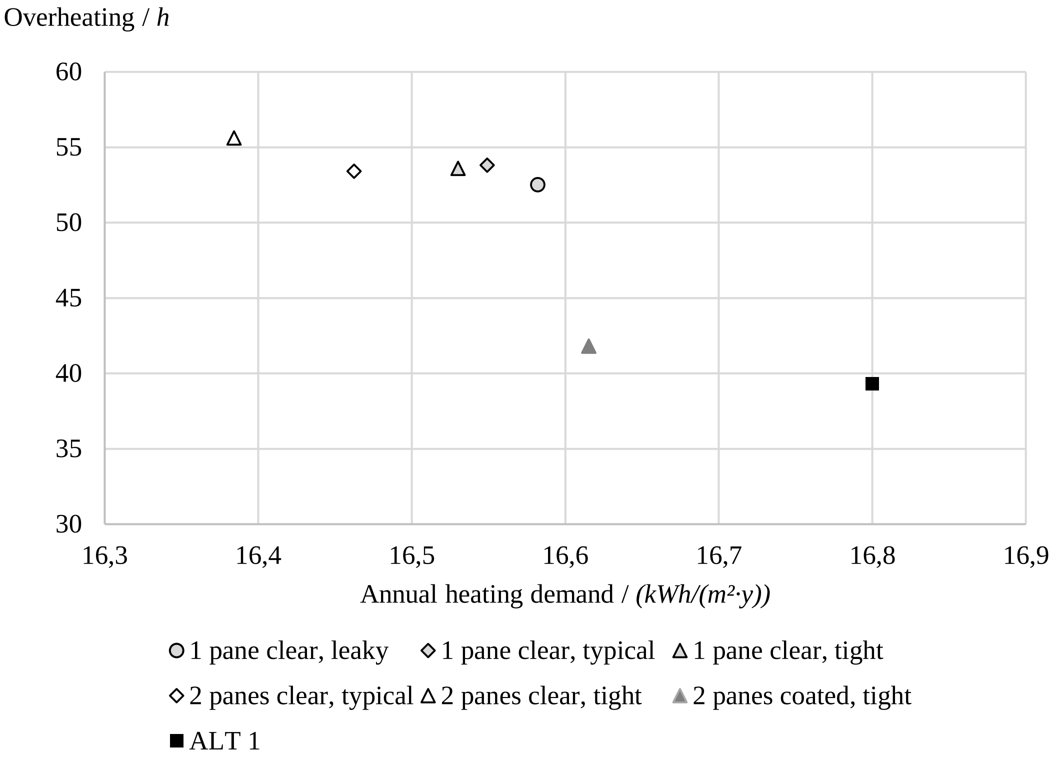


Figure 30: The effect of different DSF glazing types on annual heating demand and apartment overheating of ALT 2, low-rise lamella building in Gothenburg.

The result of different cases is very insignificant due to the small surface area and volume of the double skin façade compared to the total building envelope area and volume. Improving the thermal performance of double skin façade, by either adding a second glazed pane or improving the tightness of air space, between the two building skins, reduced annual heating demand. However, such actions also slightly increased the number of overheating hours in living spaces. Two-paned clear DSF glazing and tight DSF air space allowed to reduce the annual heating demand by 2.5 % compared to ALT 1. Nevertheless, same glazing type also had the most overheating hours in apartments.

4.8 Life Cycle Profit

4.8.1 Opaque

Figure 31 shows the LCP (Life Cycle Profit) for the low-rise and the high-rise lamella building. Each dot in the figure represents one scenario where the g_r for maintenance and energy varied from 0 % to 4 %. The most likely future scenario is represented with a thick horizontal line.

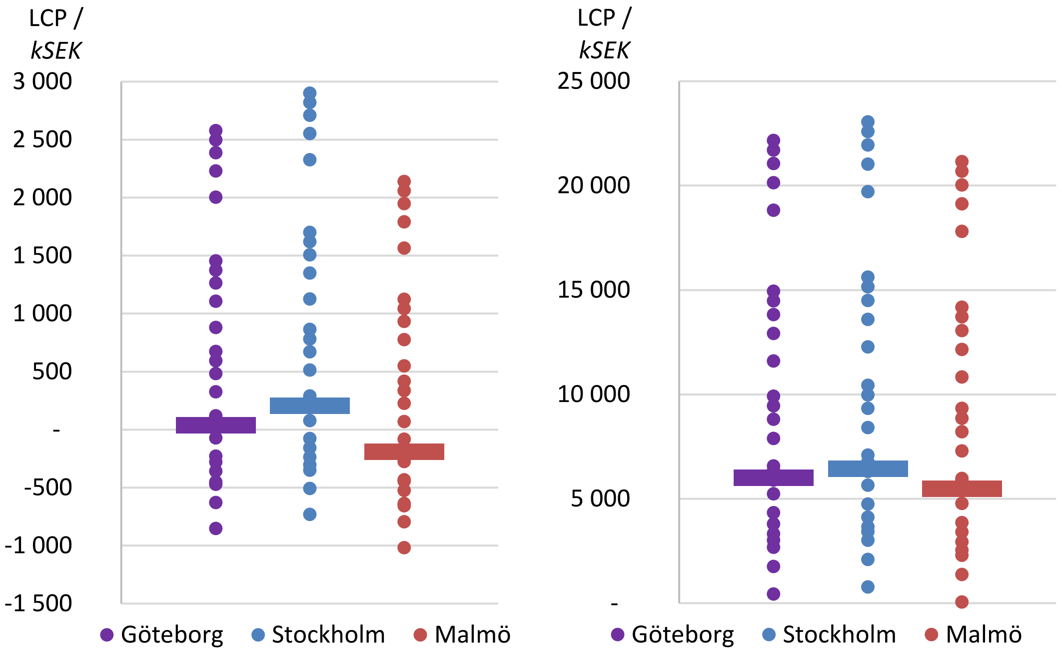


Figure 31: LCP of the Opaque solution on low-rise (left) and high-rise lamella buildings (right).

In the most likely future scenario, the opaque solution showed to be profitable for all cities for the high-rise building but not for Malmoe when it comes to the low-rise building. The profitability for the high-rise building was considered to be much greater than for the low-rise building as the energy saving potential was around 60 % larger. This saving potential was also expressed in the large range of profitability; the range for the high-rise building situated in Gothenburg varied between 400 *kSEK* to 22 000 *kSEK* while the same case only varied between –600 *kSEK* and 2 600 *kSEK* for the low-rise building. The difference in potential profits between the locations were decided by the difference in energy saving.

4.8.2 Alternative 1

Figure 32 shows the calculated LCP for Alternative 1 of low-rise and high-rise lamella building.

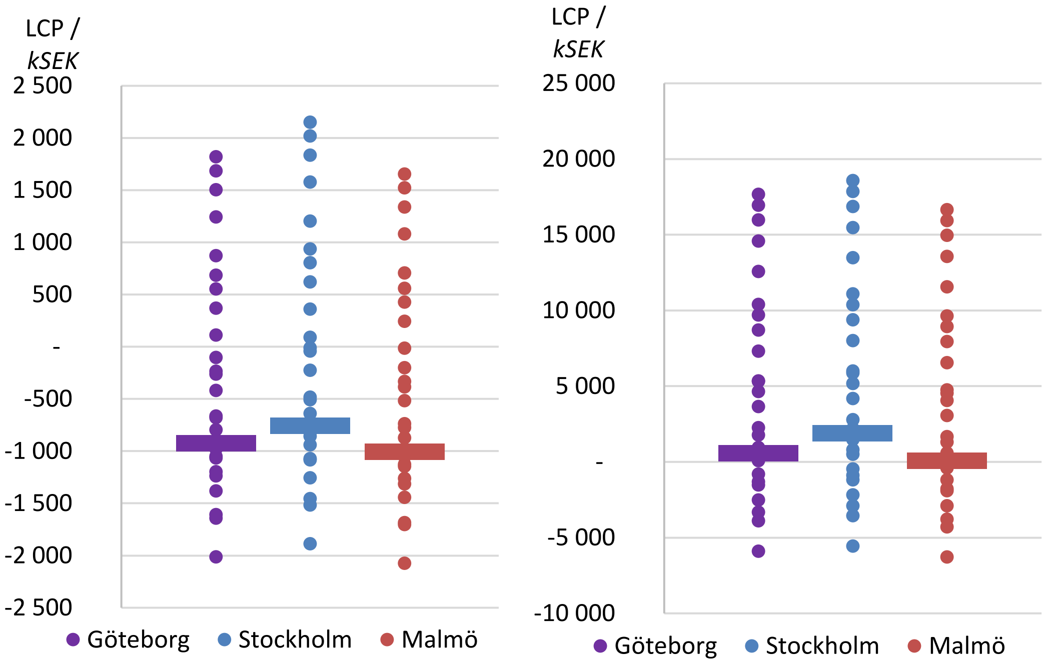


Figure 32: LCP of ALT 1 on low-rise (left) and high-rise lamella buildings (right).

Alternative 1 showed to be unprofitable for all locations when implementing it on the low-rise building, concerning the most likely future scenario. However, there were future scenarios where the investments would be considered profitable, generally when the g_r for energy was at least 3 % while the maximum allowed g_r for maintenance was 4 %. If the g_r of energy reached 4 %, any price growth rate of maintenance would be covered by the energy savings.

When implementing Alternative 1 on the high-rise building during the same future scenario the investment showed to be profitable in all three locations. The high-rise building showed to have a bigger tolerance for yearly increases in maintenance costs as well as it was not as dependent on the increase of energy costs in order to become profitable. When a future scenario included a g_r for energy of at least 2 %, the energy savings would cover all included price growth rates of maintenance and the investment would be considered profitable.

Parametric study of Alternative 1

Figure 33 shows the LCP for the chosen low-rise parametric study while Figure 34 shows the LCP for the chosen high-rise parametric study. The U and its number means the *U*-value of the apartment windows towards the balcony space (e.g. U0.8 means a *U*-value of 0.8 $W/(m^2 \cdot K)$) and the number after the hyphen together with its letter means the number of panes and its glazing type (e.g. 2PC means a two pane coated balcony glazing).

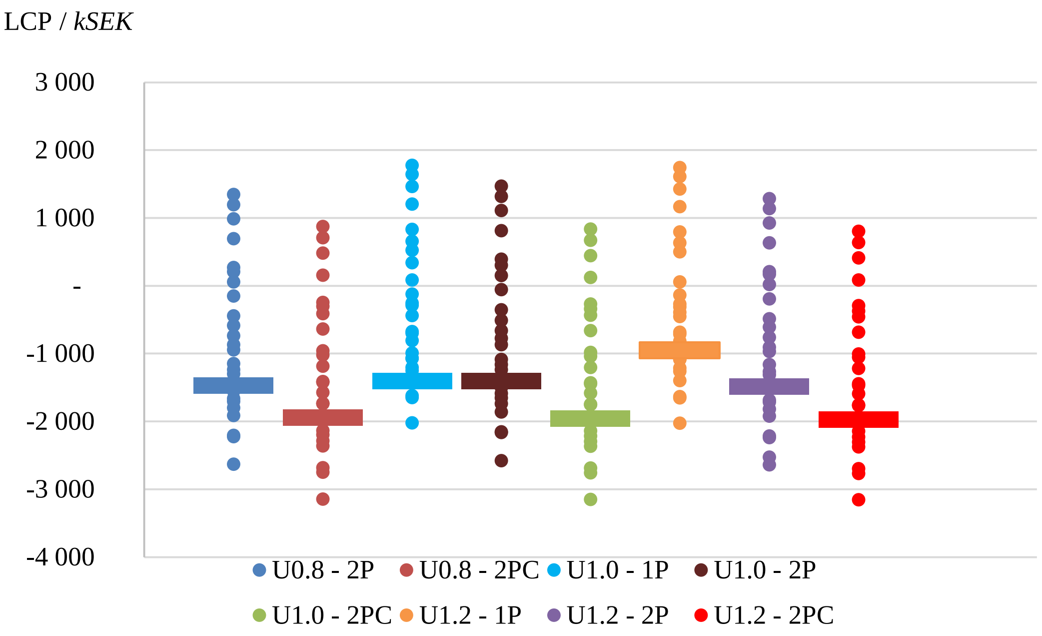


Figure 33: LCP for parametric study of Alternative 1 in low-rise lamella building situated in Gothenburg.

