Environmental and cost-effective refurbishment of a million program building, integrating daylight and architectural design

Environmental renovation

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Master thesis in Energy-efficient and Environmental Buildings

Faculty of Engineering | Lund University

Lund University

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

Master Programme in Energy-efficient and Environmental Building Design

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

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

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Keywords:

Cost-effective renovation measures, energy reduction, renovation, million program building, LCA, LCC, co-benefits, daylight, architectural design, shading.

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Abstract

Sweden's substantial buildings stock from the million programs is in need of renovations. These residential buildings were built without major attention to energy demand or architectural aesthetics. Until now, property owners have hesitated to carry out energy renovations due to the investment cost.

The aim of this master thesis was to propose an energy-efficient renovation procedure whilst taking into consideration sufficient daylight conditions and choosing materials with less negative environmental impact. Moreover, substitute the monotonous facades with a more appealing exterior. The case study building was a typical three-storey lamella house from the million program years, located in Landskrona.

The research methods of this report included primary research of on-site daylight measurements and observations, and research of literature studies. Furthermore, various simulation models within energy, carbon footprint, life cycle cost and daylight studies were developed and their results were analyzed to answer the research questions.

A retrofit package that accounted for cost-effective measures included: new low energy windows, new prefab lightweight external walls on the main facades, and insulated basement walls and roof. As a result the energy use was reduced by 50 % and the heating demand by 70 %. The most significant energy saving came from the replacement of the old windows. The energy savings alone did not pay off the investment cost. However, the co-benefits, gained from this renovation should be weighted into the decision making.

The co-benefit of sufficient daylight would lead to increased visual comfort that could further generate health benefits and increased productivity. The latter being especially important for people who work from home, as the flexible working hours are gaining popularity. Other tenants who would benefit from daylight in residential buildings the most, would be elderly; parents on maternity leave and kids; those on sick leave, among others. Thus, people who are exposed to daylight in residential buildings makes up a significant part of the society and should not be neglected of the opportunity to experience good daylighting design.

The results of the daylight study revealed that existing million program lamella building may have a favorable window to wall ratio for sufficient daylight design, however, there may be daylight oversupply in the kitchens.

Final renovation designs are proposed where the building was improved architecturally while delivering useful and sufficient daylight levels in all the rooms. The overhang study proposes the optimal shading device depth of 1.3m and balcony depth of 1.5m. The potential of home office adaptation was achieved, while the standard of Miljöbyggnad Silver was reached in 15 out of 18 living rooms.

Acknowledgments

We would like to thank our main supervisor Åke Blomsterberg at LTH/WSP, without whom this thesis would not be possible. Åke provided us with the necessary guidance and inspiration that shaped the research presented here.

We would like to thank Miklos Molnar from Division of Structural Engineering at LTH, for taking his time and giving us consultation on the structural design of the existing structure. With the help of Miklos expertise it was possible to take the necessary decisions of implementing prefabricated light-weight facades in the renovation of the particular three-story building.

Thanks to Wikells byggberäkningar AB for the one day course in Växjö, Sweden. The course provided the necessary skills to operate Wikells software that was used to calculate the investment costs. Thanks to further providing the guidance through online communication.

Further thanks goes to Johan Zellbi from Landskronahem for his patience and time, answering numerous mails throughout the thesis. Thanks for providing us with the access to the apartments during two separate building site visits. This was crucial foundation for setting up the daylight simulation models, as well as verifying them through on-site measurements. Thanks for letting us use the drawings and pictures of the reference building and surrounding area, obtained from the Landskronahem. We hope our work will serve as inspiration for new generation renovation projects!

Furthermore regarding copyright, we are thankful to Landskronahem, Miklos Molnar (LTH), Kenneth Sandin (LTH) and Emma Karlsson (WSP) for getting permission to use their material.

Big thanks to our co-supervisor Niko Gentile, who was providing his daylight expertise. Thanks for your help to shape the structure of the daylight assessment. Thanks for administrating the instruments necessary to perform the on-site daylight measurements.

Thanks to Iason Bournas for the hints on literature studies and knowledge about the daylighting design in residential buildings and in general.

We would like to express our gratitude to LTH for providing us with an office facility.

Contributions

Both authors contributed into developing the scope of the renovation project. The thesis covered a lot of different topics like, energy reduction, environmental material assessment, life-cycle costing, daylight, architecture, prefabrication and therefore had to be split between the writers.

Authors had a different background and focus of interest, therefore the tasks were subdivided as follows:

Lowe Dahlin (engineering) was responsible for IDA-ICE energy simulations, EcoSai LCA assessment and Wikells software, for obtaining the investment costs for LCC analysis.

Aija Baumane (architecture) was responsible for Diva for Rhino daylighting simulations, SketchUP models for architectural design, prefabrication assessment and performing LCC analysis.

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Abbreviations

Energy & Thermal comfort

FEBY	Forum för Energieffektiva Byggnader
BBR	Boverket's Building Regulations
DHW	Domestic hot water
SFP	Specific fan power

Daylight

cDA	Continuous daylight autonomy
DA	Daylight autonomy
DAv	Daylight availability
DF	Daylight factor
IESNA	Illuminating Engineering Society of North America
Point DF	Point daylight factor
UDI	Useful daylight illuminance

Architectural

APT	Apartment
A1 – A6	Apartments 1 to 6
LVR	Living room
KIT	Kitchen
WC	Bathroom
B1, B2	Bedroom 1, bedroom2
1F – 3F	1st to 3rd floor

Other

BREEAM	Building Research Establishment Environmental Assessment Method
LCA	Life-cycle assessment

LCC	Life-cycle costing
GWP	Global warming potential
EPS	Expanded polystyrene
XPS	Extruded polystyrene
PUR	Polyurethane
NPV	Net present value

Glossary

Energy & Thermal comfort

Overheating hours - Amount of hours when the operative indoor temperature is higher than the threshold set in the project.

Specific energy use - Energy required for heating, cooling, domestic hot water and building electricity, kWh/(m²·a)

FEBY – Swedish criteria for low-energy buildings developed by a group of experts appointed by Forum for energy-efficient buildings (FEBY).

Landskrona Energi – District heating supplier in Landskrona, Sweden

Daylight

BS EN 15251 – British Standard BS EN 15251 is the UK implementation of the European standard EN 15251. The Standard specifies indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

Continuous daylight autonomy (cDA) – Daylight metric cDA gives a partial credit for time steps when daylight does not reach the threshold that is set, however, contributes to the illuminance (Rogers, 2006)

Daylight autonomy (DA) –the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone (Reinhart, Mardaljevic & Rogers, 2006).

Daylight factor (DF) – the ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky. (Moon & Spencer, 1942)

Daylight availability (DAv) - a metric that merge daylight autonomy and useful daylight illuminance information into a single figure. (Reinhart & Wienold, 2010)

Illuminance (E) - the total luminous flux incident on a surface, per unit area, which is measured in lux (lumen/m^2).

Overlit Area – Percentage of the floor area that is considered overlit. Daylight oversupply is assumed to occur when the illuminance level is ten times higher than the user set threshold for more than 5% of occupancy hours.

Point DF, Miljöbyggnad Silver - Miljöbyggnad Silver level requires point DF of 1.2% one meter away from the darkest wall, 0.80 m above the floor, halfway from the exterior envelope

Useful daylight illuminance (UDI) – UDI determines when the daylight levels are "useful". Daylight range is subdivided between the categories of being "too dark", "useful", "too bright" (potential for glare), and latest addition "supplementary" (when some electric lighting might be necessary).

Other

BREEAM - Building Research Establishment Environmental Assessment Method: an established environmental certification system, developed by the Building Research Establishment, which consists of assessing, rating and certifying the sustainability of master planning projects, infrastructure and buildings.

Landskronahem - Property owner in Landskrona, Sweden

Miljöbyggnad - a Swedish system for certifying buildings in relation to energy, indoor climate and materials, developed by the Swedish Green Building Council (SGBC). It is designed to protect human health and our environment. The system offers certification in the different grades, Gold, Silver and Bronze.

Global warming potential (GWP) – Is a metric for weighting the climate impact of various greenhouse gases. It calculates carbon dioxide (CO_2), Nitrogen dioxide (NO_2), methane (CH_4), Chlorofluorocarbons (CFC), Hydro chlorofluorocarbons (HCFCs) and Methyl Bromide (CH3Br). The impact of these gases is rated against carbon dioxide, and described in total as carbon dioxide equivalents (CO2-eq).

1 Introduction

Sweden has set an energy goal to reduce energy by 20 % by 2020 and by 50 % by 2050, compared to energy use levels in 1995. In order to achieve these goals it is important to renovate the existing building stock.

Sweden's most common residential building was the three-storey "lamella house" built between 1950 and 1975. The lifespan for many of these buildings and their installation parts is about to run out and therefore the renovation need for these buildings is increasing. Whilst upgrading the maintenance need, it is a smart opportunity to implement energy saving measures.

The studied house is a three-story building from the "million program" located in Landskrona, in need of renovation. The façade is penetrated by moisture, heating demand is high and indoor thermal comfort is in poor condition.

While the renovation market is actual, so is the "window of opportunity" to implement new renovation measures, taking in consideration climate change and co-benefits, such as daylight. Therefore an environmental, cost-effective refurbishment integrating daylight and architectural design is proposed in this thesis work. Standards and recommendations aimed at in this study are presented in the following Table 1.1-1.

Table 1.1-1 Standards, recommendations and project specific targets aimed at in this study

Field of study	Standard / Recommendation	Description
Daylight	BREEAM UK	DF 2 % in kitchens; DF 1.5% in the living rooms and home offices
	Sun, Wind & Light: Architectural design strategies	DF 1-2% in bedrooms
	Project Specific: Chapter 3.8, Table 3.8-1	cDA 300 lux for 60-80 % of occupancy hours in all the apartment rooms
	Miljöbyggnad Silver	Point DF 1.2% in living rooms (primary) and kitchens (secondary)
	British Standart BS EN 15251	UDI > 3000 lx (daylight oversupply) for maximum 5% of occupancy hours
Energy	BBR	Specific energy demand – 75 kWh/(m² ·a)
	Landskronahem target	Reduce the specific energy demand by 60%
Space	"Bättre för alla" accessibility instruction in BBR	Minimum distance between kitchen countertops 1.3m
	Overhang design: "Horizontal shading devices and light shelves"	Optimal overhang design method based on the building location's latitude, in Northern hemisphere
	Overhang design: Project specific: Chapter 3.8.3, Figure 3.8-5	Optimal overhang design based on project developed method
Thermal Comfort	FEBY12	April-September, Indoor temperature above 26 °C, no more than 10 % of time (in the most exposed apartment)

1.1 Background

Between the years 1965 and 1974, 1 005 578 dwellings was built in Sweden. These buildings are normally referred to as the million program. In the early 1960, the shortage of housings grew larger. To solve the problem the parliament took the decision to within a decade, construct one million residential dwellings (Boverket, 2014).

The construction pace had steadily been increasing before the decision was taken. In 1963, 80 000 dwellings were built which increased to 90 000 in 1964. However, the decision of the million program created a long term goal of mass produced buildings (Boverket, 2014).

In order to reach the goal the construction method was rationalized and industrialized. The buildings received therefore a different expression than previously built houses.
The apartments became in greater extend determined by the external wall components, which were large in both height and length (SABO, 2017). The traditional external wall loadbearing structure was replaced by the “bookcase” structure with its loadbearing apartment separating walls. The gables were built on site and light non-bearing facades were applied (Björk, Kallstenius & Reppen, 1992).

The combined building stock from the million program were divided into three equally large quantities of dwellings; single-family houses, low rise buildings, and high-rise buildings. The most common type of building during this period was the three-story lamella building (SABO, 2017).

In 1971 the housing crisis had been solved and fewer multi residential buildings were built in the next coming years. As a result, were the property owners facing difficulties to rent out these dwellings. Nowadays there are municipalities that are demolishing apartments in the million program multi-residential areas (Boverket, 2014).

There are approximately 830 000 remaining dwellings from the period 1961-1975 of which two thirds are within the million program. 40 % of these houses are located around the larger city regions and 60 % are spread out in Sweden. A substantial amount of these 830 000 dwellings have reached the end of their lifespan and are in need of refurbishment. The investment cost has been estimated to 300 billion SEK to 500 billion SEK, concluding that it is the biggest socio-economic challenge in modern time (Industrifakta, 2011).

The buildings within the EU accounts for 40 % of the energy consumption and 36 % of the CO_2 emissions. Approximately 35 % of the buildings are over 50 years old. “By improving the energy efficiency of buildings, we could reduce total EU energy consumption by 5-6 % and lower CO_2 emissions by about 5 %” (European Commission, 2017).

1.2 Aim and objectives

The goal of this study was to raise awareness about renovating the million program multi-storey residential buildings with environmentally friendly and cost effective solutions.

The expected renovation results should deliver significant energy reduction, while increasing the buildings value through co-benefits of daylight, architecture and environmental awareness.

The specific research questions are subdivided between the categories of energy, environmental assessment, cost, daylight and architecture.

Specific research questions are the following:

- How to achieve energy reduction by 60 % through cost- effective methods?
- Which construction materials obtain the least potential global warming impact?
- Does the lamella building have a sufficient daylight level and is suitable for a home office adaptation from daylighting perspective?
- What is the optimal solution of implementing external balconies and shadings for the improved building envelope from daylight perspective?
- How to improve the appearance of the building, making it more attractive and thus increasing its value?

1.3 Scope

The scope of this study was to find environmentally friendly and cost effective renovation solutions for the million program lamella building while incorporating co-benefits of daylight assessment and architectural quality of the building.

The project was limited to the renovation of the reference building, located in Landskrona, Sweden. The results were obtained through energy and daylight simulations, LCA and LCC calculations, literature study, on-site measurements and consultations.
The HVAC assessment was excluded.

The study was performed at LTH, Lund University, and shaped with the help of supervisors and consultants. Different software tools were used, further described in “overall approach”.

1.4 Overall approach

The thesis incorporated qualitative and quantitative research methods.

Qualitative research methods were:

- Consultations with main supervisor Åke Blomsterberg (LTH/WSP) and co-supervisor Niko Gentile (Daylighting, LTH)
- Consultation with Miklos Molnar (Divison of Structural Engineering, LTH)
- Interview with Johan Zellbi (Landskronahem)
- On-site daylight measurements (Landskrona, Sweden)
- Two building site visits (Landskrona, Sweden)
- Wikells software learning course (Växjö, Sweden)

The quantitative research methods included the literature study of previously done research about related topics and new software learning. The core software's used in this thesis are:

- Energy: IDA-ICE
- Daylight: Diva for Rhino
- Architectural design: SketchUp
- Life-cycle costing: Wikells byggberäkningar (calculations)
- Life-cycle assessment: EcoSai

1.5 Limitations

The following are limitations between the different fields:

Energy

- The renovation measures were limited to reducing the heating demand. Hence, no measures were taken to lower domestic hot water and building electricity.

Daylight

- Only fixed external overhang for shading was tested. No other type of internal manual or mechanical shadings like awnings or venetian blinds were tested, as fixed external shading, when designed properly, has the least maintenance costs and best effect on shading the unwanted direct sunlight.
- Only horizontal overhang above the window was tested for South-East facing façade. No external vertical shading devices were considered. Furthermore by testing horizontal overhang it was also possible to estimate the optimal balcony depth that acts as a shading device itself.
- The seasonal daylight variations were only considered by means of designing optimal overhang depth to shade the hot summer sun while letting the winter sun in.

- This study excluded glare calculations, as in residential spaces occupants are normally not fixed to one sitting point and are free to move the furniture, in order to find an optimal placement.
- As a result of daylight results, balcony design goals and time limitation, only two different overhang sizes 1.3 m & 1.5 m were tested between all individual daylight metrics assessed in this study.

Life cycle assessment

- The potential environmental impact of new windows and doors were not studied.
- Maintenance costs were excluded from the LCC calculations, because no mechanical installations, that would need regular maintenance, were installed.

Other

- No moisture calculations were performed.

2 Literature study

2.1 BBR requirements

The building regulation authority Boverket, shortened BBR, divides Sweden in four climate zones. Within each zone, certain specific energy demands are required to be fulfilled. Specific energy demand refers to the delivered energy of the building in terms of heating, cooling, domestic hot water and building electricity. The south region of Sweden falls within climate zone IV for which the current regulation of a multi residential building are determined to 75 kWh per m² heated floor area. New and renovated buildings are required to fulfill the demand. However, if the renovated building does not achieve the specific energy demand, the U-values of the building components, presented in Table 2.1-1, should be strived at (BBR, 2015).

Table 2.1-1 Recommended U-values for different building components (BBR, 2015)

Building component	W/(m²·K)
Roof	0.13
External wall	0.18
Ground slab	0.15
Window	1.2
Exterior door	1.2

Within the apartments, the ventilation system should be designed with a minimum airflow. Depending if the apartment is occupied or not, the limits have been set to 0.35 l/s per m² floor area and 0.1 l/s per m² floor area, respectively.

2.2 IEA Annex 56

This chapter will firstly introduce the background of the project Annex 56. Furthermore, describe the methodology that was carried out and present good examples of completed renovation projects. Finally, give an introduction to the proposed life-cycle assessment.

The project IEA EBC Annex 56 was founded due to the demand that each member of the EU must prepare renovation plans for the existing building stock. Several standards and regulations related to energy use of buildings have been developed. EU has stated that all new buildings require to be nearly zero at the end of 2020. However, these standards have mainly been addressing new buildings, and less instruction on the renovations of existing buildings. As a result it has led to expensive processes, rarely accepted by users or owners. Instead, the renovation should focus on providing the best building performance, from a cost/benefit perspective. This would include slowing down the climate change, reduce the energy consumption, adding values by the renovation at the lowest effort (investment cost, interference in the building and tenant disturbance). Therefore, a new methodology was established for building renovations (International Energy Agency, 2011).

2.2.1 Methodology

Annex 56 was performed between 2011 and 2016, with the aim to create a methodology for cost-effective renovation solution. Whilst a cost optimal renovation refers to the level of energy performance with the lowest life-cycle cost, the cost-effective renovation combines energy efficiency and carbon reduction measures. The methodology outlined the necessary basics for optimizing the cost, energy use and carbon emissions. It furthermore acknowledged renovation co-benefits such as thermal and lighting improvements. These benefits may have a significant value but are often the subject of underestimation of the full value of the refurbished building (International Energy Agency, 2014).

2.2.2 Renovation projects

This chapter will present three completed renovation projects, which were built between 1963 and 1973. Moreover, it will give an overview of the carried out processes and the investment cost, for each renovation project. The overall aim for these projects was to carry out a needed maintenance renovation and at the same time lower the energy demand. The following text has been summarized of the Swedish participation of Annex 56.

The projects were Maratonvägen (Halmstad), Backa röd (Gothenburg) and Brogården (Alingsås). In all three renovation projects new heat recovery ventilation system was installed. Moreover, fixed lighting was replaced by new energy saving bulbs, in various extents for the different projects, with the purpose to lower the building electricity. Between the projects heating renovation included different measures, from individual metering to new main heating central. The specific details of ventilation, electricity and heating renovation measures can be found in the document Annex 56 (Blomsterberg, Nilsson & Pedersen, 2016).

Only envelope improvement renovation measures were relevant to this case study, and therefore listed individually in Table 2.2-1.

Table 2.2-1 Summary of the renovation measures of Maratonvägen, Backa röd and Brogården projects

	Maratonvägen
Envelope improvements	➢ Added insulation in the roof and at the infill wall at the balconies ➢ The roof was changed from a flat roof to an inclined ➢ Airtightness was increased from 1.4 l/s per m² to 0.5 l/s per m² at 50 Pa ➢ New triple glazed windows
	Backa röd
Envelope improvements	➢ Added insulation on the envelope ➢ New balconies supported by columns in order to eliminate the thermal bridges caused by the balconies ➢ New triple glazed windows
Moreover	➢ New water, sewer and electrical system ➢ New bathrooms and kitchens ➢ New fully glazed balconies ➢ Safety doors for the apartments

	Brogården
Envelope improvements	➢ Demolished external walls and replaced by prefab ➢ Added insulation of gables, roof and ground slab ➢ Increased airtightness from 2 l/s per m² to 0.2 l/s per m² at 50 Pa ➢ Extended living space at the kitchens. The recessed wall was aligned with the living rooms (balconies were moved out) ➢ New triple glazed windows

The summary of investment cost, energy savings and rent supplement for the three Swedish projects are illustrated in Table 2.2-2.

Table 2.2-2Summary of three building renovations

	Maratonvägen	Backa röd	Brogården
Construction year	1963-1965	1971	1971-1973
Renovation completed	2011	2009	2010
Energy savings	35%	65%	60%
Investment cost	5000 kr/m²	15 000 kr/m²	20 000 SEK/m²
Pay back for energy relat-ed measures	Information not avail-able	< 25 years	< 17 years
Rent supplement	15%	35%	35%
Evecuated /remained during renovation	Remained	Eveacuated	Evacuated

2.2.3 Life-cycle assessment

The LCA-method for renovation measures in Annex 56 included processes with substantial environmental impact (Figure 2.2-1). The yellow stages are suggested to be included in the calculations, while the black stages normally show lower or negligible impact. The time when the building is operative (use stage) normally stands for the largest impact. Within Annex 56, the buildings life-cycle assessment was suggested to account for 60 years.

