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Impact of Façade Glazing on Energy Demand & Indoor Environment Quality

Process for early glazing design of office buildings

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

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Building Physics Modelling
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis 2017:BOMX02-17-78

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Examensarbete 2017:BOMX02-17-78/ Institutionen för bygg- och miljöteknik,
Chalmers tekniska högskola 2017

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Cover:
A project for the course Building Design lab. Project´s aim is to find a beneficial façade solution for a new building in Solna in Stockholm.

Department of Civil and Environmental Engineering.

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ABSTRACT

Façade glazing parameters have large influence on energy demand and indoor environment quality in office buildings. However, the scientific background in this area is vague. The objective of this study is to use IDA ICE building simulation tool and investigate the impact of window-to-wall ratio and g-value on heating, cooling and lighting demand, as well the impact on PPD value and daylight factor in an office building in Malmö, Oslo and Reykjavik. The office building is portrayed by a study case designed according to the Norwegian passive house standard NS 3701. Hence, the results are only applicable based on this study case. Overall, this study creates a guidance for the optimal façade glazing design that aims to achieve the lowest energy demand and best indoor environment quality in an office building.

The results showed that the glazing parameters' effect on energy demand and indoor environment quality very much depends on the climate conditions in terms of the outdoor temperature and solar radiation intensity. Therefore, the façade glazing must be selected carefully for specific orientation and location.

Overall, the middle size glazing of 25% WWR and the highest performance glazing with g-value of 0.45 is the best combination for the lowest ED and best IEQ.

Contents

Preface

This study has been carried out from January 2016 to June 2017. The work is a Master study for the research group Building Technology. The study is carried out for the Department of Civil and Environmental Engineering, under Master's programme Structural Engineering and Building Technology, Chalmers University of Technology, Sweden. The study was executed at Verkis Consulting Engineer, Iceland.

The study has been carried out with senior engineer Baldur Jonasson as a guidance and assistant Professor Pär Johansson as supervisor. All equipment and compendium were facilitated by Verkis Consulting Engineer. My Thesis opponents are highly appreciated for their help. I would also like to thank Max Tillberg at Bengt Dahlgren for his co-operation and involvement.

Finally, it should be mentioned that the study could not have been done without the generosity of the IDA ICE staffs at EQUA.

Reykjavik June 2017

Bjartur Guangze Hu

Notations

AHU	*Air handling unit*
CAV	*Constant air volume*
DF	*Daylight factor*
ED	*Energy Demand*
ESO	*External shading object*
GIA	*Gross internal area*
IEQ	*Indoor Environment Quality*
PPD	*Percentage predicted Dissatisfied*
$\mathbf{T_{vis}}$	*Visible solar transmission*
VAV	*Variable air volume*
WWR	*Window-to-wall ratio*

1 Introduction

The energy use and indoor comfort of a perimeter zone in an office building depends on several glazing design decisions; glazing orientation, glazing area, shading condition and glazing property (EWC, 2016). In building projects, it is crucial to make good decision in early stage, otherwise it could lead to unpredictable effects and even devastating problems in later stage. Façade glazing is one of many subjects that require much consideration during early design phase. It is important to recognise the impact of façade glazing parameters when the aim is to achieve efficient Energy Demand (ED) and healthy Indoor Environment Quality (IEQ).

1.1 Background

Energy efficient buildings are vital to sustainability in the coming decades. While many things about the future remain unclear, one thing is certain, the world population will keep on rising and more people will be living in urban areas, which means an increased demand for new buildings. Consequently, there will be an unprecedented increase in energy use. The counteraction is to build more energy efficient buildings, and the incredibly inefficient nature of today's building design needs to change.

Façade glazing on modern office buildings is a popular subject among architects and designers. But the actual impact of façade glazing on ED and IEQ is unclear. This study aims to investigate and understand the impacts of façade glazing on ED and IEQ in office buildings. By understanding these effects, designers can take better decisions regarding façade glazing in early design process, thus avoiding late stage validations. Easily applicable tools and guidelines for early design process would make the design process less inconvenient and shorten the design process drastically.

1.2 Purpose

Glazing parameters have large influence on ED and IEQ. However, the scientific background in this area is vague. This study aims to use IDA ICE building simulation tool and investigate the impacts of two façades glazing parameters, window-to-wall ratio and g-value, on ED and IEQ of an office room in Malmö, Oslo and Reykjavik. This provides guidance for designers in early stage to make them aware of the impacts of these two glazing parameters on ED and IEQ. Thus, assisting designers to choose appropriate glazing design to minimize energy demand and guaranteeing good indoor environment quality for office buildings.

1.3 Method

The study consists of several approaches; research on passive house standards and regulations, data collection of requirements regarding ED and IEQ from standards, developing a score table for ED and IEQ, test setup of the study case in IDA ICE, evaluation procedure with IDA ICE simulations and result analysis with graphs.

The study started with a research on regulations and standards from Sweden, Norway and Iceland on ED and IEQ. The research led to the recognition of three ED elements and three IEQ elements. Also, the importance of two glazing parameters, one physical and one material aspect of glazing.

Requirements on heating, cooling and lighting demand from the Passive house standard NS 3701 were collected, as they represent the ED elements. Requirements on daylight factor, thermal comfort summer and winter from Miljöbyggnad were collected, as they represent the IEQ elements. A score table for ED and IEQ elements was developed enable to evaluate the glazing parameters under various circumstances.

The study case was modelled in IDA ICE building simulation tool. The goal of the study case is to emulate an office environment according to passive house standard NS 3701 and Miljöbyggnad. Many simulations of the study case under various conditions were conducted in IDA ICE. The climate data in IDA ICE were obtained for Malmö, Oslo and Reykjavik.

The results from the simulations were analysed with graphs. This made it more efficient to observe the many effects of glazing's impact on the ED and IEQ. The results were also evaluated against the score table of ED and IEQ.

1.4 Limitations

Climate data for Reykjavik, Malmö and Oslo were used for the simulations. The dry-bulb outdoor temperature and solar radiation intensity were the central focus of this study. Any effect of humidity was regarded as minor effector on the results.

The two glazing parameters investigated for this study were window-to-wall ratio and g-value. The impacts of these two parameters on energy demand and indoor environment quality were investigated separately.

The energy demands of the study case were examined on a yearly basis, given in kWh/m^2 per year. The study case has not been optimized based on the heating and cooling power demand, i.e. the peak heating and cooling power is not covered by the study.

2 Theoretical background

This study focuses on three Nordic countries; Iceland, Norway and Sweden. Regulations and standards from Iceland, Norway and Sweden on office's ED and IEQ were collected and compared. Then a study case was constructed in IDA ICE Building simulation tool. The study case represents an office room, where all assumptions made for the study case were based on the Norwegian Passive house standard NS 3701.

Two glazing parameters were investigated in this study, one physical and one material aspect of glazing. The physical parameter was Window-to-wall ratio (WWR) and the material parameter was g-value (also known as solar heat gain coefficient). The evaluation process was executed in IDA ICE where glazing parameters were evaluated against ED and IEQ in various conditions. These conditions are called basic condition criteria, which includes three Nordic cities, four cardinal directions and a synthetic external shading object. The glazing parameters was evaluated against three ED elements and three IEQ elements. The elements are heating, cooling and lighting demand for ED, and thermal comfort summer, thermal comfort winter and daylight factor for IEQ.

2.1 Passive house

There is a demand for more energy efficient buildings with healthy indoor climate. Strict design regulations and standards have led to the recognition of passive houses as modern environmentally friendly buildings with extremely low energy use and very good indoor environment quality. The term passive, has now become widespread and success in numerous European countries. Strict requirements for design and construction has led to the recognition of passive design as modern environmentally friendly buildings with extremely low energy demand and very high indoor environment quality.

The demand for more energy efficient buildings in the cold climate of the Nordic countries have led to many passive implementation in regulations and standards to advance this transition. This study focuses on the Norwegian NS 3701 Passive House standard. It is a rigorous, voluntary standard for energy efficiency. The standard provides pattern to construct buildings with extremely low energy use, requiring little energy for space heating and cooling (Ayre, 2014).

Briefly, the passive house technique can be explained by designing a building with better energy efficiency by minimizing heat loss through the building envelope, through effective ventilation and by utilizing heat from the housing, electrical appliances and solar heat gain. This means an air-tight envelope with extra thick insulation, and windows and doors with low U-values. Compared to normal construction, a passive house construction needs to fulfil further requirements regarding limited range of heating, cooling and lighting demand. Figure 2.1 demonstrates some of the fundamental passive house measures.

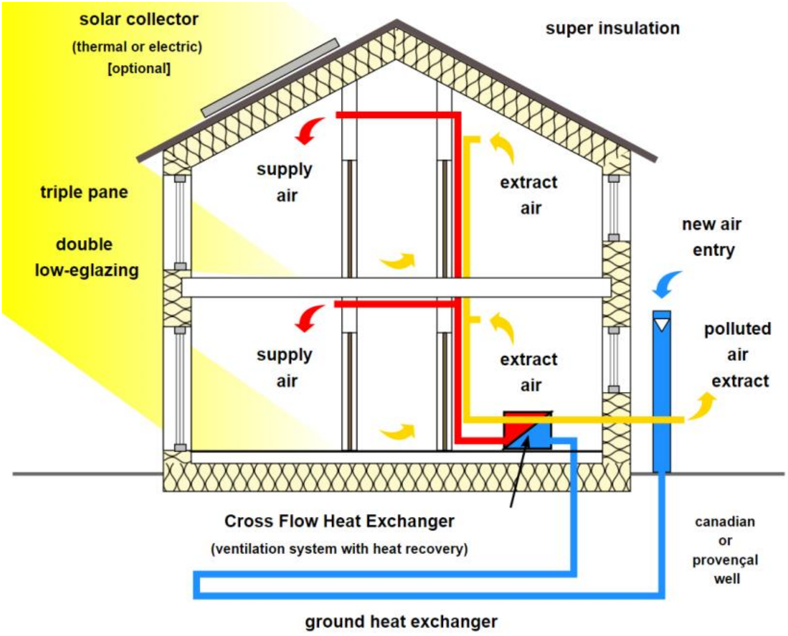

Figure 2.1 Passive house measures for better energy efficiency (https://sv.wikipedia.org/wiki/Passivhus).

2.2 Basic condition criteria

The basic condition criteria consist of three locations, four cardinal directions and a synthetic external shading option. The different combination of these basic condition criteria sets up the climate circumstance for the study case when it undergoes the evaluation process in IDA ICE.

2.2.1 Locations

The locations are; Reykjavík in Iceland, Oslo in Norway and Malmö in Sweden. These three Nordic cities were chosen because they are large urban areas and are separated by 4 – 5° difference in latitude, see Figure 2.2. In IDA ICE, the location data come from ASHRAE Fundamentals 2013 (ASHREA 2013), which include climate data and default wind profile data for urban area. ASHRAE stands for American Society of Heating, Refrigerating and Air-Conditioning Engineers, and it focuses on building systems, energy efficiency, indoor air quality, refrigeration and sustainability technologies.

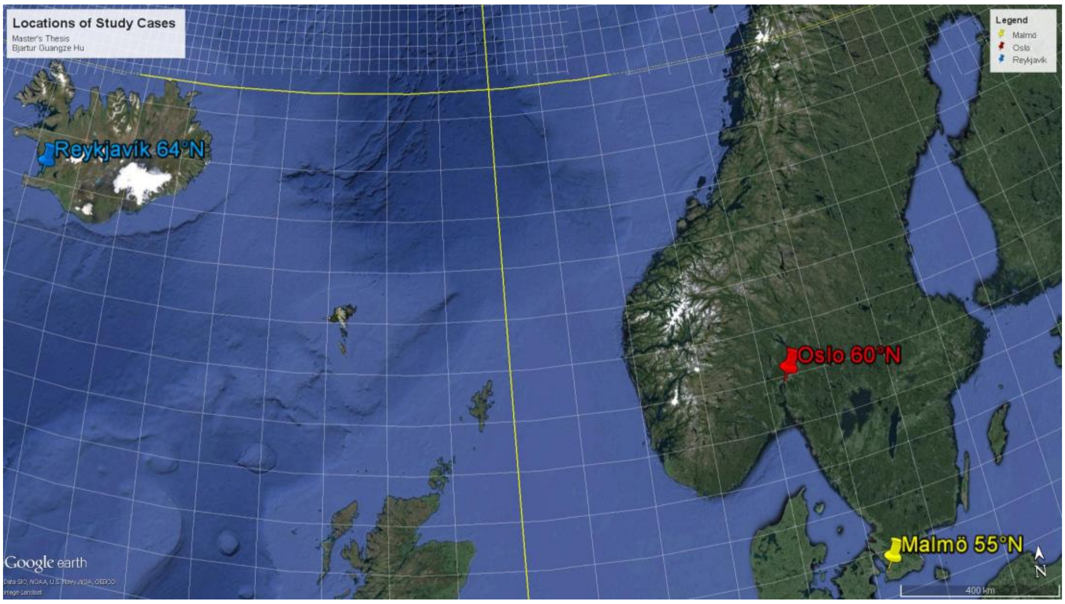

Figure 2.2 Locations for the study case.

The ASHRAE 2013 climate data model is an algorithmic model that calculates and delivers the following data: dry-bulb temperature (°C), relative humidity of air (%), wind speed (m/s), cloudiness (%), sunlight direct normal radiation (W/m^2) and sunlight diffuse radiation on horizontal surface (W/m^2). The most important climate data for this study is the dry-bulb temperature. After observation of temperature records from each location's meteorological offices, the ASHRAE climate data in IDA ICE was selected carefully for each location. Not only it had to be reliable, but also logical to the current climate change from the past till upcoming future. An absolute year's overview of each month's average temperature in Reykjavik, Oslo and Malmö are shown in Table 2.1. It is important to notice that Oslo has a mean dry-bulb temperature of 6.7°C, which is in between the mean dry-bulb temperature in Reykjavik and Malmö. But Oslo has the three hottest months in May, June and July, and the two coldest months in December and January.

Table 2.1 Temperature data from ASHRAE 2013 that was used for the study case in IDA ICE.

	Reykjavik	Oslo	Malmö
Month	Dry-bulb temperature (°C)		
January	-0.2	-3.8	1.5
February	-1.1	-0.9	0
March	0.4	0.9	2.8
April	3.8	4.6	7.3
May	6.5	11.9	11.6
June	9.5	14.7	14
July	11.2	17.5	16.2
August	10.7	16.6	16.9
September	8	11.1	13
October	4.9	6.7	8.4
November	2.1	1.8	4.2
December	0.5	-1.6	1.8
Annual average	**4.7**	**6.7**	**8.2**

2.2.2 External shading objects

There is a likelihood that buildings have external shading objects (ESO) nearby, it could be a hill in rural area or other high-rise buildings in urban city. Study has shown that when external shading object exists, the building under study experiences different magnitude of solar heat load on its façade. The façade splits into two zones, above and below 50 m in elevation. The façade experiences great amount of solar heat load above 50 m but only small amount below 50 m. When no external shading objects are around, the magnitude of solar heat load on façade does not alter with elevation differences. IDA ICE proved this theory as it showed no change in energy demand when the study case was at 25 m or 75 m above ground elevation.

Figure 2.3 Sunlight exposure diagram demonstrates the impact of nearby buildings (building design lab, 2015).

Figure 2.4 shows that the study case has two options of external shading object, one with no external shading object and the other one with a synthetic external shading object. The study case is located at 25 m above ground elevation with a synthetic external shading object directly 20 m in front. The object is 25 m wide and 50 m tall with zero transparency, which should resemble a nearby building as an external shading object. When no external shading object exists, the study case's elevation does not matter regarding ED and IEQ. Consequently, the study case at 25 m height level represents the entire façade.

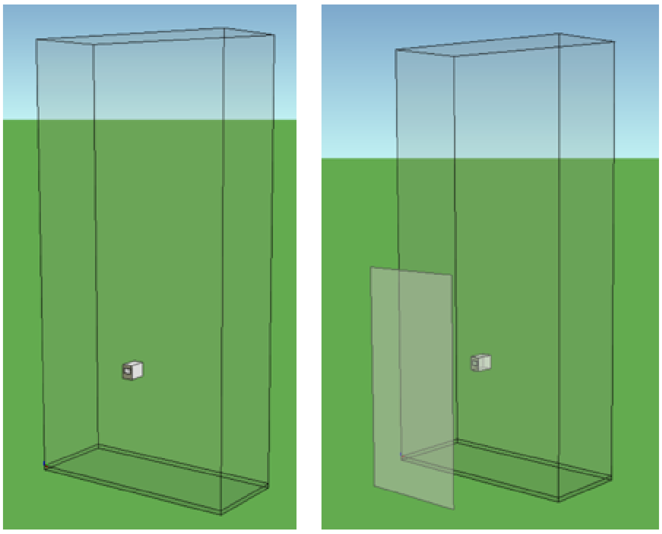

Figure 2.4 No external shading object and synthetic external shading object.