The figure shows that by altering the construction to less insulating windows within the balcony and a better insulating balcony structure does not give a profitable outcome in the most likely future scenario. The larger investment costs for a more insulating balcony structure result in a smaller possibility of profit since the energy savings are not large enough. Since the investment costs are larger, they are generally never considered to be profitable unless the price growth rate of energy increases by 4 % each year.

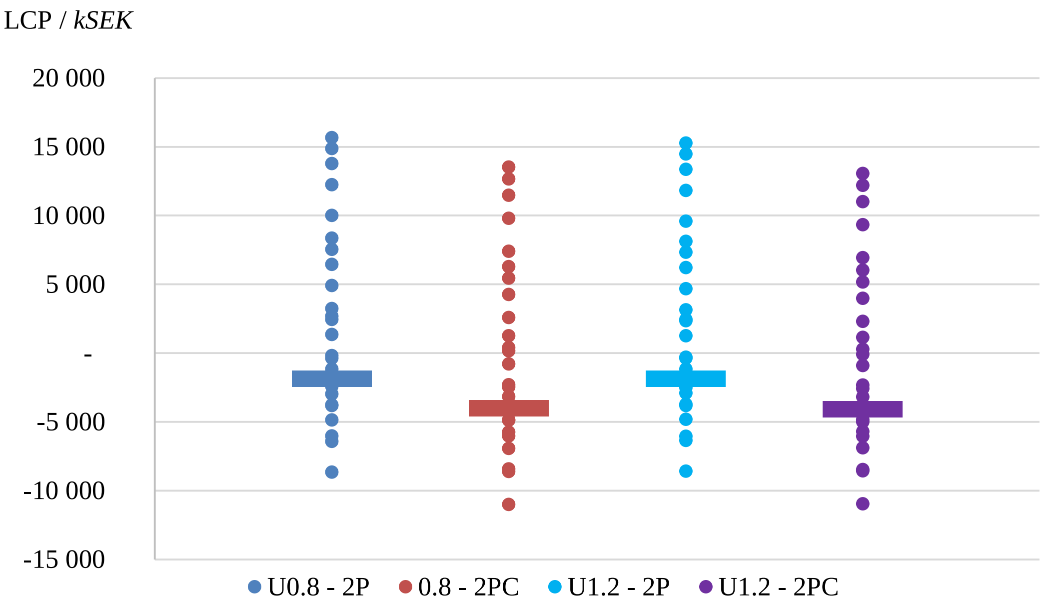


Figure 34: LCP for parametric study of Alternative 1 in high-rise lamella building situated in Gothenburg.

As expected it was found that coating the balcony glazing results in a lower LCP. However, it was also found that when applying the windows with the lowest unit price (*U*-value = 1.2 *W/(m²·K)*) the LCP was not higher than when using better insulating windows with modestly higher unit price.

4.8.3 Alternative 2

Figure 35 shows the LCP concerning Alternative 2 where 2P stands for a two-paned glazed façade and 2PC stands for a coated two-paned glazed façade.

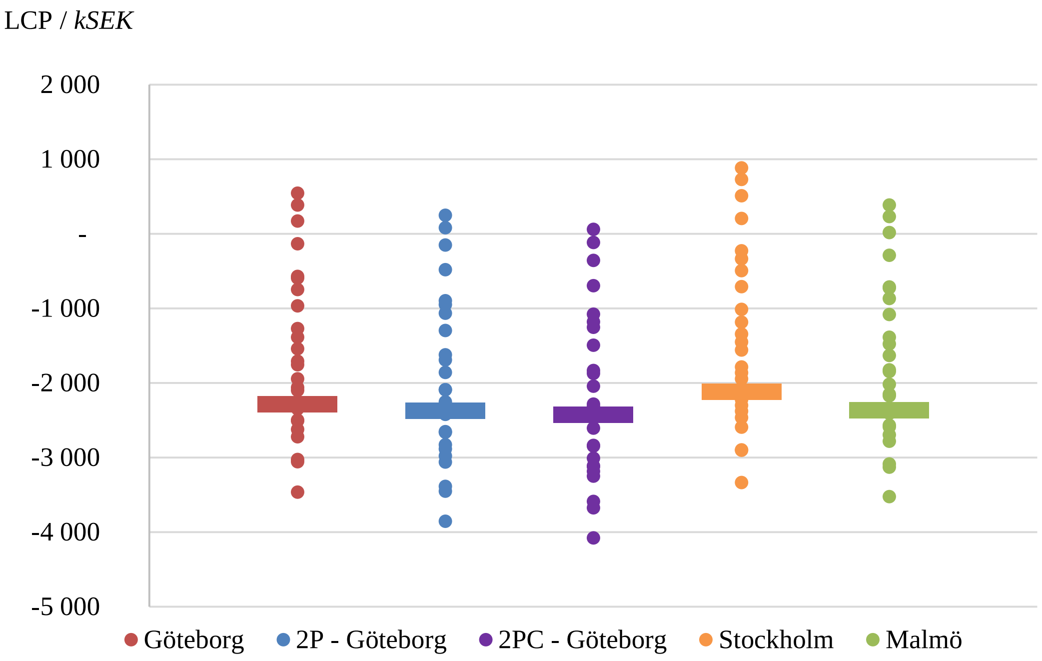


Figure 35: LCP for parametric study of Alternative 2 in low-rise lamella building.

Alternative 2 generally showed to be the least profitable solution. The Alternative 2 base case generally showed to be profitable when the g_r for energy was 4 % while the g_r for maintenance did not reach 3 *%*. If the building was situated in Stockholm there was a slightly higher tolerance for a yearly price increase concerning maintenance costs. It could reach 3 *%* (if the g_r for energy stayed at 4 *%*) and still be considered to be profitable. Figure 34 shows that the choice of either two-paned- or two-pane coated glazing structures are generally unprofitable in all future scenarios but the one including a g_r for energy of 4 *%* and *0 %* for maintenance, if the building is situated in Gothenburg.

4.8.4 Apartment rent increase

Table 14 shows the needed monthly rent increase normalized by apartment square meter in order to make the investment economically feasible for the base cases concerning Alternative 1 and Alternative 2 for the low-rise building.

Table 14: Monthly apartment rent increase of ALT1 and ALT2 for the low-rise building in order to make the renovation profitable.

Case	**Monthly apartment rent increase / (*SEK/m²*)**
ALT 1 Gothenburg	6.1
ALT 1 Stockholm	5.0
ALT 1 Malmoe	6.7
ALT 2 Gothenburg	15.1
ALT 2 Stockholm	14.0
ALT 2 Malmoe	15.6

The calculations showed that Alternative 2 was in need of a significantly higher rent increase in order to make the investment economically feasible. Alternative 1 showed to be in need of at least of the rent increase compared to Alternative 2 in order to make the investments profitable. The rent increase was linked directly to the LCP of each alternative, if the investment showed tendency of a larger economic loss, the rent was also in need of a larger rent increase.

5 Discussion

The balcony and glazing industry often promote their products as energy-saving measures with bold statements about their effect and efficiency. However, in reality, the effectiveness of these products can significantly vary from case to case and are impacted by other parameters that were tested in this study. As mentioned above, a glazed balcony provides more value than an unglazed balcony. However, changing the properties of a balcony could raise the risk of moisture damages. Warm humid balcony air will during the warmer months be transferred by underpressure from the ventilation system into the apartments. This humid air has to be handled by the ventilation system and interiors in the apartment. It is important to have this in mind when designing the HVAC system. Warmer humid air will be transferred into the balcony during the colder months and possibly cause condensation on the glazing. Choosing balcony frames made of aluminum makes the construction more resilient towards moisture damages.

Protruding balconies can be perceived as an extension of the building envelope and Alternative 2 is a good solution to create a clean surface and an integrated balcony design. However, since it is common that most tenants in the Million Programme building are elderly, the functionality may have to be prioritized over design in order to be able to keep these elder tenants after a renovation.

Both glazed solutions consisted of keeping the current balcony slab and increase its size by extending it along the facade. There is a possibility to tear down the existing balcony slabs and replace them with new column supported slabs. This construction type would eliminate the current cold bridges between the balcony slab and apartment floor structure, which can cause cold floorings close to the balcony. The column-supported balcony would however raise the renovation costs and make the project even less economically feasible.

Glazed balconies also give the opportunity to integrate photovoltaic (PV) cells in glazed surfaces and if it is integrated in the prefabrication phase, the additional costs are not considered to be very costly. The energy-savings from the PV cells could be used for property electricity in order to pay back for the investment costs for the balconies. There is shown to be a higher demand on the market for less transparent balcony glazing in order to gain more privacy. A solution for this could include transparent PV cells, which generate electricity and obscure the transparency of the lower parts of the glazed balconies. However, the PV efficiency is temperature dependent, thus a thorough investigation should be carried out before implementing them on any of the studied solutions.

Even though the balcony constructions with a double pane glazing showed to be more expensive, it could be useful to have an insulated balcony glass. It is not uncommon that tenants tend to extend the “balcony season” by using electrical heaters and thus it is necessary to insulate the balcony in order to reduce the thermal losses from them.

ALT 1 and ALT 2 had a more positive outcome than the Opaque solution possibly because glazing the balconies allows closing the balcony space and thus reducing the convection losses. In addition to reducing convection losses, it increases the balcony temperature, which as result reduces the thermal conductivity of windows and doors adjacent to balcony space if compared with the Opaque solution. Subsequently lower thermal conductivity results in lower *U*-value, which improves the thermal resilience of a structure. Since most of the façade area facing balcony space consists of glass, the *U*-value of glass could be of higher importance than the *U*-value of opaque materials. However, it must be remembered that all these speculations are very sensitive towards building orientation and solar radiation levels.

Authors of this work believe that the reason why building industry is hesitant with implementing glazed spaces as a renovation strategy is lack of information on how they affect the building energy demand and indoor thermal comfort. Although, glazed spaces have additional values, they are very often overseen due to higher investment costs than traditional insulation methods. The common opinion is that glass results in energy losses and thus cannot be an energy-efficient design alternative to opaque surface materials.

5.1 Opaque solution

It can be suggested that the energy consumption of FTX ventilation system, located in façade panels, of low-rise lamella building should not be higher than in high-rise building due to smaller ventilation rate and velocity, which as a result decreases the pressure drops and thus the energy used to operate the system.

There should be enough space to accommodate four ducts, one for every floor, placed in parallel in the opaque parts of the facade between apartment windows on both longitudinal facades. The distance between the windows was approximately 1200 *mm* on both longitudinal facades, which gave about 150 *mm* spacing available between ducts. Ducts were placed in the same manner as in high-rise building, 10 *mm* away from the interior concrete wall to avoid heat propagation through that wall and increase the replicability.

Ventilation ducts would not be a part of prefabricated façade panels on the façade with balconies or DSF in both proposed alternatives for low-rise lamella building like they are in the Opaque solution. Ductwork would instead be insulated with 100 *mm* thermal insulation on the three surfaces facing balcony space and 10 *mm* on the surface adjacent to the external wall and then attached to the original façade as a separate element. These amounts of insulation would allow meeting the conditions of the Opaque solution. In addition, air temperature inside the balcony during heating season was always higher than the outside temperature, which would reduce the thermal losses from ductwork when compared to the Opaque solution. Considering these factors, it can be suggested that the energy loss through ductwork in ALT 1 and ALT 2 of low-rise lamella building should not be larger than that obtained in the Opaque solution.

Ventilation principle, layout and duct geometry in ALT 1 of high-rise building was identical to one used in the Opaque solution, therefore it can be assumed that ALT 1 would have equal energy loss through ductwork as the Opaque solution.

5.2 Shading factor

According to the results presented in chapter 4.2, shading factor was more impactful on balcony glazing than windows due to a larger effective surface area. Therefore, it can be suggested that larger glazed surfaces would have a higher effect on annual heating demand and overheating than those of smaller area. It also affected the apartment overheating more than it did annual heating demand.