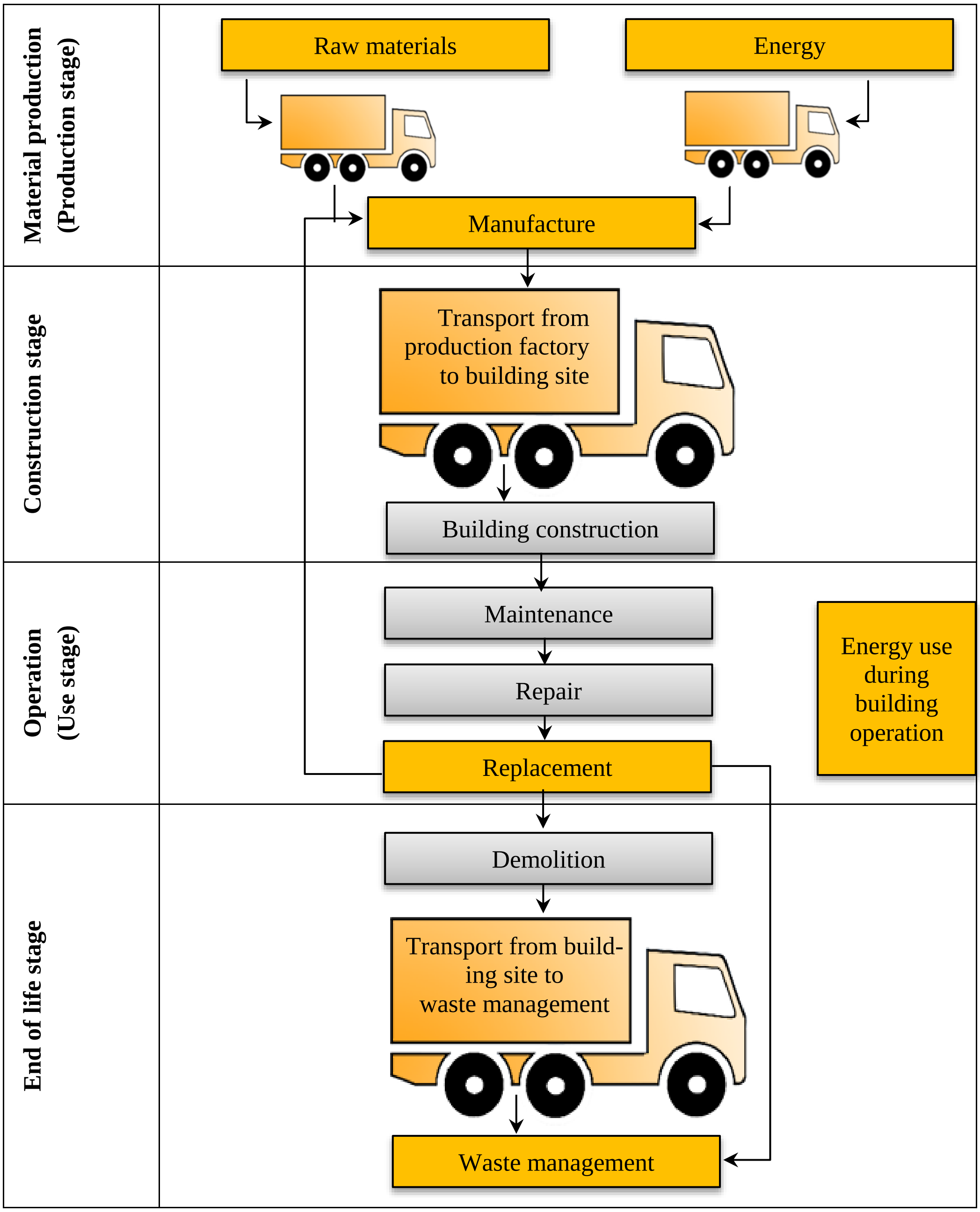

Figure 2.2-1 The buildings life-cycle, divided into sub stages

2.3 Trees as carbon sinks

A study performed by (Lippke et al., 2004) found that instead of keeping the wood in forests grow for hundreds of years it is environmentally beneficial to frequently harvest, and construct buildings with wood material rather than build with concrete and steel, which consume more fossil fuel during manufacturing. Trees absorb carbon dioxide during its growth and if left untouched, the stored carbon returns back to the atmosphere, thus remaining CO2 neutral.

Wood is the only material that can store carbon in large quantities for a longer period of time. According to Lehmann (Lehmann, 2012) can one cubic meter of wood store about one ton of CO2. "The emissions associated with harvesting, transports, and processing sawn wood products are small compared to the total amount of carbon stored in the wood" (Kunic, 2013). Wood is therefore, despite taking into account the production phase, the only construction material that has a negative carbon footprint.

2.4 Insulating million program building

A normal method to decrease a building's heating demand is to supplement the building envelope with added insulation. However, it is of importance to investigate the condition of the existing, or preserved part of the element. The choice of insulation material, added to the construction element will affect its extent of dehydration. A study within Lund University (Molnár et al, 2013) was carried out in order to analyze two insulation materials (mineral wool and EPS) ability to enable the aerated concrete to "breathe", and therefore dry out. The studied house (Figure 2.4-1) was built in Kyrkbyn, Gothenburg in the early 1950s and was constructed with 200 mm of aerated concrete and 65 mm brick façade. The brick façade together with the mortar had been worn down, due to weather and wind. The lack of an air cavity between the aerated concrete and brick induced the concrete to absorb water, which was furthermore penetrated to the wallpaper and inside the apartments.

The reference wall was compared with two system of additional insulation and exterior plaster; one with 50 mm mineral wool, the other with 50 mm EPS. Figure 2.4-2 represents the water content (kg/m²) in the aerated concrete for three studied cases; reference wall (blue line), EPS wall (green line) and the wall with added mineral wool (red line).

Figure 2.4-1 Studied building before renovation. Photo: Kenneth Sandin, LTH (Molnár et al., 2013)

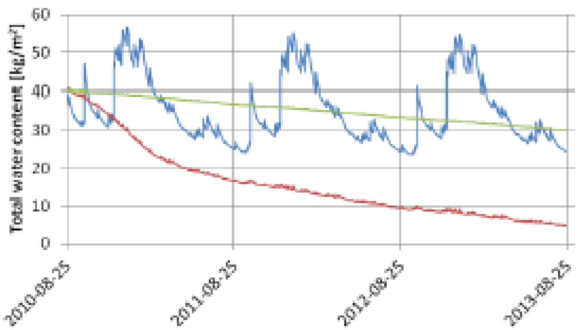

Figure 2.4-2 Total water content (kg/m²) in the aerated concrete layer of the external wall for reference wall (blue), added insulation of EPS (green) and mineral wool (red) (Molnár et al., 2013)

In Figure 2.4-3 and 2.4-4, five different lines represent their depths in a cross section of the aerated concrete. 0-4 cm (blue line) corresponds to the part of concrete towards inside, and 16-20 cm (purple line) correlates to the outer part.

The simulations with the mineral wool obtained a larger dehydration rate compared to EPS. The large vapor resistance of EPS, prevented dehydration towards the outside, and the rate was therefore decreased. Whilst EPS obtained a uniform moisture distribution over the aerated concrete, mineral wool received a rapid dehydration in the outer layer (purple line) and less in the core of the material.

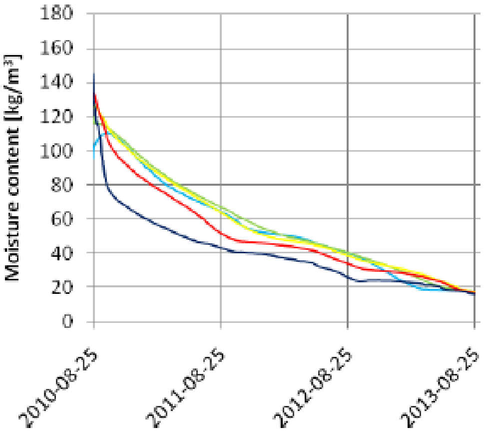

Figure 2.4-3 Moisture content in aerated concrete at different depths with plastered mineral wool (Molnár et al., 2013)

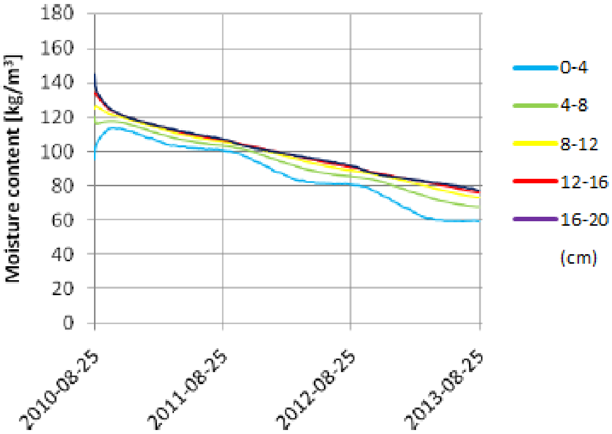

Figure 2.4-4 Moisture content in the aerated concrete at different depths with plastered EPS (Molnár et al., 2013)

The field study in Kyrkbyn, Gothenburg revealed that the added insulation of mineral wool had a favorable effect on the moisture content in the external walls.

2.5 Prefabrication in Annex 50 and TES facades

Annex 50 is a report of cooperative work performed under the International Energy agency (IEA) programme of Energy Conservation in Buildings and Community Systems, called “Prefabricated systems for low energy renovation of residential buildings”.

The objectives of this Annex have been the development and demonstration of an innovative whole building renovation concept for typical apartment buildings. The concept is based on largely standardized façade and roof systems that are suitable for prefabrication. (IEA, 2011)

Some of the advantages of prefabrication according to Annex 50 include (IEA, 2011),

- Achieving energy efficiency and comfort for existing apartment buildings comparable to new advanced low energy buildings
- Optimized constructions and quality and cost efficiency due to prefabrication;
- A quick renewal process with minimized disturbances for the inhabitants.

Annex 50 concept of the development of prefabricated retrofit systems suggests three fundamental aspects (IEA, 2011):

- The modules are standardized in construction, layers, and joints
- The modules are flexible in architecture, form, and cladding
- The modules can be combined with each other and with non-prefabricated (conventional) retrofit options

According to Annex 50 there are two different approaches for retrofit module design: fully prefabricated solution or prefabrication of the areas around the window, as there is the highest density of details.

The inspiration of prefabricated renovation project was Technical College in Risør, a coastal town on the west shore of the Oslo fjord in Norway. The school was retrofitted with TES Energy façades and improved roof insulation. TES Energy Facade was a pre-fabricated timber building system with a high quality of ecological performance (Lattke, 2011). TES Energy Facade was run under the trans-national ERA-NET Wood Wisdom-NET Research Programme (2006-2011) between Finland, Norway & Germany.

The project was the first one in Norway to refurbish with the TES facades. The renovation measures resulted in energy reduction from 325 kWh/m²a to 49 kWh/m²a, a saving in energy use of 275 kWh/m²a. (REF) The goal of the research project was to develop a façade renovation method (TES method) based on large scale, timber based elements for the substantial improvement of the energy efficiency of a renovated building, which would be applicable throughout Europe. The target of the TES method is primarily focused on the building's energy efficiency improvement and as a consequence in the reduction of GHG[1] emissions (Lattke, 2011).

TES Energy façade normally has HVAC installed in the elements, however, there is an exception with type of wall that is classified as TES-envelope concept. This category is not purely related to the integration of sub-components from building service systems. The entire timber framed element is part of a reactive building skin influencing buildings energy consumption (Ott er al., 2014). The new exterior wall reduces the transmission losses that leads to the energy savings, however, proof of a good sound insulation and moisture must be tested.

Risør Technical College consisted of two-story main building and one-story wing built in mid-1960s. In the process of renovation the existing facades were demolished and *replaced with prefabricated TES façade elements.* The building had a concrete structure where columns were bearing the prefabricated floor elements (Larsen & NTNU, 2010), similarly to the structure of the lamella type building examined in this study.

The TES elements consisted of two parts: inner (98mm) and outer (198mm). The inner part was placed between the concrete floor and ceiling, fixed with concrete screws (Figure 2.5-1, to the left). The outer part was attached to the outside of the façade, resting on the steel brackets

[1] GHG is a gas in an atmosphere that absorbs and emits radiation within the thermal infrared range. This process is the fundamental cause of the greenhouse effect

fixed to the concrete foundations, and connected to the inner part with the screws (Figure 2.5-1, to the right). Between the two parts there was a tolerance gap filled with mineral wool. The external cladding was attached to the outer façade layer (Larsen & NTNU, 2010).

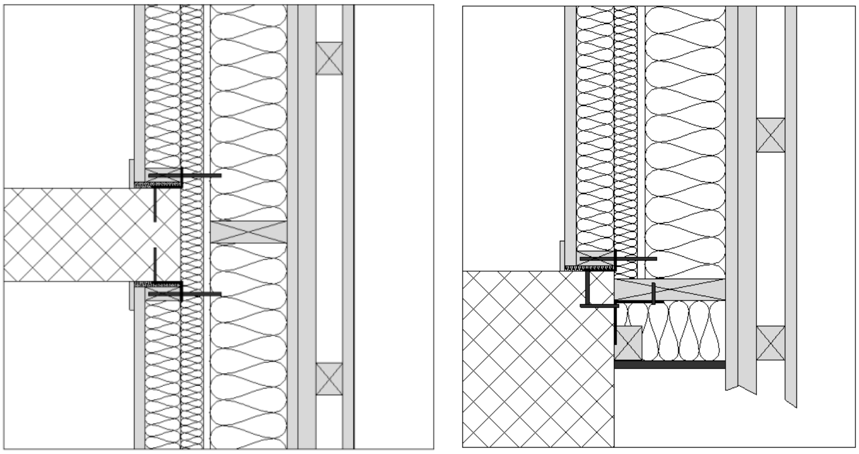

Figure 2.5-1 Construction details. To the left: External wall panels and story partition; To the right: External wall panels and foundation, - principle sketches by Aija Baumane, based on Risør Technical College construction drawings (Larsen & NTNU, 2010)

The elements with windows where build off site in controlled environment of the Treby-ggeriet Company, and on site assembly took only one day. This particular school renovation example demonstrates how it is possible to renovate with prefabricated light-weight timber walls in two-story building, with a similar structural envelope, like the case study, while achieving high energy performance.

This particular school renovation example demonstrates how it is possible to renovate with prefabricated light-weight timber walls in two-story building, with a similar structural envelope as the case study examined in this master thesis, while achieving high energy performance.

2.6 Daylight

It could be asked, why to look at daylight? Daylight can act as free energy source through possible electricity savings during day hours and heating savings from solar radiation during winter. Simultaneously, however, excessive daylight can result in visual and thermal discomfort, like glare and overheating. The right amounts of daylight gives a good visual comfort and can further improve existing thermal comfort, thus overall increasing occupant's wellbeing in the building.

Having a well and smart daylit space, not only increases the occupants experience, it also generates multiple benefits, like: positive effect on human health and productivity; reduction in energy demand and decreased load on buildings HVAC systems, that leads to economical savings and positive environmental impact; increased value of the building through certification systems and finally increased social value, that goes beyond predictable measures.

When the building is designed in a manner that more daylight reaches the interior space, it usually simultaneously provides increased views towards outdoors. Research has shown that a good view versus no view results in increased productivity, mental function, and memory recall. Research has also shown that hospital patients with good views heal faster than those with no view or a poor view (Lechner, 2015).

For these and other reasons the visual comfort should be taken into account in all the buildings designed for humans, including the residential sector. By spending most of our time indoors, we are likely to be exposed to the daylight on large extend and be affected by it, both at work and home.

Further chapters will present:

- Relevant daylight theory
- Desired illuminance levels in an office and residential buildings,
- Different simulation types and their respective metrics
- Different certification systems and regulations in Sweden or abroad, but relevant for Swedish context and residential spaces

2.6.1 Theoretical background

The *light* that we see is the portion of the electromagnetic spectrum to which our eyes are visually sensitive too. The power with which light is emitted from a source weighted for the human eye sensitivity, is called *luminous flux* and is measured in *lumens*.

Some of the lumens from a light source will illuminate a particular surface. Illuminance thus is equal to the number of lumens falling on a unit area of a surface and is measured in lux Illuminance is calculated with eq.1.

$$Illuminance = \frac{Luminous\ flux}{Area} \qquad [\text{ lux }] \qquad \text{Eq. (1)}$$

Where: Luminous flux, lumen (lm)
Area in square meters (m^2)

According to the book *SUN, WIND & LIGHT* illuminance levels in buildings depend on both the desired subjective experience of a space and more objective, task-oriented criteria. In general, more light is required for tasks with higher difficulty, longer duration, lower contrast, higher risk and smaller size; older people will also require more light (DeKAY & Brown, 2014).

The daylight that enters the building through a window can have several sources: direct sunlight or direct daylight, or indirect daylight that comes from reflective surfaces, such as the ground, nearby buildings among others, see Figure 2.6-1.

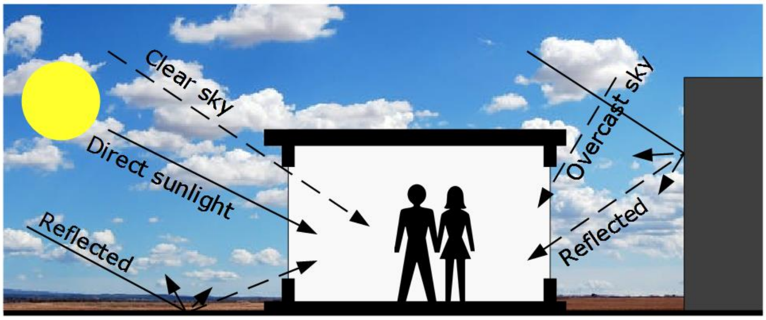

Figure 2.6-1 Daylight sources

When light strikes a surface it is reflected, transmitted or absorbed. The reflectance factor range is from 0 to 1 and it determines how much light is reflected. The transmittance has the same range, however, it gives a measure of the fraction of light that passes through a surface (through a window glass, for example).

All the surfaces used in the daylight simulations are Lambertian materials, which means they are perfect diffusers. In the reality the surface characteristic will have an effect of how the light is reflected. For example a very smooth polished surface will produce specular reflections (one angle, like in a mirror), while matte surfaces will scatter the light to produce diffuse reflections.

To better understand direct sunlight and different sky dome luminance effect on the daylight in the building, it is important to get familiar with the following sky types:

- Clear sky - A sky condition with few or no clouds, usually taken as 0 –2 tenths covered in clouds. Clear skies have high luminance and high radiation.
- Partly cloudy sky – A sky is usually between 2 –8 tenths covered in clouds. The condition is between clear and overcast. Skies in this category are highly variable and difficult to predict.
- Overcast sky – The sun cannot be seen. 8 -10 tenths of the sky is covered in clouds. Overcast skies generally have lower luminance and lower radiation.

Full definitions can be found in the book *Sun, Wind & Light*. Other sources will subdivide the sky types into more categories, however, it is most important to understand two extremes – clear sky with sunlight and overcast sky. According to Lechner, if the building's daylight design works under both conditions, then it is very likely to also work under other sky types (Lechner, 2015).

2.6.2 What is the optimal daylight level for a home office?

In this study it was further examined if the apartments in the million program lamella residential buildings could be adapted to a home office, from a daylight perspective. Work plane requires a higher illuminance than simple leisure tasks.

Having a higher illuminance requirement for residential buildings can be further motivated as reasonable renovation measure, due to increased space flexibility. We live in the modern times when self-study, startups and flexible working schedules are common. The average employee is not as bound to his working desk as he used to be. There is a certain amount of flexibility present today, when the approach on economy and businesses is ever changing. Residential buildings, designed with proper daylight, increases the tenants visual comfort and allows to perform visually more demanding tasks, like office work among others, at home.

Residential space is also often a home for people who have entered the retirement. It is proven that older people need a higher illumination. As human eye ages, pupil area decreases and loss in light transmittance occurs, resulting in less light falling on the retina[2]. Old observers require twice the recommended illuminance, while young observers require one half the illuminance (IES, 2017).

According to Illuminating Engineering Society of North America (IESNA) Lighting Handbook a residential building requires between 50- 200 lux of illuminance, with simple orientation and occasional visual task activities. However, general office work with visual tasks would require 300-500 lux (IESNA, 2000). The illuminance recommendations are for middle-age observers (25-65).

As IESNA presented a wider range of acceptable illuminance target values it was necessary to further evaluate optimal daylight level for a possible home office.

Today most of our work is computer based. Cantin and Dubois presents a method for assessing daylight quality in office, where occupant is sitting at the computer desk. They argue that the lower end of 300-500 lux range is appropriate, where task is substantially screen-based (Cantin & Dubois, 2011). Screen with white background and black text can have, for example, luminance of ~ 90cd/m², contributing to the illumination levels for the worker.

There are several lighting studies performed, where occupant behaviour is monitored, to examine when the artificial light is turned on and off. Love found in his studies that the light switching depends both on the individuality of the person as well as the daylight availability (Love, 1998). Reinhart and Voss performed a study on monitoring manual control of electric lighting and blinds for 10 daylight offices in Germany. One of the findings was that at ~ 240 lux minimum desktop illuminance the probability of switching on the electric lighting decreased, without further decreasing for higher illuminances (Reinhart & Voss, 2002). This suggests that employees felt comfortable with 240 lux illuminance for working with the computer.

These findings in addition to other research underlines that the ranges for optimal illuminance can vary, however, in order to decide on common illuminance level for combination of well-lit residential space and possible home office a threshold of 300 lux per was chosen for the daylight simulations.

2.6.3 Static and dynamic simulations

There exists static and dynamic computer simulations that are represented with different daylight metrics in their calculations. Dynamic daylight performance metrics are based on

[2] Retina - A layer at the back of the eyeball that contains cells sensitive to light, which trigger nerve impulses that pass via the optic nerve to the brain, where a visual image is formed.

time series of illuminances or luminances within a building. These time series usually extend over the whole calendar year and are based on external, annual solar radiation data for the building site. The key advantage of dynamic daylight performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site together with irregular meteorological events (Reinhart, Mardaljevic & Rogers, 2006). Static simulation will only consider IES standard overcast sky.

Dynamic daylight simulations involve (a) a pre-processing step during which a set of daylight coefficients is calculated for each sensor point and (b) a post processing step during which the daylight coefficients are coupled with the climate data to yield the annual time series of interior illuminances and luminances. Both steps are fully automated within the above mentioned programs6 In the case of Daysim[3], calculation times are roughly eight times longer for dynamic compared to static simulations at current processor speeds (4GHz) (Reinhart, Mardaljevic & Rogers, 2006).

2.6.4 Daylight factor

Typical daylight metric calculated with static simulation is the *daylight factor (DF)*. The daylight factor is defined as the ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky (Moon & Spencer, 1942). Daylight factor is calculated according to equation 2.

$$DF = \frac{E_{\ indoor}}{E_{\ outdoor}}\ x\ 100 \qquad [\ \%\ ] \qquad \text{Eq. (2)}$$

Where: E_{indoor} – The interior illuminance at a point on a given plane, lux

$E_{outdoor}$ – The outdoor illuminance measured at the same time as indoor, under an overcast sky, lux

The Table 2.6-1 gives a brief description of how different levels of daylight factor are experienced in the space.

Table 2.6-1 Different daylight factor levels and their corresponding descriptions

DF, %	Description
Below 1	Dull gloomy appearance, electric lighting masks daylight variation
1 - 2	Usually optimum balance of electric lighting and daylight
4 - 5	Totally daylit room
Above 5	Probable thermal, visual discomfort, “noise” & other problems

The daylight factor method is widely used and considered as one of the simplest method to describe the amount of daylight received on a specific point in a room (Iversen, 2013).

[3] DAYSIM is a validated, RADIANCE-based daylighting analysis software that models the annual amount of daylight in and around buildings. (Reinhart C. , 2017) *DAYSIM is used in this project.*

Daylight factor is good for rather fast daylight estimates, however, the limitations of DF calculations are broadly discussed in lighting community. The most relevant limitations for this master thesis research study are listed as following:

- Direct sunlight and non-overcast skies are not considered
- Building orientation is not considered
- Measured DF values varies due to variable sky luminance distributions under real overcast sky, compared to the CIE overcast sky definition

Due to above mentioned DF limitations, other metrics needed to be considered.

In Sweden the Miljöbyggnad rating system is commonly used and it is based on Boverket's Building Regulations (BBR) for good daylighting design. Both BBR and Miljöbyggnad demands point DF to be located one meter away from the darkest wall, 0.80 m above the floor, halfway from the exterior envelope, without specifying the room. Miljöbyggnad Silver level requires DF 1.2% while BBR demands DF 1%.