2.2.3 Cardinal directions

Orientation is an important factor when providing a building with passive energy efficiency and thermal comfort. Building orientation should be decided carefully in the early design process. Façade's orientation in the north, south, east and west experiences different magnitude of solar heat and daylight. A southern orientation is preferred due to the ability to shade the summer sun to reduce unwanted solar heat gain while still capturing daylight to reduce the lighting demand. The angle of the summer sun is much higher, while the angle of the winter sun is lower which allows light and heat to possibly enter the space. The north oriented facades receive good ambient and indirect daylight, where solar heat gain, direct light and glare issues can be minimized. But, possible heat loss through window unit should be considered. Due to the low sun angles, glare and increased solar heat gain, it is harder to control on the east and west facades (EWC, 2016). Figure 2.5 and 2.6 show the magnitude of solar radiation intensity on the north, south, east, and west façade during a summer and winter day in Stockholm.

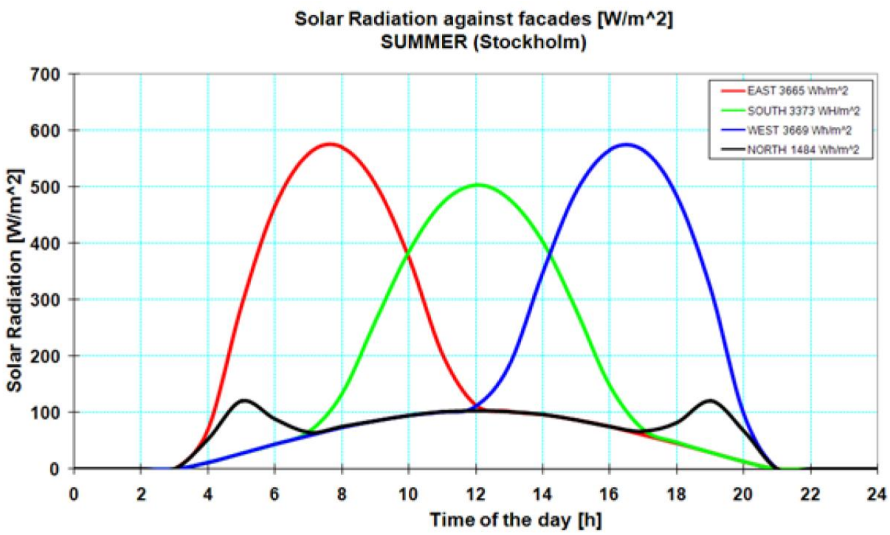

Figure 2.5 Solar radiation on facades in Stockholm during a summer day (Trüschel, 2015).

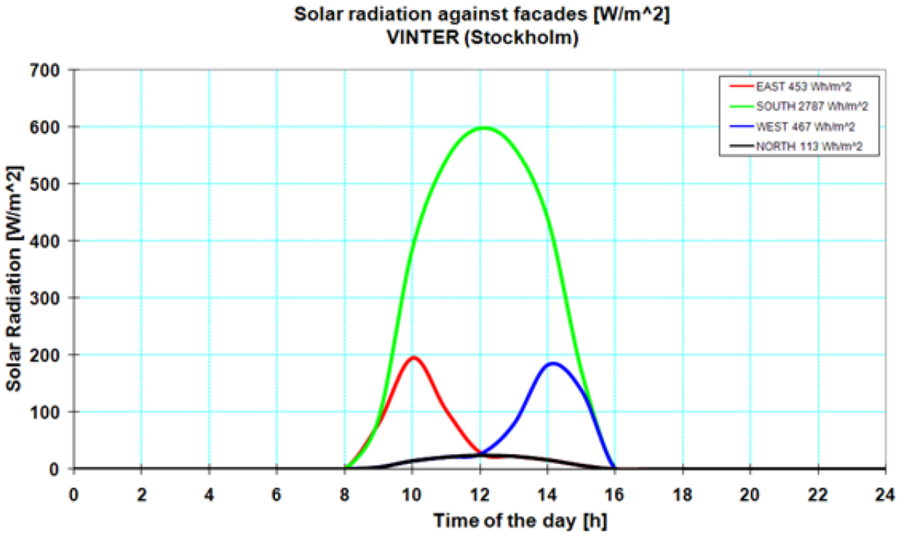

Figure 2.6 Solar radiation on facades in Stockholm during a winter day (Trüschel, 2015).

2.3 ED and IEQ

In EU, over half of the electrical energy and nearly one third of the heat energy is used in buildings. When designing new buildings often only relatively limited additional investments are needed to make them very energy-efficient (Enno, 2015). Energy demand in office buildings can be decreased by following more energy efficient standards and regulations, so the energy could be better used for other things than heating or cooling houses. Three large energy consumer in an office building are heating, cooling and lighting. This study focuses on these three energy demands, as they are the ED elements for this study.

Indoor environment quality is equally important as energy demand. For instance, the salaries of office workers are many times higher than the cost of operating a building in developed countries. Consequently, even small improvements in human performance and productivity following improvements of IEQ can result in a substantial economic benefit (Lan et al., 2016). The addition of good IEQ to energy efficient buildings is very beneficial. If an energy efficient measure also improves the indoor environment it will lower the health risk, increase comfort, increase productivity and always be cost efficient (Olesen, 2016). In an indoor environment, there are numerous factors that affect a person's sense of well-being and its work performance, among those shown in Figure 2.7. This study focuses only on temperature and lighting, more specific the thermal comfort level during summer and winter, and the daylight admission measured in daylight factor described in Chapter 2.3.7, as they are the IEQ elements for this study.

An important reason for choosing these ED and IEQ elements is because they contradict each other. ED's heating-cooling demand contradicts with IEQ's thermal comfort level. Because thermal comfort is one of the factors that is directly connected to the HVAC system that controls the indoor temperature. ED's lighting demand contradicts with IEQ's daylight factor. These contradictions make it is possible to detect if it is feasible to sacrifice IEQ to reduce ED or is it more beneficial to decrease ED rather than improving IEQ.

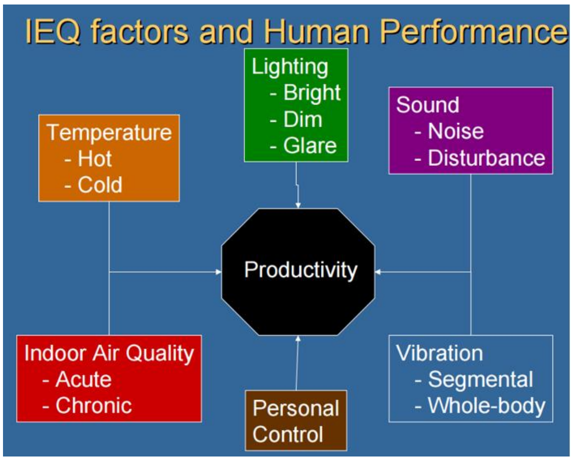

Figure 2.7 Indoor environmental quality factors that affect the productivity and work performance (Hedge, 2001).

2.3.1 Standards

Observation was done to compare the difference in requirements for ED and IEQ from various building standards and regulations from the three Nordic countries; Iceland, Norway and Sweden. In the end, Norwegian Passive-house Standard NS 3701 and Swedish Miljöbyggnad were chosen for this study. Passive-house Standard NS 3701 sets the benchmark for ED elements' requirements and Miljöbyggnad sets the benchmark for IEQ elements' requirements. These requirements can be seen in Table 2.2 and 2.3. Main reason for adopting the ED and IEQ requirements from NS 3701 and Miljöbyggnad is because they had rather tough criteria compared to other regulations and standards. Another more distinct reason is because NS 3701 contains all three ED elements examined in this study, and Miljöbyggnad contains all three IEQ elements.

Table 2.2 ED requirements from NS 3701.

	Heating Demand	Cooling Demand	Lightning Demand
NS 3701 Passive house Standard Professional buildings - Office buidling	Net heating need: ≤ 20,1 kWh/m2 year	Net cooling need: ≤ 9,4 kWh/m2 year	Net lighting need: ≤ 12,5 kWh/m2 year

Table 2.3 IEQ requirements from Miljöbyggnad.

	Daylight Factor	Thermal comfort summer	Thermal comfort winter
Miljöbyggnad New Construction - Officies	(Gold rating) DF ≥ 1,2% + ≥ 80% of users satisfied	(Gold rating) PPD ≤ 10 % + ≥ 80% of users satisfied	(Gold rating) PPD ≤ 10 % + ≥ 80% of users satisfied

The Norwegian passive house standard NS 3701 defines passive house for commercial buildings, and includes definitions and requirements for heat loss, heating demand, cooling demand, energy for lighting and minimum requirements for individual building components. The standard also provides requirements on leakage figures, test procedures, methods of measurement and reporting of energy performance on completion of professional buildings.

Miljöbyggnad is a Swedish system for certifying buildings in relation to energy, indoor climate and materials. The building is examined in relation to fifteen different indicators with respect to energy, indoor environment and materials. Each indicator is measured and assessed to give a final rating for the entire building.

2.3.2 Score table for ED and IEQ

The three ED elements are; heating, cooling and lighting demand, and the three IEQ elements are; thermal comfort summer, thermal comfort winter and daylight factor. These elements are converted to a score table, with the purpose to rate the façade glazing parameters by giving them a grade from 0 to 10. The range of each score table element is based on requirements from NS 3701 and Miljöbyggnad, but are adjusted accordingly to the worst and best evaluation results of the study case.

Table 2.4 presents the score table for the three ED elements, and Table 2.5 presents the score table for the three IEQ elements. Each score table element's range is split in ten equal intervals and is grated from 0 to 10, 10 being the best score. After each evaluation, the study case receives a score from each score table element based on its performance. The number of intervals is decisive, because they separate the evaluation results. The more intervals, the clearer is the differences, thus more precision in results. The number of decimals for each element is based on the output results from IDA ICE.

Table 2.4 Score table for ED elements.

Heating demand		Cooling demand		Lighting demand	
$kWh/m^2 * year$	*Score*	$kWh/m^2 * year$	*Score*	$kWh/m^2 * year$	*Score*
< 4.7	*10*	< 0.1	*10*	< 4.4	*10*
4.7 – 6.4	*9*	0.1 – 1.6	*9*	4.4 – 4.7	*9*
6.5 – 8.1	*8*	1.7 – 3.2	*8*	4.8 – 5.1	*8*
8.2 – 9.8	*7*	3.3 – 4.8	*7*	5.2 – 5.5	*7*
9.9 – 11.5	*6*	4.9 – 6.4	*6*	5.6 – 5.9	*6*
11.6 – 13.2	*5*	6.5 – 8	*5*	6 – 6.3	*5*
13.3 – 14.9	*4*	8.1 – 9.6	*4*	6.4 – 6.7	*4*
15 – 16.6	*3*	9.7 – 11.2	*3*	6.8 – 7.1	*3*
16.7 – 18.3	*2*	11.3 – 12.8	*2*	7.2 – 7.5	*2*
18.4 – 20	*1*	12.9 – 14.4	*1*	7.6 – 7.9	*1*
> 20	*0*	> 14.4	*0*	> 7.9	*0*

Table 2.5 Score table for IEQ elements.

Thermal comfort summer		Thermal comfort winter		Daylight factor	
PPD (%)	*Score*	PPD (%)	*Score*	DF	*Score*
< 5.24	*10*	< 5.24	*10*	< 0.22	*10*
5.24 – 5.4	*9*	5.24 – 5.4	*9*	0.22 – 0.3524	*9*
5.41 – 5.57	*8*	5.41 – 5.57	*8*	0.3525 – 0.4849	*8*
5.58 – 5.74	*7*	5.58 – 5.74	*7*	0.485 – 0.6174	*7*
5.75 – 5.91	*6*	5.75 – 5.91	*6*	0.6175 – 0.7499	*6*
5.92 – 6.08	*5*	5.92 – 6.08	*5*	0.75 – 0.8824	*5*
6.09 – 6.25	*4*	6.09 – 6.25	*4*	0.8825 – 1.0149	*4*
6.26 – 6.42	*3*	6.26 – 6.42	*3*	1.015 – 1.1474	*3*
6.43 – 6.59	*2*	6.43 – 6.59	*2*	1.1475 – 1.2799	*2*
6.6 – 6.76	*1*	6.6 – 6.76	*1*	1.28 – 1.4124	*1*
> 6.76	*0*	> 6.76	*0*	> 1.4124	*0*

2.3.3 Heating

Room heating is a large energy consumer in office buildings in cold climate. In IDA ICE, the heating demand consists of space heating and AHU heating. NS 3701 has a minimum heating requirement of ≤ 20.1 kWh/m^2 per year for an office building. This value is incorporated into the worst and best heating evaluation results of the study case. The worst condition is in the north façade in Reykjavik which has the highest heating demand, and the best condition is in the south façade in Malmö which has the lowest heating demand. Eventually, the score table has a heating demand range of 4.6 – 20 kWh/m^2 per year, see Table 2.4.

2.3.4 Cooling

The cooling demand in IDA ICE consists of space cooling and AHU cooling. The outdoor temperature at which the internal heat has the same magnitude as the heat losses from the room is called balance temperature. As building techniques improved, windows became better insulated and the use of heat generating office equipment increased, the balance temperature sank dramatically. This means that modern offices have a heat surplus nearly all the time while they are in use (Enno, 2015). According to NS 3701 calculation method in Table 2.6, the maximum cooling demand allowed for an office building is 9.4 kWh/m^2 per year. This indicates that the dimensioned outdoor temperature (DUT_s) is equal to 26.7 °C for Oslo, as it turned out to be 26.8°C when using ASHRAE 2013 climate data for the warmest 50 hours in Oslo. According to ASHRAE 2013 climate data, Malmö has a DUT_s of 30 °C and 20 °C in Iceland. So, by using the NS 3701 method in Table 2.6, the maximum allowed cooling demand in Reykjavik is 0 kWh/m^2 per year, and 14.4 kWh/m^2 per year in Malmö. This forms the score table range for cooling demand of 0 – 14.4 kWh/m^2 per year, see Table 2.4.

Table 2.6 Requirement from NS 3701 for the maximum allowed cooling energy use.

DUT_s	Highest calculated net specific energy need for cooling $kWh/(m^2 * year)$
> 20°C	$\beta * (20 - DUT_s)$
≤ 20°C	0
$\beta = 1{,}4$ (for office building) is a cooling demand coefficient depending of the building's category. DUT_s is dimensioned outdoor temperature (°C) during summer for the annual highest 50 hours' temperature.	

2.3.5 Lighting

Electric lighting can be reduced by using smart lighting but also by providing more daylight through windows by using design strategies such as light redirection (EWC, 2016). According to NS 3701, the annual maximum allowed net specific energy demand for lighting in office buildings is 12.5 kWh/m^2 per year. This requirement is adjusted to the worst and best lighting evaluation results of the study case. The worst condition is in the north façade in Reykjavik which has the highest lighting demand, and the best condition is in the south façade in Malmö which has the lowest lighting demand. Eventually, the score table for the lighting demand has a range of 0 – 7.9 kWh/m^2 per year, see Table 2.4.

2.3.6 Thermal comfort

Air temperature is the commonly used indicator of thermal environment and productivity research. Inadequate thermal conditions expressed by both elevated or too low temperatures has significant negative effects on the human performance (Lan et al., 2016). Thermal comfort is a condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation. An accurate way to evaluate thermal comfort level is through Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), see Figure 2.8. The PMV/PPD model establishes a relationship between perceptions and climate factors. One of the factors that the relationship includes is the air and radiation temperatures, as well as metabolic rate and types of clothing (Enno, 2015). In total, there are six factors taken into consideration when designing for thermal comfort. The environmental factors include air temperature, radiant temperature, relative humidity, and air velocity. The personal factors are metabolic rate (activity level) and clothing.

Table 2.7 The six thermal comfort design factors.

Thermal comfort	Description
Metabolic rate (met)	The energy generated from the human body
Clothing insulation (clo)	The amount of thermal insulation the person is wearing
Air temperature	Temperature of the air surrounding the occupant
Radiant temperature	The weighted average of all the temperatures from surfaces surrounding an occupant
Air velocity	Rate of air movement given distance over time
Relative humidity	Percentage of water vapor in the air

In this study, an analytical measurement and evaluation of the thermal comfort level in the study case was carried out using PPD index for summer and winter climate. June, July and August are the hottest months and were used as summer climate. The average PPD value during occupancy time in these three months becomes the thermal comfort summer PPD value. This approach also applies for December, January and February, which are the coldest months and were used as winter climate. The score table range for the summer and winter PPD is 5.24 – 6.76, see Table 2.5. This range is within the Gold certification according to Miljöbyggnad.

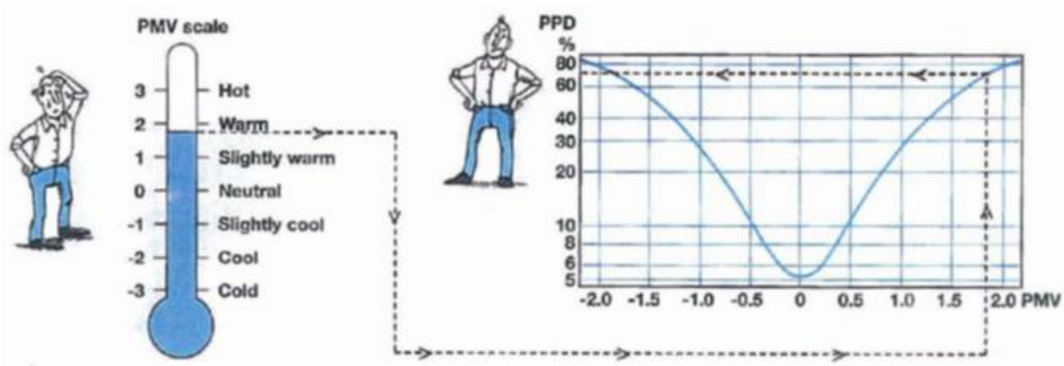

Figure 2.8 PMV and PPD index (Trüschel, 2015).