Altering shading factor changed the amount of solar energy that could be transmitted through a glazed surface. Higher shading factor reduced solar heat gains, which subsequently increased the heating demand but decreased overheating in apartments. No shading factor meant that all available solar irradiation landed on the glazed surface and the original glass transmittance was the used design value, while 0.5 shading factor meant that the original glass transmittance was reduced by half.

As expected, the combination with no shading factors had the lowest annual heating demand and most overheating hours. However, such a case was highly unrealistic and had only a scientific value since windows were shaded by projecting balconies already. The base input combination of 0.5 shading factor on balcony glazing and no window shading factor matched with the 0.3 balcony glazing and 0.5 window shading factor combination, which in the opinion of authors could be a realistic case in an urban environment, where majority of the reference buildings are located in.

It can be suggested that on-site solar radiation measurements should be obtained from inside the balcony and apartment to accurately assess the shading factor of windows and any other glazed surface installed in front of them. There are many factors that can affect the amount of solar radiation landing on a glazed surface, building geometry, balcony depth, surrounding buildings and other large obstacles in a near distance.

Since shading factor is not location but rather surrounding environment dependent and is affected only by the obstacles in nearby distance, this parametric study was only conducted for the reference location (Gothenburg). It can be expected to have a similar trend in other locations that have similar built density.

5.3 Location

Three different locations – Gothenburg, Malmoe and Stockholm were studied to investigate the replicability potential of the proposed design alternatives. They are all characterized by different weather conditions and latitude, which suggested that strategies found efficient in one location might not be as proficient in others.

Most energy reduction by applying ALT 1 or ALT 2, was reached in Malmoe and Stockholm for low and high-rise lamella buildings respectively. It was noted that location Gothenburg has the least energy saving potential from the three studied locations disregard of the alternative or building geometry. It can be argued that it is due to lower annual solar radiation levels, which are vital when using glazed spaces as thermal insulator instead of conventional insulation methods. Lower annual solar radiation was also the reason why all alternatives had the fewest apartment overheating hours in Gothenburg and not Malmoe or Stockholm.

All studied alternatives exceeded FEBY (2012) thermal comfort standard in Stockholm. Significantly higher summer solar radiation can be argued as the main cause for such phenomenon, which is partly caused by the high latitude of Stockholm. High latitude increases summer day length and thus the amount of potential sun hours. Moreover, the solar radiation incidence angle on a vertical surface is lower in Stockholm, therefore, larger fraction of all solar radiation falls directly on the respective surface increasing the solar heat gains and reducing the reflected solar radiation. As a result, apartment overheating in Stockholm was more significant than in Gothenburg or Malmoe. The noted overheating levels suggested performing a study of passive cooling measures.

5.4 Orientation

According to authors of this work, the apartment plan layout and building geometry of lamella buildings suggested up to five potential orientations ranging from east to west. Although, the orientation of existing buildings that in reality are facing different cardinal directions cannot be changed, the scientific approach of this study would allow pointing out which of the existing buildings may have the highest energy saving potential. The original orientation of low-rise building was that the façade with balconies was facing southwest, whilst longitudinal facades with balconies were facing southeast and southwest in case of high-rise building.

Southern orientation was found to be the most favourable and offered the highest energy saving potential in case of low-rise lamella building due to higher direct solar irradiance levels during heating season. South oriented glazed spaces resulted in best thermal comfort in living spaces due to smaller direct solar irradiance levels during cooling season and balcony slabs that behaved as passive shading devices and did not allow the high summer sun to shine directly on the glazed surfaces below. Changing the cardinal directions of the façade with glazed balconies had less significant impact on annual heating demand than previously expected. Nevertheless, orientation had a major impact on apartment overheating.

West orientation of glazed spaces resulted in the highest overheating in living spaces due to the low evening sun that was shining directly on the glazed surfaces, that the balcony slab above, which otherwise behaved as a shading device, could no longer shade from direct sun rays. It added to the accumulated heat by east facing glazed surfaces, which absorbed solar heat during morning hours and other parts of building envelope, e.g. roof, that received direct solar radiation over the day.

Orientation had even less significant impact in case of high-rise lamella building than low-rise, resulting in only 1 % difference in annual heating demand between the best and worst performing cases. It can be argued that such a finding is linked to the simplifications of the high-rise building IDA-ICE model in which all apartments located on the same floor and facing same cardinal direction were merged into a single zone, thus balancing the effect orientation. Moreover, glazed balconies were located on both longitudinal facades facing opposite directions subsequently reducing the impact of orientation even more. The original case with southeast-northwest orientation of glazed balconies was found to be the most energy-efficient, however, it had the most apartment overheating hours. This was due to low and direct summer evening sun, which shone directly through the glazed balconies and apartment windows that were not shaded by the balcony slab from the apartment above. Most heating on annual basis was required when facades with glazed balconies were facing west and east due to lower annual solar radiation levels than any other two opposite cardinal directions.

Least apartment overheating in high-rise building was simulated when both longitudinal facades were facing north and south. Northern orientation meant that there was only indirect solar radiation falling on the glazed balconies and windows, while the balcony slabs facing opposite direction, south, were shielding the apartment windows adjacent to balcony space from direct sun radiation during cooling season, therefore reducing the overheating potential.

5.5 Balcony design

All balcony heavy structures were designed in 10 *cm* thick lightweight concrete, which was the suggested perfect thickness and material found in the state-of-art literature review. Low-rise lamella building had generally lower annual heating demand, fewer overheating hours and larger result differences between the studied parameters than high-rise building. Although, there were many variables between the two cases, it can be argued that building and balcony geometry were two of the more important factors for such a result.

Low-rise building had a 0.39 *GWR* compared to 0.48 *GWR* of high-rise building, thus there were more thermal transmission losses through building envelope and annual heating demand in the high-rise building. The increased balcony length allowed to cover larger façade surface area and increased the volume of passive heat absorbing space, which consequently increased solar heat gain storing capacity of balconies. The recessed balcony type of high-rise building did not allow extension along the façade, therefore the effect on annual heating demand and overheating hours was not as significant as in the low-rise building. Furthermore, the low-rise balcony had two to three external surfaces - glazing, concrete wall and external floor or roof, while the high-rise building had only a single external surface – glazing.

Since the aim of this study was to find cooling strategies with either lowest annual heating demand and/or fewest apartment overheating hours, windows with a *U*-value of 1.0 were not studied on high-rise lamella building after it was found that they had a median performance in low-riser. Similar strategy was applied when windows with a *U*-value of 1.2 were combined with cooling measures, where only the best performing strategies found in low-rise building were studied on the high-riser. This simplification method was considered valid as the trend in overheating hours was definite. It was expected that coated balcony glazing would have the fewest overheating hours while the clear two-paned tight balcony glazing would have the lowest annual heating demand according to findings from cooling measure study in low-rise lamella building.

It was found that *SHGC* used in this work had a higher effect on annual heating demand and overheating than different *U*-values or balcony air-tightness for the two reference buildings in Gothenburg, Malmoe and Stockholm. All three locations had very similar weather conditions on annual basis except for direct normal radiation, which was almost twice higher in Stockholm than in the other two locations (see Appendix C). The findings of the study suggested that impact of *SHGC* could be directly linked to façade orientation, solar radiation and area of glazed surface. The larger the glazed surface and/or solar radiation, the higher the impact of *SHGC* could be. The different air-tightness values studied in this work were the least impactful from the three studied parameters. The impact of balcony air-tightness could be directly linked to the annual mean outdoor temperature. The authors believe, that it might be due to the fact that moving air has worse heat storing abilities than lightweight concrete which was used in balcony structures. Thus, the solar heat that air absorbs while being in the balcony space is released at a faster rate than from the heavy balcony structures. Which as a result reduces the impact of balcony space air-tightness compared to balcony glazing *SHGC* or *U*-value. It can also be argued that there might be a breaking point at which outdoor air temperature becomes more impactful than the solar radiation and thus increases the impact of balcony air-tightness. Therefore, it can be argued that these findings should not be directly applied in all locations where the Swedish Million Programme building are located without a further study. However, it must be remembered that balcony is an unheated space and thus the effect that air-tightness has on it cannot be compared to the effect that air-tightness has on a heated living area.

Coated two-pane balcony glazing had approximately two times lower *SHGC* than a clear two-pane glazing. Coating the balcony glazing resulted in the fewest overheating hours and highest annual heating demand from the studied balcony glazing types due to reduced solar heat gains. However, the impact of coating was more significant on overheating than heating demand. Thus, it was found to be used as a possible passive cooling alternative. *SHGC* had a slightly higher impact on low-rise lamella building than high-rise due to larger balcony glazing surface area.

A combination of 0.8 *U*-value windows, two-paned balcony glazing and an air-tight balcony space always performed best in annual heating demand regardless of building and balcony geometry and location. Its improved thermal resilience allowed reducing transmission losses. However, it also improved heat accumulation within the balcony space and apartments, which as a result increased the number of overheating hours.

Window *U*-value had a higher impact on annual heating demand in high-rise lamella building than low-riser, whereas the difference between best and worst performing windows, 0.8 and 1.2 *U*-value, respectively, was 6 *%* in low and 10.5 *%* in high rise building. Although, change of window *U*-value had a very little effect on overheating hours in the low-rise building, where the maximum difference between 0.8 and 1.2 *U*-value windows was only 6 *%*, it had a more significant impact in the high-rise building where the differences in the studied cases ranged from 20 to 25 *%*. One of the main reasons for this was a higher *GWR* in high-rise building with larger effective surface area, which consequently led to higher result differences.

Decreasing window *U*-value had a more significant effect on annual heating demand than reducing balcony-glazing *U*-value instead. Such behaviour could be explained by a fact that windows were adjacent to heated indoor spaces and thus had a direct impact on them, whilst balcony glazing had only an indirect effect since they were not adjacent to the heated indoor space. However, the finding was completely opposite for overheating. Reducing balcony-glazing *U*-value impacted the overheating more than reducing window *U*-value. Lower balcony glazing *U*-value allowed to reduce the thermal losses through the glazed surface and as a result accumulate more heat, which not only contributed to lower annual heating demand, but also more overheating hours during cooling season. Moreover, reducing the *U*-

value of balcony glazing had a higher impact in high-rise lamella building since it was the only balcony surface with a direct outside exposure.

Improving the air-tightness of balcony space had a similar effect on annual heating demand and number of overheating hours in apartments as improving thermal resilience of glazed surfaces. An air-tight balcony space lost heat at a slower rate than a leaky balcony space, which allowed using the buffer zone more efficiently from an energy perspective. Air-tightness had equally large impact on both reference buildings.

All studied combinations in low-rise building parametric study met the FEBY thermal comfort requirements in Gothenburg, while in Stockholm only coated balcony glazing was sufficient enough to meet the same standard, which was also the case for the parametric study performed for high-rise building and its reference location Gothenburg. Such result suggested a study of cooling measures.

The addition of second glazed surface on one side of balconies resulted in very insignificant changes in annual heating demand and apartment overheating hours. The heating demand slightly increased since the glazing had a worse U-value than the 100 *mm* thick lightweight concrete balcony wall that it replaced, meaning that heat escaped at a faster rate. There was also a slight decrease in apartment overheating hours due to same reasons. In addition, exchanging concrete with glass reduced the heat storing capacity of balcony space. However, it can be argued that adding a second glazed balcony surface could potentially increase the daylight levels in the apartments and the added value of such design alternative can be greater than the insignificant deviations in annual heating demand and apartment overheating.

It can be argued that the amount of energy saved by glazing balconies is dependent on U_m value of building envelope. Glazing balconies for buildings with higher U_m value would have larger energy savings, while buildings lower U_m value would have smaller energy savings. Since both buildings have already been super insulated by the Opaque solution, the impact of glazing balconies and various altered parameters was relatively small. In addition to the low U_m value, it is also the fact that these glazed space cover only up to one third of all building envelope area.