There are no requirements on minimal average DF specifically for the residential spaces in Sweden.

Recent research, *Climate connectivity in the daylight factor basis of building standard* showed that median diffused outdoor illuminance in London (51.15° N) was almost the same as in Copenhagen (55.63° N), thus 14.100 lux and 14.200 lux respectively (Mardaljevic & Christoffersen, 2017). This discovery intuitively suggests that BREEAM UK proposed daylight factor targets for residential buildings in the United Kingdom, might also be used as informative guide for the master thesis case study, located in Sweden. This given that both are calculated with the median diffused outdoor illuminance.

BREEAM UK for multi-residential buildings suggests follwing DF design:

- 1.5% DF for 80% of floor area for 1 credit for living rooms, dining rooms, studies (including home office).
- 2% DF for 80% of floor area for 1 credit in Kitchen
- The additional requirement was that 80% of the working plane in each kitchen, living room, dining room and study (including any room designated as a home office under HEA 20-Home Office – Code for Sustainable Homes) must have a view of the sky.

2.6.5 Climate-based daylight metrics

There are different weather dependent simulation based metrics. Most common one is Daylight autonomy.

Daylight autonomy (DA) is defined as the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone (Reinhart, Mardaljevic & Rogers, 2006) – 300 lux was set to be the target illuminance in this study, based on the literature study discussed in Chapter 2.6.2.

Further research discovered that also partial daylight contribution to illuminate levels indoors is beneficial, thus *continuous daylight autonomy (cDA)* was proposed (Rogers, 2006). Daylight metric cDA gives a partial credit for time steps when daylight does not reach the threshold that is set, however, contributes to the illuminance. For example if 300 lux is required, but 150 lux is reached by natural daylight, 300/150= 0.5 point is given at that specific time step. Hereby we could conclude that continuous daylight autonomy might be supplemented with electrical lighting, while daylight autonomy would be treated as an independent light source.

According to the daylighting lecture from the Lund University, the cDA can be subdivided in following ranges based on the percentage of occupancy hours when the target illuminance is met (Dubois & Du, 2016):

- 80-100 % - Excellent
- 60-80 % - Good
- 40-60 % - Acceptable
- 40-20 % - Poor

However, daylight autonomy and continuous daylight autonomy lack to inform if there is oversupply of daylight occurring in the space that could lead to glare[4].

Therefore it is important to look at another metric, called Useful Daylight Illuminance (UDI) that was proposed by Mardaljevic and Nabil in 2005. UDI determines when the daylight levels are ‘‘useful’’. UDI was originally divided in three illuminance ranges, as follows:

- Space is too dark < 100 lux
- Useful UDI range 100-2000 lux
- Space is too bright > 2000 lux

The upper threshold of 2000 lux shows when there is oversupply of daylight that could lead to visual and/or thermal discomfort, according to the reported occupant preferences in daylight offices (Reinhart, Mardaljevic & Rogers, 2006). However, later studies on UDI showed that: “There is significant debate regarding the selection of 2000 lux as an ‘upper threshold’ above which daylight is not wanted due to potential glare or overheating. There is little research to support the selection of 2000 lux as an absolute upper threshold” (New Building Institute, 2017).

Moreover, Cantin and Dubois (Cantin & Dubois, 2011) claimed that after their study was conducted in 2010, it was suggested by (Mardaljevic, Heschong & Lee, 2009) that the UDI scheme could be enhanced by dividing the “useful” UDI 100-2000 lx range into two: a “supplementary”100-500 lx and an “autonomous” 500-2000lx range.

Lindelöf and Morel proposed in their paper “Bayesian estimation of visual discomfort” a method that estimated objectively occupant’s visual discomfort in small office rooms de-

[4] Glare - The perception caused by a very bright light or a high contrast of light, making it uncomfortable or difficult to see. (DeKAY & Brown, 2014)

pending on the horizontal workplane illuminance. They claim that discomfort probability is very high below 200 lux, has its global minimum at 500 lux, and then increases gradually for larger illuminances, until it reaches the maximum at 3000 lux (Lindelöf & Morel, 2008). Thus suggesting that 3000 lux is the optimal illuminance threshold for identifying daylight oversupply that leads to visual discomfort. According to Rogers and Goldman, a daylight oversupply is assumed when the DA is ten times the designed illuminance (Rogers & Goldman, 2006). In this thesis research the target illuminance is 300 lx, making the daylight oversupply threshold at 3000 lx.

However, the concept of a constant factor of ten times the design illuminance is based on intuition rather than documented research (Reinhart, Mardaljevic & Rogers, 2006). Reinhart & Wienold believes that other thresholds may be defined, based on the daylight glare probability metric. This explains why sometimes the maximum illuminance threshold is found to be 2000 lux instead.

Based on research and project adopted threshold of 300 lux mentioned earlier, UDI was subdivided between the following four illuminance categories:

- Below 100 lx - “undersupply” range
- 100-300 lx - “supplementary” range
- 300-3000 lx - “autonomous” range
- Greater than 3000 lx – oversupply of daylight

The last metric investigated in this study was Daylight availability. *Daylight availability* is a metric that merge DA and UDI information into a single figure. (Reinhart & Wienold, 2010) The results are displayed on a plan drawing that is divided into two areas: one that indicates DA (gradient color) and another showing were the space is overlit (near the window; uniform color). The over lit area presents a warning that is invoked if there is an oversupply of daylight for at least 5% of the occupancy schedule. The 5% criteria is an analogue method to thermal assessments according to British Standard BS EN 15251 (BSI, 2007), based on European Standard EN 15251.

3 Methodology

The following chapter describes the case study building in terms of the design, technical description and structural analysis. Furthermore, the proposed architectural changes and renovation measures are introduced.

3.1 Reference building

The investigated case study building is located in the outskirts of Landskrona. The site plan is illustrated in Figure 3.1-1. Built in 1974, it was constructed at the end of the “million program” era. The three-storey building consists of 18 apartments, three staircases and a basement with two laundry rooms. The property owner (Landskronahem) owned by the Landskrona municipality is the leading public housing landlord in the city. As an agreement between the municipality and the social services, the apartments accommodate socially exposed tenants for short-term periods.

Figure 3.1-1 Site plan, reference building in red, block number 19

The reference building is provided with district heating and domestic hot water from a main central, located in a nearby building. The district heating pipes between the buildings are situated in the ground, thus the most part run in the basement spaces. The heat losses from these pipes contribute to the heating of this area. There is no additional heating in the basement, nevertheless it is considered as a heated floor area. The district heating is distributed through radiators to the apartments and staircases, and is the main heating source for the building. All the bathrooms have been newly renovated and energy efficient water taps were installed. The ventilation system consists of mechanical exhaust air with fans situated on the roof, extracting air from the bathrooms and kitchens.

The existing window to wall ratio is 38% for the balcony facade, 29% for the entrance façade (excluding staircase walls) and 3% for gables. Facades are illustrated in Figures 3.1-2 and 3.1-3.

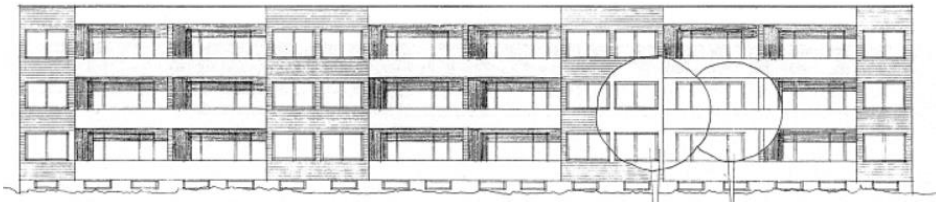

Figure 3.1-2 South-East facade (balcony facade)

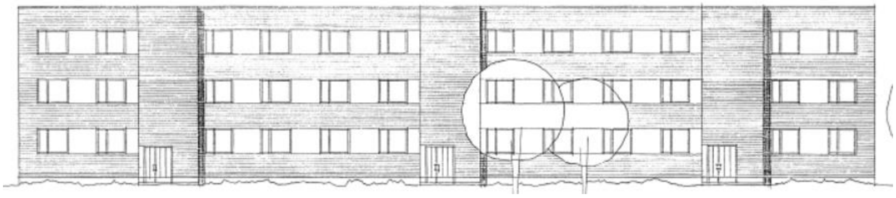

Figure 3.1-3 North-West facade (entrance facade)

The plan drawing shown in Figure 3.1-4 visualizes the layout of six apartments (A1-A6). Gridlines A-G goes through the load bearing walls, while gridlines 1-3 indicates facades and staircase separation walls. The area for each apartment is 80 m^2 including two bedrooms (B1,B2), on the NW side. Kitchen (KIT) and living room (LVR) is located on the SE side. In the core of the apartment, corridor, storage, and two newly renovated bathrooms are placed. There are three staircases in the building.

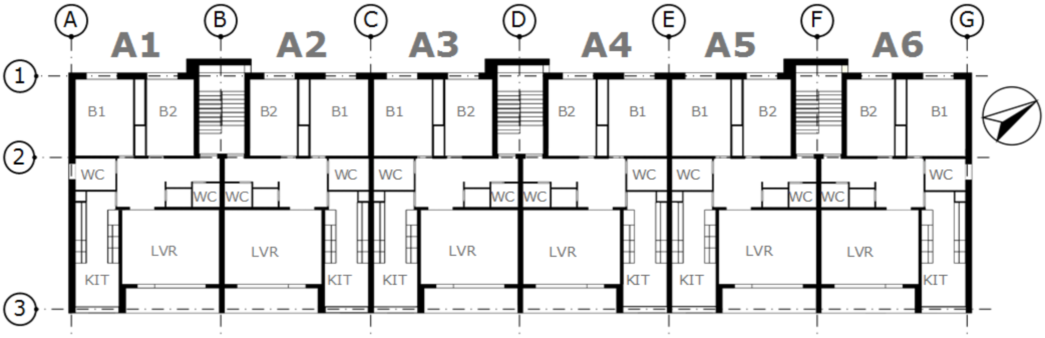

Figure 3.1-4 Floor plan, third floor, reference building

The balconies in all apartments are long and narrow, similarly like the kitchens. See Figure 3.1-5. In terms of space, the living rooms and bedrooms are better designed.

Figure 3.1-5 Balcony (left); Kitchen (middle, right), Photo: Aija Baumane

3.2 Structural analysis

After consulting with the structural engineer Miklos Molnar[5] at Lund University, the structural analysis of the building was performed. See Figure 3.2-1 for the results.

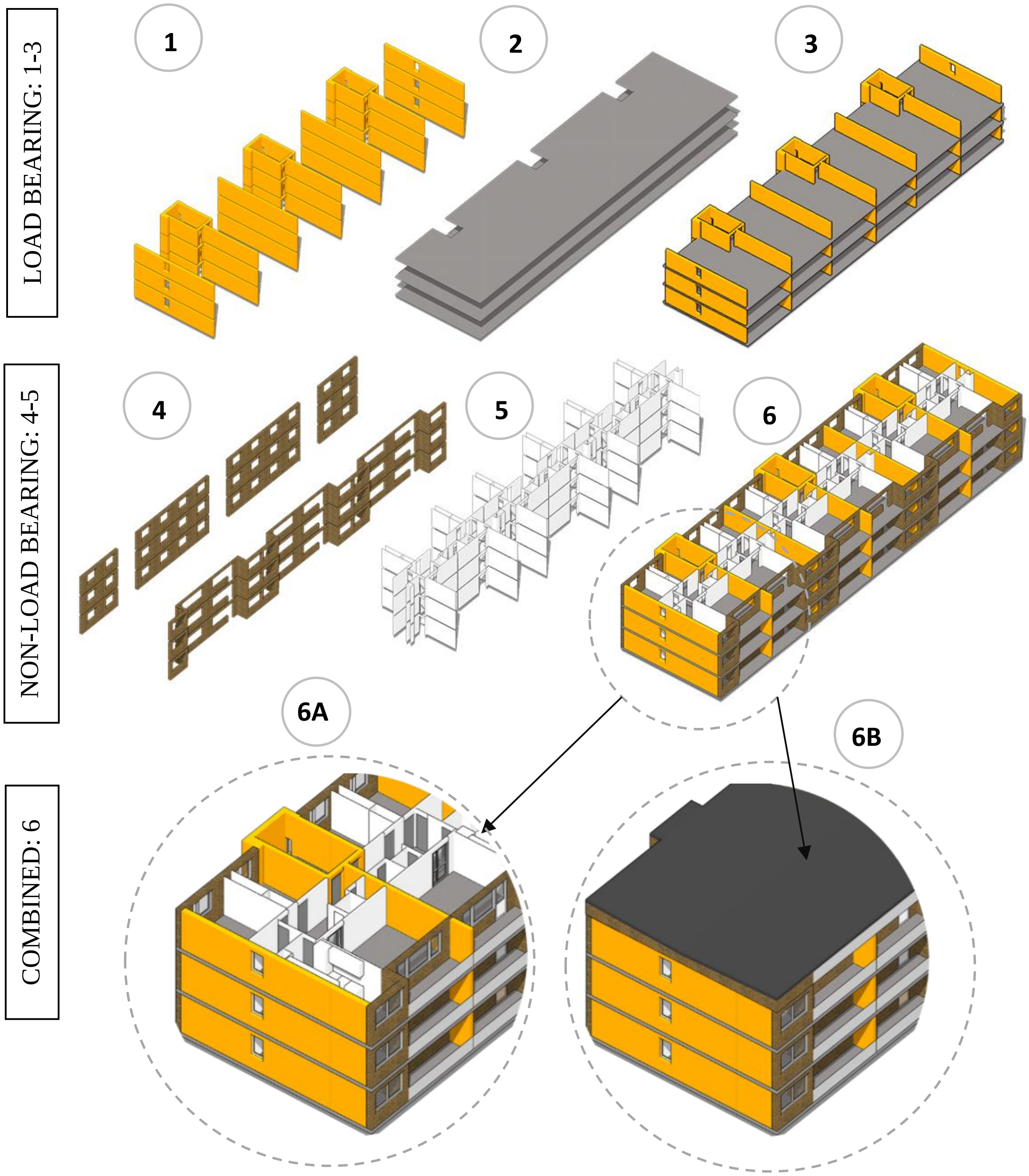

Figure 3.2-1 Structural analysis of the building: 1-3: Load-bearing building components; 3-5: Non load-bearing building components; 6 - Combined

[5] Head of office at Division of Structural Engineering, LTH; Meeting: February 15th, 2017

Figure 3.2-1 stage 1-2 visualizes the load-bearing parts of the building, colored orange and grey. The story partitions indicated in stage 2 rests on the load bearing walls together forming the loadbearing book-case structure, shown in division three.

It is assumed, based on the houses built at that time that partitions are made from prefabricated deck elements, spanning parallel to the facades, resting on the load bearing parts. Share forces from the deck element laying on two load bearing walls are divided equally to both sides and transferred down to the basement, and further down to the foundations (basement and foundations excluded from the structural analysis illustrated here). The span length is indicated with modular lines A-G in Figure 3.1-1.

Stages 4 and 5 show light weight constructions, external facades and internal walls.
Stage 6 shows combined skeleton of the house, 6A – with final appliances of installed windows, doors and kitchens, 6B – with the roof.

Based on structural analysis it was decided that facades (stage 4) can be replaced with light weight prefabricated wall elements. The gables and the external staircase wall had to be renovated in a way that load bearing function is not disturbed.

The picture in Figure 3.2-2 was taken by Landskronahem during the demolishing of the neighboring building that has the same type of construction as the investigated case.

Figure 3.2-2 A demolished neighbouring building. Photo: Landskronahem

The photo confirms the book-case internal loadbearing structure, including the gables, while the longitudinal façade is clearly light weight.

3.3 Renovation measures

The process started with investigating different possibilities of renovating the building. Issues related to the existing construction were identified through literature studies and dialogs with the client, Landskronahem. The case study building was constructed in the same way as the house in Kyrkbyn, Gothenburg, described in chapter 2.4. Both buildings had the same problem of water damaged concrete material in the external walls. Because of the absence of an air cavity, penetrated water had been absorbed by the concrete layer and was in need of renovation.

Landskronahem was also considering upgrading the existing mechanical exhaust ventilation system to a heat recovery ventilation system (described in 2.2). However, the implementation of this system required large installation costs, mainly related to reinforcing the roof. It was decided to be a non-cost-effective procedure and was therefore not implemented in this report.

Landskornahem's intention of the renovation and the measures that this report addressed can be seen in Table 3.3-1.

Table 3.3-1 Renovation measures

Measure	Landskronahem	Thesis
Heat recovery ventilation system	x	
Additional insulation on the external walls	x	x
Drain and insulate the cellar	x	x
New windows and balcony doors	x	x
New balconies - reduce the thermal bridges by moving out the balconies	x	x
PV:s	x	
Interior layout changes		x
Additional roof insulation		x

According to Johan Zellbi[6], it was unlikely to reduce the domestic hot water usage any further, in that sense that the building already was equipped with energy efficient water taps. This report targeted reduction of the heating demand in order to meet BBR on specific energy demand in a cost-effective procedure, and simultaneously obtain "good" daylight conditions.

3.3.1 Architectural changes

It was an architectural goal to improve the appearance of the building, making it more attractive and increasing its value. Improving the housing stock in the area could lead to social benefits beyond quantifiable, like increased wellbeing of the tenants.

As the envelope needed to be refurbished, the option for choosing new materials emerged. Not only for the inner layers, but also for the cladding, that determines the outer appearance of the building itself. The positive environmental impact and virtue of aesthetically pleasing appearance of the wood made it a favorable choice.

Wood on facades can be used in different colours and patterns, visually separating long facades, breaking monotonous appearance. Wood can be further implemented in creative external shading devices, which will eliminate unwanted solar gains and visual discomfort. Construction design details like implementation of transparent glass railing rather than opaque, would deliver additional daylight indoors.

The original building design had built-in balconies, adjacent to the living room space. According to the WSP report (Karlsson, 2016), the balcony slab was presumably an extension

[6] Project leader at Landskronahem, meeting: January 10th, 2017

of the intermediate floor and as a result, constituted for significant thermal bridge (Figure 3.3-1). It was consequently decided by the authors of this thesis, to eliminate the thermal bridge by replacing the external wall and mount the new pre-fab wall on the outer part of the slab. As a result the existing slab would only be located on the interior side of the building. It was an energy efficient measure that eliminated thermal heat loss through the existing balcony slab and also led to a more compact building shape.

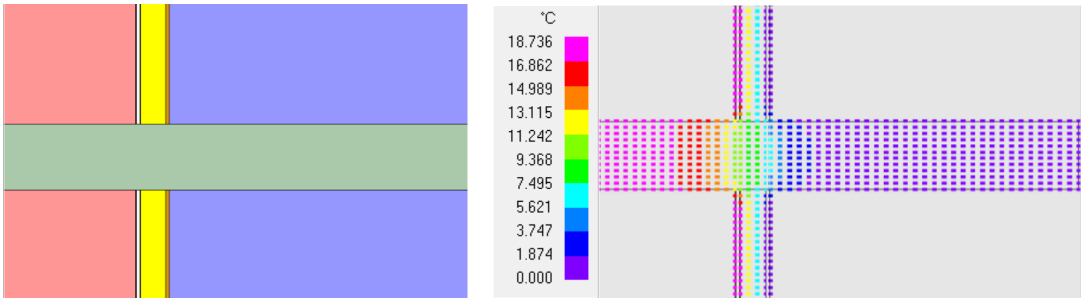

Figure 3.3-1 To the left: thermal bridge at the concrete balcony projection. To the right: node points with the temperatures, where the coldest nodes indoors are about 13°C, and 0°C, outdoors. (Karlsson, 2016)

The new balcony construction was discussed with the structural engineer [7]Miklos Molnar at LTH. One of the technical solutions proposed was to connect each balcony slab to the existing storey partition slab with reinforcement through several connection points. As mentioned earlier, this new design solution would significantly reduce the thermal bridge compared to the existing balcony construction.

The existing kitchen was narrow and did not comply with the “Bättre för alla” space design instructions, thus it was decided to adopt an open plan concept for the kitchen. The existing separating wall was removed (Figure 3.3-2, in red) and a new half- separating wall was installed. In order to increase the width between the kitchen countertops to the minimum requirement of 1.3m, the new wall was built with 170 mm displacement from its original position (Figure 3.3-2, in blue). During a site visit the existing staircases were perceived as dark and disconnected from the outer space, as a result of insufficient daylight from narrow corner windows. Thus new, larger windows were installed while the existing windows were removed. Moreover, light weight facades were replaced with new, prefabricated external wall elements, while load bearing gables and staircase walls were partly preserved. The external wall renovation is further explained in Chapter 3.3-4 Prefabrication and Chapter 3.3-5 Insulating the existing structure.

[7] Head of office at division of Structural Engineering, LTH; Meeting: February 15th, 2017

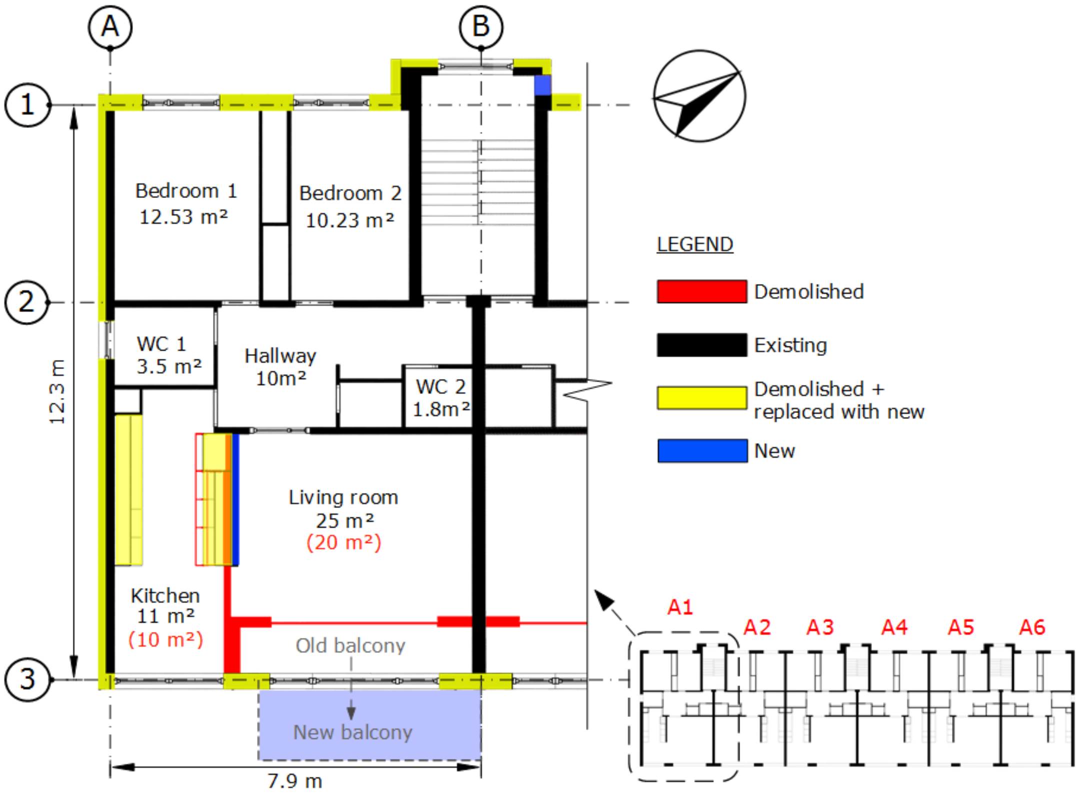

Figure 3.3-2 Renovation plan drawing, of apartment A1 including the staircase

For the improved building, new external balconies were fixed to the façade. The design proposals consisted of two options – symmetric and variable design, illustrated in Figure 3.3-3.