2.3.7 Daylight

With larger and more populous cities, the building density increased, which resulted in lack of daylight in buildings. With more knowledge and understanding of daylight, and its benefits, the interest increased, which resulted in the formulation of daylight factor (DF). The DF is the most widely used method of establishing compliance with building code and regulation requirements. It must not be mistaken, that the daylight factor is an indicator for daylight performance, rather than an actual measure of it. The DF has limitations of taking no account of building location, sun position, façade orientation, and provides no indications of glare and visual comfort. Although the daylight factor lacks realism, practitioners have become accustomed to it (Thordardottir, 2016). The DF is calculated by dividing the horizontal work plane illumination indoors by the horizontal illumination on the tested building's roof. It is expressed in percentage, the higher the DF, the more natural light is available in the room, see Figure 2.9. The results of the study case's worst and best evaluations in terms of DF give a score table range of 0.22 – 1.41, see Table 2.5. According to Miljöbyggnad, a daylight factor above 1.2 receives a gold certification.

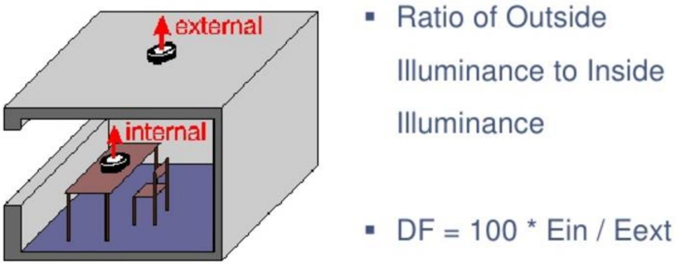

Figure 2.9 Definition of the daylight factor (Wasilowski, 2009).

In this study, the daylight factor is expressed as an average. Figure 2.10 demonstrates the average daylight factor evaluation of the study case in IDA ICE. The average daylight factor is the arithmetic mean of the sum of point measurements taken at a height of 0.85 m in a grid covering the whole floor area of the room (CLEAR, 2017).

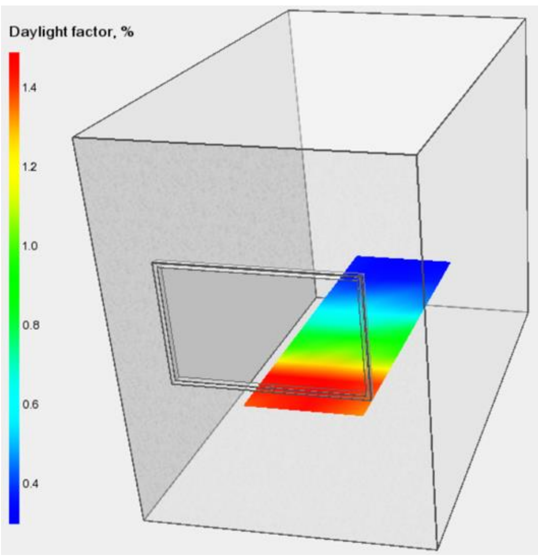

Figure 2.10 The study case under daylight evaluation in IDA ICE. In this example, the study case has a WWR of 25%. The daylight simulation date is irrelevant.

2.4 Façade glazing parameters

There are certain façade glazing design decisions that are generally known to affect the IEQ and are commonly used in passive houses. These strategies include: giving occupants personal control over operable windows, employing daylight and reducing ambient light levels by using task lighting. Occupants in passive houses are on average more satisfied (Abbaaszadeh et al., 2006).

The façade glazing parameters chosen for this study have impact on the building's heating, cooling and lighting demand, as well having impact on the IEQ in terms of thermal comfort and daylight admission. This study examines window-to-wall ratio (WWR) as the physical aspect of glazing and g-value (also known as solar heat gain coefficient) with visible transmittance (T_{vis}) as the material aspect of glazing.

2.4.1 Physical aspect of glazing: WWR

Window-to-wall ratio (WWR) is the percentage of glazing area divided by the exterior envelope wall area (EWC, 2016). The study case has an exterior wall area of 7.68 m^2. Three WWR alternatives were examined for this study; 20%, 25% and 30%. This WWR range is indeed small, where many new office buildings have much larger façade glazing area. The impact of WWR on the ED and IEQ within this small range might not translate accurately when predicting for the impact of higher WWR. Therefore, a reliability study is conducted with higher WWR in Appendix A to understand fully the relationship. This helps to choose the most accurate regression type to demonstrate the impact of 20 – 30% WWR on ED and IEQ, which can also be used to predict for impact of higher WWR.

In addition to WWR, the shape and placement of the glazing have different effect on daylight admission. Figure 2.11 demonstrates that the widest and highest placed window (blue line) provides the most daylight admission in a room. More sunlight might increase the cooling demand and diminish thermal comfort, but for the sake of daylight admission, regardless of WWR, the window for the study case is constructed with wider width than length and has a high elevation above floor, see Figure 2.12.

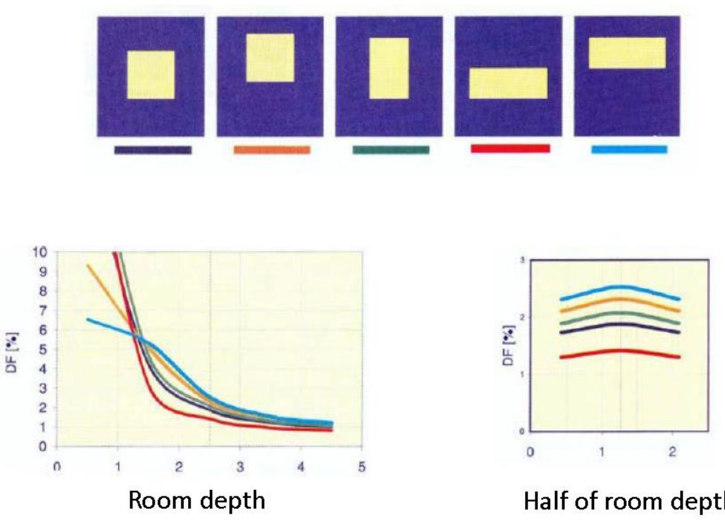

Figure 2.11 Daylight admission of different window shapes and height level (Österbring, 2015).

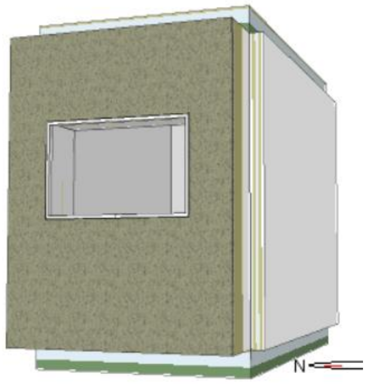

Figure 2.12 Study case with 20% WWR. The window has a wide width and a high elevation above floor.

2.4.2 Material aspect of glazing: g-value

Facade glazing can be designed with a higher WWR by using high-performance glazing material that may or may not be used in combination with interior and exterior shading strategies. These designs reduce the unwanted solar heat gain through the large glazing area, while still allowing for natural daylight to enter spaces which results in reduced electric lighting use. There are four properties of window that are the basis for quantifying energy performance; U-value, g-value, visible transmittance (T_{vis}) and air leakage (EWC, 2016). Only g-value in association with T_{vis} have impact on every ED and IEQ elements. For that reason, this study examines these two properties as material aspect of glazing.

A major energy-performance characteristic of window is the ability to control solar heat gain through glazing by its g-value. Regardless of outside temperature, heat can be gained through windows by direct or indirect solar radiation. Solar heat gain through windows is a significant factor in determining the cooling load of many commercial buildings. The g-value of glazing ranges from above 80% for uncoated water-white clear glass to less than 20% for highly reflective coatings on tinted glass (EWC, 2016). Solar heat gain coefficient (SHGC) is analogous to the g-value when it refers to the solar energy transmittance of the glass alone.

IDA ICE has a large database of glazing selections. The selected three glazing types have g-value of 0.19, 0.33 and 0.45. These were used to investigate the impact of g-values on ED and IEQ. For U-value below 1.4 W/m^{2}K, it is rare to find g-value much lower than 0.19 or much higher than 0.45. Unlike WWR, there is no need to investigate g-values outside of this range, especially for g-value higher than 0.45. This is because glazing types with g-value higher than 0.45 have poor U-value, which is not suitable for new office buildings in present day. But there is a development in low U-value windows without diminishing the g-value. This way, the window prevents heat loss to outside without decreasing the capability of accepting sunlight admission to indoor.

Visible transmittance (T_{vis}) is an optical property that indicates the amount of visible light transmitted through the glass. It affects energy by providing daylight that creates the opportunity to reduce electric lighting and its associated cooling loads. Visible transmittance is influenced by the glazing type. Visible transmittance of glazing ranges from above 90% for uncoated water-white clear glass to less than 10% for highly reflective coatings on tinted glass. A typical double-pane insulating glass unit has a T_{vis} of around 78%. This value decreases somewhat by adding a low-E coating and decreases substantially when adding a tint, see Figure 2.13. It is common to have windows that reduces the solar heat gain, but also reduces the visible transmittance. However, new high performance tinted glass and low E-coatings have made it possible to reduce the solar heat gain with little reduction in the visible transmittance. Because, the idea of separating the solar heat gain control and light control is very important (EWC, 2016).

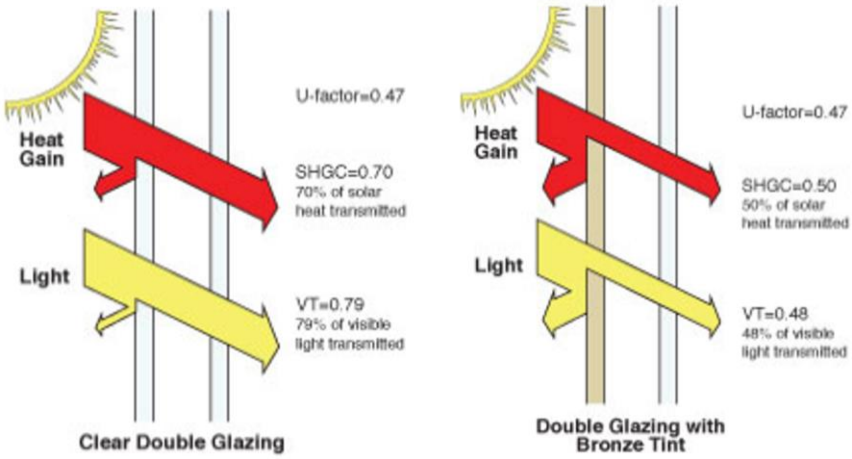

Figure 2.13 Double glazing unit with same U-value, but different g-value and T_{vis}.

The three different glazing types used for this study are presented in the Table 2.8. As mentioned before, it is common that glazing which reduces solar heat gain also tend to reduce visible transmittance. These three glazing types are no exceptions, as g-value decreases, so does T_{vis}. These three glazing types share the same values for all other glass properties, i.e. 0.837 for internal and external emissivity and 1.1 W/(m^{2}K) for U-value.

Table 2.8 Glazing types and their material properties selected for the study case.

Glazing system	g-value	T_{vis}
Pilkington Suncool 30/17 (6C(30)-15Ar-4) [1]	0.19	0.3
Pilkington Arctic Blue (6ab-15Ar-S(3)6) [2]	0.33	0.48
Saint-Gobain D4-15 m. Parsol Green+ar+Planitherm ultra	0.45	0.7

[1] Pilkington Insulight 6C(30)- 15Ar-4 (2-glass) with outer glass Suncool 30/17, cavity width 15 mm argon, inner glass Optifloat Clear. LT (daylight)=30%

[2] Pilkington Insulight 6ab-15Ar-S(3)6 (2-glass) with outer glass Arctic Blue, cavity width 15 mm argon, innter glass Optitherm S3. LT (daylight)=48%

3 Technical approach

The empirical part of this study revolves around the software IDA ICE for simulating different scenarios for the same study case. The main purpose of the software is simulating different parameters for a building such as heating energy demand, zone temperatures, average PPD and many others. It provides the opportunity to estimate the indoor conditions of any area of a given study case for any desired time-period. Running a simulation requires a 3D modelling of the study case, configuration and various inputs (Güngör, 2015).

3.1 IDA ICE

IDA ICE building simulation tool evaluates building performance in terms of energy efficiency and indoor climate. It accurately models the building and its systems, thus ensuring the lowest possible energy demand and the best possible indoor environment quality. IDA ICE performs whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy demand of the entire building.

The most important IDA ICE calculations benefited for this study are the full zone heat balance, including specific contributions from the sun, occupants, equipment, lighting, ventilation, heating/cooling devices, surface transmissions, air leakage and thermal bridges. Also, the calculation of the solar influx through windows with a full 3D account of the surrounding shading objects, where the full non-linear Stephan-Bolzmann radiation with view factors is used to calculate the radiation exchange between surfaces. At last, the calculations of the air and surface temperatures (Kalamees, 2004).

The model library of IDA ICE was written in the Neutral Model Format (NMF), which is a program for modelling the dynamical systems by using differential algebraic equations. IDA ICE is a general-purpose simulation environment, which consists of the translator, solver, and modeller. The translator is the outline of the study case, where all the essential features are defined before simulation, see Figure 3.1. The solver is the simulation process, where IDA ICE conducts the calculations for the requested outputs during a specific time-period. The modeller is the output formats, where the results are given in values and graphs, see Figure 3.2.

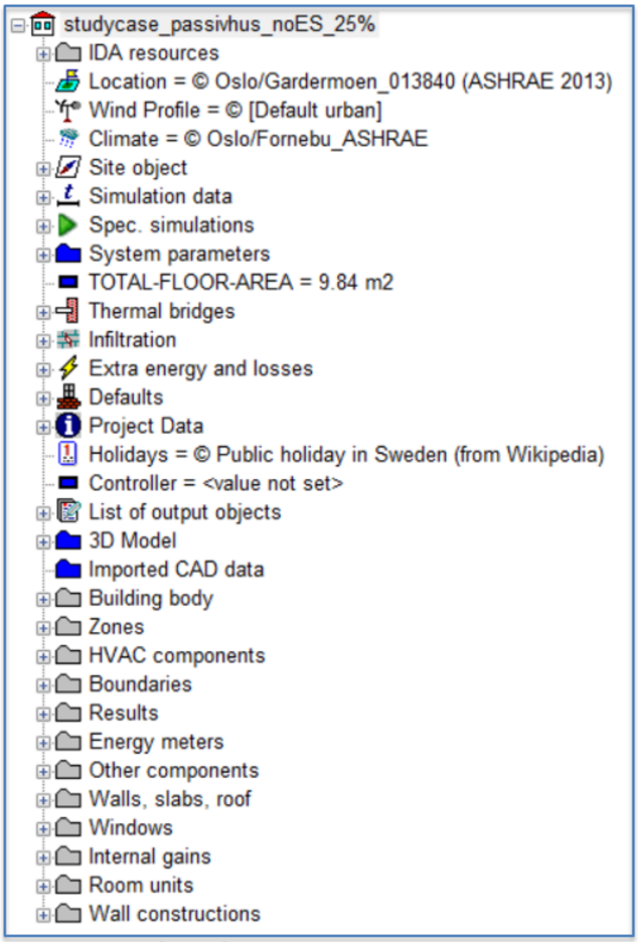

Figure 3.1 The outline of the study case. All the essential features of the outline had to be defined in detail before the simulation of the building.

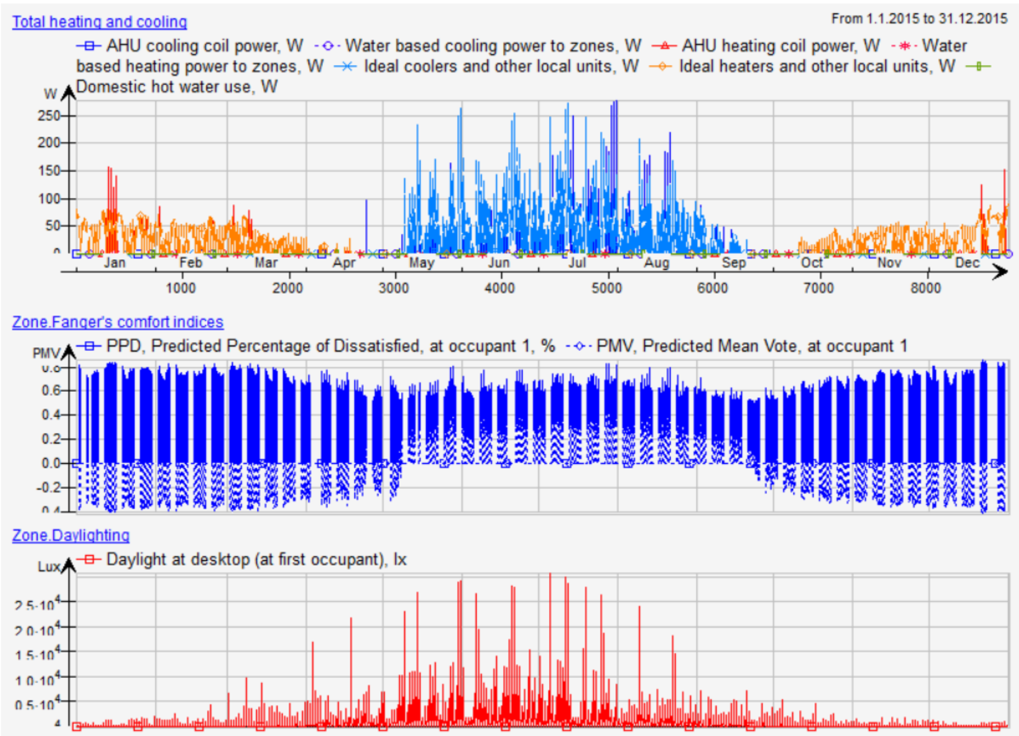

Figure 3.2 The examined results for this study are the annual heating, cooling, comfort indices and daylighting.