Although mutual relation between various balcony glazing and window types, as well as addition of second glazed surface to the balcony space was not studied in Malmoe, it can be expected that the annual heating demand should be lower than that obtained in Gothenburg and Stockholm, while the overheating would be slightly higher than in Gothenburg, but lower than in Stockholm. These assumptions are based on the location study discussed earlier.

Prefabrication of balconies can be suggested as viable option to reduce building construction time, improve the quality of work and also minimize construction costs. Each balcony can be designed as a separate module, with concrete slab, an external wall and all the necessary glazing, and then installed on the existing building façade. However, the structural supporting system must be prepared in advance and on site.

In order to have deeper understanding of balcony geometry impact on annual energy demand and overheating in apartments, it is advised to perform a study of how the respective parameters vary according to changes in balcony length-to-depth ratio, glazing opening technique, balcony glazing frame location and fixing method.

5.6 Overheating trends

Overheating and its relation to the proposed design alternatives and their parameters was one of the major areas assessed in this study. Although this study was not aiming at reaching passive house requirements, it was only FEBY (The Swedish Centre for Zero Energy-buildings, 2012) that had clear and detailed criteria for thermal comfort; therefore, it was used as a reference. FEBY 12 (2012) suggested overheating to be measured in hours that exceed 26 *°C* during April to September, which cannot exceed 10 *%* of all hours in the respective period. The respective passive house standard required overheating to be measured on annual basis, which also meant in times when most tenants might be away from home.

Most of the overheating occurs at evenings when solar heat has accumulated in the living spaces over the day. However, when a building has two facades that have a significantly larger surface area than the other facades like buildings in this study, sun can only shine on one of the longitudinal facades at a time, meanwhile the other long façade on the opposite side will lose heat. Since the U_m value has been increased in ALT 1 and ALT 2 by not adding extra insulation to the external walls adjacent to balcony space, heat will be lost at a faster rate than in the Opaque solution and thus overheating hours are reduced. In case of low-rise lamella building, the extended balcony slabs behave as passive shading devices and thus reduce the solar radiation that can be transmitted through windows in the façade where balconies are located. Some of these windows were not shaded in the Opaque solution where the original balcony length along the façade was more than twice shorter.

Overheating potential was more significant in high-rise building due to fact that apartments were facing only one cardinal direction, except for those in the corners, and as a result would have thermal transmission losses through one façade only, increasing the heat accumulation within the respective space. However, it was not possible to point out which specific apartment had the highest potential of overheating in the high-rise building since its IDA-ICE model was simplified and all apartments on the same floor facing same direction were merged into a single zone. However, it can be argued that apartments with smaller building envelope area over one m^2 of living space would have more overheating hours than those with higher envelope to living space ratio. Meaning that an apartment which had an adjacent floor, ceiling and interior walls to other apartments would have higher overheating than similar apartment with lesser adjacent surfaces to other apartments because there would be smaller surface area that would transmit hot air to outside and thus relieve the heat accumulation.

It can be suggested that overheating is a function of orientation, glass to wall ratio, form factor, U_m-value and the floor distance from ground level.

There were no thermal comfort requirements for balconies at the time of this work; therefore, the overheating in them was not thoroughly studied. However, it was noted that there is a potential for overheating starting from mid spring to mid-autumn and that temperatures in balconies could reach as high as 40 °C.

5.7 Passive cooling measures

High-rise building had more overheating than the low-rise building due to different balcony geometry that had fewer external surfaces. Moreover, the extended balcony length in case of low-rise building behaved as a passive shading device. It shaded windows on the floor below that were exposed to direct summer sun in the original building with shorter balcony length, which as a result reduced the overheating hours in the apartments. As noted in chapter 5.5, balcony length along the façade could not be increased in case of high-rise building, thus all windows that were not facing balcony space remained unshaded.

Opening balcony-glazing during June to August, annual *PI* opening schedule and coated glass proved to be efficient passive cooling techniques for the studied buildings. Since the effectiveness of manual window opening is dependent on tenants, energy and thermal comfort were negatively affected if glazed balconies were kept open during other months than June to August. Using an automatic system, which was replicated by using a PI schedule in IDA-ICE, could reduce the sensitivity of these parameters. Automatic systems could respond to the dynamic changes in the outdoor conditions and open or close the glazing according to the desired temperature set points without requiring any tenant interference.

Opening balcony glazing significantly increased the air change rate in balconies and thus allowed to remove excess heat when the outside air temperature was lower than that of the balcony air. Moreover, such cooling method did not alter annual heating demand significantly if it was applied from June to August when majority of the overheating hours occurred. The overheating hours in apartments were reduced to comfortable levels for both studied locations of low-rise building and only for high-rise building located in Gothenburg. In addition, the overheating hours rapidly decreased by opening larger areas of the balcony glazing, meaning that most opened strategy (80 % open) had the least apartment overheating. Balcony opening strategy failed to reduce the overheating in apartments to comfortable levels for high-rise building located in Stockholm. Most opened alternative had 1675 overheating hours in apartments, which significantly exceeded the 436.8 hour FEBY (2012) requirement. Although, opening apartment windows during the times of peak cooling demand could be an effective solution, it was not considered as a separate passive cooling, but paired with balcony opening in *PI* schedule. Opening the balcony glazing in other months than June, July and August increased annual heating demand; therefore, it would be vital for tenants to follow the instructions proposed in this work. The preliminary study of opened balcony glazing areas showed that such a cooling strategy is only effective if 20 % or more of balcony glazing is opened. Openings of less than that were ineffective.

PI schedule strategy was an improved version of manual window opening. It allowed to automatically opening both balcony glazing and windows. *PI* schedule replicated an effect of perfect tenant behaviour or an automatic opening system and opened balcony glazing only when the outdoor air temperature was lower than the balcony air temperature. It also opened windows adjacent to apartments and balcony space only when the apartment air temperature was lower than that of the balcony air. Such an opening scheme allowed dynamic mutual interaction between outdoors, the buffer space (balcony) and indoors. Consequently, it was the only cooling strategy that always met the FEBY (2012) thermal comfort standard in living spaces and had the fewest overheating hours disregard of location, building or balcony geometry. Windows were not separately opened as a passive cooling strategy but only in the *PI* schedule. However, it can be argued that if windows were opened along with 80 % opened balcony glazing, the overheating hours in apartments would be lower than those noted for 80 % opened balcony glazing only. In addition, it could be that keeping the balcony glazing open also in May and September, in addition to the tested period of June to August, could reduce the overheating hours in the respective case even more. That could perhaps avoid using an automatic system, however, it must be studied in more depth.

The separate comb design, individual air inlets and outlets for every balcony, allows to reduce the impact of tenant behaviour on neighbouring apartments, where tenant A would not be directly impacted by actions of tenant B. Therefore, eliminating a case where an opened balcony for one or more apartments would increase the heating demand and alternates the thermal comfort of neighbouring apartments.

Although using coated glazing lowered the number of overheating hours to comfortable levels, it had a permanent effect on passive solar heat gains by reducing the energy transmitted through the glass. Eventually, lesser solar heat could reach and instantly heat the indoor spaces or be stored in thermal mass for later use, therefore the annual heating demand increased. Although coating was always the second most effective cooling measure behind *PI* schedule, it did not meet the FEBY (2012) thermal comfort requirements for high-rise building in Stockholm, having 1089 overheating hours.

It is advised to use a centrally controlled climate system to avoid overcooling living spaces when tenants keep the balcony glazing or doors open long enough to increase the heating demand in the apartment. Such system would turn of the heating supply in the particular room in which the balcony glazing or doors are opened for longer time-periods. This strategy would force tenants to close the balcony doors, which would reduce the amount of lost energy.

Window coating was not studied in this work since windows facing southwest had very little direct sun due to the balcony geometry that shaded them during majority of the year while windows facing north-east were not considered to be major contributors to apartment overheating. Also, shading devices were not considered in this study because their shading abilities are highly dependent on their type, geometry, reflectance etc.; however, it can be argued that an automatic external shading device could possibly outperform coated glass. When closed, they would reduce the solar transmittance even more than coating, while transmitting as much or slightly lesser solar heat gains as a clear window. Automatic shading devices would also have a dynamic response to changing outdoor conditions. However, such systems would most likely require higher initial and maintenance costs than balcony opening or coated balcony glazing.

Although opening balcony glazing was not proposed as an independent cooling strategy for balcony spaces but only used as technique to reduce the apartment overheating, it can be argued that this principle allows excess heat extraction from balconies without increasing the annual heating demand. However, conditions that the glazing is kept open only until the point where the air temperatures between balcony and apartment reach equilibrium state would have to be met. Once the equilibrium temperature conditions between the respective spaces are reached, the balcony glazing must be closed. In order to make this strategy more efficient, the authors suggest using an automatic opening system with cooling temperature set back value similar to that used for apartments, if the balcony space is desired to be occupied during late spring, summer and early autumn.

Although cooling measures in Malmoe were not studied, it can be argued that all the measures working in Stockholm would also work in Malmoe since Stockholm had the most overheating according to location study discussed earlier in this work.

5.8 Double skin facade

Glass skin was installed in front of the existing southwest facing façade in the areas that were not covered by balconies – in front of all staircases, basement and utility rooms. Addition of DSF reduced annual heating demand, obtained from ALT 1, by 1.2 to 1.5 *%* depending on location. The highest difference in annual heating demand between ALT 1 and ALT 2 was reached in Gothenburg, while the least in Stockholm. The total annual energy demand for low-rise lamella building located in reference location Gothenburg after glazing the existing brick façade was 45.5 *kWh/(m²·y)*.

The impact of various DSF air change rates on annual heating demand was smaller than expected. However, it could be explained by three reasons. Firstly, the DSF covered only 7 *%* of the total building envelope area. Secondly, it was only adjacent to utility rooms on ground floor and staircases, thus the DSF had an indirect effect on apartments. The heat gained by DSF had travel either through balconies or utility rooms to enter the living spaces. Thirdly, the heavy structure behind the DSF contains insulation, therefore limiting the heat transmittance from DSF to indoor spaces. Considering all the above-mentioned factors, the DSF impact on annual heating and overheating in apartments is hardly noticeable. Although overheating in DSF was not considered important since it did not have a significant effect on overheating in the living spaces, it was still noted to validate the sensitivity of DSF when it comes to different air change rates.

The parametric study of various DSF glazing types was performed in order to optimize ALT 2 and find ways to reduce heating demand and apartment overheating even more. Two different scenarios were found. First, lowest annual heating demand and most overheating hours in apartments were reached by installing clear two-paned glass skin. Second, fewest overheating hours in apartments and most heating demand by installing coated two-paned glass skin. Both scenarios had the opposite effect. External or intermediate shading device that closes once a certain temperature in the DSF air space is reached could be an effective solution to reduce overheating without alternating the heating demand.

It can be suggested that increasing south, southeast or southwest facing DSF surface area and volume could potentially decrease the annual heating demand even further.

Parametric study on various DSF glazing types was only studied for the reference location (Gothenburg), however, it can be argued that the trend between the different glazing types should be similar in other locations. Cooling measures were not tested on DSF. However, stack effect through openable vents at the bottom and top of every DSF zone could be considered as a possible passive measure. That could be an effective strategy to extract excess heat when the air temperature in DSF cavity exceeds a specific temperature.

5.9 Life Cycle Profit

From the three different solutions, the opaque was shown to have the largest profit potential. This finding was mainly caused by the facts that glazed balconies and facades had a higher construction and maintenance cost together with the insufficient energy savings compared to the investment costs. However, the differences in profits between the different alternatives are not considered to be significant enough to become the deciding factor when choosing the best alternative.

The high-rise building showed to have chances of large profit income but it comes with high risks of deficits. When comparing the two buildings' cost of yearly heating, the savings for the high-rise building was 33 % larger. With such larger savings, a future scenario where the g_r for heating increases leads to a larger profit. In addition to this, it could be argued that since the form factor of high-rise was larger than for the low-rise building there is also a bigger opportunity to save energy (i.e. money) for the investment. The high-rise buildings' larger building envelope also makes the investment sensitive towards increases in price growth rates for maintenance. The returns of investments (ROI) for the high-rise building and the most realistic future scenario are 32 % and 3 % for the opaque solution and Alternative 1, respectively. For the low-rise building the ROIs are 0.7 %, -16 % and -35 % for the Opaque solution, Alternative 1 and Alternative 2 respectively.