The symmetric design had the balconies placed as their original symmetry suggested, always adjacent to the living room. In the variable design balconies were adjacent to either kitchen or living room, depending on the room location on the façade. The decision of the balcony sequence on the façade in the variable design was based on the daylight results.

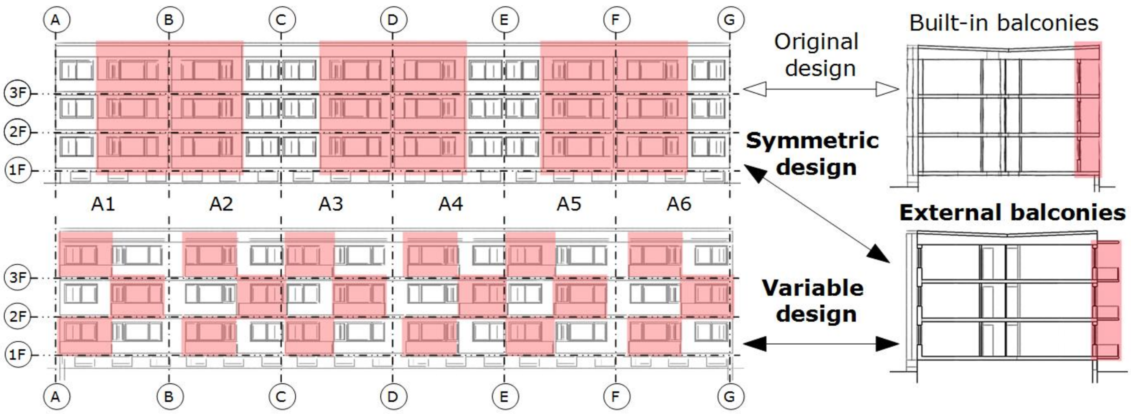

Figure 3.3-3 South-East facade design variations, different placement of the balconies

The new floor plan, that has the same interior layout for either variable or symmetric design, is presented in Figure 3.3-4.

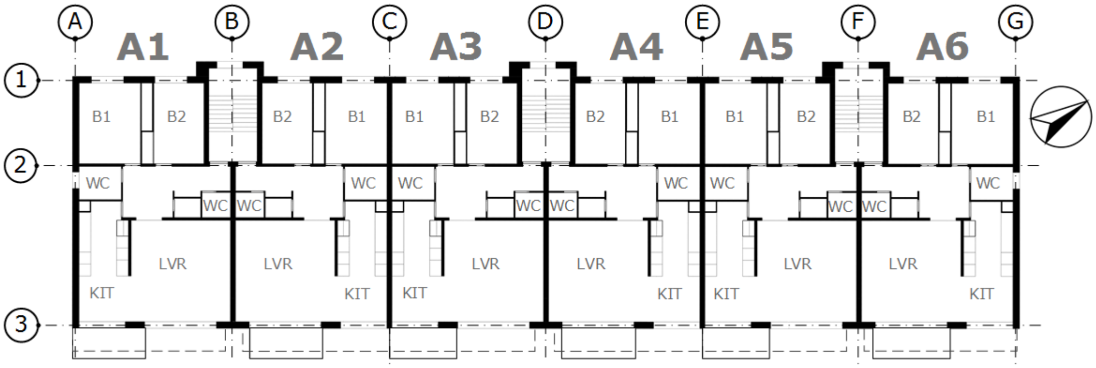

Figure 3.3-4 Floor plan, third floor, variable design (balcony placement)

3.4 Prefabrication

Million program lamella building typology was examined and an appropriate pre-fab module designs were proposed according to the design guidelines described in the literature study, chapter 2.5 Prefabrication in Annex 50 and TES facades.

The prefabricated light weight timber walls were chosen for the renovation of the Northwest (NW) and South-east (SE) façades, which does not carry any vertical loads. The window to wall ratios in the wall elements were kept the same as in the original walls – 29% (NW) & 38% (SE). Each façade was subdivided in 18 wall units, one for each apartment. The façade division is shown in Figures 3.4-1 and 3.4-2

Figure 3.4-1 Prefabricated facade elements, North-West facade

Figure 3.4-2 Prefabricated facade elements, South-East facade

An example of the SE façade element that was constructed from wooden load bearing parts, wooden external cladding and wood fiber-wool insulation, is presented in Figure 3.4-3. The

NW façade element size was 6.22m x 2.75m while the South-West element size was 8.04m x 2.75m. There were 36 wall elements in total.

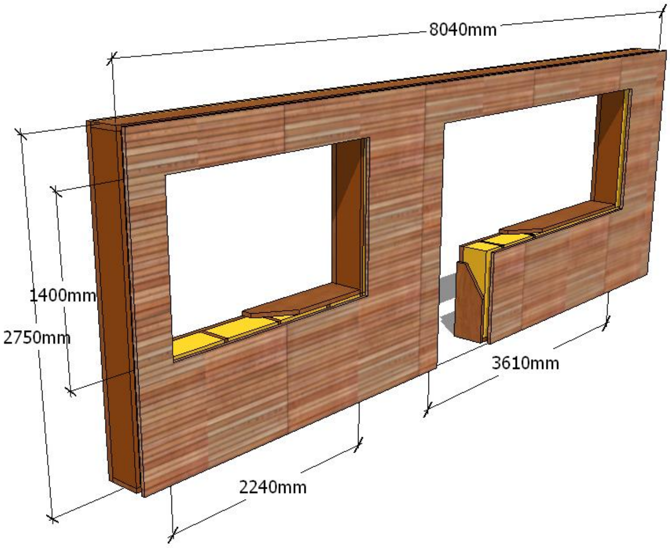

Figure 3.4-3 South-West facades prefab element, construction: wood + insulation

Three types of wall constructions were designed, in order to estimate the environmental impact of the different options, further described in chapter 3.7 Life-cycle assessment. The walls consisted of timber, concrete or steel in combination with insulation. Finished wall elements had an equal U-value of 0.170 W/m2K, in order to make the material load-bearing mass results comparable.

For the steel wall the Swedish manufacturer of prefabricated wall and roof elements ELEMENTUM eco AB was chosen. The chosen ELEMENTUM Eco AB wall (Elementum, 2017) with a U-value of 0.170 W/m2K was constructed of 120 x 2mm steel profiles, with distance center to center 600mm (Figure 3.4-4). To obtain the final steel volume, the total profile length in one element was calculated and then multiplied by the manufacturer's given width and depth.

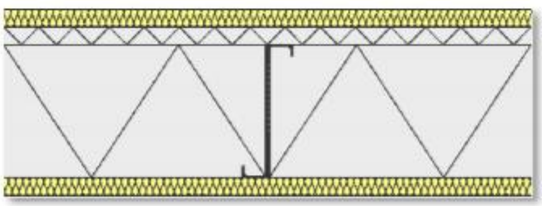

Figure 3.4-4 ELEMENTUM Eco AB steel profile wall construction (Elementum, 2017)

The smartTES wooden prefabricated façade elements were used in LCC calculations, as the cost information was confirmed through manufacturer source in Germany. However, the element construction information was not detailed enough to calculate the wood volume in it and therefor other assumptions were made. It was assumed that in a light weight timber wall, 10% of its volume was wood. According to the Danish origin insulation company Rockwool, using their product Flexibatts 37 (Rockwool, 2017) such a wall with a U-value of 0.170 W/m²K was 260mm thick. Timber volume was then calculated by using manufacture's given thickness of the wall, tree percentage in it and project calculated element area. Concrete layer in a concrete prefab light weight external wall was assumed to be 120 mm thick. The assumption was based on the common sizes for the precast concrete elements. The thickness was then multiplied by the previously calculated element area, to obtain the concrete mass volume. Because a pre-fab sandwich wall element is made layer by layer, it was not necessary to calculate further insulation thicknesses before obtaining the concrete mass.

3.5 Insulating existing structure

The necessity to enable dehydration of preserved constructions elements, such as the aerated concrete in the external gable wall and the ground slab, required certain characteristics of the material, described in chapter 2.4- Insulating million program building.

The concrete in the gables supported the load bearing book case structure. It was therefore decided to only remove the damaged brick and retain the concrete layer. However, due to its water content, a non-hygroscopic, "breathable" insulation material needed to be implemented. Mineral wool is such a material that is very effective to prevent rainwater from penetrating and in the same time enable the wall to dry out.

Large heat losses occurred through the ground slab because of absent insulation. Adding insulation above the ground slab is a known moisture risk. The relative humidity (RH) in the soil is always close to 100 %. It is of importance to avoid adding a tight insulation material on top of the ground slab, which would prevent the upward dehydration. Furthermore, if the drainage layer beneath the slab do not functions as it should, the upper edge of the slab could reach RH levels as in the soil. (Kumlin, A. & Tannfors, J., 2006).

In Table 3.5-1, the existing and suggested building components is shown, which determined the U-values of respective case. The following actions were taken in respect of lowered heating demand, environmental impact of the materials, and necessity to dry out preserved loadbearing components.

Table 3.5-1 Building components before and after renovation

	Existing[8,9]	New
Gable wall /Staircases	13 mm gypsum board 200 mm aerated concrete 120 mm brick	200 mm aerated concrete 200 mm insulation 30 mm air cavity 25 mm wood cladding
Long side wall	13 mm gypsum board 200 mm aerated concrete 120 mm brick	Prefabricated light weight wall 12 mm OSB board 120x45 mm studs, cc 600 200 mm wood fibre wool 18 mm impregnated wood fibre plate 48 mm ventilated air cavity 48 mm horizontal slats 20 mm wood cladding
Infill wall	9 mm Eternit 3.4 x 7 wooden laths 12 mm asphalt board 95 mm mineral wool Gypsum 13 mm	Same as above
Ground slab	200 mm concrete	200 mm concrete 60 mm insulation 40 mm floor coating
Basement wall	300 mm concrete	300 mm concrete 200 mm insulation
Attic	250 mm concrete 100 mm mineral wool	250 mm concrete 300 mm insulation
Roof	23 mm wood Paperboard substrate 2-layer paperboard	Same as the original

[8] (Karlsson, 2016)
[9] (Björk, Kallstenius & Reppen, 1992)

3.6 Energy and thermal comfort calculations

The energy simulation software IDA ICE (version 4.7.1) was used in order to simulate the specific energy demand (heating, domestic hot water and building electricity) and thermal comfort of existing and proposed refurbished building.

3.6.1 Energy

The apartments, the staircases and the cellar were divided into zones in the model (Figure 3.6-1). The cellar was not heated, though included in the energy declaration as a heated floor area. The attic and roof were combined, due to a simplification of the model. Therefore the zones of the upper apartments were connected to the roof construction, with maintained U-value.

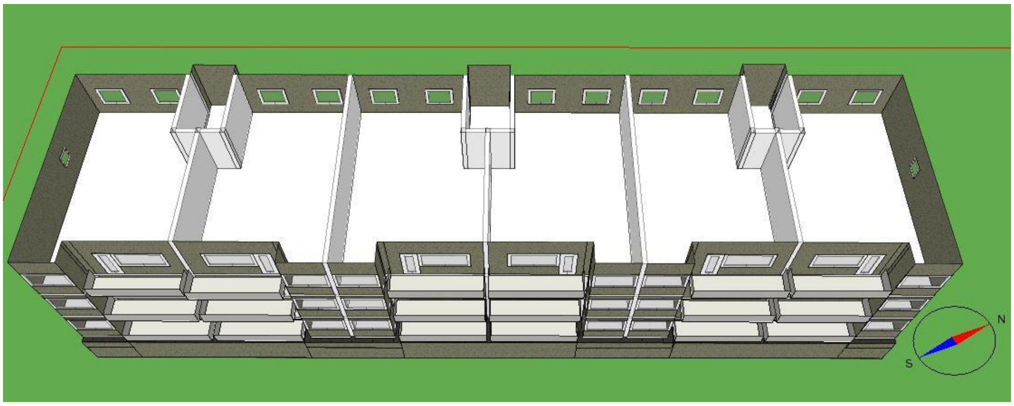

Figure 3.6-1: 18 Apartments, 3 staircases and 1 cellar were divided into zones in IDA ICE

An updated version of the building regulation, named BEN1, was published in late 2016. One of the differences from previous versions was that the indoor temperature should be simulated with 22 °C instead of 21 °C. However, according to Landskronahem, the set point in apartments is 21 °C and was therefore selected in the energy model. Furthermore, the recommended amount of 2.18 occupants for a three-room apartment was implemented in the model. Input data for existing and renovated building are presented in Table 3.6-1.

The internal gains of lighting and equipment was determined based on a household electricity level of 40 (kWh/m² ·a) (VVS Företagen, 2009), out of which 70 % can be accounted for. Furthermore, rooms within the apartments should have the possibility to ventilate the indoor air through a window or opening to the outdoor air. Because of these airflows an additional standard value of 4 (kWh/m² · a) should be integrated in the heating demand (BEN1, 2016).

Table 3.6-1 Input data, IDA ICE

Orientation	30° Northeast		Comments
Location (weather file)	Malmö Sturup		
Heated floor area (m^2)	2144	2256	
Construction U-values/(W/(m^2 · K))	Before	After	
Gable wall	0.56	0.13	
Long side wall	0.56	0.16	
Infill wall	0.51		
Ground slab	3.48	0.46	
Basement wall	2.89	0.17	
Roof	0.39	0.12	
Entrance door	1.4	1.2	
Balcony door	2.7	1.1	
Gable window	1.4	0.8	
Long side window	2.7	0.8	
Ground properties	1.4		
Thermal bridges/(%)[10]	20	10	Estimated
Infiltration/(l/(s·m^2 ext.surf.)) at 50 Pa	1	0.5	Estimated
Installation system			
Exhaust air only/(l/s. m^2)	0.35		
SFP/(kW/m^3/s))	0.88		
Window airing - open window at indoor temperature above/(°C)	25		
Setpoints/(°C)			
Heating apartment	21		
Heating staircase	15		
Heating cellar	Non heated		
Cooling	No cooling		
DHW (kWh/m^2 ·a)[11]	25		
Building electricity/(kWh/m^2)[12]	17		
Internal gains[12]			Schedule
Lighting/(W/m^2)	3		10 h/day
Equipment/(W/m^2)	1.5		Always on
Occupants/(person/apartment)	2.18		14 h/(day ·person)

[10] (Larsson & Berggren, 2015)
[11] (BEN1, 2016)
[12] (Göransson, 2006)

3.6.2 Thermal comfort

Passive cooling is a design approach that aims to improve the indoor thermal comfort with low or nil energy use. Furthermore, Lechner (Lechner, 2015) argues that the first strategy should be to include the appropriate shading in order to minimize heat gains into the building. Secondly, remove the heat from the building by using passive cooling. One example is cross ventilation, of which the indoor air are “both pushed and pulled through the building by a positive pressure on the windward side and a negative pressure on the leeward side”. The third and last strategy should be to implement mechanical cooling, in order to reduce the overheating hours.

FEBY 2012 is a document that was created as a consequence of the EU directive to adapt the building codes to “near zero energy buildings”. Within the document, a general advice is given regarding indoor temperature. This report has examined the overheating hours in the renovated building and related it to the following description; “During the period April – September, the indoor temperature should not exceed 26 °C for more than 10 % of the time in the most exposed room or part of the building”. The definition “part of the building” was interpreted as the most exposed apartment in the investigated house.

A parametric study was carried out by quantifying the overheating hours. Firstly, the effects of the shading elements were examined. Moreover, passive cooling was implemented. It was done by setting the PI temperature control system of the windows, which were opened when the indoor temperature reached 25 °C.

3.7 Life-cycle assessment

Life cycle assessment (LCA) also known as cradle-grave analysis is an ISO standardized method that addresses the environmental aspects and potential environmental impacts of a product throughout its life cycle. It consists of four phases (Figure 3.7-1); defining the goal and scope, collecting data in the life cycle inventory, estimating the impact and finally interpreting the result. (Khasreen, 2009)

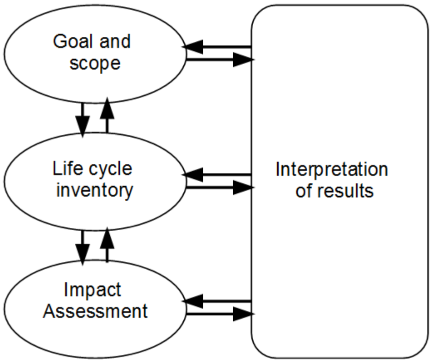

Figure 3.7-1 Life-cycle assessment model

Global warming potential (GWP) is a metric for weighting the climate impact of various greenhouse gases. It calculates carbon dioxide (CO_2), Nitrogen dioxide (NO_2), methane (CH_4), Chlorofluorocarbons (CFC), Hydro chlorofluorocarbons (HCFCs) and Methyl Bromide (CH3Br). The impact of these gases is rated against carbon dioxide, and described in total as carbon dioxide equivalents. The time of which the gases are present in the atmosphere is specified to 100 years (Shine, 2004).

Further on, the ISO standard for LCA was supplemented with formulation for mentioned phases (Table 3.7-1). Note that the results of a life cycle assessment are geographically dependent. Hence, the results of the LCA carried out in Europe are therefore not applicable in other continents.

Table 3.7-1 LCA standard description

Phase	Description	Project
Goal/ scope definition	LCA purpose	Carry out an energy renovation and consequently lower the buildings operational energy, whilst adopting the most environmental friendly materials in the procedure
	Functional unit -Define and quantify analyzed product	The environmental impact of a renovated residential building for at least 60 years per U-value of 0.2 (W/m² ·K) of the insulation product
	System boundaries -Life-cycle -Geography	 -Cradle-grave -Europe
	Assumptions	Only heating demand
Inventory analysis	Collecting the needed data to specification in Goal/scope	Eco-sai software, EPD
Impact assesment	Impact factors	GWP
Interpretation	Interpretation of results	See Results (chapter 4.2)

Alternative materials, which could be used for the energy renovation, were analyzed.

3.7.1 Description of EcoSai

The software EcoSai was used for gathering the investigated materials environmental impact in respect of GWP. The software calculated the materials impact depending on the product stage, use stage and end-of-life-stage. For each stage the software accumulated certain processes which are specified in Table 3.7-2.

Table 3.7-2 the lifecycle stage and their activities of which EcoSai calculates GWP

Product stage	Extraction of raw materials Transport to factory Production of material
Use stage	Replacement (see product stage) Energy use during building operation
End-of-life-stage	Demolition Transport to sorting/disposal sites (recycling, land-fill, incineration plants) Disposal

Furthermore, the software was implemented with district heating in order to evaluate the environmental impact of the buildings energy usage. Table 3.7-3 shows the emission statistics per delivered kWh, from the supplier Landskrona Energi. (Energiföretagen, 2017)

Table 3.7-3 Carbon emissions per delivered kWh from district heating supplier

Emission/(kg CO2-eq/kWh)		Energy input/(%)			
Combustion	Transport/ production	Recycled	Renewable	Other	Fossil
0.041	0.004	71	12.9	16	0.2

The next chapter will present the materials that were examined for the proposed energy renovation. The operational energy was studied separately concluding that its impact due to heating demand remains constant if the insulation materials obtain equal U-values.

3.7.2 Materials and operational energy

Figure 3.7-2 represents the approach of estimating the GWP impact due to material selection and the building's operational energy in form of heating demand. The material impacts were further on divided into insulation and loadbearing materials. Eleven insulation products and three loadbearing elements were investigated.

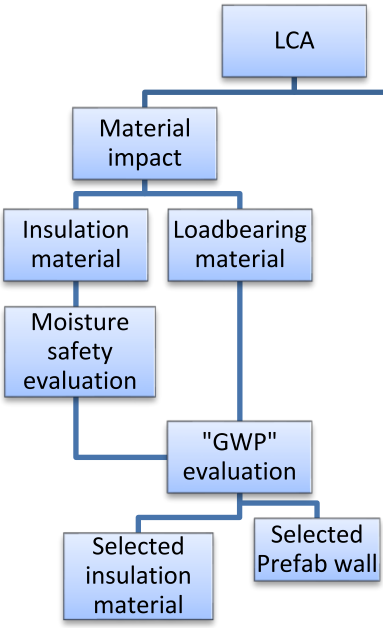

Figure 3.7-2 LCA scheme

The insulation materials footprint were compared for each material's respective U-value, determined to 0.2 (W/m²·K). The materials were compared per unit area (m²), only altering the thickness to achieve the chosen U-value. This meant that a material with lower thermal conductivity (λ), received less thickness than a material with higher rate of heat transfer. The investigated materials' conductivity varied between 0.031 and 0.05 (W/m·K) with corresponding thicknesses from 155 mm to 250 mm. The properties of the studied insulation materials can be seen in Table 3.7-4.

Table 3.7-4 Properties of investigated insulation materials, obtained from Eco-sai

Material	Thermal conductivity (W/(m·K))	Density (kg/m³)	Life span (years)
Glass wool (low density)	0.031	22	30
Glass wool (high density)	0.031	100	30
Rock wool	0.038	60	30
Foam glass	0.038	100	30
Wood fibre wool	0.038	43	40
Wood fibre panel	0.05	130	40
EPS	0.038	20	30
XPS	0.036	25	30
Polyurethane PUR	0.03	50	30
Cellulose	0.048	80	30
Cork	0.042	70	30

The comparison between the load bearing materials (Table 3.7-5) was performed due to the materials respective volume of the determined prefab element, explained in chapter 3.4 Prefabrication.

In the case of the steel profiles, the software showed insufficient values in terms of the end-of-life-stage. An additional source was therefore studied. Hence; carefulness of comparing different databases must be applied. Environmental product declaration (EPD) is a standardized database of quantifying the life-cycle environmental impact of a product or system. A declaration of a steel profile, produced in Sweden, showed that 95 % of the material was recycled and furthermore obtained negligible, end of-life-stage impact (EPD, 2017).

Table 3.7-5 Properties of investigated load bearing materials, obtained from Eco-sai

Load bearing material	Volume (m^3)	Density (kg/m^3)	Lifespan (years)
Steel	0.15	7800	50
Aerated concrete	1.67	700	40
Timber	0.4	450	40

The materials lifespan varied from 30 to 50 years concluding that all materials needed to be replaced during the studied period.