4 Test setup of the study case

An office room should cover at least 10 m^2, as architects commonly suggest 2.4 x 4.1 m, which is considered as normal size (Tollånes, 2007). The height should at least be 3 m for a typical office room (Enno, 2015). Eventually, the study case was constructed with a 2.4 x 4.1 m floor area and a height of 3.2 m. Gross internal area (GIA) of the study case is 9.84 m^2, i.e. the floor area contained within the building, measured to the internal face of the external walls.

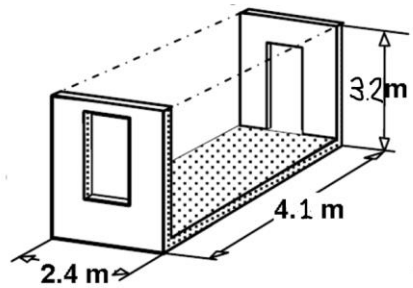

Figure 4.1 The study case of an office room.

Before the evaluation process, the study case had to be well defined in IDA ICE building simulation tool so it reflects an office room. All the essential input parameters of the study case are given in Appendix B. The original model was modified in five steps, where the room's heating demand is reduced after each step. The five steps are; building envelope insulation, smart lighting, internal heat gain, efficient air handling unit and restricted glazing area. All assumptions made were based on NS 3701 passive house standard requirements. In this way, the study case certifies as a passive office design. The main aim is to construct a study case that requires an annual heating demand below 20.1 kWh/m^2 in the north façade in Reykjavik. This is because out of the three locations examined in this study, the north façade in Reykjavik has the coldest average outdoor temperature and the least solar radiation, which makes it most challenging to achieve a heating demand ≤ 20.1 kWh/m^2 per year.

4.1 Modification steps

Before analysing the study case, various parameters and specifications had to be determined and adjusted, so the study case reflects as a standardized passive house for office building. The energy demand is reduced through passive measures such as extra insulation, utilization of daylight admission, specified internal heat gain, good air handling unit and limited glazing area. The study case was exactly modified according to these five passive house measures.

4.1.1 Modification step 1 – Building envelope insulation

In IDA ICE, the different envelope parts separate the study case from the outdoor. The geometry, material layers and their properties define the envelope parts. Passive house buildings employ high insulation to significantly reduce the heat transfer through the walls, roof and floor compared to conventional buildings. NS 3701 passive house standard proposes a U-value of 0.10 – 0.12 W/m^2K for external walls. By increasing the insulation thickness of the study case's external wall, the study case achieved a U-value of 0.11 W/m^2K. Since this study only explores the façade area, the study case's internal wall, ceiling and floor are irrelevant, because they have no connection with the outdoor climate and are adiabatic, i.e. they share the same temperature as other areas of the building's indoor climate. According to NS 3701, the so called normalized thermal bridge has to be ≤ 0.03 W/m^{2}K. The normalized thermal bridge is an estimate of the total thermal loss of all thermal bridges of a building. The normalized thermal bridge of 0.03 W/m^{2}K suggests almost very little existence of thermal bridges. The study case has three thermal bridges that are relevant to this study. They are external wall/internal slab joint, external wall/internal wall joint and external window perimeter. These thermal bridges are limited to obtain a total normalized thermal bridge of 0.02 W/m^{2}K.

Table 4.1 Building envelope properties for the study case.

Building element	Value	Description
Wall construction	U-value = 0.11 W/m^{2}K	250 mm concrete 290 mm XPS insulation 75 mm light weight concrete
Glazing area	1.92 m^2	1.6 x 1.2 m or 25% of the façade area
Thermal bridge	0.02 W/m^{2}K	External wall/internal slab joint = 0.0072 W/mK External wall/internal wall joint = 0.0072 W/mK External window perimeter = 0.0144 W/mK
Infiltration	0.6 h^{-1}	NS 3701 Passive house standard

The study case's glazing properties are presented in Table 4.2. NS 3701 requires a g-value ≤ 0.15 and a U-value ≤ 0.8 W/m^{2}K. These requirements are quite extreme compared to other standards and regulations, so these requirements are eased for this study case. In the evaluation process, the impact of the g-value on the ED and IEQ is investigated specifically as a material aspect of glazing with three g-value alternatives.

Table 4.2 Glazing properties for the study case.

Solar heat gain (g-value)	Solar transmittance (T-value)	Visible transmittance (T_{vis})	U-value	Internal emissivity*	External emissivity*
0.33	0.26	0.48	1.1 W/m^{2}K	0.837	0.837
* The emissivity of the material's surface is its effectiveness in emitting energy as thermal radiation.					

4.1.2 Modification step 2 – Smart lighting

Lux in photometry, is used as a measure of the intensity perceived by the human eye of the light that hits or passes through a surface, see Figure 4.2. It is recommended that occupant's desk should have 400 – 500 lux (NS EN, 2011). So, the controller set points for daylight at workspace is set to be 400 – 500 lux for the study case in IDA ICE. This means, when the indoor workspace is below 400 lux the lighting activates and above 500 lux the lighting deactivates. In this way, the indoor lighting will add the additional lux needed when solar daylight is insufficient of guaranteeing minimum 400 lux. This lighting control system serves to provide the right amount of light when it is needed. The lighting control system is employed to maximize the energy savings from the lighting system and to satisfy NS 3701 passive house standard. Lighting control systems are often referred to under the term smart lighting. For the study case, the lighting control is scheduled according to the occupancy time, which is 12 hours a day, from 06:00 – 18:00 and 5 days a week for an office building (NS 3031, 2012). NS 3701 allows maximum 8 W/m^2 lighting use for an office building, this is about 80 W for the study case of 9.84 m^2. So, the study case is installed with two 40 W lamps. The most lighting demand is during winter when the sunlight is weak. During a working day, the most lighting demand is during morning and evening when solar daylight is insufficient.

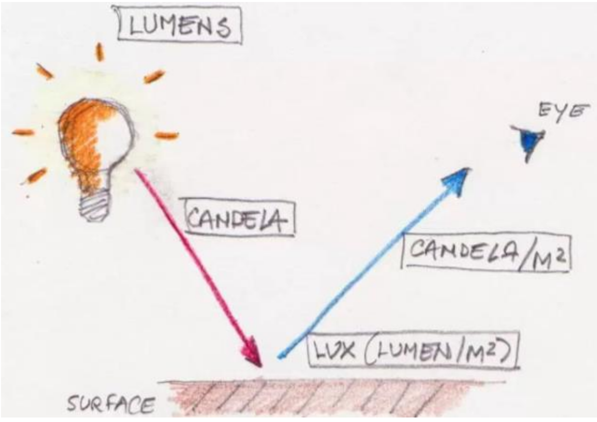

Figure 4.2 Lux is the metric unit of measure for illuminance of a surface. One lux is equal to one lumen per square meter. Lumen is the flux emitted within a unit solid angle by a point source with a uniform luminous intensity of one candela (Earth & Architecture, 2014).

4.1.3 Modification step 3 – Internal heat gain

It is important to define the convenient clothing and action level of an office occupant because clothing and action level affect the perception of climate, which directly relates to occupant's thermal comfort level (Enno, 2015). For this study, the study case's occupant has a met value of 1.2 and clo value of 0.85±0.25, where ±0.25 means that the clothing is automatically adapted between limits to obtain comfort. The selected met and clo value is recommended for an office occupant. The unit met is used for metabolism, and is used to define the rate of energy use by a body and the resulting generation of heat. By definition, 1 met generates 58.2 W of heat per m^2 of body area. The unit clo is a clothing unit, used to measure the thermal insulating capacity.

Other heat sources installed in the study case are office equipments. According to NS 3701, equipment in an office emits 6 W/m^2 heat to the surroundings, this is about 59 W internal heat gain for the study case. The internal heat emission from occupant and equipment helps to decrease the heating demand, i.e. less energy for space heating is needed, but cooling demand might increase during summer.

Table 4.3 Internal heat gains for the study case.

Heat load	Value	Schedule
Lighting	80 W	Control strategy in accordance with smart lighting. On during 06:00 to 18:00 in weekdays. Off on weekends and holidays.
Equipment	59 W	In use during 06:00 to 18:00 in weekdays. Not in use on weekends and holidays.
Occupant	1.2 met 0.85±0.25 clo	Working hours 06:00 to 18:00 in weekdays. Lunch break between 12:00 to 13:00. Nonworking on weekends and holidays.

4.1.4 Modification step 4 – Efficient air handling unit

According to NS 3701, the lowest allowed variable-air-volume (VAV) air flow for office is 6 $m^3/(m^2h)$ during working hour and 1 $m^3/(m^2h)$ during non-working hour. In IDA ICE, this is converted to a constant-air-volume (CAV) system with 1.67 $L/(m^2s)$ during working hour and 0.28 $L/(m^2s)$ during non-working hour. This is because CAV system can be represented as a VAV system by taking 80% of its maximum air flow (Hauksson, 2016). Furthermore, NS 3701 requires minimum 80% heat exchanger temperature efficiency in an air handling unit. A rotary heat exchanger can have as much as 87% temperature efficiency. This is used for the study case.

Table 4.4 Relevant AHU properties for the study case.

HVAC system	Value	Description
Room temperature set-points	Minimum: 21°C Maximum: 24°C	The control action of HVAC systems depends on these temperature set-points.
Humidity and CO_2	Humidity: 20%-80% Level of CO_2: 700-1100ppm	Values are for ideal heaters & coolers. Ambient CO2: 400
Air flow	Working hour: 1.67 $L/(m^2s)$ Non-working hour: 0.28 $L/(m^2s)$	CAV-system
Supply air temperature	16°C	Constant supply
AHU efficiency	87%	Rotary heat exchanger
AHU schedule	Always on	
Room heating	100% efficiency Unlimited capacity	District heating
Room cooling	100% efficiency Unlimited capacity	Electric cooling

4.1.5 Modification step 5 – Restricted glazing area

NS 3701 recommends that building's glazing area should be restricted because of the large transmission heat loss through glazing. This is adapted as window-to-wall ratio (WWR) for this study. The study case's total façade area (glazing included) is 7.68 m^2. Later in the evaluation process, the impact of WWR on ED and IEQ is investigated specifically as a physical aspect of glazing with three WWR alternatives. As for now, the study case is adjusted to a WWR of 25%.

4.2 The final study case

After each modification step the total annual energy demand is decreased. The heating demand is also decreased after each step except after step 2, smart lighting. Eventually, after the 5 modification steps, the study case's heating demand has reached its target, i.e. a heating demand below 20.1 kWh/m^2 per year for the coldest condition in the north façade in Reykjavik. In addition, the total energy demand is within the energy frame of 115 kWh/m^2 for an office building according to the Norwegian building regulation TEK10. The study case is now ready for the evaluation process.

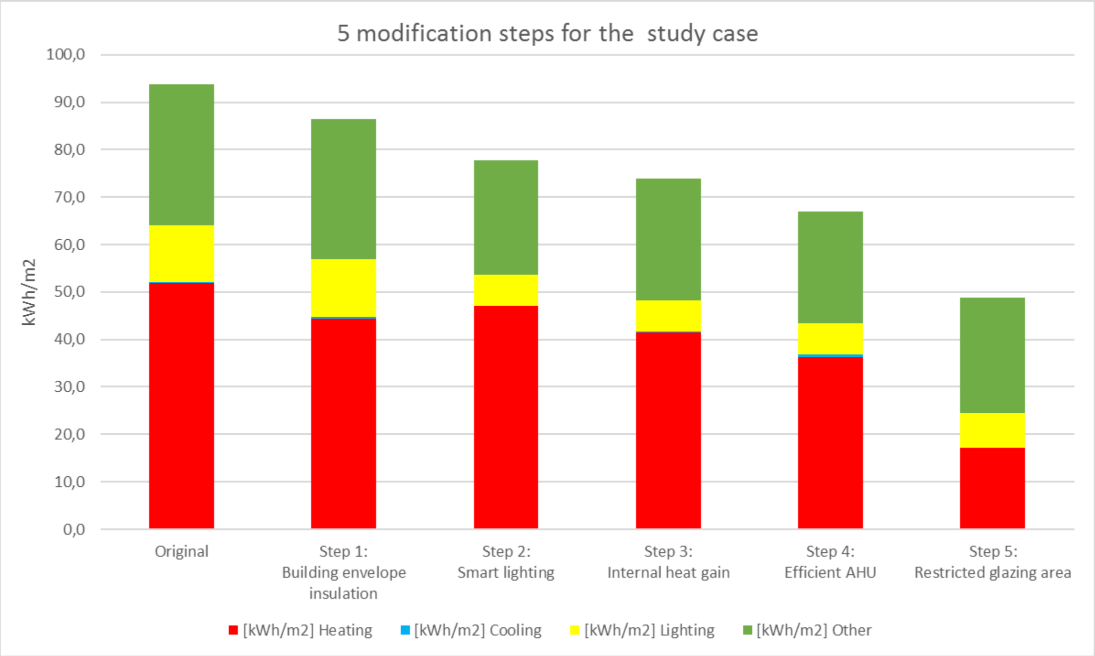

Figure 4.3 Five modifications steps to reduce the energy demand of the study case, with a specific target of reaching a heating demand ≤ 20.1 kWh/m^2 per year.

5 Evaluation process

The study case constructed in IDA ICE is evaluated in different conditions with the chosen glazing parameters. Each evaluation obtains a score according to the ED and IEQ score table. Over 100 evaluations were conducted and each had a distinct effect on the score table elements. The basic condition criteria consist of three locations, two external shading options and four cardinal directions. The façade glazing parameters consist of two aspect of glazing, one physical aspect in terms of WWR and one material aspect in terms of g-value. Each aspect has three alternatives. The score table elements consist of three ED elements; heating, cooling and lighting demand, and three IEQ elements; thermal comfort summer, thermal comfort winter and daylight factor.

The evaluation process in IDA ICE is best described by Figure 5.1. The process is about putting the façade glazing parameters in different basic conditions to investigate the impact on the score table elements.

The results from each IDA ICE evaluation is given in systems and building's energy report shown in Appendix C and D. These results from all the evaluations are gathered and graphed to analyse the impact of glazing on ED and IEQ. The impact of WWR on ED and IEQ is examined first, then the impact of g-value on ED and IEQ. Finally, the glazing parameters are graded by the ED and IEQ score table.

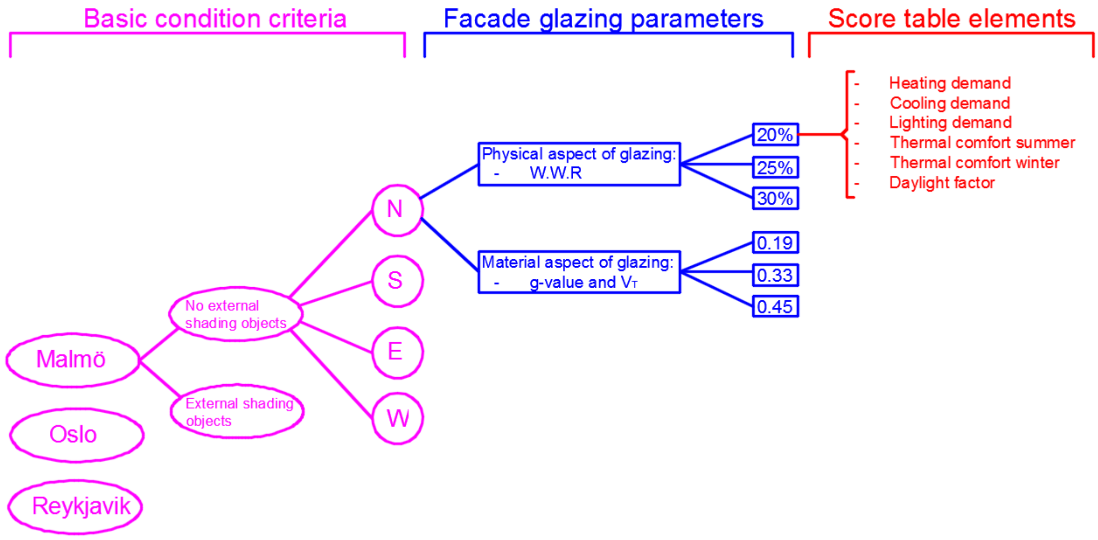

Figure 5.1 The evaluation process.