All the proposed solutions were compared to a renovation that only aimed to prolong the lifespan of the building. With the Swedish climate goals for 2050 in mind, all buildings from the Million Programme may have to be renovated more energy-efficiently than to only prolong their life spans. Thus, this study could possibly be more complete if the LCP of Alternative 1 and 2 were put in perspective with the Opaque solution.

When comparing the obtained results with previously described results under Ch. 2.3, one could say that what was found in this study corresponded to previous findings by others. By halving the specific energy demand, the investments were generally in need of a rent increase to be considered profitable. Two of the four presented cases in Ch. 2.3 were considered profitable, while in this study, five out of six cases of a corresponding refurbishment method (Opaque solution) were considered profitable. It could be argued that this study has a lower demand of profitability (yield of 4 %) than what is normally demanded by other companies around Sweden. However, feedback from a Landskronahem representative (member of the Swedish public housing companies) has confirmed that a dividend yield of 4 % was a reasonable assumption.

Increasing the rent was a viable profitability increasing measure of proposed renovation strategies. It was calculated for the most likely future scenario and would not mean that the measure automatically makes the project profitable. Many apartments from the Million Programme are in use by people who are more or less inelastic towards raised rents as mentioned in Ch. 2.3.1, and the possibility of raising the rent is probably much higher in housing cooperatives. According to a reference from Balco (Palmgren, 2017), a rent increase of up to 500 *SEK* is possible when glazing the balconies. Rent increases for Alternative 1 (up to 6.7 *SEK/m²*) could be considered possible for the low-rise building, while Alternative 2 (up to 15.6 *SEK/m²*) showed to be close to yearly rent increase according to SABO (2015) and may not be possible to afford for all tenants.

The results do not vary much whether the building is located in Stockholm, Gothenburg or Malmoe. It is believed that similar refurbishments on similar buildings from the Swedish Million Programme situated in climate zone three or four could expect similar results. The LCP results could be applied as early phase estimation whether the project could have a potential of becoming profitable or not.

5.10 Added values

As mentioned in Ch. 2.3.1, energy-efficient renovations and even general renovations come with difficulties for the tenants during construction time. As it was possible to halve the specific energy use by glazing balconies and implementing a glazing façade it could give the tenants a more satisfied view on the energy-efficient renovations. Glazed balconies make the climate in the balcony more pleasant during the spring and autumn as the glazing makes use of the milder solar radiation. It makes it possible to use it as an additional room during the warmer six months and possibly as a storage room during the rest of the year. Glazing the balconies could even be considered to be a cheap option to gain a larger apartment when current apartment prices in Stockholm could reach up to 100 *kSEK/m²*.

Furthermore, the added glazing improves the safety that comes with closing the outside access to the balcony space. An addition, glazed spaces could also possibly reduce the outdoor noise, as some parts of it would be reflected by the hard surface of glass. It can be argued that glazed spaces improve the life span of materials that they are installed in front of by shielding them from weather caused wear and tear, for example, balcony slab lifespan by reducing the corrosion potential of reinforcement bars. In general glazing balcony increases its versatility and practicality.

It could be argued that the glazed alternatives do have a more appealing architectural appearance and by implementing more glazing to the Million Programme could help erasing the view on the building stock as “monotone buildings” and “concrete boxes”. Glazing renovations could help raising the attractiveness of the areas and perhaps even give the community something to feel proud of. This could be one of many measures in order to tackle the alienation that is present in a few communities.

6 Error assessment

6.1 IDA-ICE model design

The high-rise building model was simplified in IDA-ICE so that all apartments on the same floor facing same direction, northwest or southeast, were merged into a single zone. Every floor consisted of two large zones. Such an approach evens out thermal gains and losses across the whole zone. Therefore, the peak loads and overheating was less extreme than it should be in reality. Moreover, apartments located in corners and uppermost floor would have a larger envelope area over one m^2 of living space than those in the mid-section having only one external surface adjacent to the space. Thermal losses would thus be more significant in the apartments with larger building envelope area adjacent to them.

6.2 Tenant behaviour

Different possible scenarios of tenant behaviour were not addressed in this study due to their complexity and uncertainty. All parameters, except for cooling measures, were studied with closed balcony glazing and windows. However, it can be expected that tenants will open both of them during times when such behaviour does not have any positive effect neither on thermal comfort nor heating demand. Tenant behaviour has a significant effect on annual heating demand and thermal comfort and any deviation from the behaviour used in this study will alter them. In order to account for window opening by tenants, SVEBY (2009) suggests adding 4 $kWh/(m^2 \cdot y)$ to the estimated annual heating demand, which can be added to all the presented results in the sensitivity analysis of this work except for those in Ch.4.1. The authors of this work expect that unless the tenant behaviour is irrational, the results will not change significantly and the required annual energy levels will remain below those suggested by Swedish BBR (Boverket, 2014).

7 Conclusions

A mix of opaque materials and glazed spaces gives a possibility to improve the building appearance without an increase in the annual energy demand compared to a purely opaque insulated building envelope. The implementation of glazed elements showed to be more beneficial for apartment overheating reduction compared to a fully opaque insulation approach. The improved indoor thermal comfort by glazed spaces was, however, costly and the total life cycle profit should be put into perspective with other benefits that come with glazed spaces for the building owner.

It was concluded that the opaque- and the two glazed-alternatives could reduce the specific energy demand for a typical low-rise lamella building from the Million Programme from 127 *kWh/(m²·y)* to 52 *kWh/(m²·y)* and therefore fulfil the energy requirements from the Swedish Building Code. It was also shown that the two glazed alternatives generally could reduce the overheating hours, compared to the opaque solution, by 68 *%* (55 hours) and 62 *%* (70 hours) for Alternative 1 and Alternative 2, respectively. Thus, the indoor thermal comfort requirements of FEBY 12 were met. However, the low-rise building situated in Stockholm did not meet the requirements for any of the renovation strategies and passive cooling measures were proposed as a solution. It was also concluded that the glazed- and opaque-alternatives could reduce the specific energy demand for a typical high-rise lamella building from 118 *kWh/(m²·y)* to 56 *kWh/(m²·y)* and thus reach the Swedish Building Code. The glazed alternative reduced the apartment overheating hours from 23 *%* to 51 *%*, compared to the opaque solution, dependent on where the building was situated and represent in hours; 540 in Gothenburg; 722 in Malmoe; 2 206 in Stockholm. Thus neither of the locations met the FEBY 12 requirements for thermal comfort, which lead to suggestion of possible cooling strategies.

Findings of sensitivity analysis suggested that energy saving and thermal comfort improving potential of glazed spaces is sensitive towards orientation, solar radiation levels, glazed area, balcony glazing and apartment window properties, balcony air-tightness and building envelope U_m value among others.

It was concluded that none of the proposed glazed alternatives had the same profit potential as the Opaque renovation alternative which in the most likely future scenario could expect a profit of 100 *kSEK* and 6 000 *kSEK* for the low-rise and high-rise building respectively. The first proposed glazed alternative (generally -800 *kSEK* and 800 *kSEK* in profit for the low-rise and high-rise building, respectively) was more prone to become profitable than the second proposed alternative (generally -2 200 *kSEK* in profit for the low-rise building). It was found that the investment and maintenance costs for Alternative 2 were too high in comparison to the energy savings. It was also concluded that the high-rise building was more prone to give profitable outcomes for the investments and was considered to be the building were the first alternative has the largest potential of being implemented.

The findings of this study outlined the potentially best renovation strategy if glazed elements are to be used. Such strategy would keep a balance between the lowest annual energy demand and best indoor thermal comfort. The respective alternative should consist of a glazing *U*-value of 0.8 *W/(m²·K)* for the apartment windows together with a two-paned balcony glazing which still allows transmitting large amounts of solar radiation. The annual heating demand results showed that the balcony space should have around one air change per hour. Potential apartment overheating could be solved by simply opening up the balcony and the apartment windows. In addition to this, a DSF can be added for architectural purposes if such strategy can be economically justified. It will create a smooth façade surface when combined with projected glazed balconies. Glazed spaces must be oriented towards south, southeast or southwest to be able to compete with opaque insulation.

Generally, it is recommended for housing companies to implement the fully opaque solution as it showed to have a larger potential of becoming profitable. However, the insignificant difference in heating demand between the glazed and opaque alternatives means that a mix of opaque and glazed elements should be chosen in order to use the benefits that comes with glazed spaces (e.g. better indoor climate, protects the façade and adds more storage and possible living space at times). It is also suggested that implementing glazed balconies together with opaque elements could be an option if the building is situated in communities with stronger household economies since the investment is in likely need of a rent increase in order to become profitable. It would also in the eye of the authors give the Million Programme a more appealing appearance and help erasing the lack of involvement from architects caused by the industrially standardized construction methods.

8 Summary

There were around one million apartments built in Sweden during 1965 to 1974 as a part of the *Swedish Million Programme*, half of them being concentrated in or around Stockholm, Gothenburg and Malmoe. These buildings are now considered unattractive monotone concrete boxes. Around 65 *%* from The Million Programme building period are low-rise lamella buildings, while high-rise lamella buildings take 20 *%* of the share. There is an urgent need to renovate energy inefficient ventilation systems, leaky windows, worn down balconies, weathered facades and replace old sanitary pipes. The total investment cost for the Million Programme has been estimated to be around 300 to 500 billion *SEK* and has become one of the most discussed socio-economical and housing policy topics in Sweden. The Swedish Association of Public Housing Companies (SABO) had around 300 000 apartments that were in a need of refurbishment in 2009.

The aim of this study was to investigate the energy saving and thermal comfort potential of adding glazed spaces to existing building façades. In addition, compare them with a fully Opaque solution. Two different glazed alternatives were proposed and their impact on annual energy demand and thermal comfort in living spaces was assessed on low and high-rise lamella buildings in Stockholm, Gothenburg and Malmoe. The first glazed alternative was based on the Opaque solution that had FTX ventilation system and supply air ducts built in prefabricated façade elements; it supposed that the existing recessed balconies of high-rise lamella building were glazed but projecting balconies of low-rise lamella building exchanged with longer and glazed ones. Surfaces adjacent to balcony space were kept original and non-renovated. Second glazed alternative was only performed on low-rise lamella building and built upon the first alternative, with addition of double skin façade to the existing southwest facing façade adjacent to staircases and utility rooms. All results presented in this work were obtained using IDA-ICE indoor climate and energy simulation tool. Both glazed alternatives were investigated in a sensitivity analysis. The presented solutions life cycle profit were analysed through various different future scenarios where the price growth rate of energy and maintenance varied from 0 *%* to 4 *%* and the real yield were set to 4 *%*. If any solution had low profit potential, a specific rent increase was found for the most realistic future scenario in order to make it profitable. Additional benefits of glazed alternatives were also discussed.

It was found that glazed alternatives reduced the annual heating demand by up to 4 *%* compared to the Opaque solution. Low-rise building had a smaller annual heating demand and fewer apartment overheating hours than high-rise mainly due to different building and balcony geometry. South was found to be the most favourable orientation for glazed solutions, resulting in lower annual heating demand and fewest overheating hours in living spaces. The specific annual energy demand for low-rise lamella building located in Gothenburg was 46 $kWh/(m^2 \cdot y)$ for ALT 1 and ALT 2, while the ALT 1 of high-rise resulted in 53 $kWh/(m^2 \cdot y)$ in same location. The Opaque solution showed to have the most profit potential, as the investment cost was lower than for the two glazed solutions. Alternative 1 showed to have a bigger profit potential on the high-rise than the low-rise building. When implementing Alternative 1 on the high-rise building all cities showed a profitable investment in the most plausible scenario, while the same future scenario did not show a potential of profitability on the low-rise building. Alternative 2 on the other hand showed to be the least profitable solution as it was in need of a much higher future energy price without a significant increase in maintenance cost in order to become profitable. Rent increases were needed for Alternative 1 and Alternative 2 in the low-rise building and would as highest reach 6.7 *SEK/m²* and 15.6 *SEK/m²* respectively.