The buildings operational usage over the lifespan of 60 years was firstly studied of which impact the building had if no energy renovation would be carried out. Consequently, yield the same heating demand as the existing case. It was compared with the impact the building obtained due to lower heating demand, by insulating the envelope in order to achieve the specific energy demand requirement.

3.8 Daylight

The daylight evaluation had two major parts. First part consisted of examining the daylight potential and problems in the existing building design. During the study, the simulation model was verified through on-site daylight measurements. The second part consisted of an overhang parametric study for the improved building.

The following daylight metrics were examined throughout the daylight study:

- Daylight factor (DF)
- Daylight autonomy (DA)
- Continuous daylight autonomy (cDA)
- Daylight availability (DAv)
- Useful daylight illuminance (UDI)

The overhang category consisted of balconies and external shading devices that had different functions. While both eliminated unwanted solar gains, the balcony further had to provide a functional size. When the optimal balcony and shading depth was determined, they were arranged in two different options – symmetric and variable design, described in Chapter 3.3.1. The potential of one architectural design being better over another from daylight perspective was examined. This evaluation, however, was case-specific, as one of the major prerequisite was to achieve the Swedish certification Miljöbyggnad Silver demand for the point DF value, primary in the living rooms, and secondary in the kitchens. Bedrooms were excluded as these spaces would be mainly used for the sleeping.

Other daylight metric targets have been discussed in the literature study (Chapter 2.6 - Daylight), as well as presented in the Table 3.8-1.

Table 3.8-1 Different daylight metric targets for the case study building (latitude 56 °)

<table>
<tr><th>Daylight metric</th><th>KIT</th><th>LVR</th><th>HOME OFFICES</th><th>BED</th><th>Source</th><th>Priority 1-2, Guideline 1-2</th></tr>
<tr><td>Average DF, %</td><td>2
3.5 - 9</td><td colspan="2">1.5
2 - 3.5</td><td>-
1 - 2</td><td>BREEAM UK
SUN-WIND-LIGHT</td><td>G1
G2</td></tr>
<tr><td rowspan="2">Point DF, %</td><td colspan="4">Half way in the room, one meter from the darkest wall, 0.8m above the floor. Room not specified.</td><td></td><td></td></tr>
<tr><td colspan="4">≥ 1.20
≥ 1</td><td>Miljöbyggnad (Silver)
BBR</td><td>P1
P2</td></tr>
<tr><td></td><td colspan="2">RESIDENTIAL SPACES</td><td colspan="2">OFFICES</td><td></td><td></td></tr>
<tr><td rowspan="3">Average DA, lux</td><td colspan="2">100 - 200</td><td colspan="2">200 - 500</td><td>IESNA</td><td>G</td></tr>
<tr><td colspan="4">ALL ROOMS</td><td></td><td></td></tr>
<tr><td colspan="4">300</td><td>Literature study, Chapter 2.6.2</td><td>P</td></tr>
<tr><td>cDA</td><td colspan="4">300 lux for 60-80% of occupancy time</td><td>Literature study, Chapter 2.6.5</td><td>P</td></tr>
<tr><td>UDI > 3000 lux</td><td colspan="4">For maximum 5% of occupancy time</td><td>1) British Standard BS EN 15251
2) Literature study, Chapter 2.6.5</td><td>P</td></tr>
</table>

The specific targets were examined for both residential and office purposes, to examine the potential of turning the lamella building apartment into a home office. In the last column of Table 3.8-1 the primary project targets are marked with “P” as for *priority* and the secondary targets are marked with “G” that were used as *guidelines*, to evaluate the obtained daylight results. If in the same daylight metric category had two sources that suggested different daylight levels, the priority or guideline were subdivided in in primary and secondary importance with “1” or “2” correspondingly.

For example, the primary guideline for average DF was the BREEAM UK source, marked with G1, however, SUN-WIND-LIGHT that suggested higher DF values, was used as a secondary guideline - G2.

Simulations were performed for all the rooms in each of the 18 apartments. The further chapters will introduce a detailed method of each daylight study part.

3.8.1 Daylight simulation model

The 3D building models were created in SketchUp, and then imported into Rhino. The project specific material properties and simulation settings were then implemented in the model, in order to perform all the daylight simulations in Diva for Rhino. The results were examined graphically and also analyzed in Microsoft excel.

There were four 3D daylight models in total, each evaluated daylight conditions in all the 18 apartments and the three staircases:

1. Existing design;
2. New design without shading;
3. New design with 1.5m overhang;
4. New design with overhang depth as defined in chapter 3.8.3

Building component properties such as opaque material reflectance and translucent material transmittance are important parameters to affect how daylight is distributed in the space. The actual reflectances of the surfaces in reference case building were estimated using the pictures, taken during the first site visit. The NCS colour code obtained from the images was further translated into reflectance value by using Jaloxa colour picker data base (JALOXA, 2017). Non obtained material surface reflectances were estimated using DIVA for Rhino standard values. General input data and reflectance values are presented in Tables 3.8-2 and 3.8-3 respectively.

Table 3.8-2 Input data, DIVA for Rhino

Parameter	Input
Climate file	Copenhagen, Denmark
Occupancy Schedule	8am to 6pm – 3650 h / a
Target illuminance	300 lux
Ambient bounces	5
Simulation grid	0.45 m x 0.45 m
Node height	0.8 m

Table 3.8-3 Reflectance for building components, DIVA for Rhino

Building component	Reflectance factor
Interior walls	0.7
Floor	0.3
Basement walls	0.5
Ceiling	0.7
Doors	0.5
Facade	0.3
Shading	0.4
Partition	0.3
Roof	0.3
Staircase	0.2
Surroundings	0.3
Window frames	0.7
Ground	0.2
Furniture	0.5

The 8am to 6pm schedule was chosen to estimate maximum effect of the overhang on the daylight and daylight provision over the whole year. Moreover the schedule fits with extended working hours, further assessing residential space possible adaptation to a home office.

Estimated reflectance and transmittance values were kept the same in the old and the new design, in order to better evaluate the actual effect of the fixed overhang.

3.8.2 Verification of the simulation model

In order to validate the simulated daylight results, on site daylight measurements were performed. The measuring tools included: two lux meters, reflective surface and reflectance meter. Landskronahem had provided the authors with an empty apartment A6-1F to perform the on-site daylight study that consisted of the following measurements:

- Reflectances of the main surfaces and window glass transparency
- Daylight factor calculation including overcast sky measurements

The DF calculation was limited to the kitchen only, as it was the least furnished of all the apartment rooms (Figure 3.8-1, left). Shading created by the neighboring buildings was also implemented in the simulation model (Figure 3.8-1, right).

Figure 3.8-1 Kitchen interior (left), view through the kitchen window (right), Photos: Aija Baumane

The transmittance of the window was calculated according to the equation 3.

$$Glass\ transparency = \frac{E_{indoors}}{E_{outdoors}} * 100 \qquad [\ \%\ ] \qquad \text{Eq. (3)}$$

Where: $E_{indoors}$ = Vertical illuminance falling on the glass indoors, lux
$E_{outdoors}$ = Vertical illuminance falling on the glass outdoors, lux

As it was not possible to implement the measured material properties in the simulation model due to time limitations, the deviations in measured and simulated DF were predicted.

In order to measure correct daylight factor, the sky needed to be completely overcast (Mischler, 2017). The ratio between the vertical illuminance (on the façade) and the global illuminance must be 0.396, however, ratios between 0.36 and 0.44 are judged acceptable. Any other ratio would mean that the sky distribution is substantially different and thus the daylight factor will be different as well (Dubois M.-C. D., 2016). During the on-site measurements the overcast sky ratio, calculated with the equation 4, was 0.36 that is at the threshold of the acceptable range.

$$Overcast\ sky = 0.36 < \frac{E_{vertical}}{E_{global}} < 0.44 \qquad \text{Eq. (4)}$$

Where: $E_{vertical}$ = Vertical illuminance falling on the façade, lux
E_{global} = Global illuminance, lux

The following step was to create a measurement grid in the kitchen, illustrated in Figure 3.4-1. The grid properties were following:

- Distance between the grids points was 0.5m
- Center line was approximately between the kitchen counter tops
- The starting row was 0.5m from the window
- The measuring height was 0.8m
- There were 32 points in total

Apartment A6-1F, Kitchen

Figure 3.8-2 Daylight factor measurement grid, kitchen, apartment A6-1F

For each point daylight factor was calculated using equation 2, described in Chapter 2.6.4. The obtained results were compared with the already simulated values.

3.8.3 Optimal overhang design parametric study

One of the renovation objectives was to implement new balconies on the south-east facade, however, they would create a shade on the windows below. Therefore it was important to choose a balcony depth that functioned as an effective shading while providing a good visual comfort and served the balcony function. Thus an "optimal balcony depth" was further assessed as an "optimal overhang depth" in an parametric study. It was also considered that an optimal overhang design could be implemented as a shading device for the other SE facing windows, in case of daylight oversupply.

Advantage of the overhang is that while it shades, the view outdoors is not obstructed, unlike with the interior blinds. The optimal overhang depth depends on the window height, latitude and climate. For example, the larger opening, the longer the overhang.

Overhang is the most effective way to shade south facing windows in the summer (Rungta & Singh, 2011), however, as the façade's offset from south increases, the effectiveness of the overhang decreases. Even though the examined façade is orientated south-east, it was decided to consider "overhang design for winter and summer sun" as a possible starting point to be used in project daylight simulations.

An optimal overhang depth that shades the summer sun, while the winter sun is let in, providing solar gains, is illustrated in Figure 3.8-4, however, suggested benefits of the winter solar gains were not studied.

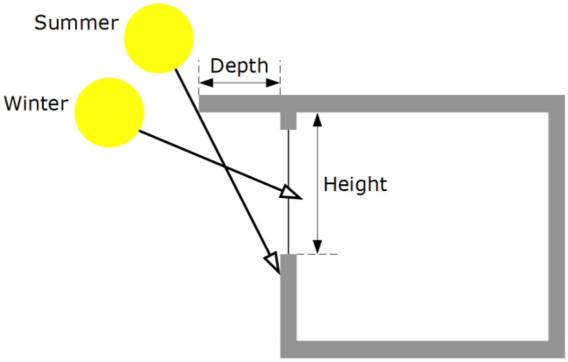

Figure 3.8-3 Overhang design for winter and summer sun

The equation 6 provides a quick method for determining the projection of a fixed overhang (Rungta & Singh, 2011).

$$Projection = \frac{Opening\ height}{F\ factor} \qquad [\text{ m }] \qquad \text{Eq. (6)}$$

Where:

Opening height= Height from window seal to ceiling, m, see Figure 3.8-4
F factor = 1.3 to 1.5 for North latitude 56° (Rungta & Singh, 2011)

The F factor used to calculate the optimal overhang depth consists of a range of values. The highest value would provide 100% shading at noon on June 21st while the lower values would shade until August 1st.

The existing and the new window sill to ceiling height is 1.65m. According to the Eq.6 optimal results for the overhang are:

1) Projection = 1.65 / 1.5 = 1.1m (100% shading at the noon on 21st of June)
2) Projection = 1.65 / 1.3 = 1.3m (100% shading at the noon on 1st of August)

The results of overhang design for summer and winter sun suggested that any overhang depth larger than 1.3m would shade more sun than necessary. Consequently a 1.3m depth was considered for the shading devices, however, not for the balconies, because of the following two reasons:

1) The original build-in balconies were 1.3m in depth and the design goal for both - the authors and the client Landskronahem - was to increase their size.

2) “Bättre för alla” accessibility instruction suggested a balcony depth of 2.1m for handicap accessibility that is much larger than the optimal overhang design method suggested.

Therefore a minimum depth of 1.5m was taken as a starting point for the daylight simulations and used in the project specific overhang design method, presented in Figure 3.8-5.

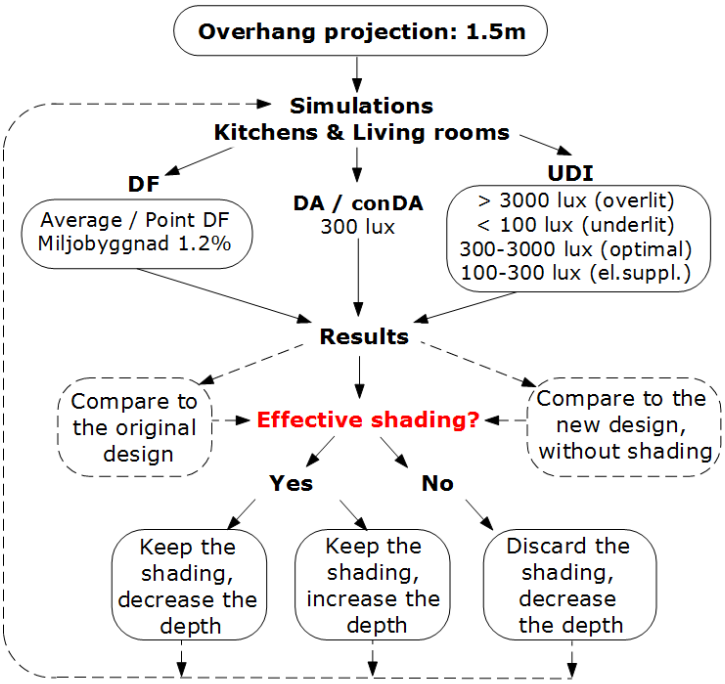

Figure 3.8-4 Project specific method for overhang sizing

The overhang effect on daylight results were compared in all the apartment kitchens and living rooms, following specific daylight targets depending on the room. The comparison was further compared to 1) Unshaded new design and 2) Original design.

The method presented in 3.8-5 was repeated for two different overhang sizes, depending on the results, a shorter or longer depth was chosen for the second round with a 0.2m increment.

The final step was a theoretical proposal of two different architectural design options - symmetric and variable designs presented in Chapter 3.3-1. The designs consisted of different placement of the balconies and shading devices, adjacent to either the kitchens or living rooms. The simplified diagram of the design process for architecturally integrated multi-purpose overhang design that serves either as a balcony or shading device, is illustrated in Figure 3.8-5.

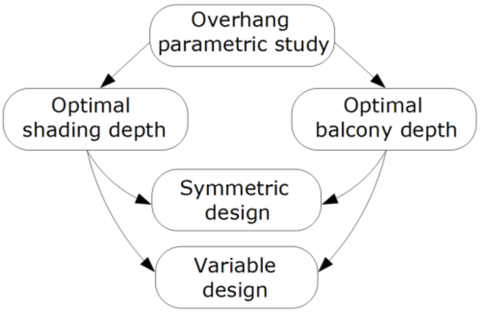

Figure 3.8-5 Architecturally integrated multi-purpose overhang design approach

Due to the time limitation, the symmetric and variable designs were not individually simulated. In case of the results indicating that optimal balcony and shading device depths are not the same, the window with larger overhang was considered to have a negligible shading effect on the window with the shorter depth overhang.

3.9 Life-cycle cost analysis

Life-cycle cost (LCC) calculations were performed in order to find out the operational cost savings and rent cost supplement to achieve possible investment payback. Moreover, a market sensitivity analysis was carried out, were different real rates of interest and real price change rates were tested.

The following formulas 7, 8 and 9 were used in all the calculations.

$$F = P(1+i)^N \quad \text{[SEK]} \quad \text{Eq. (7)}$$

$$P = F(1+i)^{-N} \quad \text{[SEK]} \quad \text{Eq. (8)}$$

Where:

F= Future value, SEK
P= Present value, SEK
N= Number of years
i= interest rate

$$P = A_1\left[\frac{1-(1+g)^N(1+i)^{-N}}{i-g}\right] \quad \text{[SEK]} \quad \text{Eq. (9)}$$

Where: P= Present value, SEK
A_1= Value at first year (calculated with eq.7), SEK
g= real price change (when i=real rate of interest), %
N= *Number of years*

According to Johan Zellbi, Landskronahem used a real interest rate of 4 %, inflation of 2 %, a yearly price increase of 2 % and a calculation time of 15 years. Considered that the investigated building had not been a subject of a major renovation for 43 years (at the time when this report was written), the calculation time was set to 40 years.

In the sensitivity analysis the yearly district heating price change was calculated with three different scenarios; 0%, 2% and 4 %.The prerequisites for the LCC calculations are presented in Table 3.9-1.

Table 3.9-1Prerequisites for the LCC calculations

Prerequisites	
Calculation time/ years	40
Annual real rate of interest/ %	4
Inflation rate/ %	2
Annual real district heating price increase/%	2
District heating prices for Landskrona Energi (incl. 25 % VAT)	
Jan-Mar + Nov-Dec/ (SEK/ kWh)	0.62
Apr-May + Sep-Oct/ (SEK/ kWh)	0.32
Jun-Aug/(SEK/kWh)	0.12
Price per subscribed power/(SEK/kW)	441

The heating supplier Landskrona Energi charges for a power part and a consumption part. The power part is an added annual fee, and defined by Landskrona Energi as the building's required power at -12 °C outdoor temperature. Depending on the overall subscribed power, the price per kW (power) varies. Landskronahem had five multi-residential buildings that shared the same main central. Their total subscribed power resulted in category 4, with the most economical price per kW of power (Table 3.9-2).

Table 3.9-2 The power part of the district heating price

Category	Subscribed Power, kW	Price SEK/ kW
1	15 – 60	752
2	61 – 175	628
3	176 – 1400	509
4	> 1401	441

The heating load for the base case and improved building was simulated in IDA ICE at -12 °C outdoor temperature. The required power for the respective cases was multiplied by the price per kW. Furthermore, the district heating use over the year is divided in three different price categories (Landskrona Energi, 2017).

The prices for labour and material of the suggested renovation were obtained from the software Wikells byggberäkningar (version 4.21) while costs for the windows and balcony doors were taken from Elitfönster (Elitfönster, 2017). Renovation costs are presented in Table 3.9-3.

Table 3.9-3 Costs per renovation measure

Renovation measures	Amount	Material + labour Price/kSEK
Demolishing		
External materials	900 m² brick, 500m² concrete	409
Windows	114 pcs	48
Balcony doors	18 pcs	10
Internal walls (kitchen)		35
Transport to waste		57
Waste fee		128
Opening (hole for windows) in Staircases	17 m²	26
Total (demolishing)		**713**
Excavation for cellar wall	length 120m, depth 2 m	193
New external walls		
Cellar		141
Gables		410
Roof		115
Staircases		186
Prefab; Long side external wall	476 m²	1092
Windows	36 pcs entrance facade (openable)	416
	36 pcs kitchen (18 openable+18 fixed)	280
	36 pcs balcony (18 openable +18 fixed)	312
	6 pcs gables (openable)	30
Balcony doors	18	191
New internal walls (kitchen)		730
Balconies	18	348
TOTAL (EXL. VAT)		**5 213**
+ VAT 25%		**6 516**

The existing rent is 950 SEK/m² per year. The floor area of 80 m² concludes the monthly rent of 6333 SEK. In correspondence with Johan Zellbi[13] the acceptable rent supplement was 400 SEK resulting in a final rent of 1350 SEK/m² and year. It was strived not to exceed this limit.

[13] Project leader at Landskronahem, Email conversation, 26 April 2017

Apart from the energy related renovation measures, included in the LCC calculation, there are benefits that are not possible to financially evaluate, however, they are bringing an added value to the building. Based on the thesis renovation targets, they are:

- New, spacious living rooms
- Open-kitchen concept
- Easier accessibility
- Increased window size in the staircases
- A better indoor climate
- Measured daylight quality
- Daylight target dependent architectural design proposals
- Living in the building that is renovated through environmentally conscious choices

4 Results

4.1 Energy and thermal comfort

The following chapter presents the results of the existing and suggested refurbished building. Furthermore, it shows the iteration process of cost effective savings measures. Finally, the overheating hours in the improved building were analyzed.

4.1.1 Energy

The energy simulation of the existing building yielded an energy demand of 139 (kWh/m²·a), which was 6% lower than the energy declaration. Furthermore, Landskronahem's estimate for the energy demand was about 140 (kWh/m²·a). In all the presented energy results, Figure 4.1-1 and Figure 4.1-2, the obtained simulated values are added with window airing of 4 (kWh/m²·a).

The improvements of the building were directly aimed to lower the heating demand. Added insulation on the building components reduced the U-value. The infill wall at the built in balconies were torn down and aligned with the outer wall. This procedure scaled down the wall area by 15 % (on the SE façade) and as a consequence, the building's heat losses. Moreover, the thermal bridges at the extended intermediate floor were also removed. The overall thermal bridges (added to average U-value of construction elements) were reduced to 10 % in the energy model. Finally, the infiltration was decreased, due to a larger extent of airtight building.

The renovation measures resulted in that the heating demand decreased from 97 to 32 (kWh/m²·a). Finally, it resulted in an energy demand of 74 (kWh/m²·a).

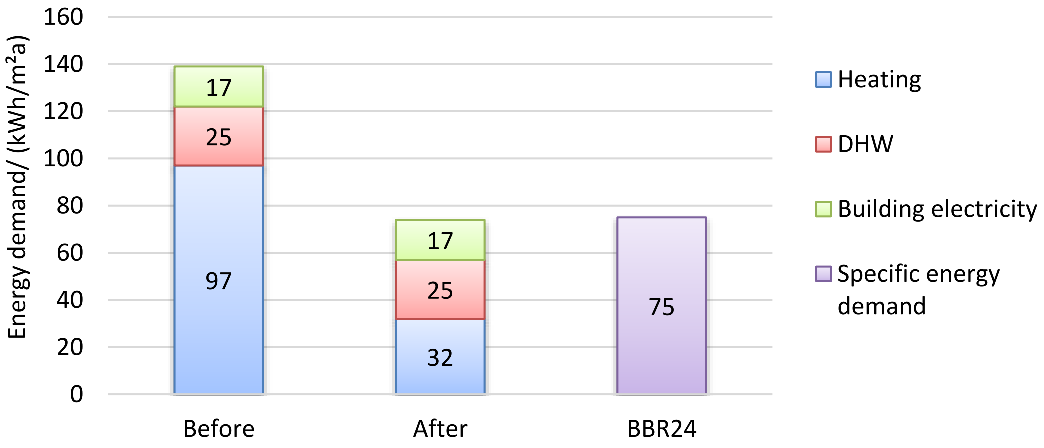

Figure 4.1-1 Energy demand for existing and renovated building

The final heating demand of 32 (kWh/m² ·a) was determined through simulations of potential savings for each construction element (Figure 4.1-2). Firstly, the new building envelope (2256 m²) was applied with improvements for all the building components. The result of this action was named “fully insulated envelope”. The parametric result of not insulating certain part of the building can be seen in Figure 4.1-2. The “limit” bar refers to the maximal allowed heating demand with the prerequisites of DWH and building electicity, in respect of BBRs specific energy demand (75 kWh/m² ·a) . Insulating the ground slab accounted for 2 kWh/m²·a, however, presumed large initial costs. The doors in the basement would have to be raised due to the present alignment with the floor. Further costs were connected to the implementation of moisture safe materials and the necessity to let the concrete slab “breath”. Therefore this measure was not considered as an cost-effective method and the slab was suggested to be exluded from the renovation.