6 Analysis of results

The outcome of the evaluations is analysed through graphs, so the impact of glazing parameters on ED and IEQ becomes more evident. Further observation was done for higher than 30% WWR in Appendix A. This increases the reliability of the relationship between WWR and ED-IEQ for the limited WWR range of 20-30%, as well determining the most accurate regression types. The WWR evaluations have a constant g-value of 0.33, while g-value evaluations have a constant 25% WWR for Malmö and Oslo, but 30% WWR for Reykjavik. This is because these WWR have the best total score in terms of ED and IEQ after WWR evaluations, see Chapter 6.5.

6.1 Impact of WWR on ED

The evaluation results vary with locations, orientations and WWR values. ED elements are heating, cooling and lighting demand. The impact of WWR on each ED element is examined independently. The results are first presented with four graphs, then analysed and explained afterwards.

Relationship of WWR and Heating demand

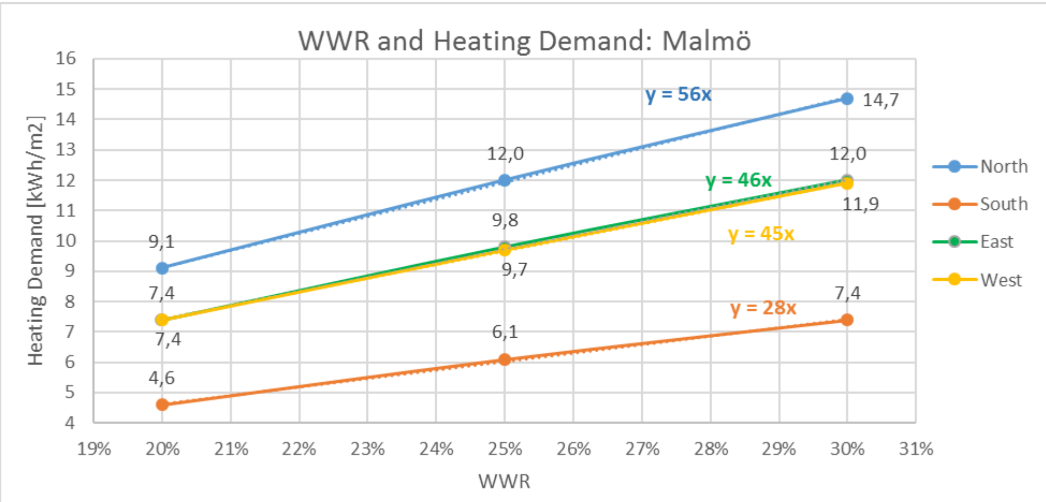

Figure 6.1.1 Relationship between heating demand and WWR in Malmö.

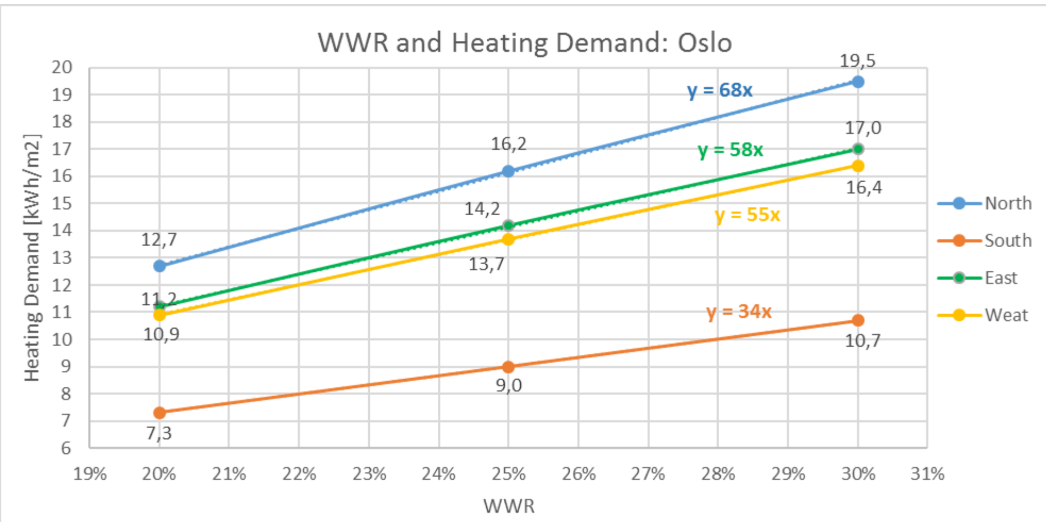

Figure 6.1.2 Relationship between heating demand and WWR in Oslo.

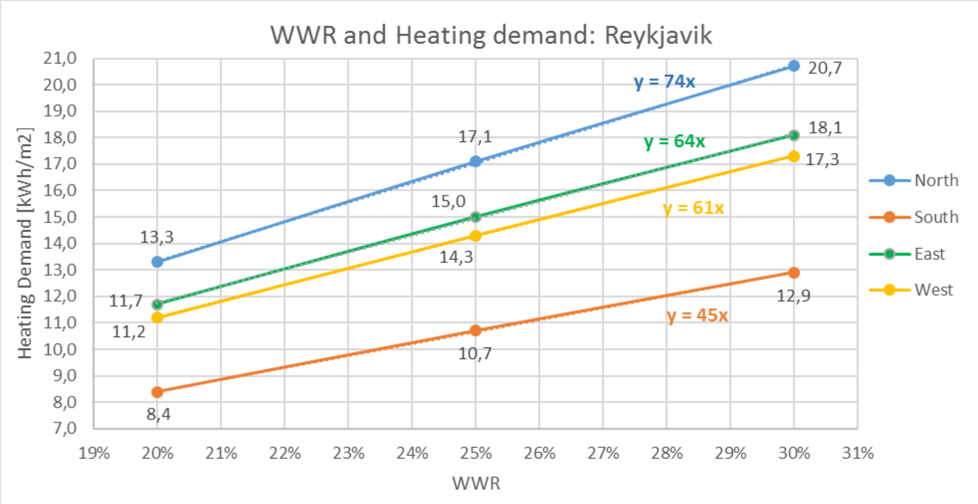

Figure 6.1.3 Relationship between heating demand and WWR in Reykjavik.

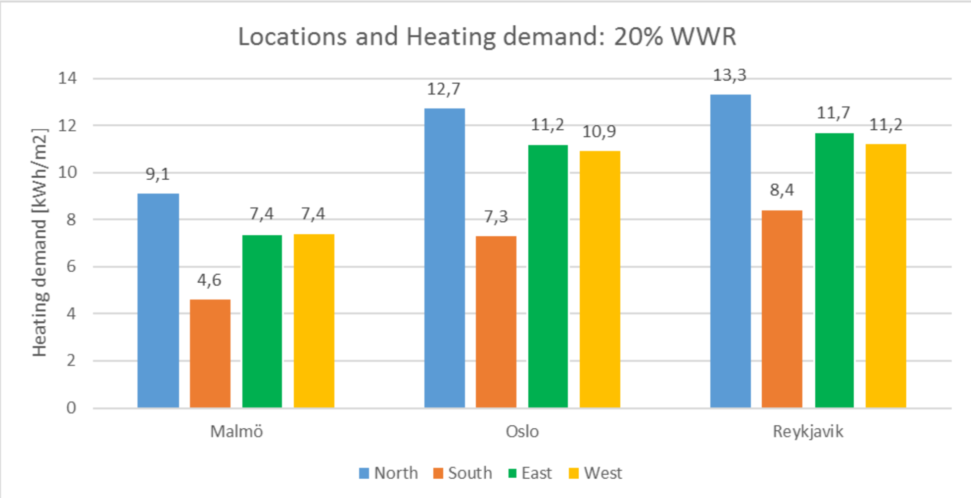

Figure 6.1.4 Location comparison – heating demand and WWR.

Figure 6.1.1 – 6.1.3 indicate that heating demand increases linearly with increasing WWR. The relationship is illustrated with linear regression. Reason for heating demand increase with increasing WWR is due to the domination of the glazing heat transmission loss. The heating demand is always highest for the largest WWR, i.e. 30%, independent of location and orientation. North façade always has the highest heating demand and south façade the lowest at each location. Furthermore, north façade has the fastest heating demand increase with increasing WWR, whereas slowest heating demand increase is in the south façade. This is because south façade receives the most annual solar heat load compared to other façades. Heating demand increases exactly two times faster in the north than south façade in Malmö and Oslo, but with a lower increase rate in Reykjavik. The east and west façade fall closely together, and lie between the north and south façade, closer to north. The east façade always has higher heating demand and faster heating demand increase rate than the west.

When heating demand reduction is desired, decreasing WWR in north facade should be the first choice. Alternatively, lowering WWR is the optimal solution. In this case, 20% WWR obtains the lowest heating demand. Figure 6.1.4 indicates that the heating demand for each orientation increases with increasing latitude, because of less solar heat gain and lower outdoor temperature. Malmö has the lowest heating demand, whereas Reykjavik the highest.

Relationship of WWR and Cooling demand

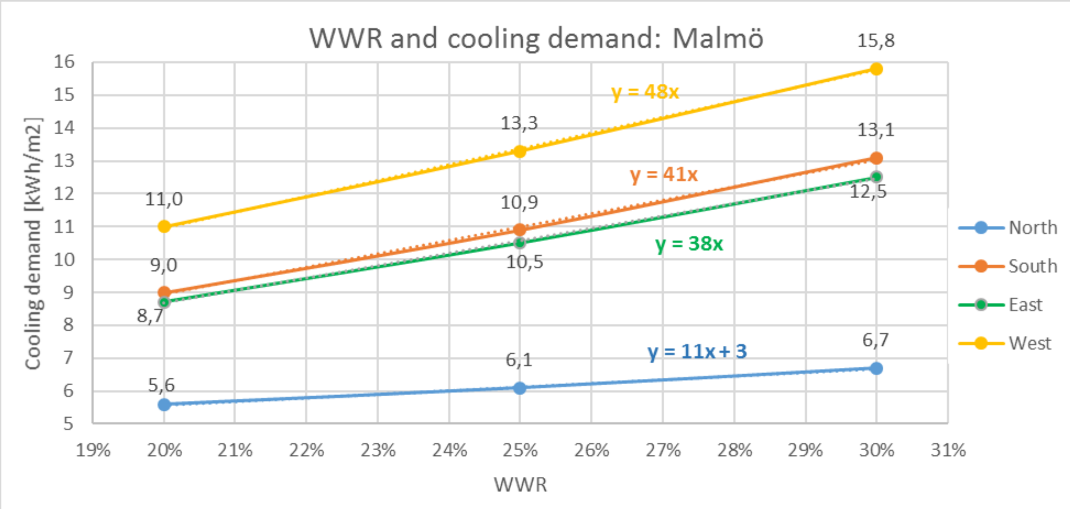

Figure 6.1.5 Relationship between cooling demand and WWR in Malmö.

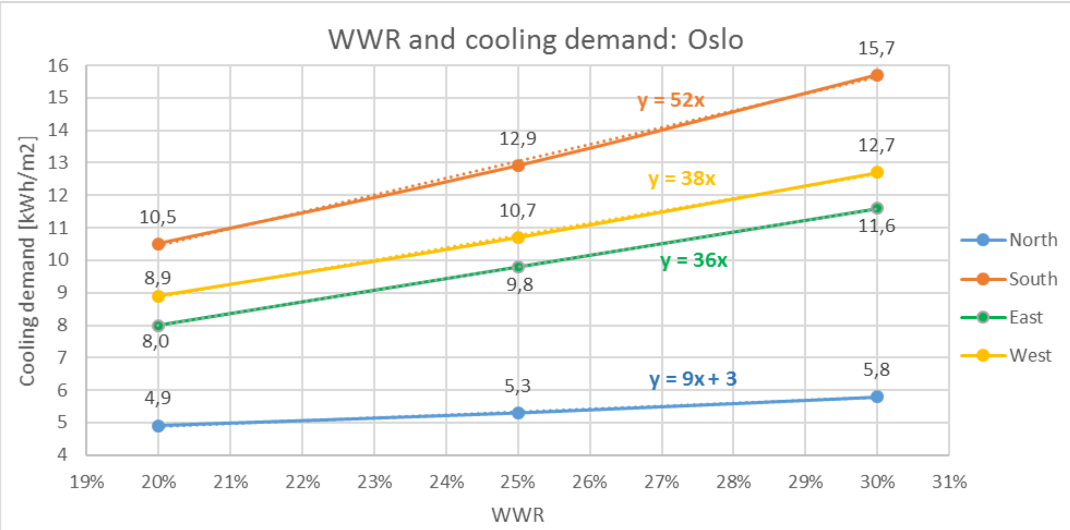

Figure 6.1.6 Relationship between cooling demand and WWR in Oslo.

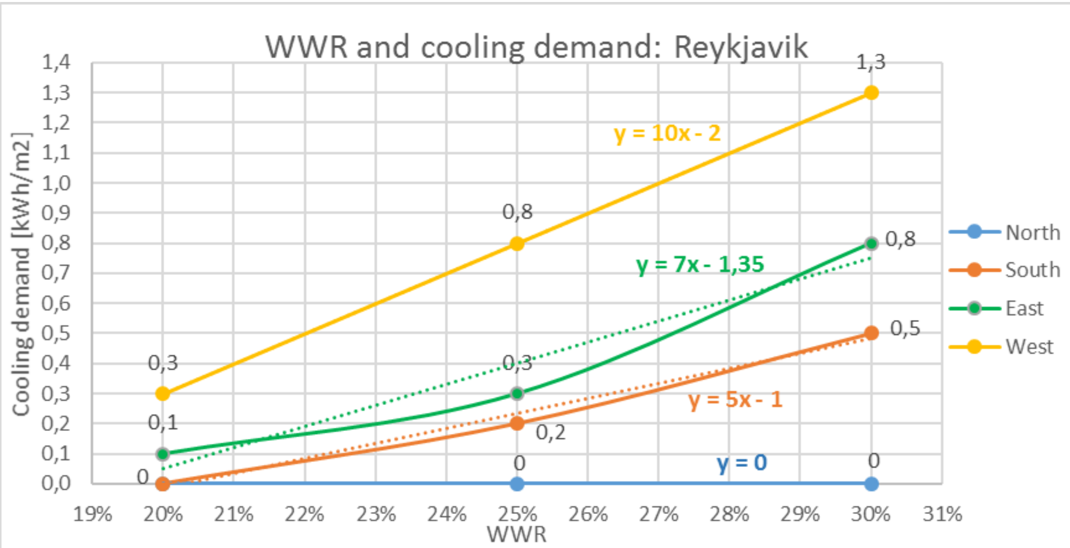

Figure 6.1.7 Relationship between cooling demand and WWR in Reykjavik.

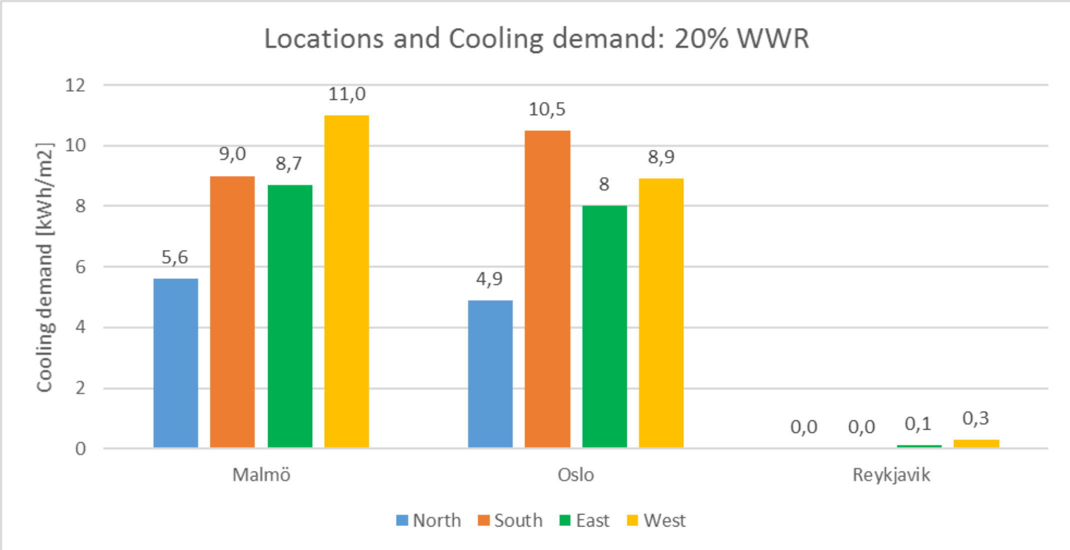

Figure 6.1.8 Location comparison – cooling demand and WWR.