The high-rise building was more likely to give a profitable outcome of the investments. The finding was thought connected to the fact that the building had 60 *%* larger energy saving potential which made it more resilient towards lower energy price growth rates. It can also be connected to the fact that the high-rise building had a larger floor area compared to building envelope than the low-rise building, which in turn could mean that it had a higher energy saving potential (i.e. save money) for the same investment. Higher *SHGC*, lower window and balcony glazing *U*-value, more airtight balcony space all decreased building annual energy demand but increased apartment overheating. *SHGC* of balcony glazing had a higher impact on annual heating demand and apartment overheating than window and balcony glazing *U*-value or balcony and DSF air-tightness in all studied cases. Although apartment overheating was significantly reduced by the glazed alternatives, it still exceeded the targeted standard in some cases and thus required proposition of cooling measures. Balcony glazing opening proved to be an effective passive cooling measure, significantly decreasing the apartment overheating hours. *PI* schedule, a replication of automatic system or perfect tenant behaviour, that supposed balcony and window, adjacent to balcony space, opening when the temperatures exceeded 26 *°C* in balconies and apartments, was found to be the most effective passive cooling strategy. It was the only cooling solution that always reduced the overheating to comfortable levels for both buildings in all locations.

9 Literature

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APPENDIX A

Table 15 shows the energy use for base case conditions.

Table 15: base case energy conditions of low-rise lamella building.

Energy use	Description	Notes
Ventilation	Exhaust air ventilation with heat recovery and a heat pump. Heat pump is at the end of its lifetime and thus assumed to have a COP of 1.	BeBo report
Heating	Heating production from district heating with auxiliary using oil. Some of the heat production comes from the heat pump. As a simplification, it was assumed that all heating is provided by district heating.	BeBo
DHW	Exhaust air-water heat pump NIBE F2300-20 (25 years old, needs replacement 5 *kW* and 3 hot water tanks of 500 *l*). Auxiliary heater is electricity. Thus, a COP of 1 was assumed.	BeBo

Modelling in IDA-ICE:

Note: IDA is “only” used to estimate the space heating need and energy use by the ventilation fans. The other energy use is estimated externally.

Table 16: base case conditions for IDA-ICE model of low-rise lamella building.

Parameter	Value	Reference	Notes
Heating			
Climate file	Gothenburg (Säve)	IDA	
Indoor temperature	20 *°C* in apartments, 16 *°C* in the rest of the spaces (staircases and basement)	Measured BeBo report Assumed by NCC	Checked in the model
DHW	25 $kWh/(m^2 \cdot y)$	SVEBY	Calculated externally
Efficiency of the heating system	10 *%* losses of all the heating need.	Described in FEBY, the value of 10 *%* was assumed since window opening is already considered separately.	This is taken into account by the efficiency of the heating system in IDA
Shading	Shading factor 0.5	SVEBY	For the base case windows 0.68 *

			0.5 in SHGC.
SHGC (Solar Heat Gain Coefficient)	SHGC = 0,68 exist. windows SHGC = 0,52 new windows	Assumption NCC	
Ventilation	0.29 $l/(s\cdot m^2)$ → changed to the minimum required of 0.35 $l/(s\cdot m^2)$	0.29 $l/(s\cdot m^2)$ measured (BeBo)	The minimum required was assumed to compare with the base case
Kitchen fan losses	46 *l/s* during 0,5 *h/day* per apartment. When added as infiltration 46 *l/s**60 *s/min**30 *min/day* = 82800 *l/day* = 0.958 *l/s* *18 apartments = 17,25 *l/s* (whole building) = 17,25 *l/s* / 2219 m^2 (envelope area) = *0.0078* $l/(s\cdot m^2)$ *envelope*	Assumption NCC	Added as infiltration into the building model.
Air-tightness at ±50 *Pa*	0.4 $l/(s\cdot m^2)$ building envelope. According to EN ISO 13789:2008 this can be set to a fixed infiltration rate of 2.5 *%* of q50 → 0.4*0.025 = 0.01 $l/(s\cdot m^2)$ + 0.0078 (kitchen fan) = 0.0178 $l/(s\cdot m^2)$ (envelope)	Measured (BeBo) Miljöbyggnad in IDA	
Hot water circulation to keep all taps warm	28 *W/apartment* = 28 *W* / 82 m^2 = 0.34 W in average	Assumption NCC	Inserted in IDA as internal heat gains together with the rest
Internal heat gains from dwelling used electricity	30 $kWh/(m^2\cdot y)$, from which 70 *%* can be accounted. 30 kWh/m^2 / 8760h * 0.7 = *2.4* W/m^2		
Internal heat gains from inhabitants	80 *W/persons*, SVEBY accounts for 14 *h/person* for a 3-room apartment. 2.18 *per/apartment* / 82 m^2*/apartment* = 0,027 *persons/*m^2 This means 80 *W/pers* *	SVEBY	To avoid setting a schedule for the inhabitants the heat gains were distributed during the whole day

Sum of internal gains	14 *h* /24 *h* = 47 *W/pers* continuously. 47 *W/pers* * 0,027 *persons/m*^{2} *= 1.26 W/m*^{2} 4 *W/m*^{2}, 24 *h/day*		
Window openings	Additional 4 *kWh/(m²·y)*	SVEBY	Added externally in Excel not in IDA
Addition for thermal bridges (simplification)	20 *%* of the total UA-value. Losses by thermal bridges decrease for a better building envelope since the 20 *%* is kept.	BBR - Handbok för energihushållning enligt Boverkets byggregler – edition 2, Boverket August 2012.	
Savings with exhaust air-water heat pump			
Yearly COP for the heat pump	Since the lifetime of the heat pump has passed the COP was assumed to be 1.	Assumption	Assumed that the heat pump provides all energy to DHW
Property used electricity			
Energy to pumps	1 *%* of total heating need	Assumption NCC	
SFP	1.85 *kW* ventilation fans	Checked on site (BeBo report)	Divided equally for supply and return fans
Others (lighting, elevator)	Lighting (stairs, entrée and lobby room) and elevators	SVEBY Excel sheets	Estimated separately. Energy used by the machines in the washing room were not counted as internal gains

APPENDIX B

Accuracy assessment of IDA-ICE

In Figure 35, the horizontal axis represents different time step and tolerance values. For every time step, there were 3 tolerance values ranging from 0.02 to 0.005 simulated. They are presented in diagonal, cross and divot hatchings from highest to lowest value respectively. Annual heating demand is presented on the primary vertical axis with bars. Overheating hours in apartments are presented on secondary vertical axis with markers. Combination of 1.5 *h* time step and 0.02 tolerance is the least accurate, whilst one with 0.5 *h* time step and 0.005 tolerance is the most accurate.

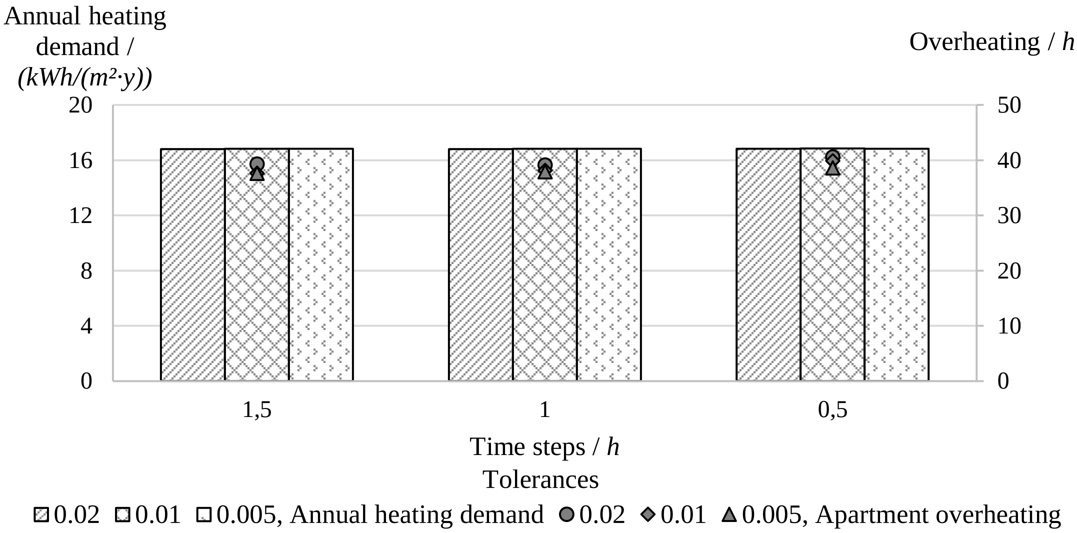

Figure 35: Accuracy assessment of times step and tolerance values on ALT 1, low-rise building in Gothenburg.

As the time steps were decreased both heating demand and overheating hours in apartments slightly increased. However, reducing the tolerance values increased annual heating demand but decreased the overheating hours. Highest annual heating demand was received in the combination with 0.5 times steps and 0.01 tolerance value, whilst most overheating hours occurred in the case with 0.5 time steps and 0.02 tolerance value. The difference between the base case with least and most accurate settings was 0.2 % in annual heating demand and 1.8 % in apartment overheating hours, which was considered neglectable. However, the simulation time of least accurate setting combination was twice shorter than for the most accurate. Therefore, the combination of highest time step and tolerance values, 1.5 *h* and 0.02, respectively, were selected as the input values for base models of all proposed design alternatives.

APPENDIX C

The Table 17 below represent the varying monthly weather conditions by means of dry-bulb temperature, relative humidity of air, direct and diffused radiation in Gothenburg, Malmoe and Stockholm.

Table 17: Annual weather conditions in Gothenburg, Malmoe and Stockholm.

	Variables											
	Dry-bulb temperature / °*C*			**Rel. humidity of air / %**			**Direct normal radiation / (W/m^2)**			**Diffuse radiation on horizontal surface / (W/m^2)**		
Location	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Jan.	1.7	1.5	-2.5	91.1	88.9	90.8	30.3	34.2	50.9	11.7	14.9	10.5
Feb.	-0.4	0.0	-2.2	89.5	92.0	82.0	44.8	37.5	76.8	26.8	28.3	27.5
Mar.	2.0	2.8	1.5	78.0	85.5	73.8	71.1	59.6	111.1	54.1	58.4	54.3
Apr.	5.9	7.3	6.5	77.6	76.2	65.4	118.7	112.5	173.7	80.6	91.2	82.9
May	10.7	11.6	11.1	76.9	75.1	68.8	145.6	166.8	235.5	110.1	112.6	110.0
June	14.3	14.0	14.8	74.3	79.2	65.9	117.6	130.1	225.8	133.2	123.1	128.8
July	17.0	16.2	17.7	79.9	75.0	69.2	113.8	123.3	243.5	121.5	125.0	116.0
Aug.	17.1	16.9	16.6	79.7	80.8	79.7	99.9	118.0	153.0	100.5	100.0	103.6
Sept.	12.6	13.0	11.5	84.7	83.8	82.5	145.6	97.4	159.8	65.7	70.9	64.3
Oct.	8.2	8.4	7.5	88.8	87.2	86.5	117.6	61.5	90.0	33.3	40.2	35.4
Nov.	3.1	4.2	3.0	84.8	89.5	83.7	113.8	34.1	63.2	14.5	18.5	14.9
Dec.	2.0	1.8	0.7	90.5	93.0	86.4	99.9	18.6	41.5	7.6	9.8	7.6
Mean	7.9	8.2	7.3	83.0	83.8	77.9	79.2	83.1	135.7	63.5	66.3	63.2
Min	-0.4	0.0	-2.5	74.3	75.0	65.4	23.4	18.6	41.5	7.6	9.8	7.6
Max	17.1	16.9	17.7	91.1	93.0	90.8	145.6	166.8	243.5	133.2	125.0	128.8

APPENDIX D

Transmission losses

The transmission losses were analysed through the average heat transfer coefficient and obtained by using Eq. 3 (Boverket, 2016).

$$U_m = \frac{\sum_{i=1}^{n} U_i \cdot A_i + \sum_{k=1}^{m} l_k \cdot \Psi_k + \sum_{j=1}^{p} \chi_j}{A_{om}} \qquad [W/(m^2 \cdot K)] \qquad (3)$$

Where:

U_i	Heat loss coefficient for a construction part *i* in (*W/(m²·K)*)
A_i	Area for a construction part *i* towards heated indoor air in (*m²*)
l_k	Length of a linear thermal bridge *k* towards heated indoor air in (*m*)
Ψ_k	Heat loss coefficient for a linear thermal bridge *k* in (*W/(m·K)*)
χ_j	Heat loss coefficient for a punctate thermal bridge *j* in (*W/K*)
A_{om}	Enclosed envelope area towards heated indoor air in (*m²*)

However, the thermal bridges were accounted as 20 % of the total heat loss coefficient times area (*U·A).* Table 18 show the thermal properties of different building components for the original low-rise lamella building.