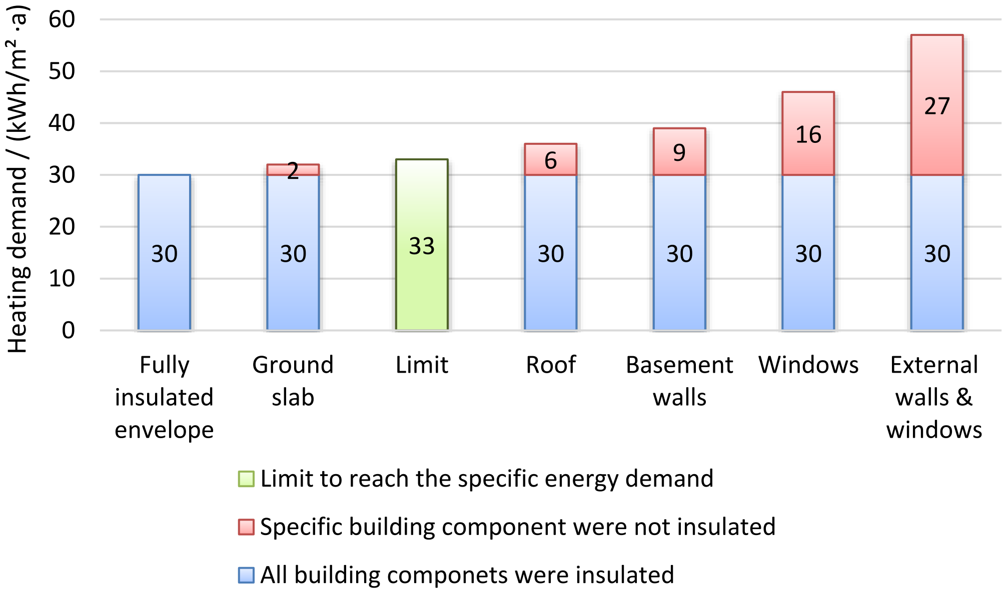

Figure 4.1-2 Heating demand by not insulating specific building component. The blue bars represent a completely insulated building. The red bars refer to the extra heating demand the building would require if a certain component was kept with its original U-value. The green bar is the maximal allowed heating demand in order to reach BBRs specific energy demand.

4.1.1 Thermal comfort

The parametric study of passive cooling techniques was performed in order to reduce the overheating hours. The most exposed apartment in the building, without shading devices, (Table 4.1-1) exceeded the operative temperature of 26 °C during 50 % of the hours between April and September. The shading elements reduced the overheating hours by 20 %. Thus, window airing obtained the most significant cooling effect.

Table 4.1-1 Overheating hours of the most exposed apartment, related to the shading devices and window airing

	FEBY- Indoor temperature[14]	
	(Hours)	(%)
No shading	2230	50
30 % Transparancy (SE: 1.5m, NW: 1.3m)	1900	43
Opaque (SE: 1.5 m, NW: 1.3m)	1770	40
30 % Transparency (SE: 1.5 m, NW: 1.3m), window airing (≥ 25 °C)	16	0.4
Opaque (SE: 1.5 m, NW: 1.3m), window airing (≥ 25 °C)	3	0.07

4.2 Life-cycle assessment

The LCA results represent the environmental impact of the global warming potential (GWP). Throughout the investigated lifespan, the following Figures include the life-cycle phases; product stage, replacement and end-of-life-stage. Finally, the proposed materials were combined in respect of their low life-cycle emission and capacity to function in a critical moisture component.

The plastic materials (EPS, XPS and PUR) obtained significantly larger impact during their lifetime, compared to the non-plastic materials. The waste management phase for these materials showed a considerable impact (Figure 4.2-1).

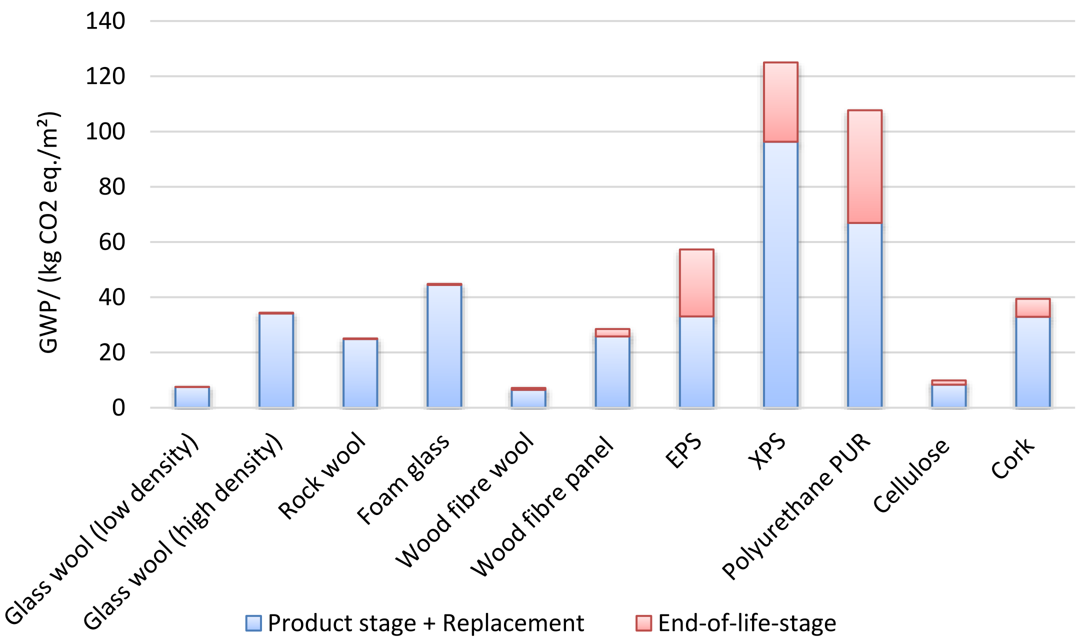

Figure 4.2-1 Emissions of insulation materials due to their respective U-value of 0.2 (W/m² ·K)

[14] FEBY- Indoor temperature during the period April-September should not exceed 26 °C more than 10 % of the time, for the most exposed part of the building.

The impact of the load bearing materials; steel, aerated concrete and timber (Figure 4.2-2) is shown from their respective volume in a prefab lightweight wall element (6.22m ·2.75m). The end-of-life-stage is not presented due to its negligible environmental impact.

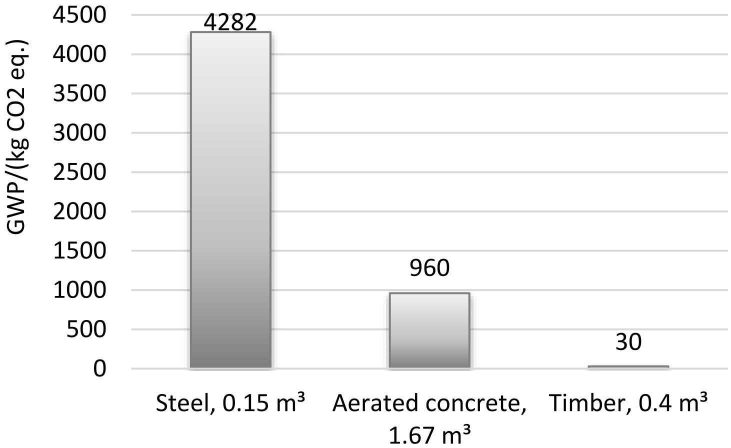

Figure 4.2-2 Emissions due to production and replacement per prefabricated element of the loadbearing materials

Differentiated for each building component, Figure 4.2-3 presents the GWP of the proposed materials and their respective amount (m^3) to fulfill the required U-values. The prefab light wall was assembled with 10 % wood and 90 % wood fiber wool. This resulted in the lowest GWP (5.7 ton CO2-eq).

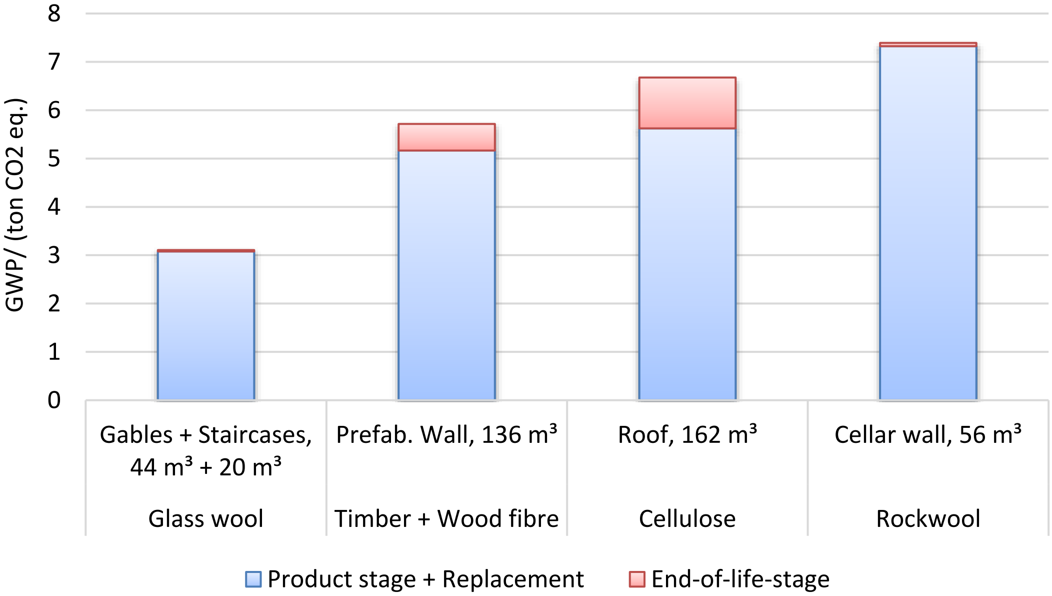

Figure 4.2-3 Total emissions per building component

Figure 4.2-4 show the usage stage in respect of the existing building's heating demand (97 kWh/m²·a) and the improved buildings (32 kWh/m²·a), and their potential emissions of 600 ton CO2-eq and 200 ton CO2-eq, respectively. The impact of the new materials resulted in 22 ton CO2-eq. The usage stage of the insulated building (including emission related to the material impact) accounted for a potential GWP cutback of 60%.

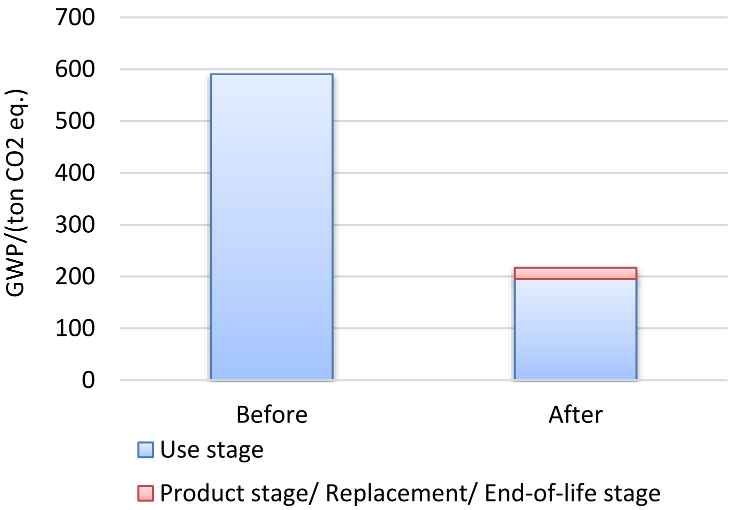

Figure 4.2-4 Operational usage of the existing and renovated building, during 60 years (blue). Material impact of production, replacement and elimination (red)

4.3 Daylight

4.3.1 Verification of the simulation model

The daylight factor measurements of the first floor corner apartment 1F-A6 showed that the obtained values (coloured black, Figure 4.3-1) are slightly greater in most of the measuring points, comparing to the simulated values (coloured red, Figure 4.3-1). The largest difference was in the back of the room.

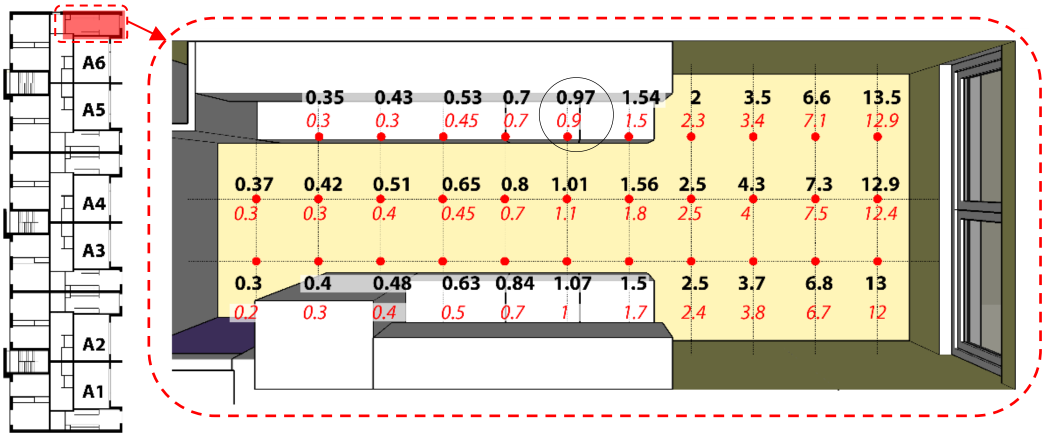

Figure 4.3-1 On-site measured DF (black) and simulated DF (red) results in percent, kitchen of the apartment 1F-A6, 32 measuring points

The average DF was 6% higher in the simulations, than the measured value. The measured average DF was 2.84% while the simulated average DF was 3.02% (based on 68 nodes in the simulation model). The average DF based on on-site 32 measuring points was slightly lower: 2.92%. The Miljöbyggnad point DF was 7% lower in simulations comparing to the measured result.

The measurement results indicated that the obtained DF values are close to the simulation results - under 10% offset. The results were judged acceptable and further CAD based daylight studies were performed.

The results of measured and simulated reflectances of the main reflective surfaces in the apartment 1F-A6 are presented in Table 4.3-1. The results showed that the interior surface reflectance estimates were fairly precise for all the main surfaces. The interior walls in the kitchen were measured to have slightly higher reflectivity in reality.

Table 4.3-1 Measured and simulated reflectances for the main reflective building components comparison

Location	Building component	Measured reflectance factor	Simulated reflectance factor
Kitchen	Interior walls	0.86	0.7
	Floor	Not available	0.3
Living room	Interior walls	0.68	0.7
	Floor	0.3	0.3
Bedroom	Interior walls	0.67	0.7
	Floor	0.4	0.3

The measured and simulated transmittance factor values are shown in Table 4.3-2. The window transparence was slightly higher in reality than in the simulations.

Table 4.3-2 Transmittance values for the transparent building components

Building component	Measured transmitance factor	Simulated transmittance factor
Double glazed window	0.75	0.7
Staircase entrance door - dark tinted glass	Not available	0.47

4.3.2 Mean daylight factor

Figure 4.3-2 presents results for average Daylight Factor (DF) in all the kitchens, living rooms and bedrooms. The analyses consists of the comparison between reference case (old design) and new designs with and without overhangs (shading), were applicable.

The average daylight factor results of 3-3.5 % in the original kitchens prove that they were very well-daylit, having nearly twice the Breeam UK suggested value. Finally the overhangs reduced average DF in half, mainly falling slightly short of suggested 2% in the kitchens, however, being above the suggested 1.5% in the living rooms. The results suggests a good potential of living room adaptation for “home offices” according to Breeam UK requirements. Bedrooms have the highest DF within the different room category that is 2.5-3%, well above the suggested 1-2%.

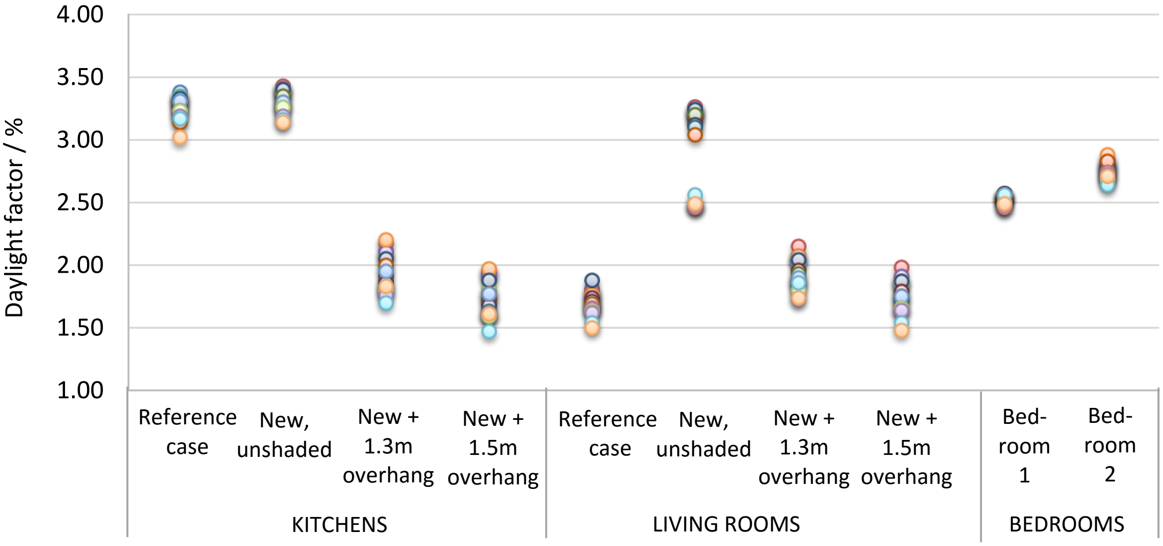

Figure 4.3-2 Mean DF per room, in all 18 apartments, for two different overhang options compared to the reference case and new design without shading. Each column consists of 18 dots representing a certain room in each of the 18 apartments.

4.3.3 Miljöbyggnad Silver point DF

The primary goal of the point daylight factor (DF) study was to achieve the Miljöbyggnad Silver in all the living rooms. The kitchens potential for obtaining the certification was also examined. The BBR suggestion of DF 1% was used as a guide for further daylight result evaluation.

It was observed that the point DF decreased from the third floor towards the lower floors in both room categories, thus making it most challenging to achieve the target in apartments located on the ground floor (1F), see Table 4.3-3. In general the point DF values were larger in the living rooms than in the kitchens. In the original design (reference case) the Miljöbyggnad Silver demand of DF 1.2% was achieved in nine living rooms comparing too only one kitchen out of 18 apartments in total.

Moreover, in some of the kitchens, the overhangs decreased the DF values nearly to half. Only six kitchens with 1.3m overhang and one kitchen with 1.5m overhang fulfilled the BBR suggested point DF of 1%. However, the DF increased in the new, renovated living rooms compared to the original design, even with shading devices present. The certification was now obtained in 15 and 10 apartments with 1.3 and 1.5m overhangs correspondingly (Table 4.3-3). Logically a larger overhang yielded a lower DF value than a shorter overhang in all the rooms.

Table 4.3-3 Miljöbyggnad point DF for the reference case and new design with two overhang options: 1.3m and 1.5m, in the kitchens and living rooms.

	KITCHENS			LIVING ROOMS		
	Reference case	New + 1.3m overhang	New + 1.5m overhang	Reference case	New + 1.3m overhang	New + 1.5m overhang
3F-A1	1.2	1.05	0.85	1.15	1.4	1.3
3F-A2	1.1	1	1	1.2	1.55	1.15
3F-A3	1.1	0.95	0.95	1.15	1.4	1.25
3F-A4	1.05	0.85	0.9	1.1	1.25	1.2
3F-A5	1.05	0.9	0.85	1.2	1.35	1.25
3F-A6	1.05	1	0.8	1.25	1.4	1.25
2F-A1	1.05	0.95	0.85	1.2	1.45	1.35
2F-A2	1	0.95	0.8	1.15	1.25	1.05
2F-A3	0.95	0.85	0.75	1.05	1.35	1.15
2F-A4	0.95	0.8	0.7	1	1.2	1.05
2F-A5	0.85	0.75	0.7	1.15	1.2	1.2
2F-A6	0.95	0.95	0.75	1.15	1.2	0.95
1F-A1	1	0.85	1	1	1.35	1.2
1F-A2	0.95	0.85	0.75	1.1	1.1	0.95
1F-A3	0.95	0.75	0.6	1.05	1.2	1.1
1F-A4	0.9	0.8	0.8	1.05	1	1.05
1F-A5	0.9	0.65	0.65	0.9	1.2	1
1F-A6	0.9	0.65	0.65	0.9	1.05	0.8

The results suggested that the optimal overhang solution for reaching the certification in the maximum amount of the apartment kitchens and living rooms would be with 1.3 m overhang depth. However, 1.3m depth was considered too narrow for the new balconies, therefore it was necessary to alter between 1.3m and 1.5m overhangs for shading device and balcony, respectively.

The two design options – symmetric and variable design – implied different balcony placements (further illustrated in method section, *Figure 3.3-3 Facade design variations, different placement of the balconies*). Five more living rooms would reach the Miljöbyggnad Silver in variable design compared to the symmetric design based on the 1.5m depth balcony placement. The third floor was not shaded by the balcony and thus could have the optimal shading depth in both designs.

Figure 4.3-3 presents the average and the point DF relation for 1.3m and 1.5m overhangs in the living rooms (LVR) and kitchens (KIT) compared to the old designs in all the 18 apartments. The red line and red dotted line specifies Miljöbyggnad Silver demand of 1.2% and BBR recommendation of 1% respectively.

The results indicated that the existing kitchens had the worst daylight uniformity between the room categories, as a result of no overhang (the existing living rooms had a built-in 1.3m balcony that performed as a shading device).

The average DF in the kitchen was reduced by nearly half when overhang was introduced, while point DF decreased only slightly. These findings suggested that the daylight in the original kitchens did not penetrate deep enough into the room.