Figure 6.1.5 – 6.1.7 indicate that the cooling demand increases linearly with increasing WWR. The relationship is illustrated with linear regression. Reason for cooling demand increase with increasing WWR is due to the domination of solar heat gain through glazing. The cooling demand is always highest for the largest WWR, i.e. 30%, independent of location and orientation. The north façade always has the lowest cooling demand at each location, while the highest is in the west façade in Malmö and Reykjavik, but south in Oslo. South façade in Oslo complies with the WWR and heating demand relationship, which suggested that south façade receives the most annual solar heat load at each location. The north façade has slower cooling demand increase rate compared the other façade, whereas fastest cooling demand increase rate is in the façade with the highest cooling demand at each location. The two façades lying between highest and lowest cooling demand share similar increase rate. The west façade has higher cooling demand and faster cooling demand increase rate than the east at all locations. The comparison between east and west façade's heating and cooling demand indicates that west façade receives more annual solar heat load therefore higher annual cooling demand, and east façade receives less annual solar heat load to compensate the transmission heat loss through window which leads to higher annual heating demand.

When the cooling demand reduction is desired, decreasing WWR in south or west façade should be the first choice. Alternatively, lowering WWR is the optimal solution. In this case, 20% WWR obtains the lowest annual cooling demand. Figure 6.1.8 indicates that the cooling demand decreases in each orientation with increasing latitude due to less solar heat load and lower outside temperature. But the cooling demand in south façade increases from Malmö to Oslo, this is because Oslo contains the three hottest months of all locations in May, June and July, see Table 2.1. Malmö has the highest cooling demand and Reykjavík the lowest.

Relationship of WWR and Lighting demand

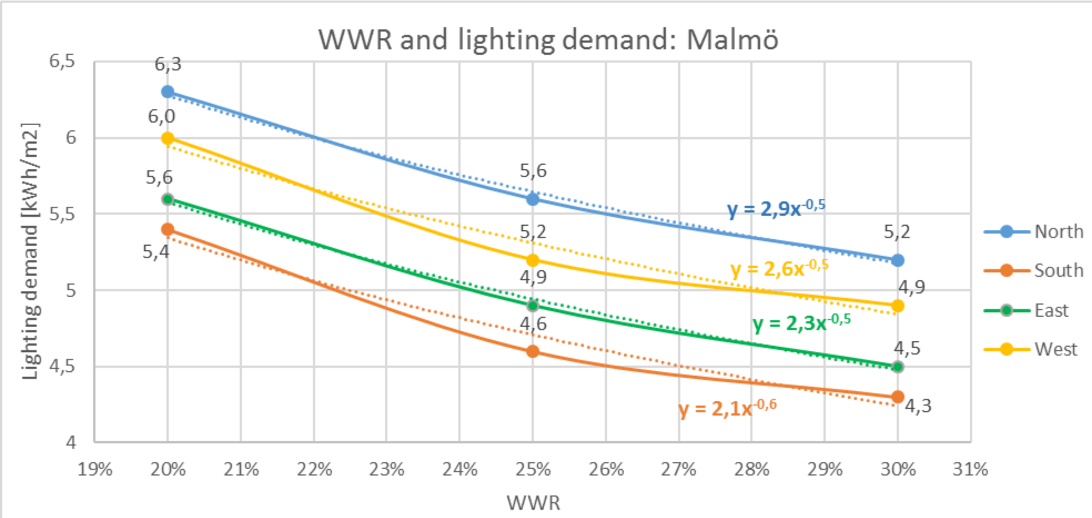

Figure 6.1.9 Relationship between lighting demand and WWR in Malmö.

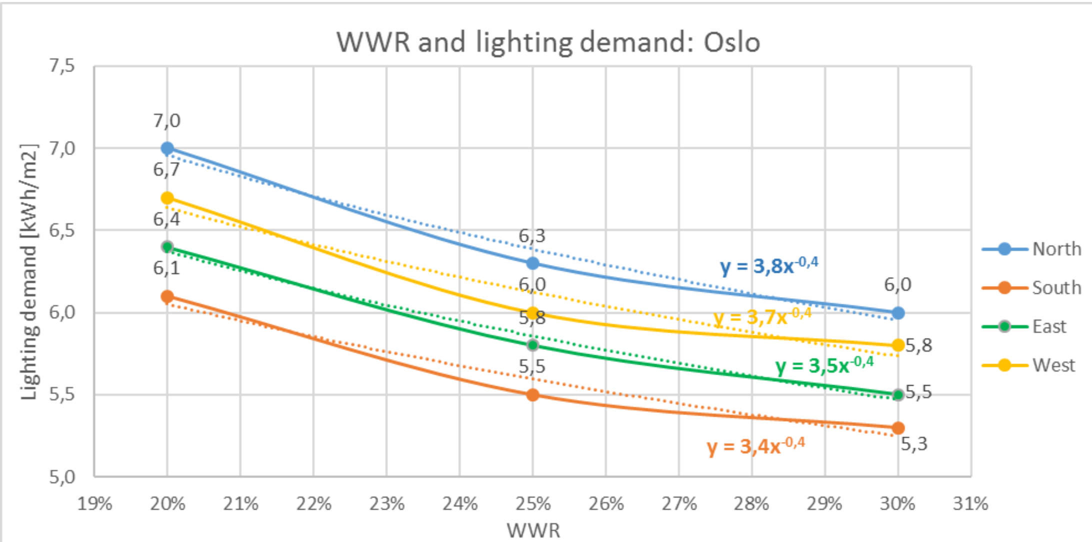

Figure 6.1.10 Relationship between lighting demand and WWR in Oslo.

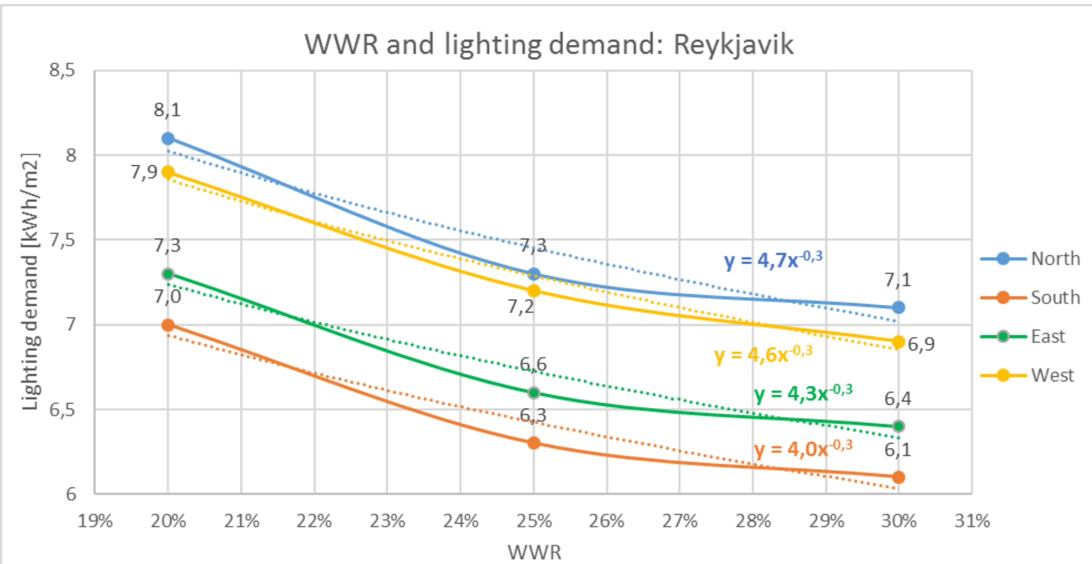

Figure 6.1.11 Relationship between lighting demand and WWR in Reykjavik.

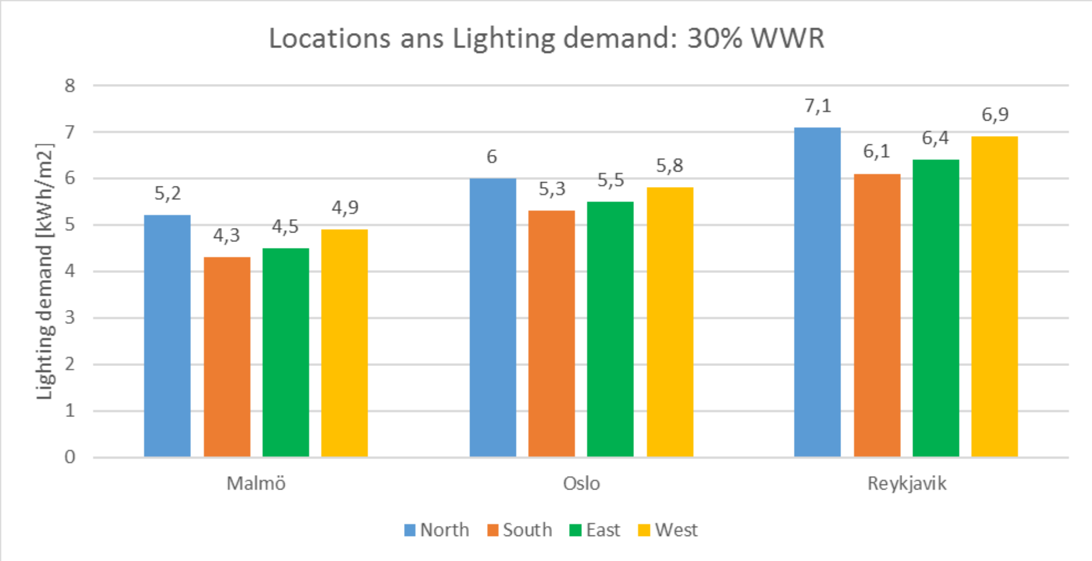

Figure 6.1.12 Location comparison – lighting demand and WWR.

Figure 6.1.9 – 6.1.11 indicate that the lighting demand decreases with increasing WWR, and is illustrated with power-law regression. Reason for lighting demand decrease with increasing WWR is due to more daylight admission through glazing area. The lighting demand is lowest for the largest WWR, i.e. 30%, independent of location and orientation. The solar path leads to uneven daylight distribution in different orientation, so the highest lighting demand is always in the north façade and the lowest in the south at each location. The east and west façade lie between the north and south façade, where west façade always has higher lighting demand than east façade. This indicates that east façade receives more daylight admission. As heating and cooling results revealed earlier that west façade has more solar heat gain than east façade. In conclusion, between the west and east façade, east receives more daylight admission and west more solar heat load. An attribute of power-law is their scale invariance. Given a relation $f(x)=ax^{-k}$, scaling the argument x by a constant factor c causes only a proportionate scaling of the function itself. So, when scaling by a constant c, it simply multiplies the original power-law relation by the constant c^{-k}. With the minor exception of south façade in Malmö, the lighting demand decrease rate described by the power function share identical power factor for all four orientations at the same location, 0.5 for Malmö, 0.4 for Oslo and 0.3 for Reykjavik. This means that all four façades at each location share equivalent lighting demand decrease rate, where the line above is simply a scaled-up version of the line below by a constant.

When lighting demand reduction is desired, increasing WWR should be proposed, independent of façade orientation. In this case, 30% WWR obtains the lowest annual lighting demand. Figure 6.1.12 indicates that the lighting demand for each orientation increases with increasing latitude because of decrease in magnitude and duration of the daylight. Malmö has the lowest annual lighting demand and Reykjavik the highest.

6.2 Impact of WWR on IEQ

Instead of using the built-in synthetic summer and winter climate in IDA ICE, each location uses its own climate data, but it is narrowed down to a specific time-period to synthesise the summer and winter weather condition at each location. The time-period for the thermal comfort summer evaluation consists of June, July and August, and for the thermal comfort winter evaluation, it consists of December, January and February.

Relationship of WWR and Thermal comfort summer

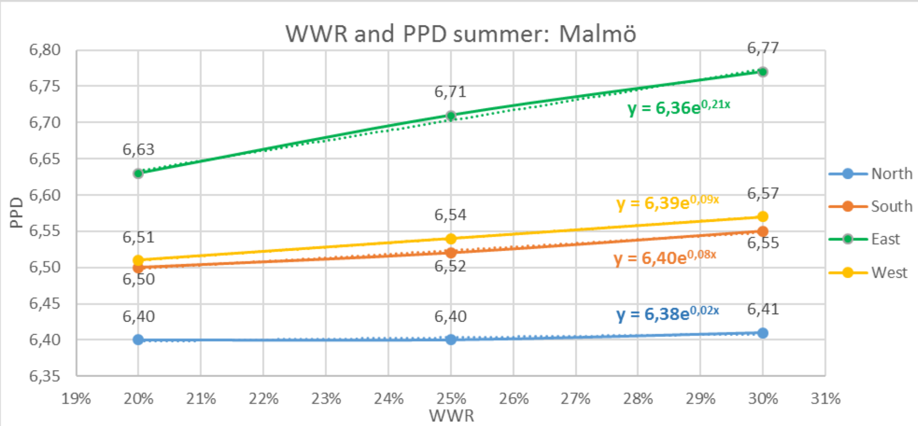

Figure 6.2.1 Relationship between thermal comfort summer and WWR in Malmö.

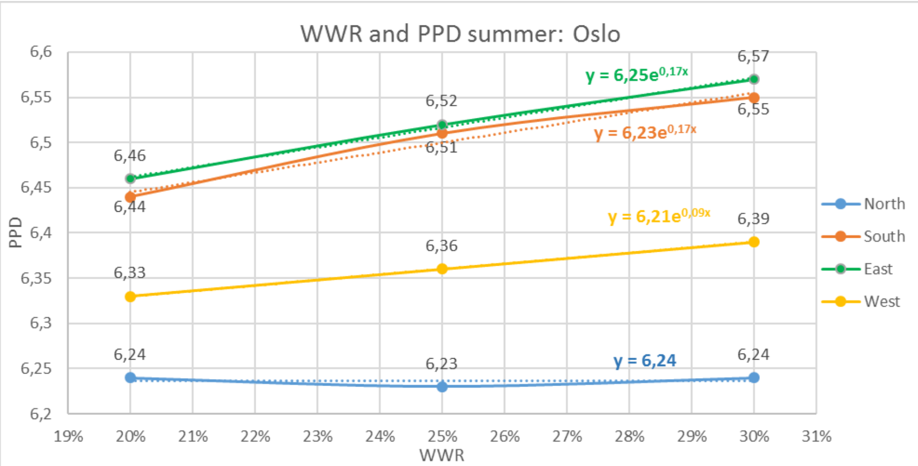

Figure 6.2.2 Relationship between thermal comfort summer and WWR in Oslo.

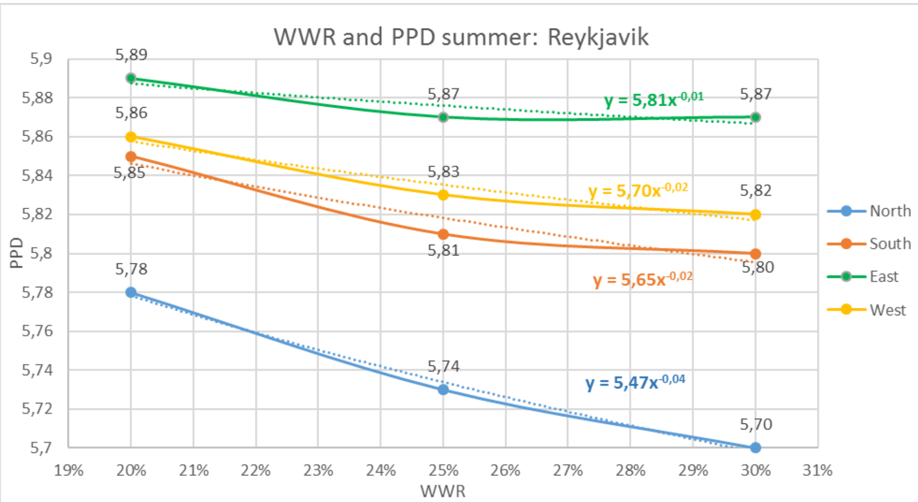

Figure 6.2.3 Relation between thermal comfort and WWR in Reykjavik.

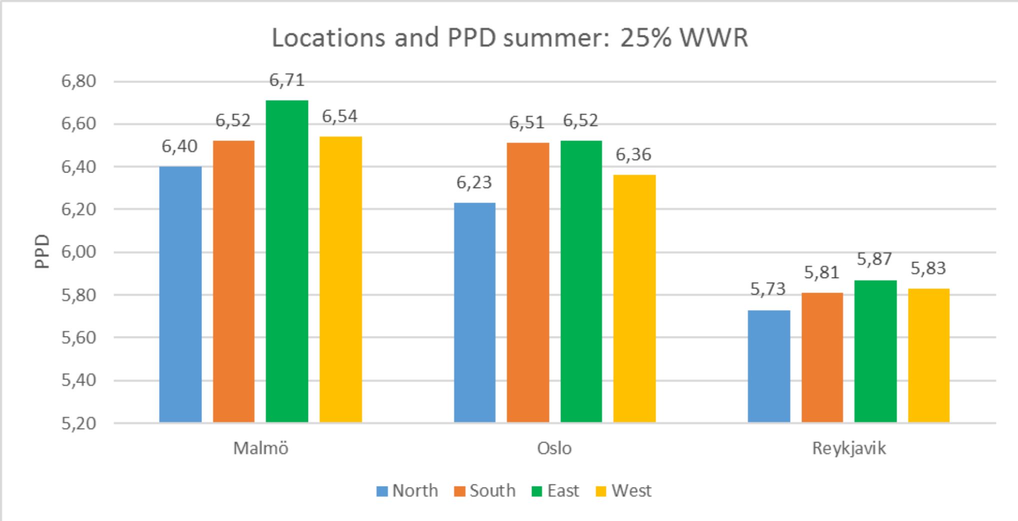

Figure 6.2.4 Location comparison – thermal comfort summer and WWR.