Table 18: Thermal properties of different construction parts from original low-rise lamella building.

Construction part	Low-rise lamella building	
	***U*-value / (W / (m²·K))**	***U·A* / (W / K)**
Roof	0.23	117.6
Wall above ground	0.31	225
Walls below ground	0.21	31.25
Floor	0.39	207.74
Windows/doors	1.6	454.6
Thermal bridges	-	182.23
Mean	0.55	-

Table 19 presents the characteristics of various constructions for the Opaque solution.

Table 19: Construction properties of the Opaque solution on low-rise and high-rise lamella buildings.

Construction part	Low-rise lamella building		High-rise lamella building	
	***U*-value / (W / (m²·K))**	***U·A* / (W / K)**	***U*-value / (W / (m²·K))**	***U·A* / (W / K)**
Roof	0.08	41.25	0.10	122.50
Walls above ground	0.15	31.30	0.13	374.72
Walls below ground	0.21	41.25	0.90	374.72
Floor	0.39	207.74	0.30	381.60
Windows/doors	0.80	227.29	0.80	1123.2
Thermal bridges	-	154.68	-	603.5
Mean	0.35	-	0.41	-

Table 20 presents the characteristics for each construction part for the first glazed solution.

Table 20: Construction properties of Alternative 1 on low-rise and high-rise lamella buildings.

Construction part	**Low-rise lamella building**		**High-rise lamella building**	
	***U*-value /** $(W / (m^2 \cdot K))$	$U \cdot A$ / (W / K)	***U*-value /** $(W / (m^2 \cdot K))$	$U \cdot A$ / (W / K)
Roof	0.08	42.08	0.10	122.47
Walls above ground renovated	0.15	79.41	0.13	283.80
Walls above ground existing	-	-	0.46	97.69
	0.287	57.86	0.50	250.39
Walls below ground	0.21	31.25	0.90	373.50
Floor	0.39	206.20	0.30	381.60
Windows/doors	0.80	227.29	0.80	1123.21
Thermal bridges	-	178.46	-	667.50
Mean	0.37	-	0.46	-

Table 21 shows the characteristics for each construction part for the second glazed solution.

Table 21: Construction properties of Alternative 2 on low-rise lamella building.

Construction part	**Low-rise lamella building**	
	***U*-value /** $(W / (m^2 \cdot K))$	$U \cdot A$ / (W / K)
Roof	0.08	42.08
Walls above ground renovated	0.15	63.48
Wall above ground existing	0.287	88.34
Walls below ground	0.21	31.25
Floor	0.39	207.74
Windows/doors	0.80	227.29
Thermal bridges	-	182.87
Mean	0.38	-

APPENDIX E

Table 22 shows the Opaque solutions renovation details for the low-rise lamella building.

Table 22: Renovation details of the Opaque solution for the low-rise lamella building.

	Type	**Width x height**	**Area / *m^2***	**Thickness / *m***	***U*-value / *(W/(m^2K))***	***g*-value**	**Material**	**Quantity**
Roof	Insulation	-	525,97	0,3	0.08	-	EPS insulation	-
	Roofing paper	-	525,97	-		-		-
Walls	Insulation	-	731	0,12	0.15	-	EPS insulation	-
	Brick	-	731	0,12		-	-	-
Windows	Clear glass	0.8 x 0.62	0,5	-	0,8	0,52	-	2
	Clear glass	1.2 x 0.62	0,74	-	0,8	0,52	-	3
	Clear glass	1.2 x 0.70	0,84	-	0,8	0,52	-	18
	Clear glass	1.4 x 0.66	0,924	-	0,8	0,52	-	12
	Clear glass	1.6 x 0.62	0,992	-	0,8	0,52	-	3
	Clear glass	1.8 x 0.62	1,116	-	0,8	0,52	-	5
	Clear glass	1.0 x 1.32	1,32	-	0,8	0,52	-	18
	Clear glass	1.6 x 0.97	1,552	-	0,8	0,52	-	3
	Clear glass	1.6 x 1.13	1,808	-	0,8	0,52	-	3
	Clear glass	1.4 x 1.32	1,848	-	0,8	0,52	-	6
	Doors	0.9 x 2.1	1,89	-	0,8	0,52	-	18
	Clear glass	3.4 x 0.62	2,108	-	0,8	0,52	-	3
	Balcony door	1.6 x 1.32	2,112	-	0,8	0,52	-	18
	Clear glass	1.8 x 1.32	2,376	-	0,8	0,52	-	18
	Clear glass	3.37 x 1.32	4,45	-	0,8	0,52	-	18
	Total		**284,1**	**-**	**0,8**	**0,52**	**-**	**-**

Table 23 shows the Opaque solutions renovation details for the high-rise lamella building.

Table 23: Renovation details of the Opaque solution for the high-rise lamella building.

	Type	Width x height	Area / *m²*	Thickness / *m*	*U*-value / *(W/(m²K))*	*g*-value	Material	Quantity
Roof	Insulation	-	1272	0,3	0.1	-	EPS insulation	-
	Roofing paper	-	1272	-		-	-	-
Walls	Insulation	-	2920,8	0,18	0.13	-	EPS insulation	-
	Plaster	-	2920,8	-		-	-	-
Door / Windows	Door	2.5 x 2.8	21,0	-	0,8	0,52	-	3
	Door	2.5 x 4	10,0	-	0,8	0,52	-	1
	Door	2.5 x 4.5	56,3	-	0,8	0,52	-	5
	Clear glass	2.1 x 2	4,2	-	0,8	0,52	-	1
	Clear glass	1.4 x 1.8	22,7	-	0,8	0,52	-	9
	Clear glass	1.4 x 2	610,4	-	0,8	0,52	-	218
	Clear glass	1.4 x 2.73	68,8	-	0,8	0,52	-	18
	Clear glass	1.4 x 2.83	380,4	-	0,8	0,52	-	96
	Balcony door	0.9 x 2.2	223,7	-	0,8	0,52	-	113
	Clear glass	0.6 x 1.8	15,1	-	0,8	0,52	-	14
	Total		***1412,5***	**-**	-	-	-	**-**

Table 24 shows the Alternative 1 renovation details for the low-rise lamella building.

Table 24: Renovation details of ALT 1 for the low-rise lamella building.

	Type	**Width x height**	**Area / m²**	**Thickness / m**	***U*-value / (W/(m²K))**	**g-value**	**Material**	**Quantity**
Roof	Insulation	-	525,97	0,3	0.08	-	EPS insulation	-
	Roofing paper	-	525,97	-		-		-
Walls	Insulation	-	529,4	0,12	0.15	-	EPS insulation	-
	Brick	-	529,4	0,12		-	Red brick	-
Windows	Clear glass	0.8 x 0.62	0,5	-	0,8	0,52	-	2
	Clear glass	1.2 x 0.62	0,74	-	0,8	0,52	-	3
	Clear glass	1.2 x 0.70	0,84	-	0,8	0,52	-	18
	Clear glass	1.4 x 0.66	0,924	-	0,8	0,52	-	12
	Clear glass	1.6 x 0.62	0,992	-	0,8	0,52	-	3
	Clear glass	1.8 x 0.62	1,116	-	0,8	0,52	-	5
	Clear glass	1.0 x 1.32	1,32	-	0,8	0,52	-	18
	Clear glass	1.6 x 0.97	1,552	-	0,8	0,52	-	3
	Clear glass	1.6 x 1.13	1,808	-	0,8	0,52	-	3
	Clear glass	1.4 x 1.32	1,848	-	0,8	0,52	-	6
	Doors	0.9 x 2.1	1,89	-	0,8	0,52	-	18
	Clear glass	3.4 x 0.62	2,108	-	0,8	0,52	-	3
	Balcony door	1.6 x 1.32	2,112	-	0,8	0,52	-	18
	Clear glass	1.8 x 1.32	2,376	-	0,8	0,52	-	18
	Clear glass	3.37 x 1.32	4,45	-	0,8	0,52	-	18
	Total		**284,1**	-	**0,8**	**0,52**	-	-
Parametric 1	Clear glass	0.8 x 0.62	0,5	-	1	0,52	-	2
	Clear glass	1.2 x 0.62	0,74	-	1	0,52	-	3
	Clear glass	1.2 x 0.70	0,84	-	1	0,52	-	18

	Clear glass	1.4 x 0.66	0,924	-	1	0,52	-	12
	Clear glass	1.6 x 0.62	0,992	-	1	0,52	-	3
	Clear glass	1.8 x 0.62	1,116	-	1	0,52	-	5
	Clear glass	1.0 x 1.32	1,32	-	1	0,52	-	18
	Clear glass	1.6 x 0.97	1,552	-	1	0,52	-	3
	Clear glass	1.6 x 1.13	1,808	-	1	0,52	-	3
	Clear glass	1.4 x 1.32	1,848	-	1	0,52	-	6
	Doors	0.9 x 2.1	1,89	-	1	0,52	-	18
	Clear glass	3.4 x 0.62	2,108	-	1	0,52	-	3
	Balcony door	1.6 x 1.32	2,112	-	1	0,52	-	18
	Clear glass	1.8 x 1.32	2,376	-	1	0,52	-	18
	Clear glass	3.37 x 1.32	4,45	-	1	0,52	-	18
	Total		**284,1**	**-**	**1**	**0,52**	**-**	**-**
Parametic 2	Clear glass	0.8 x 0.62	0,5	-	1,2	0,52	-	2
	Clear glass	1.2 x 0.62	0,74	-	1,2	0,52	-	3
	Clear glass	1.2 x 0.70	0,84	-	1,2	0,52	-	18
	Clear glass	1.4 x 0.66	0,924	-	1,2	0,52	-	12
	Clear glass	1.6 x 0.62	0,992	-	1,2	0,52	-	3
	Clear glass	1.8 x 0.62	1,116	-	1,2	0,52	-	5
	Clear glass	1.0 x 1.32	1,32	-	1,2	0,52	-	18
	Clear glass	1.6 x 0.97	1,552	-	1,2	0,52	-	3
	Clear glass	1.6 x 1.13	1,808	-	1,2	0,52	-	3
	Clear glass	1.4 x 1.32	1,848	-	1,2	0,52	-	6
	Doors	0.9 x 2.1	1,89	-	1,2	0,52	-	18
	Clear glass	3.4 x 0.62	2,108	-	1,2	0,52	-	3
	Balcony door	1.6 x 1.32	2,112	-	1,2	0,52	-	18
	Clear	1.8 x 1.32	2,376	-	1,2	0,52	-	18

	glass							
	Clear glass	3.37 x 1.32	4,45	-	1,2	0,52	-	18
	Total		**284,1**	-	**1,2**	**0,52**	-	-
Balcony structure	Extended slab	-	10,4	0,1	-	-	Light weight concrete	24
	Balcony walls	-	4,03	0,1	-	-	Light weight concrete	36
	Total	-	***394,68***	-	-	-	-	**18**
Glazing	Balcony glazing	6.87 x 2.5	16,7	-	5,79	0,88	One pane clear glass	18
	Total	-	***300,6***	-	-	-	-	-
Parametic 1	Balcony glazing	6.87 x 2.5	16,7	-	2,71	0,8	Two panes clear glass	18
	Total	-	***300,6***	-	-	-	-	-
Parametric 2	Balcony glazing	6.87 x 2.5	16,7	-	2,71	0,32	Two panes coated	18
	Total	-	***300,6***	-	-	-	-	-

Table 25 shows the Alternative 1 renovation details for the high-rise lamella building.