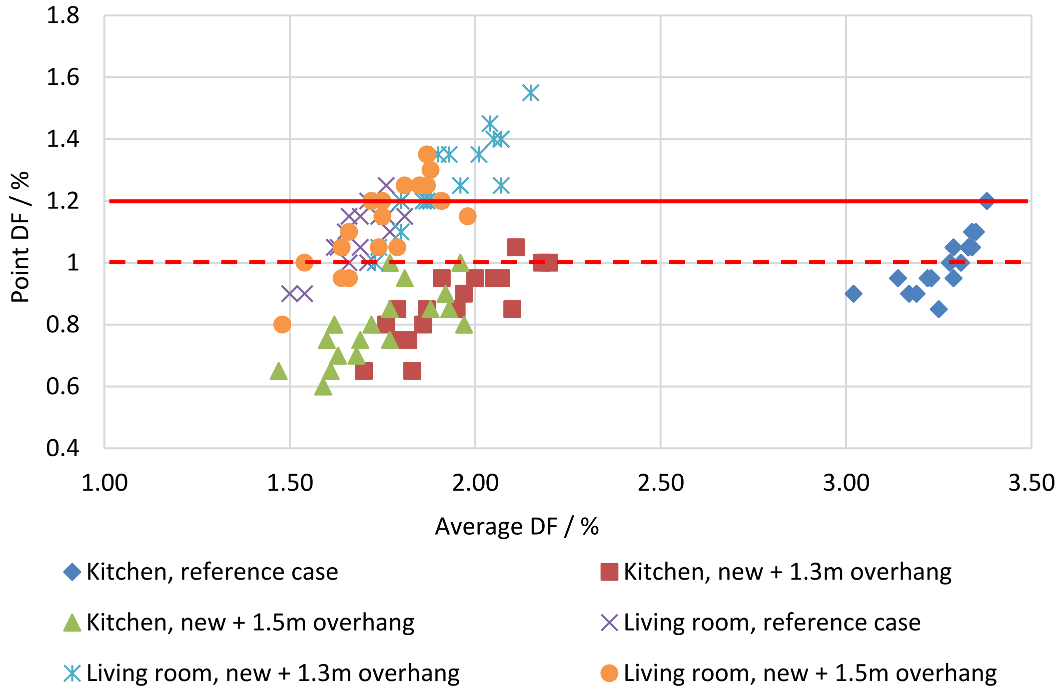

Figure 4.3-3 Average and point DF relation for different overhang options comparing to the reference case

4.3.4 DA and cDA

Figures 4.3-4 and 4.3-5 illustrates the average values of cDA and DA f. The particular metric study consists of four room categories with either 1.3m or 1.5m overhang, which is further compared to the reference case and the new design without the shading device.

In general continuous daylight autonomy is between 60-80 % in all the cases, which is within the target level of well daylit space. However, both DA and cDA were about 8-10% greater in the living rooms than in the kitchens for all the design options (Figure 4.3-4 and 4.3-5). The "best" daylight levels were achieved with the unshaded new designs, and the "worst" with largest overhangs projection of 1.5m.

Overhangs of 1.3m and 1.5m performed differently in the kitchens comparing to the living rooms, because the original room geometries were significantly different.

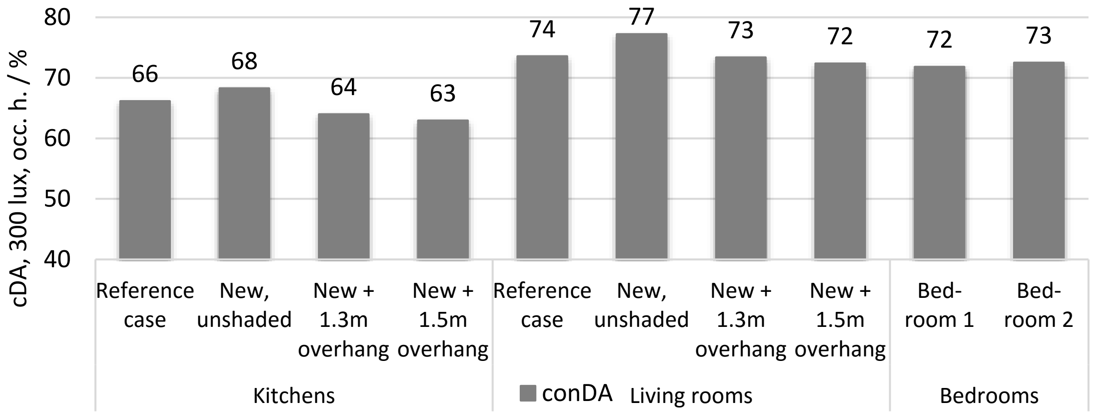

Figure 4.3-4 Continuous daylight autonomy, 300 lux, per room, in all 18 apartments, for 2 type of overhang options compared to the reference case and new design without shading

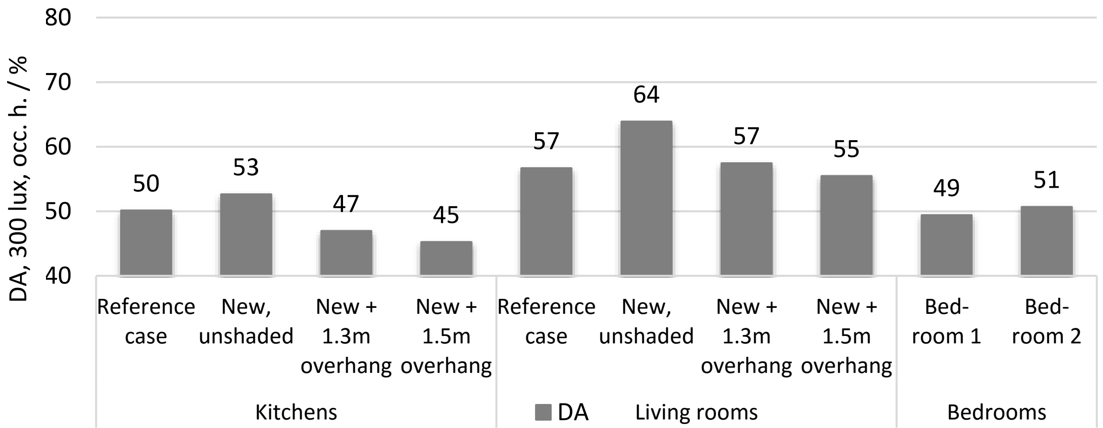

Figure 4.3-5 Daylight autonomy, 300 lux, per room, in all 18 apartments, for 2 type of overhang options compared to the reference case and new design without shading

The results of continues daylight autonomy showed that the daylight on the second and third floor staircases, has increased almost by two-fold after implementing the new windows, see Figures 4.3-6. Originally daylight on ground floor was sufficient and therefor no daylight affecting changes were proposed.

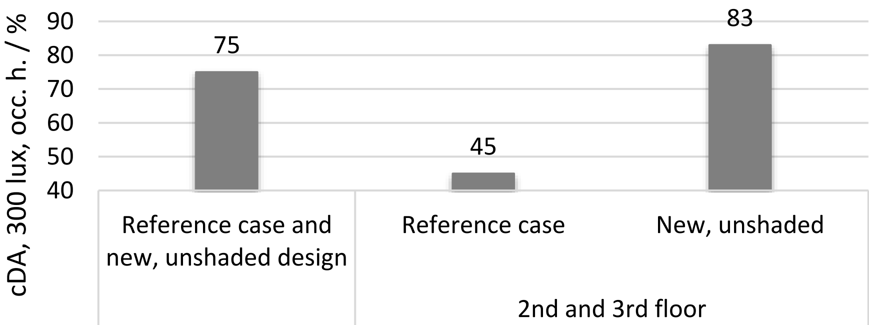

Figure 4.3-6 Continuous daylight autonomy, 300 lux, per three staircases (ground floor) and six staircases (2nd & 3rd floor)

Daylight analysis for all the apartments individually is further presented in Figures 4.3-7 and 4.3-8 for the kitchens and living rooms correspondingly.

The daylight gradually decreased from third floor down in both rooms. However, the corner apartments (A1 & A6) on each floor had a slightly higher daylight than the apartments located in the middle of the building block (A2-A5).

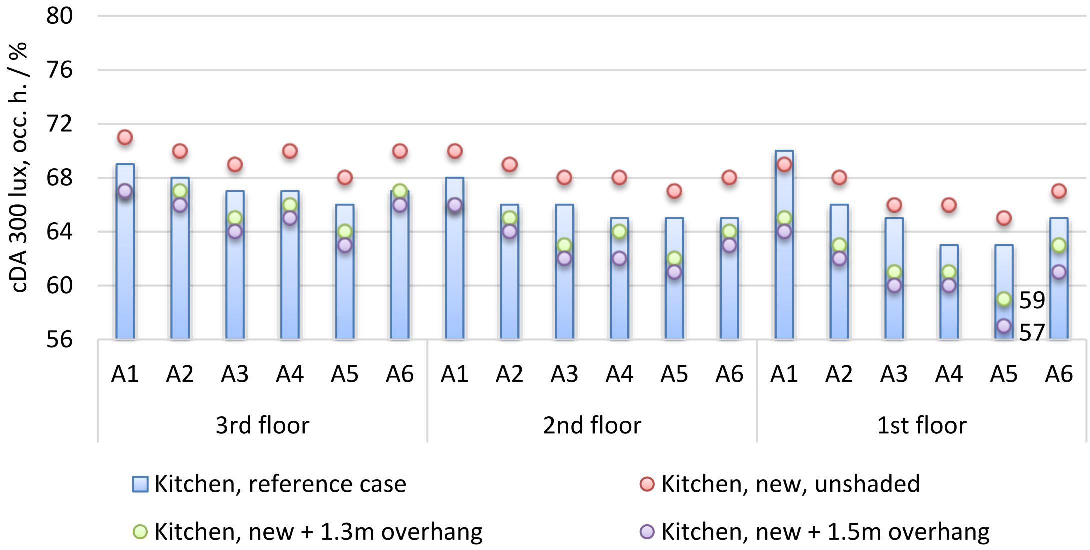

Figure 4.3-7 Continuous daylight autonomy 300 lux, in kitchens for different shading options compared to the old design, in all 18 apartments

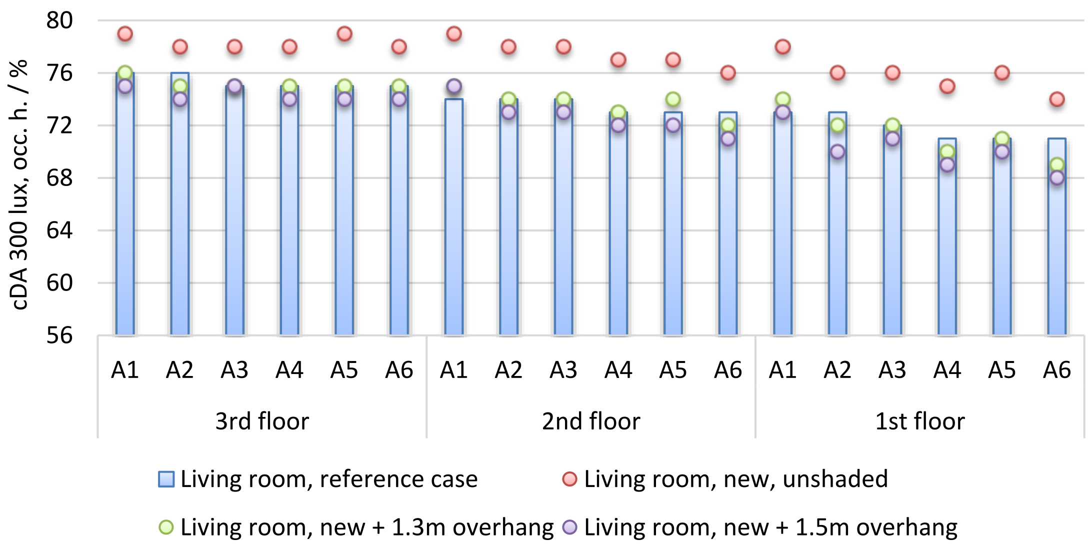

Figure 4.3-8 Continuous daylight autonomy 300 lux, in living rooms for different shading options compared to the old design, in all 18 apartments

4.3.5 Useful daylight illuminance

Useful daylight illuminance (UDI) in Figure 4.3-9 presents when daylight falls between the following ranges: underlit, when illuminance is under 100 lux; supplementary, between 100 and 300lux; useful or autonomous, between 300 and 3000lux and finally when daylight over-supply occurs – illuminance is over 3000 lux.

The results of UDI analysis demonstrated that there was a significant oversupply of daylight occurring in the existing kitchens. The threshold of five percent overlit time was exceeded by twofold, while the living rooms were within the accepted range. In the new architectural design without the overhang the issue remained, moreover now also the living rooms were in need of shading. Ultimately when the overhang was introduced the overlit time was acceptable in all the kitchens and living rooms, by either 1.3m or 1.5m depth.

Furthermore between the room divisions the kitchens also showed underlit areas for the largest amount of the occupied hours - around 30%. This was approximately 10% more than in any other room category.

Overall bedrooms and living rooms with the overhangs were independently daylit half of the occupied time, that was 10% more than the kitchens. However, bedrooms showed the most optimal UDI results by having 80 % of the time reaching either autonomous or supplementary level.

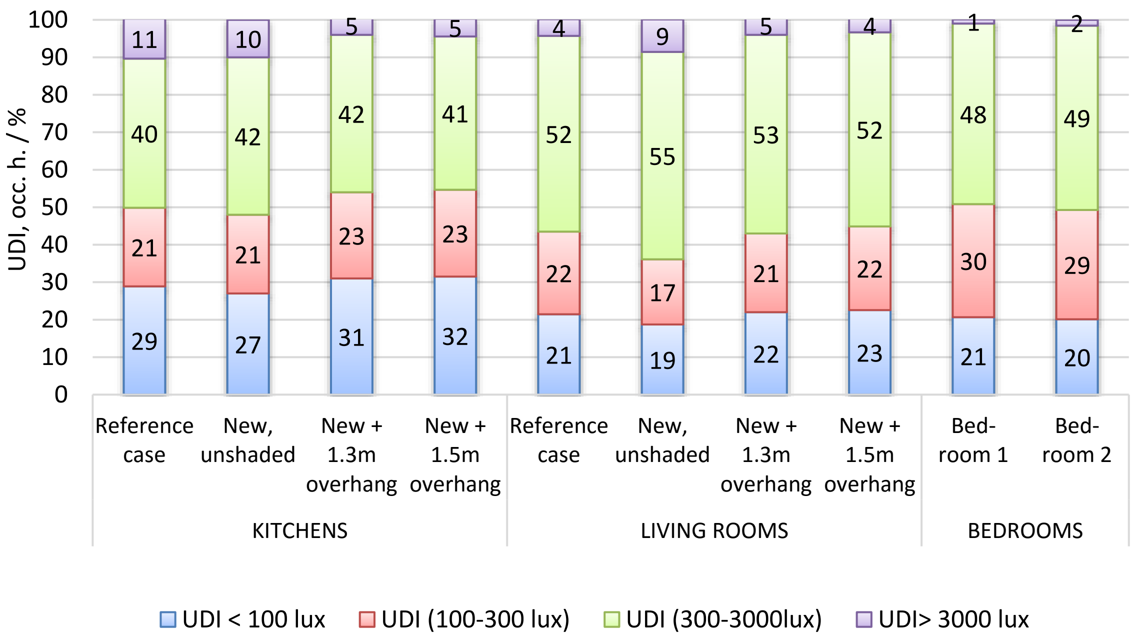

Figure 4.3-9 Average UDI for all the apartments, in three room categories –kitchens, living rooms and bedrooms, for different design options – reference case; new design with extended walls and open kitchen, no shading; new design with either 1.3m or 15m overhang

4.3.6 Overlit areas

To examine the overhang and the new architectural design effect on the overlit hours and areas, the same apartment located at the third floor corner (3F-A6) was investigated for daylight oversupply.

Figures 4.3-10 and 4.3-11 illustrates when UDI exceeded 3000 lux between 0- 40% of occupied hours for the reference case, new design without overhang and two overhang options. The pink line on the floor plan displays, where the threshold of UDI > 3000 lux was exceeded for at least 5% of occupied hours. One daylight square in the plan drawing was 0.45m x 0.45m, thus the overlit time in specific place in the room could be easily determined.

As earlier UDI analysis suggested the original kitchens had oversupply of daylight, same as the new kitchens, without the shading device. For either of the designs the oversupply occurred as deep as 2.7m inside the kitchen or/and living room. The areas within 1.8 meter from the window peaked over 3000 lux for as much as 20-40 % of occupied hours. The new window in the staircase had introduced a slight daylight oversupply.

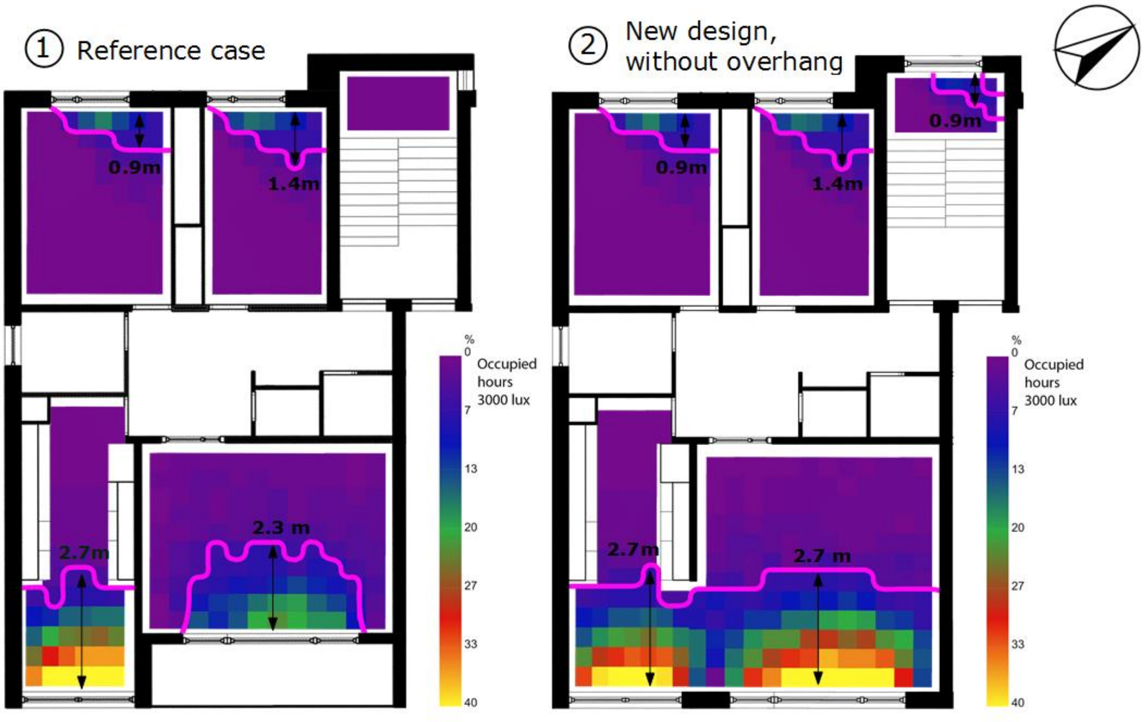

Figure 4.3-10 Overlit areas in the reference case (1) and new design without the overhang (2)

The overhangs proved to effectively decrease the depth of the overlit areas, in the kitchens and living rooms from 2.7 m to 1.8m (Figure 4.3-11). Moreover the overlit hours closer to the window had also significantly decreased, to 10-20%. However, both overhang depths seemed to have a similar performance, thus the final choice between either one of them should be further motivated based on other daylight results.

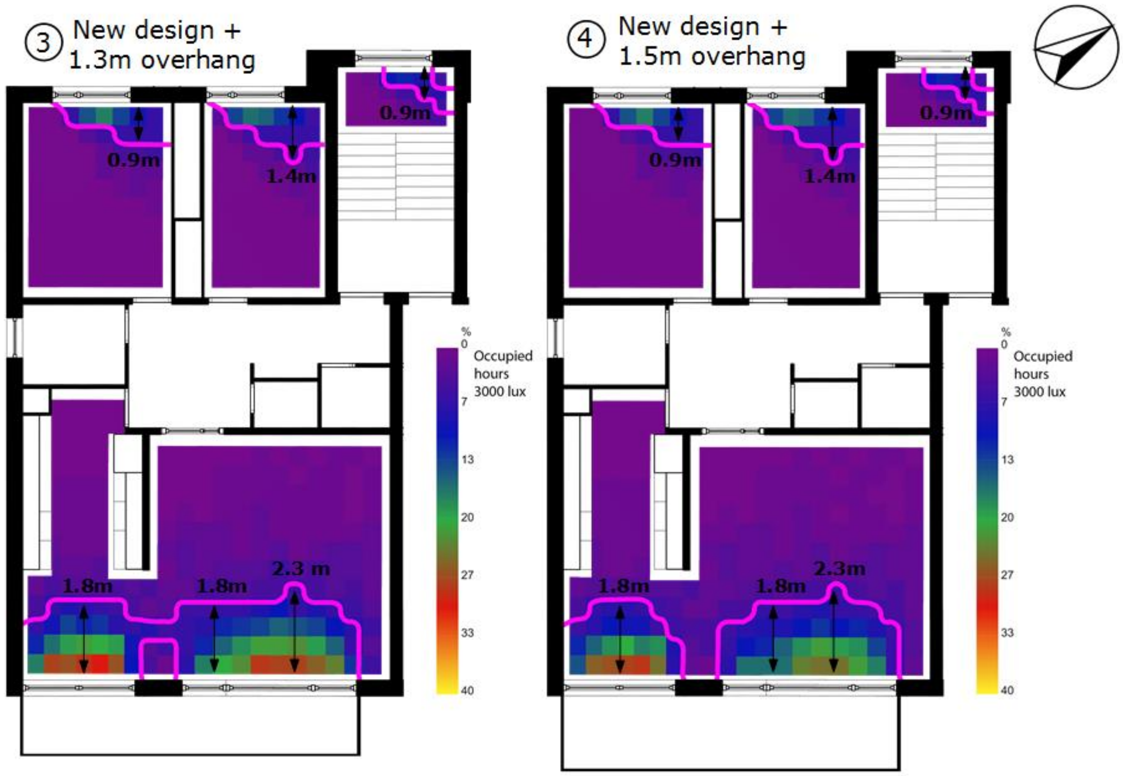

Figure 4.3-11 Overlit areas for the new design with 1.3m overhang (1) and 1.5m overhang (2) for the kitchens and living rooms

4.3.7 DA and cDA for different design options

The results presented in Figure 4.3-12 demonstrates that all the apartments falls within "good" cDA range that is between 60-80%. Continuous daylight autonomy is on average 20% larger than daylight autonomy in all the design cases. Hence, the brief daylight estimate for different designs indicates very similar daylight performance. However, the obtained cDA and DA values are an average result of all the rooms in 18 apartments together, and therefore needs to be further studied.