Figure 6.2.1 – 6.2.3 indicate that the summer PPD increases in Malmö and Oslo, but decreases in Reykjavik with increasing WWR. This relationship is illustrated with exponential regression. Reason for summer PPD increase and decrease with increasing WWR is because of the low outdoor air temperature and insufficient solar radiation intensity during summer in Reykjavik. During summer in Reykjavik, the indoor heat escapes out through glazing transmission at a higher rate than the solar heat coming in. More of this occurs when WWR increases, in that case, the room cools down further while PPD value gets better, i.e. lower. This rule does not apply for Malmö and Oslo, since the summer outdoor temperature is not as low as in Reykjavik, and the solar radiation intensity is stronger. So, the transmission heat loss is not as dominating as it is in Reykjavik. During summer in Oslo and Malmö, the heat inside does not escape enough by glazing transmission heat loss to compensate the solar heat gain when WWR increases. Therefore, the room temperature increases, so does the PPD-value and gets worse. The summer PPD is always highest for the largest WWR in each orientation in Malmö and Oslo, this is the opposite in Reykjavik, where the smallest WWR receives the highest PPD. The highest summer PPD is always in east façade and the lowest in north at each location. The summer PPD increases most in east façade and least in north façade in Malmö and Oslo with increasing WWR, while the summer PPD increases least in east façade and most in north façade in Reykjavik. This is because of the difference in magnitude of solar heat load acting on different orientation. This confirms that the north façade indeed has the least solar heat load during summer, where the transmission heat loss overpowers the solar heat gain the most in the north façade. While the east façade has the largest solar heat load during summer, where the transmission heat loss can't compensate the entire solar heat gain.

When summer PPD reduction is desired, reducing WWR in Malmö and Oslo should be proposed, but increasing WWR in Reykjavik. Here, 20% WWR obtains the lowest summer PPD in Malmö and Oslo, but 30% WWR in Reykjavik. It is safe to say, that in all cases, the summer PPD is not heavily influenced by WWR variations. Figure 6.2.4 indicates that the summer PPD decreases with increasing latitude for each orientation. This is because of the outdoor summer temperature decreases as location increases in latitude. Malmö has the highest summer PPD and Reykjavik the lowest.

Relationship of WWR and Thermal comfort winter

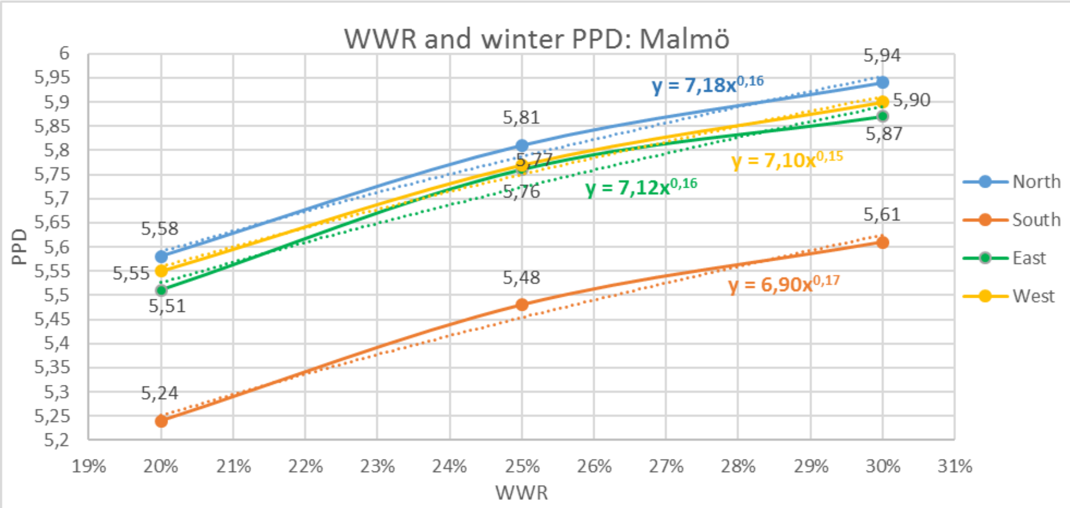

Figure 6.2.5 Relationship between thermal comfort winter and WWR in Malmö.

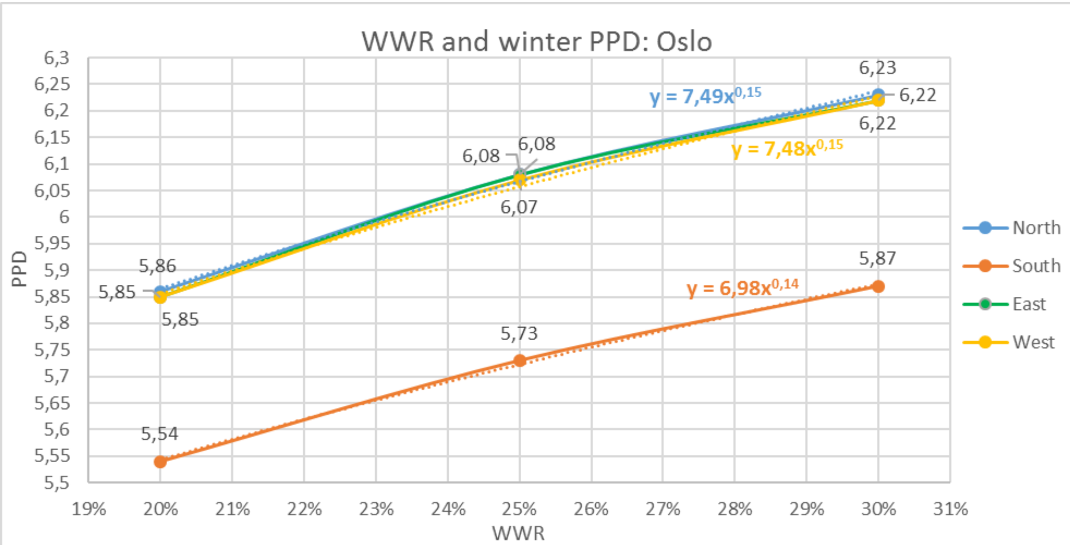

Figure 6.2.6 Relationship between thermal comfort winter and WWR in Oslo.

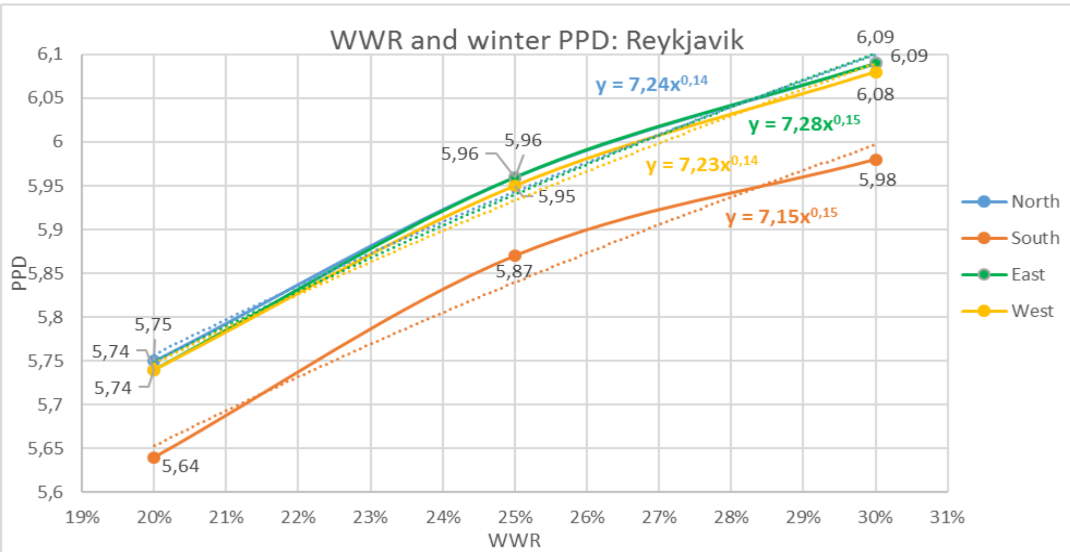

Figure 6.2.7 Relationship between thermal comfort winter and WWR in Reykjavik.

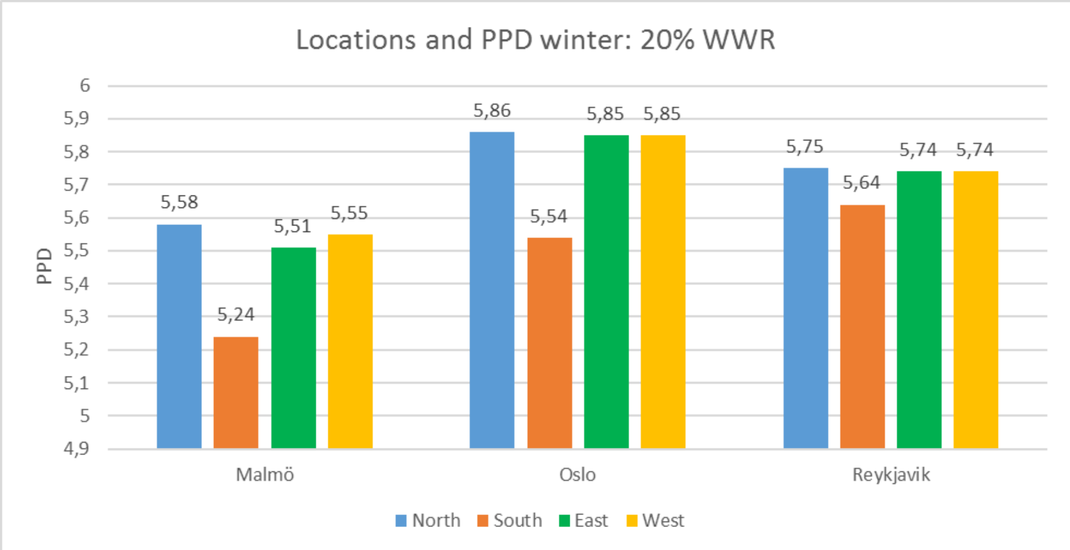

Figure 6.2.8 Location comparison – thermal comfort winter and WWR.

Figure 6.2.5 – 6.2.7 indicate that the winter PPD increases with increasing WWR. This relationship is illustrated with power regression. Reason for winter PPD increase with increasing WWR is due to the low winter outdoor temperature and limited solar heat gain. The room temperature decreases as heat is lost through glazing transmission in a much higher rate than the incoming solar heat when WWR increases. Therefore, PPD gets worse and increases, this is demonstrated in Figure 6.7.1. The winter PPD increases more than summer PPD does with increasing WWR. The winter PPD is always highest for the largest WWR, i.e. 30%, independent of orientation and location. The lowest and best winter PPD is in the south façade at each location, this is due to the south façade has the most solar heat gain during winter, so it compensates more with the glazing transmission heat loss, resulting in a warmer indoor temperature, thus lower winter PPD. The other three façades lie closely together. The winter PPD increase rate described by power function share approximately identical power factor, 0.13-0.16, for all facades and locations. This means that all four facades at each location share roughly equal winter PPD increase rate with increasing WWR, where the line above is a scaled-up version of the line below by a constant.

When the winter PPD reduction is desired, reducing WWR in the north, west and east façade should be proposed. Here, 20% WWR is most desirable for low winter PPD. It is safe to say that in all cases, the winter PPD is not heavily influenced by WWR variations. Figure 6.2.8 indicates that the winter PPD increases from Malmö to Oslo, but then decreases from Oslo to Reykjavik. This is because Oslo has the coldest months during winter, even colder than Reykjavik. Malmö has considerably lower winter PPD compared to Oslo and Reykjavik.

Relationship of WWR and Daylight factor

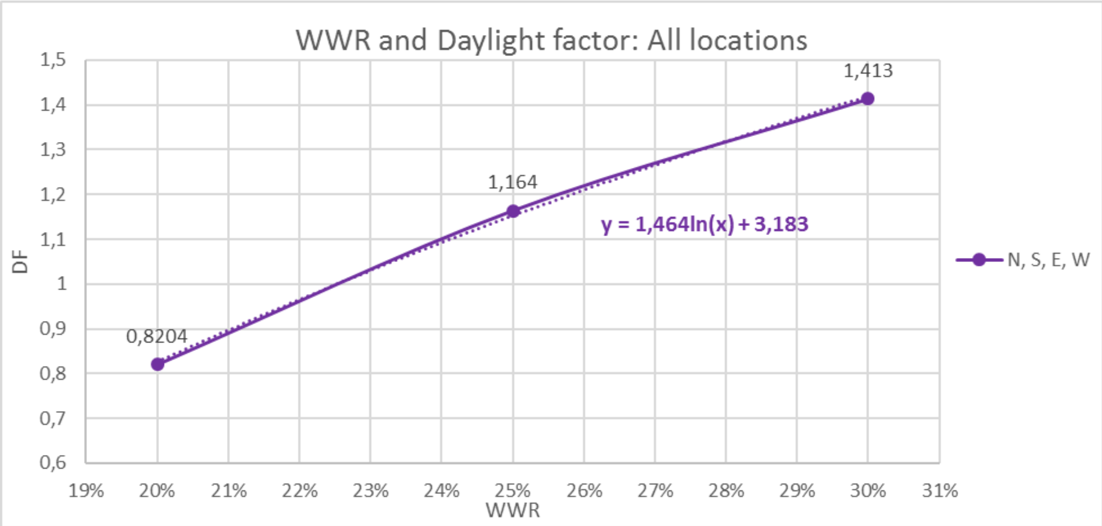

Figure 6.2.9 Relationship between daylight factor and WWR for all locations.

Daylight factor increases with increasing WWR. This relationship is illustrated with natural regression. Reason for this increase is due to more daylight admission penetrating through glazing with increasing WWR. As mentioned before, daylight factor is independent of orientation and location. So here, the daylight factor is the same for all locations and orientations. When daylight factor increase is desired, increasing WWR is the obvious solution. Here, 30% window obtains the highest and best daylight factor.

6.3 Impact of g-value on ED

The evaluation results vary with locations, orientations and g-values. ED elements are heating, cooling and lighting demand. The impact of g-value on each ED element is examined independently. The second order regression is the only regression type used here, as it is the most accurate.

Relationship of g-value and Heating demand

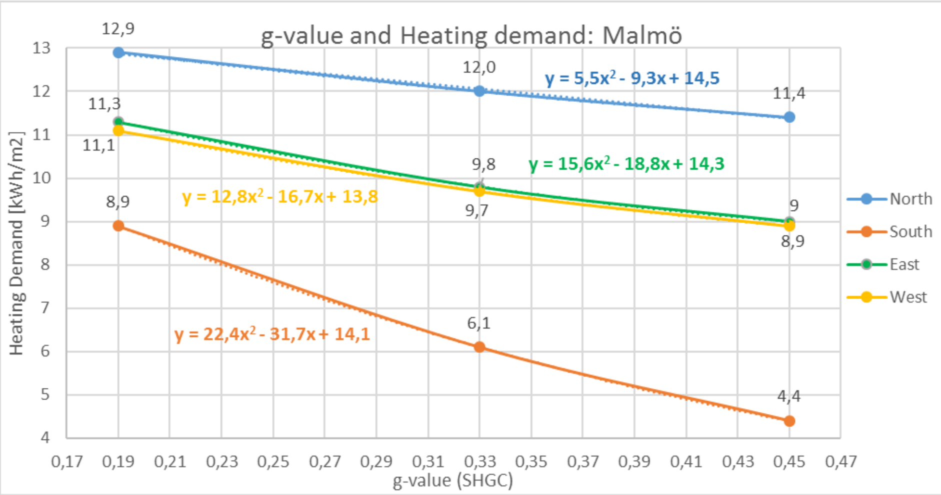

Figure 6.3.1 Relationship between g-value and heating demand in Malmö.

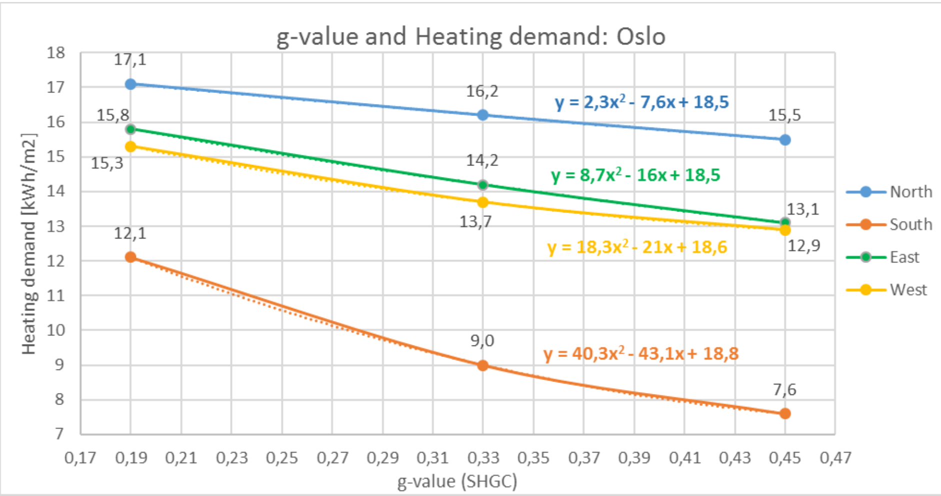

Figure 6.3.2 Relationship between g-value and heating demand in Oslo.