Table 25: Renovation details of ALT 1 for the high-rise lamella building.

	Type	**Width x height**	**Area / m^2**	**Thickness / m**	**U-value / $(W/(m^2K))$**	**g-value**	**Material**	**Quantity**
Roof	Insulation	-	1272	0,3	0.1	-	EPS insulation	-
	Roofing paper	-	1272	-		-	-	-
Walls	Insulation	-	2212,349	0,18	0.13	-	EPS insulation	-
	Plaster	-	2212,349	-		-	-	-
Door / Windows	Door	2.5 x 2.8	21,0	-	0,8	0,52	-	3
	Door	2.5 x 4	10,0	-	0,8	0,52	-	1
	Door	2.5 x 4.5	56,3	-	0,8	0,52	-	5
	Clear glass	2.1 x 2	4,2	-	0,8	0,52	-	1
	Clear glass	1.4 x 1.8	22,7	-	0,8	0,52	-	9
	Clear glass	1.4 x 2	610,4	-	0,8	0,52	-	218
	Clear glass	1.4 x 2.73	68,8	-	0,8	0,52	-	18

	Clear glass	1.4 x 2.83	380,4	-	0,8	0,52	-	96
	Balcony door	0.9 x 2.2	223,7	-	0,8	0,52	-	113
	Clear glass	0.6 x 1.8	15,1	-	0,8	0,52	-	14
	Total	-	***1412,5***	-	-	-	-	-
Parametric 1	Door	2.5 x 2.8	21,0	-	1	0,52	-	3
	Door	2.5 x 4	10,0	-	1	0,52	-	1
	Door	2.5 x 4.5	56,3	-	1	0,52	-	5
	Clear glass	2.1 x 2	4,2	-	1	0,52	-	1
	Clear glass	1.4 x 1.8	22,7	-	1	0,52	-	9
	Clear glass	1.4 x 2	610,4	-	1	0,52	-	218
	Clear glass	1.4 x 2.73	68,8	-	1	0,52	-	18
	Clear glass	1.4 x 2.83	380,4	-	1	0,52	-	96
	Balcony door	0.9 x 2.2	223,7	-	1	0,52	-	113
	Clear glass	0.6 x 1.8	15,1	-	1	0,52	-	14
	Total	-	***1412,5***	-	-	-	-	-
Parametric 2	Door	2.5 x 2.8	21,0	-	1,2	0,52	-	3
	Door	2.5 x 4	10,0	-	1,2	0,52	-	1
	Door	2.5 x 4.5	56,3	-	1,2	0,52	-	5
	Clear glass	2.1 x 2	4,2	-	1,2	0,52	-	1
	Clear glass	1.4 x 1.8	22,7	-	1,2	0,52	-	9
	Clear glass	1.4 x 2	610,4	-	1,2	0,52	-	218
	Clear glass	1.4 x 2.73	68,8	-	1,2	0,52	-	18
	Clear glass	1.4 x 2.83	380,4	-	1,2	0,52	-	96
	Balcony door	0.9 x 2.2	223,7	-	1,2	0,52	-	113
	Clear glass	0.6 x 1.8	15,1	-	1,2	0,52	-	14
	Total	-	***1412,5***	-	-	-	-	-
Balcony glazing	Clear glass	2.71 x 1.66	72,0	-	5,4	0,88	One pane clear glass	16

	Clear glass	2.71 x 3.8	164,8	-	5,4	0,88	One pane clear glass	16
	Clear glass	2.5 x 8.41	63,1	-	5,4	0,88	One pane clear glass	3
	Clear glass	2.5 x 8.3	41,5	-	5,4	0,88	One pane clear glass	2
	Clear glass	2.71 x 8.45	572,5	-	5,4	0,88	One pane clear glass	25
	Clear glass	2.71 x 8.41	159,5	-	5,4	0,88	One pane clear glass	7
	Clear glass	2.71 x 8.3	314,9	-	5,4	0,88	One pane clear glass	14
	Total	**-**	***1388,2***	**-**	-	-	-	**-**
Parametric 1	Clear glass	2.71 x 1.66	72,0	-	2,64	0,8	Two pane clear glass	16
	Clear glass	2.71 x 3.8	164,8	-	2,64	0,8	Two pane clear glass	16
	Clear glass	2.5 x 8.41	63,1	-	2,64	0,8	Two pane clear glass	3
	Clear glass	2.5 x 8.3	41,5	-	2,64	0,8	Two pane clear glass	2
	Clear glass	2.71 x 8.45	572,5	-	2,64	0,8	Two pane clear glass	25
	Clear glass	2.71 x 8.41	159,5	-	2,64	0,8	Two pane clear glass	7
	Clear glass	2.71 x 8.3	314,9	-	2,64	0,8	Two pane clear glass	14
	Total	**-**	***1388,2***	**-**	-	-	-	**-**
Parametric 2	Coated glass	2.71 x 1.66	72,0	-	2,64	0,36	Two pane coated glass	16
	Coated glass	2.71 x 3.8	164,8	-	2,64	0,36	Two pane coated glass	16
	Coated glass	2.5 x 8.41	63,1	-	2,64	0,36	Two pane coated glass	3
	Coated glass	2.5 x 8.3	41,5	-	2,64	0,36	Two pane coated glass	2
	Coated glass	2.71 x 8.45	572,5	-	2,64	0,36	Two pane coated glass	25
	Coated glass	2.71 x 8.41	159,5	-	2,64	0,36	Two pane coated glass	7
	Coated glass	2.71 x 8.3	314,9	-	2,64	0,36	Two pane coated glass	14
	Total	**-**	***1388,2***	**-**	-	-	-	**-**

Table 26 shows the Alternative 2 renovation details for the low-rise lamella building.

Table 26: Renovation details of ALT 2 for the low-rise lamella building.

	Type	**Width x height**	**Area** ***/ m²***	**Thickness** ***/ m***	**U-value /** ***(W/(m²K))***	***g*-value**	**Material**	**Quantity**
Roof	Insulation	-	525,97	0,3	0.08	-	EPS insulation	-
	Roofing paper	-	525,97	-		-		-
Walls	Insulation	-	394,7	0,12	0.15	-		-
	Brick	-	394,7	0,12		-		-
Windows	Clear glass	0.8 x 0.62	0,5	-	0,8	0,52	-	2
	Clear glass	1.2 x 0.62	0,74	-	0,8	0,52	-	3
	Clear glass	1.2 x 0.70	0,84	-	0,8	0,52	-	18
	Clear glass	1.4 x 0.66	0,924	-	0,8	0,52	-	12
	Clear glass	1.6 x 0.62	0,992	-	0,8	0,52	-	3
	Clear glass	1.8 x 0.62	1,116	-	0,8	0,52	-	5
	Clear glass	1.0 x 1.32	1,32	-	0,8	0,52	-	18
	Clear glass	1.6 x 0.97	1,552	-	0,8	0,52	-	3
	Clear glass	1.6 x 1.13	1,808	-	0,8	0,52	-	3
	Clear glass	1.4 x 1.32	1,848	-	0,8	0,52	-	6
	Doors	0.9 x 2.1	1,89	-	0,8	0,52	-	18
	Clear glass	3.4 x 0.62	2,108	-	0,8	0,52	-	3
	Balcony door	1.6 x 1.32	2,112	-	0,8	0,52	-	18
	Clear glass	1.8 x 1.32	2,376	-	0,8	0,52	-	18
	Clear glass	3.37 x 1.32	4,45	-	0,8	0,52	-	18
	Total		**361,3**	**-**	**0,8**	**0,52**	**-**	**-**
Balcony structure	Extended slab	-	10,4	0,1	-	-	Light weight concrete	24
	Balcony walls	-	4,03	0,1	-	-	Light weight concrete	36
	Total	-	***394,68***	**-**	**-**	**-**	**-**	**-**
Glazing	Balcony	6.87 x 2.5	16,7	-	5,79	0,88	One pane	18

	glazing						clear glass	
	Total	-	***300,6***	-	-	-	-	-
Double skin facade	Glazing facade	-	134,7	-	5,79	0,88	One pane clear glass	-
Parametric 1	Glazing facade	-	134,7	-	2,71	0,8	Two panes clear glass	-
Parametric 2	Glazing facade	-	134,7	-	2,71	0,32	Two panes coated	-

Table 27 shows the base cases' different construction costs for the investigated solutions.

Table 27: Different construction costs for the investigated renovation solutions.

		L Opaque	H Opaque	L Alt.1	H Alt.1	L Alt.2
Passive system	Facades	1 792 302	6 282 683	885 217	2 486 234	556 669
	Windows	1 771 990	5 770 156	1 771 990	5 770 156	1 771 990
	Balconies	-	-	2 770 879	4 412 452	2 770 879
	Glazed facade	-	-	-	-	428 211
	Roof + gutters	367 229	1 460 116	367 229	1 460 116	367 229
Active system	Ventilation	595 541	666 205	595 541	666 205	595 541
	Scaffolding	410 091	2 363 634	410 091	2 363 634	410 091
	Tenant Relocation	411 812	2 271 484	411 812	2 271 484	411 812
	Investment	5 348 965	18 814 278	7 212 759	19 430 281	7 312 422

Opaque solution

Table 28 shows the proposed maintenance measures and their respective cost for the Opaque solution for the high-rise and low-rise lamella-buildings. All construction and maintenance costs were taken from Wikells sektionsdata (Wikells, 2012) calculation tool and provided by Rikard Nilsson from the division of Construction Management at Lund University.

Table 28: Proposed maintenance measures and their respective costs in the Opaque solution of high-rise and low-rise lamella buildings.

			High-rise lamella building	**Low-rise lamella building**
Construction part	**Measure**	**Life span / *years***	**Cost / *kSEK***	**Cost / *kSEK***
Facades	New finish of plaster/brick	15	319.750	235.500
Windows	Change of windows	25	5 839.156	1 882.560
	Painting	15	218.880	-
		8	-	23.079

Roof	Roofing felt	25	327.222	199.704
Ventilation system	New damper, fire dampers, silencers	30	331.000	146.754
	Adjustment, cleaning of AHU	15	897.505	152.504
	Mandatory ventilation inspection	3	39.516	12.888
	New filters	1	21.250	5.100

All the maintenance costs were added together and spread out as a yearly cost over the life span.

Alternative 1

The same maintenance as in the Opaque solution was also considered for the Alternative 1. However more maintenance was added concerning the glazed balconies, see Table 29.

Table 29: Proposed maintenance measures and their respective costs in Alternative 1 of high-rise lamella building.

Building	Measure	Life span / *years*	Cost / *kSEK*
Low-rise lamella	Change of balcony structure	30	478.440
High-rise lamella			2 239.226

Alternative 2

In addition to previous mentioned costs, Alternative 2 included the maintenance cost for the added glazed skin, see Table 30.

Table 30: Proposed maintenance measures and their respective costs in Alternative 2 of low-rise lamella building.

Construction part	Measure	Life span / *years*	Cost / *kSEK*
Façade	Change of façade-glazing	30	214.106

Parametric studies

The difference in cost for the studied windows showed to be so small that it was neglected as maintenance cost but included in the initial building cost. Different balcony glazing costs was hard to find, but an assumption was made that the glazing part from the total cost accounted for 35 *%*. The glazing part of the total cost was doubled for the structure with two-paned glazing and additionally 850 *SEK/m²* glass was added to the coated two-pane balcony structure cost (Janson, 2017).

Different glazing costs for the second alternative were hard to find as well. Since DSF consist of more glass compared to a balcony structure, the total cost of the glazing was assumed to account for 50 *%* of the total cost. The glazing part of the total cost was doubled for the structure with two-paned glazing and additionally 850 *SEK/m²* glass was added to the coated two-pane DSF structure cost.

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