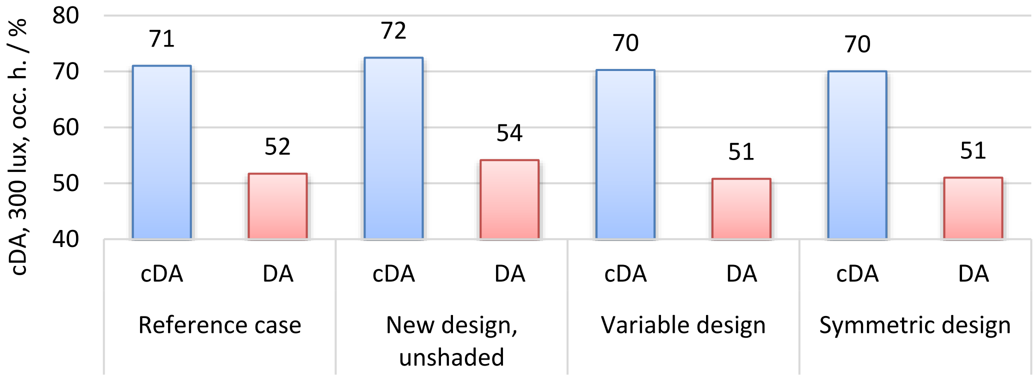

Figure 4.3-12 Continuous daylight autonomy and daylight autonomy 300 lux, on average in 18 apartments, for the old design compared with the three design options

The cDA comparison between different floors and apartments in Figure 4.3-13 showed that the natural daylight decreased from the third floor down. The cDA of 300 lux is reached between 69 to 73% of occupancy hours in all the design cases. The corner apartments A1, on all the floors, and A6, on 1st floor, showed 1-2% higher cDA compared to the other apartments on the same floor. 1 to 2% accounts for 9-18 occupancy hours between 8am to 6pm. All the four design categories followed the same trend. Variable and symmetric design options yielded slightly lower values than the reference case. Unshaded new design, however, performed very similar.

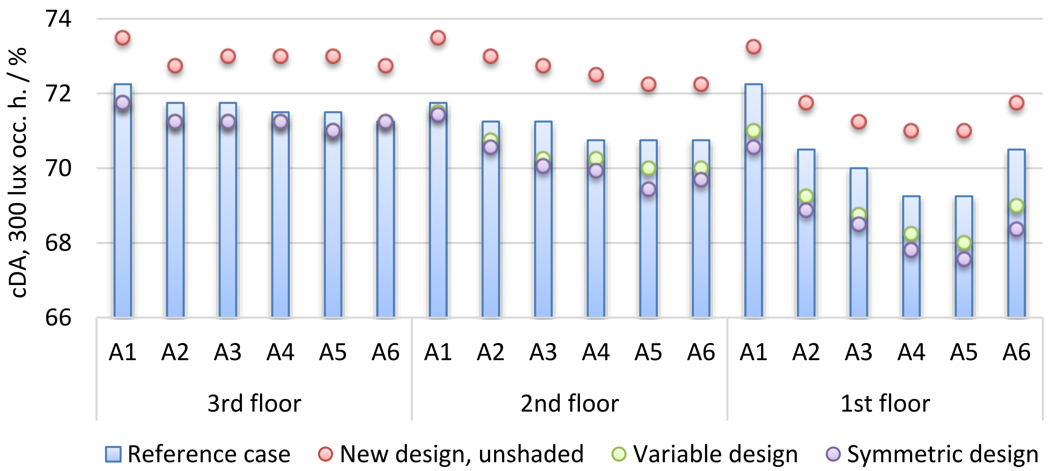

Figure 4.3-13 Continuous daylight Autonomy of 300 lux, on average per apartment, for three design options compared to the old design

4.4 Life-cycle cost

The proposed renovation measures had an investment cost of 6.58 million SEK (including 25% VAT), which correspond to 3800 SEK/m² heated floor area. The following results present the NPV sensitivity analysis over a calculation time of 40 years including the predicted NPV with 2% of district heating price increase, according to Landskronahem. The district heating price was additionally calculated with no price change and a yearly price increase of 4%. All the NPVs were calculated with 4% interest rate. The results of different NPV scenarios for reference case and environmental building are presented in Figure 4.4-1.

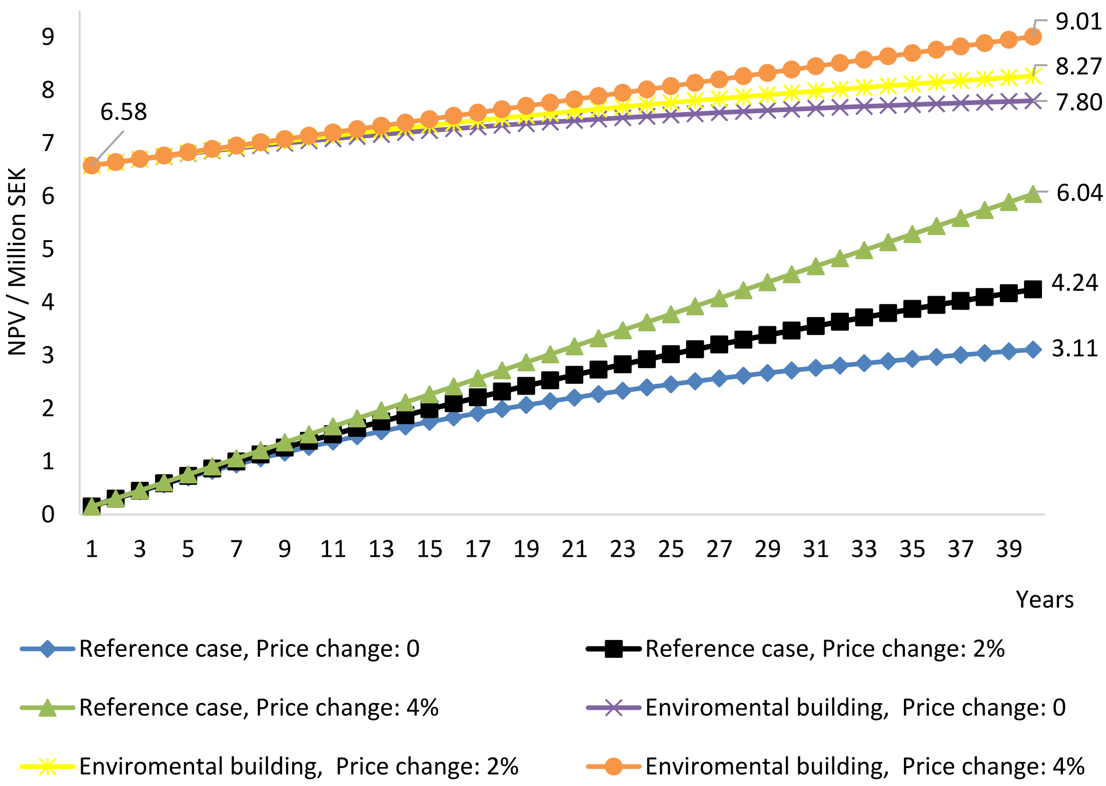

Figure 4.4-1 Sensitivity analysis of district heating price change for reference case and environmental building

The results showed that after 40 years the price increase based only on the operational costs were 2.55 million SEK higher in the non-renovated building, due to high heating demand (black and yellow lines). However, due to high investment cost of the renovation, the payback of the costs including the investment was not reached.

The operational costs were compared between the proposed renovation and the scenario of maintained heating demand (base case). Figure 4.4-2 shows that after 40 years, 2 million SEK was saved by the means of lowered heating demand.

A rent supplement was needed in order to pay off the investment cost. Figure 4.4-2 displays the added rent cost, depending on the calculation time. The figure includes the comparison between the Landskronahem renovation and the cost-effective renovation measures performed in this thesis, referred to as the “environmental building”.

Landskronahem was willing to add maximum 400 (SEK/m² ·a) while assuming real interest rate of 4% and real price change increase of 2% for the calculation time of 15 years. With the same calculation prerequisites the environmental building managed to achieve the rent supplement of 320 (SEK/m²·a), thus not exceeding Landskronahem’s limit.

Further calculation of the rent supplement as a function of the calculation time in years demonstrated that the rent supplement for the environmental building would vary between 600 (SEK/m²·a) and 150 (SEK /m²·a) in the time period between 10 and 40 years correspondingly.

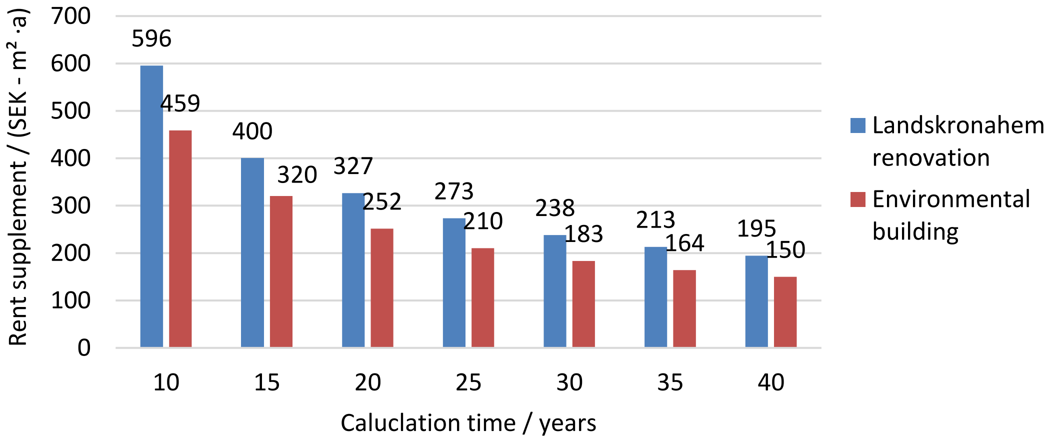

Figure 4.4-2 Rent supplement (SEK/m² · a), as a function of the calculation time with real rate interest of 4% and real price change of 2%

5 Discussion

5.1 Energy reduction measures

The suggested envelope improvements yielded a substantial decrease in heating demand, which as a result met the current BBR requirements on specific energy need. One of the reasons was the increased airtightness and lowered U-values.

Another aspect that would explain the heating reduction, were the new compact building shape. The external wall area at the South-East facade was reduced by 15% with the removal of the perpendicular walls at the recessed balconies. This led to the elimination of significant thermal bridge at the balcony slab and additionally, reduced the buildings transmission losses.

Proposed renovation measures of the case building were further analysed by the means of cost-effective energy and GWP emissions optimisation. This meant evaluating the energy efficiency of certain renovation actions related to its environmental impact and costs.

The results of insulating the ground slab with 10cm insulation and floor coating prove to be an ineffective renovation measure from cost-effective perspective. That was due to the high environmental impact of the insulation materials while not delivering significant heating demand reduction. Savings only accounted for 2 ($kWh/m^2 \cdot a$) and the ground slab was therefore left in its original condition.

The apartment with the highest operative temperature peaks was located on the top floor, situated on the gable towards south direction. This could be explained by its larger surface area, exposed to the solar radiation from the South, comparing to the other apartments. The absorbed solar radiation on the surfaces would consequently contribute to the high temperature peaks. The most overheating hours were however, obtained in the apartments located in the core of the building, on the 2^{nd} floor. A reason could be that these apartments had adjacent apartments on all sides. The heat generated from the internal gains might in a larger extent than the top apartment, warm up the core apartments and contributing to the overheating.

5.2 Life-cycle assessment

The LCA study investigated insulation and loadbearing materials in respect of the product stage, replacement and end-of-life-stage. The absorbed carbon in the trees was not included in the LCA calculation. This means that the wood products like timber, wood fibre wool and wood fibre panel would in fact obtain even lower emissions.

At any construction whether it is newly built or a renovation, the life cycle impact of materials has a risk of being neglected. The common environmental aspect is to lower the buildings energy consumption that would result in less pollution from the energy supplier.

However, the LCA results showed that is just as important to acknowledge the materials' environmental impact. The study showed that the insulation elements glass wool (low density), wood fibre wool and cellulose obtained significantly lower CO_2 –eq, compared to the least environmental friendly EPS, XPS and PUR. Even though these plastic materials are mostly containing air, the rigid material is manufactured from raw oil. The commonly applied product, EPS performed almost ten times higher impact (60 kg CO_2-eq/m²), compared to the wood fibre wool, during the studied lifespan of 60 years. XPS and PUR performed even worse.

The materials that function as the load-bearing part of the prefab wall were further studied. Products like steel, concrete and timber were compared by their respective mass per element. Even though steel had the least mass (0.15 m³) it obtained over 4200 kg CO_2-eq compared to timber which, with its mass of 0.4 m³ only obtained 30 kg CO_2-eq.

This study proposes that in order to reduce the greenhouse gases, wood-based materials should be chosen instead of steel and concrete. Moreover, it is important to increase the proportion of these materials in new and renovated buildings in order to achieve the 2020- and 2050 emission goals. Sweden further aims for net zero emissions of greenhouse gases by latest 2045. According to (Lippke et al., 2004) and (Persson, 1998), can these goals be accomplished without any supplemented costs, since wood framed buildings are economically competitive with steel or concrete single- and multifamily buildings.

5.3 Daylight

On-site daylight measurements verified that the simulation model results are trustable, however, the Miljöbyggnad point DF values in reality were slightly higher than simulations indicated. Because a lot of rooms have very small margin of achieving Miljöbyggnad Silver certification or BBR point DF demand, when choosing larger overhang, the small difference can be a decisive factor.

The advantage of striving to meet a larger illuminance target of 300 lux than normally residential spaces would have - 50 lux to 150 lux, created the option to perform more visually demanding tasks, without the need of electric lighting. Thus, the new visual comfort gives the tenant more options for the space usage based on daylight alone. Possible electric savings could be further investigated.

Daylight autonomy and daylight factor alone did not inform about the possible oversupply and undersupply of the daylight. UDI analysis identified the existing problem in the kitchens of the reference building. They had twice the acceptable overlit time. Moreover the large average daylight factor in combination with a low point daylight factor half way in the kitchen, indicated a bad daylight uniformity that is complicated to change in reality without changing the room's proportions. However, the overlit hours can be eliminated by introducing an optimal overhang depth.

The shading parametric study showed that in all the rooms, an overhang reduced the daylight compared to no overhang (except the reference case living room, due to existing balcony overhang that performed as a shading device).

When choosing between the 1.3m or 1.5m overhang, the most informative results came from point DF and UDI range over 3000 lux. For shading purposes 1.3 m depth of the overhang prove to efficiently decrease the overlit time to the acceptable limit of five percent, while delivering sufficient daylight and was therefore selected as the optimal depth for the shading device. This further confirms that the initial overhang projection method is in fact an effective way to find an optimal shading solution.

As an architectural design target, the balcony depth had to be increased compared to the earlier 1.3m depth, and therefore the overhang of 1.5m depth was studied. Due to the overhang projections effect on the daylight it was decided to not to further increase the balcony depth.

Similar daylight results with a bigger size of balconies can be achieved if the balcony depth is increased simultaneously as the internal surface reflectances are increased. This method would work until the limit of realistic and comfortable surface reflectance values is reached.

Without changing other variables, the balcony depth larger than 1.5m would yield in a lower daylight in the apartment, and thus the possible office adaptation, based on natural daylight, would be questionable.

This discovery underlines the significant impact the overhangs has on the daylight, and suggests that any depths over 1.3m for latitude 55° should be studied with more care, as sun will be shaded also after the 1st of August, letting less daylight to penetrate through the window over the year.

It could be further argued that the ”ceiling” of the maximum possible daylight (with the existing reflectance and transmittance values) for the lamella residential reference building, in fact, has been achieved. That is because the existing window to wall ratio was quite high: 29 and 38 %, mostly covering the facade from the desk height upwards. This section is the optimal placement of the window, for maximum useful daylight. Moreover larger windows at this latitude would come at the cost of the increased heading demand.

5.4 Life-cycle cost

The building renovation costs in connection with construction execution on site and tenant relocation would be significantly lower when using prefabricated elements. That is because similar building takes 4-5 working days to assemble, however, on site construction could go on as long as 6 months. This significant advantage of using pre-fab wall elements should be considered in the Swedish market, as until now it seems that only non-organic prefabrication products can be found. As a result, already tested TES wooden prefabricated facades produced in Germany were adopted for this project. As a result German price for such an element were used, however, costs and pollution due to the transportation could be included in future studies. A similar refurbishment of a two storey school using TES wooden prefabricated facades has already been executed in South-East of Norway, suggesting the validity of using prefabricated wood systems in Scandinavian climate.

According to the NPV results the payback of the renovation investment based on operational costs was not reached after 40 years. In order to reach the desired payback, further studies could investigate the option of adding extra floors. This would likely further reduce the added rent cost for the tenants.

6 Conclusions

The lifespan of many buildings that were built before and during the "million program" years are about to run out and their need for renovation are increasing. As these buildings constitute for a large energy demand, there is a great potential to carry out energy-efficient measures in the approaching renovation projects. The opportunity is here and now, and will not occur again, within the next 40 years.

While worn-out parts will be replaced with new products, it is of importance to recognize the potential climate impact of each applied material throughout its life cycle. Choosing materials with less negative footprint on the environment is not regulated, however, should be considered. After all, the environmental impact of a building is not only the energy usage but also the materials of which the house consists of.

This report has shown that plastic based insulation materials and steel products should be avoided from an environmental perspective. Otherwise, there could be a risk that these materials would constitute for larger emissions than what the lowered energy demand would provide. The results of the proposed renovation measures provided a potential cutback of greenhouse gases (GWP) with 60 % compared to the original building.

The LCC results stated that the energy cost savings for the reference building did not finance the investment cost of the renovation, during its estimated life-span of 40 years. Nevertheless, the full economic value of this renovation also involved other added values and co-benefits. These benefits are at a building level (1-5) and also at the social or macroeconomic level (6-8), listed as follows:

1. Increased thermal comfort
2. Increased living space
3. New external balconies
4. Accessibility (open plan layout and spacious kitchen)
5. Increased visual comfort
6. Increased status of the neighbourhood
7. Improved aesthetics of the building
8. Reduced global warming potential

The daylight results proved that daylight has to be measured with several metrics, as they supplement each other and help to better interpret how the natural light behaves in the apartments.

In the study it was discovered that the original lamella buildings of the same type or/and orientation (depending on the metric evaluated) had a sufficient amount of natural daylight**.** However, the kitchens were overlit for double the allowed occupancy time, which constituted for discomfort.

The new architectural designs yielded continuous daylight autonomy illuminance of 300 lux for 73% of the occupied time in living rooms and bedrooms, and 65% in the kitchens. The new proposals included an optimal shading device depth of 1.3m that eliminated the daylight oversupply were it occurred, fulfilling the British Standard BS EN 15251.

The daylight results for 1.5m balcony depth met the project targets, however indicated that a larger overhangs would shade more than it was necessary. With the 1.5m balcony depth in combination with 1.3m shading device the Miljöbyggnad Silver certification was achieved in 15 apartment living rooms in variable design compared to only 10 living rooms in the symmetric design, making variable design a better architectural design choice.

The combination of the daylight assessment suggested that there is a potential for a “home office” adaptation in the renovated apartments. The most appropriate room would be the living room, which, apart from sufficient daylight, also provides a spacious floor area and Miljöbyggnad Silver certification in most of the cases.

The daylight study concludes that these particular type of million program lamella buildings had the potential of sufficient daylight, on large extend due to favourable initial window to wall ratios of the studied facades. However, daylight needs to be measured to eliminate possible undersupply or oversupply, and a proper overhang shading can sufficiently improve the quality of the daylight while also reducing the overheating hours.

The thesis study suggests that the million program lamella building’s appearance can be improved through cost-effective energy renovation solutions using environmentally friendly materials. As a result the building’s value can be increased due to improved thermal comfort, environmental recognition and the assessment of good daylighting design.

The new prefabricated wooden facades are ensuring minimal carbon footprint, and fast on site execution, while delivering aesthetically pleasing appearance of the new, renovated construction. The variable design of the new balconies and shadings further delivers original, modern design that adds value to the surrounding neighbourhood.

7 Summary

Sweden is facing an upcoming period where many of the buildings built during the million program will be in need of an envelope renovation. The authors chose the topic of an environmental refurbishment, foreseeing the significant effect the renovation industry can leave on our environment. We are in charge of steering it towards a negative or positive path. The existing building stock in EU constitutes for 40 % of energy use and 36 % of CO2 emissions, making it a sector with great possibility. The authors further chose to approach a more appealing architectural design and study the daylight conditions, as it was believed to have a positive effect on the tenants living in the building and in the neighborhood.

The following main categories of the research project were carried out: energy reduction; life-cycle assessment; life-cycle costing and daylight. The case study building was a typical three-storey lamella house from the million program years, located in Landskrona. The energy targets and renovation scope was developed with an understanding of Landskronahem's ambitions. The goal of this study was to raise awareness about renovating the million program multi-storey residential buildings with environmentally friendly and cost-effective solutions. It was believed that the renovation results should deliver significant energy reduction while choosing environmentally friendly materials. The combination of both measures should further lead to the reduction in global warming potential.

Co-benefit of good daylight design can lead to increased visual comfort that could further generate health benefits and increased productivity. Moreover, as the flexible working hours are gaining popularity, more people might be working from home, and daylight might become an ever-actual topic in the residential spaces.

Architecturally it was the aspiration by the authors and Landskronahem to improve the appearance of the facades and implement new balconies. Prefabricated wooden facades were chosen, that incorporated environmental material choice and a cost-effective construction method. The original balconies were built-in and constituted for a significant thermal bridge. The balcony space was added to the interior eliminating the thermal bridge, and the new external balconies were attached to the facade. The optimal balcony depth was chosen through daylight studies of balcony overhang shading effect on the visual comfort of the affected apartments.

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A retrofit package that accounted for cost-effective measures included: new low energy windows, new prefab lightweight external walls on the main facades, and insulated basement walls and roof. As a result the energy use was reduced by 50 % and the heating demand by 70 %. The most significant energy saving came from the replacement of the old windows. The energy savings alone did not pay off the investment cost. However, the co-benefits, gained from this renovation should be weighted in to the decision making.

The LCA-method for renovation measures in IEA EBC Annex 56 suggested a calculation time of 60 years. All the products presented in this report were therefore studied due to their emission related to the product stage, replacement and end-of-life stage. The implemented materials accounted for 10 % of the final heating demand. By lowering the heating demand

and choosing environmentally friendly materials in the renovation process, the upcoming building renovation could potentially result in CO2-eq emission cutbacks of 60 %, compared to the existing heating demand.

The results of the daylight study revealed that existing million program lamella building may have a favorable window to wall ratio for sufficient daylight design for a home office adaptation. However, there may be daylight oversupply in the kitchens that can cause glare and visual discomfort. The British Standard BS EN 15251 for daylight oversupply was achieved in all the rooms of the renovated designs with the shading devices.

Final renovation designs were proposed where the building was improved architecturally while delivering useful and sufficient daylight levels in all the rooms. The overhang study proposed the optimal shading device depth of 1.3m and balcony of 1.5m. The potential of home office adaptation was achieved, while the standard of Miljöbyggnad Silver was achieved in 15, out of total 18 living rooms, when choosing variable design option. Due to the original kitchen design, the Miljöbyggnad Silver point DF demand 1.2% was not reached in the kitchens with shading devices.

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It is of relevance to not only significantly reduce the energy demand, but also use the earth's finite resources wisely by choosing environmentally materials in the process. The opportunity to implement these methods is now and will not occur again within the next 40 years. As many of these buildings were constructed in the similar manner, the findings from this report could be applied for several hundred thousand houses. This would as a result contribute greatly to the 2050 energy and climate goals of Sweden.

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