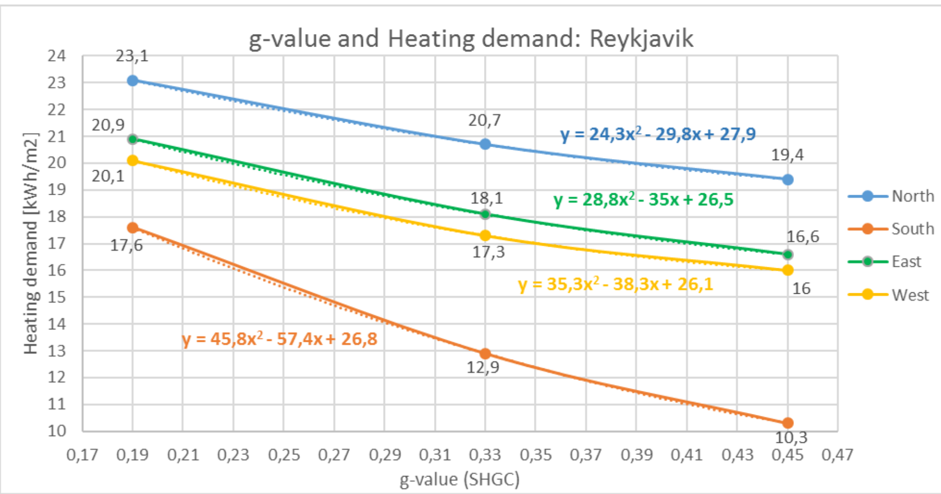

Figure 6.3.3 Relationship between g-value and heating demand in Reykjavik.

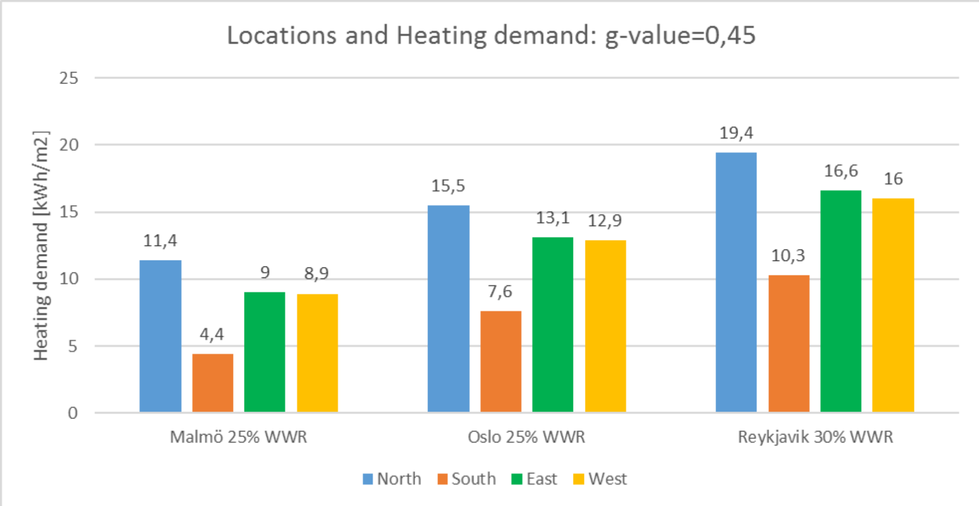

Figure 6.3.4 Location comparison – heating demand and g-value.

Figure 6.3.1 – 6.3.3 indicate that the heating demand decreases with increasing g-value. Reason is due to increase in solar heat gain, while glazing heat transmission heat loss is held at a fixed amount with a constant WWR. With south façade excluded at each location, the heating demand reduction when g-value is increased from 0.19 to 0.45 does not compensate the heating demand increase when WWR is increased from 20 to 30%. This indicates that it is tough for high performance glazing to retreat the heating demand increase from merely 10% WWR increase. The heating demand is always highest for the lowest g-value, i.e. 0.19, in each façade. The north façade always has the highest heating demand at each location. But, it has the lowest heating demand reduction with increasing g-value, whereas the most heating demand reduction is in the south façade at each location, where it also has the lowest heating demand. This is because the south façade has much more annual solar heat load than the north. So, by increasing g-value in the south façade, it allows the strong sunlight to pass through, thus decreasing the heating demand. Whereas the weak sun in the north façade does not make a big impact when g-value increases. Just like WWR and heating demand relationship demonstrated earlier, that the east and west façade fall closely together and lie between the north and south façade, closer to north. Also, in accordance with WWR and heating demand relationship, the east façade always has higher heating demand than the west, i.e. the east façade receives lower annual solar heat load than the west.

When overall heating demand reduction is desired at each location, increasing g-value in south facade should be the first choice, even though the south façade has the lowest heating demand, but it reduces the most. Alternatively, increasing g-value is the optimal solution. In this case, g-value of 0.45 obtains the lowest heating demand. Compared to heating demand increase with increasing WWR, it is more effective to decrease the WWR rather than supplying with high performance glazing with high g-value when heating demand reduction is desired. Figure 6.3.4 indicates that the heating demand increases with increasing latitude in each orientation due to less solar heat load and lower outdoor temperature. Malmö has the lowest heating demand, whereas Reykjavik has the highest.

Relationship of g-value and Cooling demand

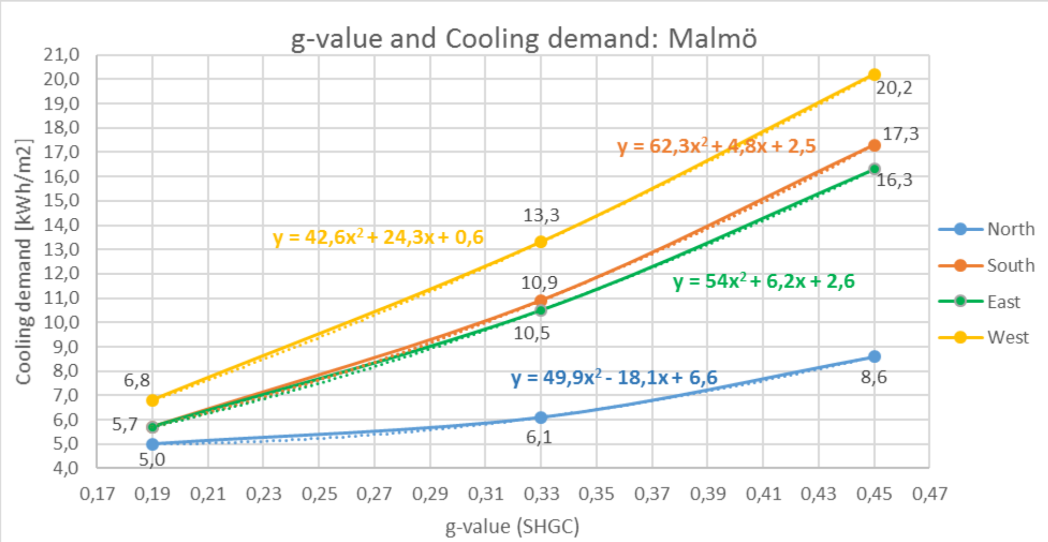

Figure 6.3.5 Relationship between g-value and cooling demand in Malmö.

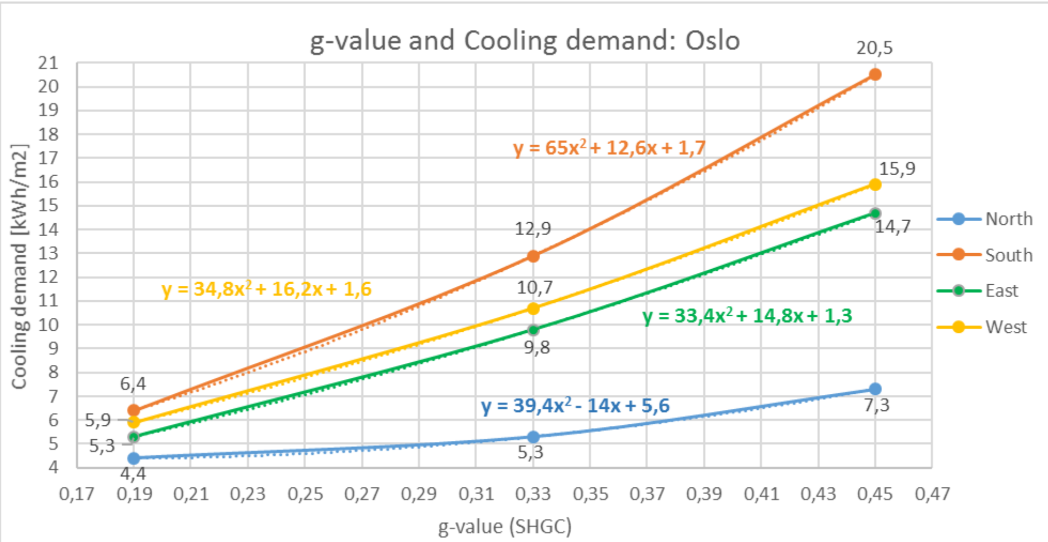

Figure 6.3.6 Relationship between g-value and cooling demand in Oslo.

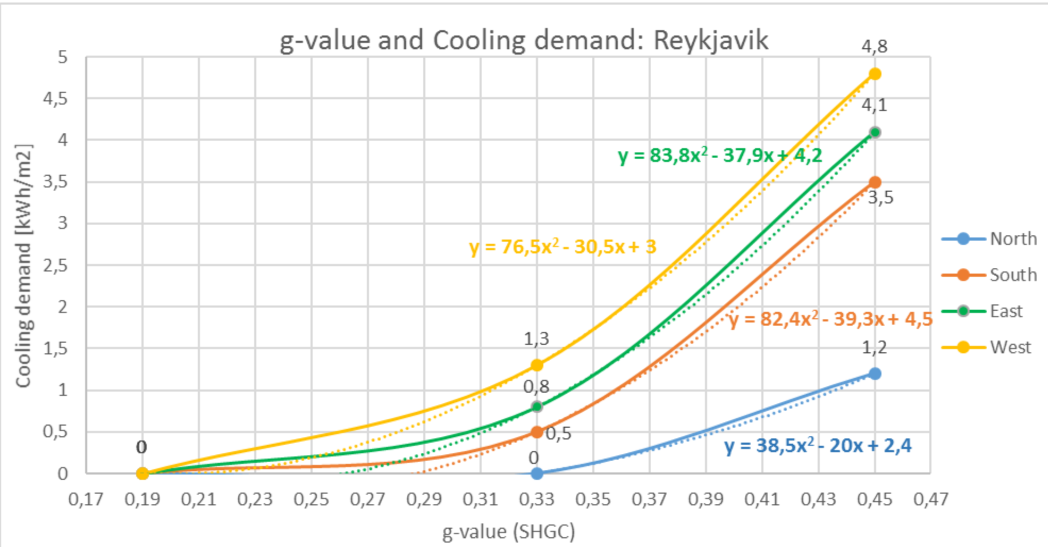

Figure 6.3.7 Relationship between g-value and cooling demand in Reykjavik.

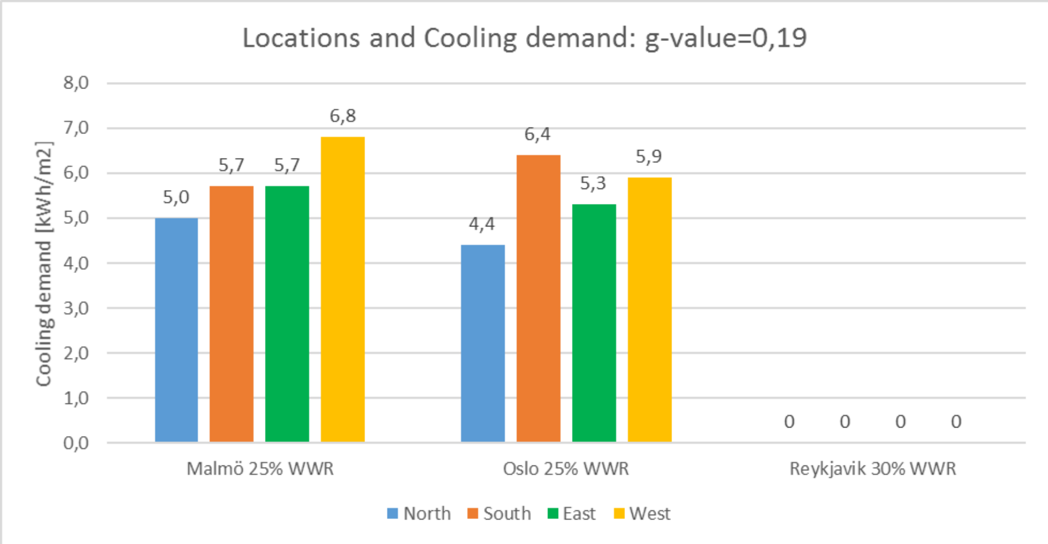

Figure 6.3.8 Location comparison – cooling demand and g-value.

Figure 6.3.5 – 6.3.7 indicate that the cooling demand increases with increasing g-value. Reason is due to increase in solar heat gain through glazing. The cooling demand increase, when g-value is increased from 0.19 to 0.45 is more than the cooling demand increase when WWR is increased from 20% to 30%. The cooling demand is always highest for the highest g-value, i.e. 0.45, in each façade. The north façade always has the lowest cooling demand at each location, while the highest cooling demand is in the south in Oslo, but west in Malmö and Reykjavik. As debated previously in WWR and cooling demand relationship, that the south façade should always have the highest annual cooling demand. Instead, the west façade in Malmö and Reykjavik has higher cooling demand than the south. The north façade has slower cooling demand increase than the other three façades when g-value is increased. All facades are convex (concave upward). Close to g-value of 0.33 is a transition point in façade's rate of change regarding cooling demand. This can be seen clearly in Reykjavik, where the cooling demand increases at a much higher rate after passing g-value of 0.33. At each location, the gap between the lowest and highest cooling demand increases when g-value is increased.

When the cooling demand reduction is desired, decreasing g-value at south or west façade should be first choices. Alternatively, lowering g-value is the optimal solution. In this case, g-value of 0.19 obtains the lowest cooling demand. Decreasing g-value from 0.45 to 0.33 with a constant WWR is more effective on the cooling demand reduction than decreasing WWR from 30% to 25% with a constant g-value. This indicates that high performance glazing with high g-value has negative effect on energy saving due to high cooling demand. Figure 6.3.8 indicates that the cooling demand in each façade decreases with increasing latitude due to decreasing solar radiation intensity. Malmö has the highest cooling demand and Reykjavík merely has no cooling demand at all. Just like WWR and cooling demand relationship showed and explained, that the cooling demand does not decrease in the south façade from Malmö to Oslo.

Relationship of g-value and Lighting demand

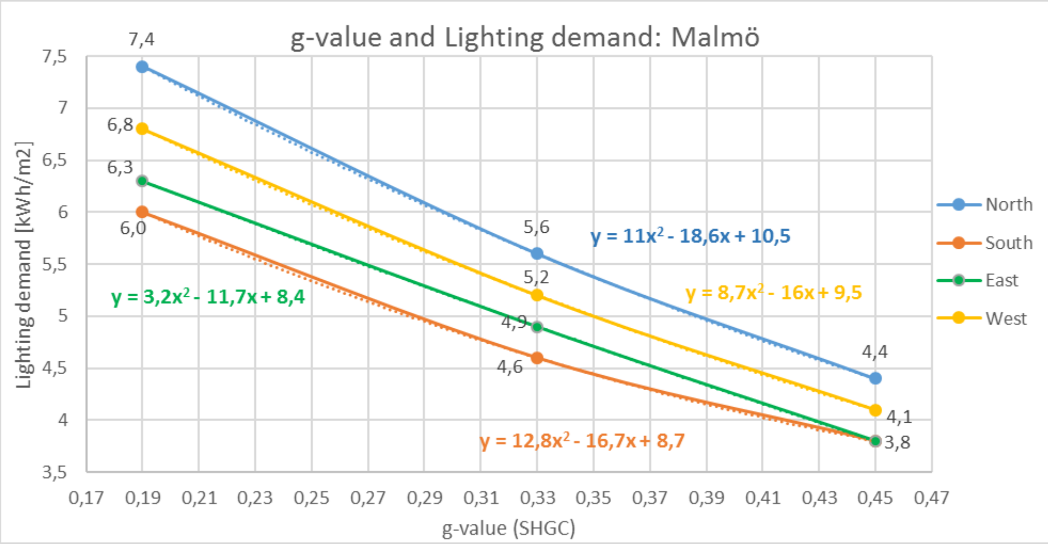

Figure 6.3.9 Relationship between g-value and lighting demand in Malmö.

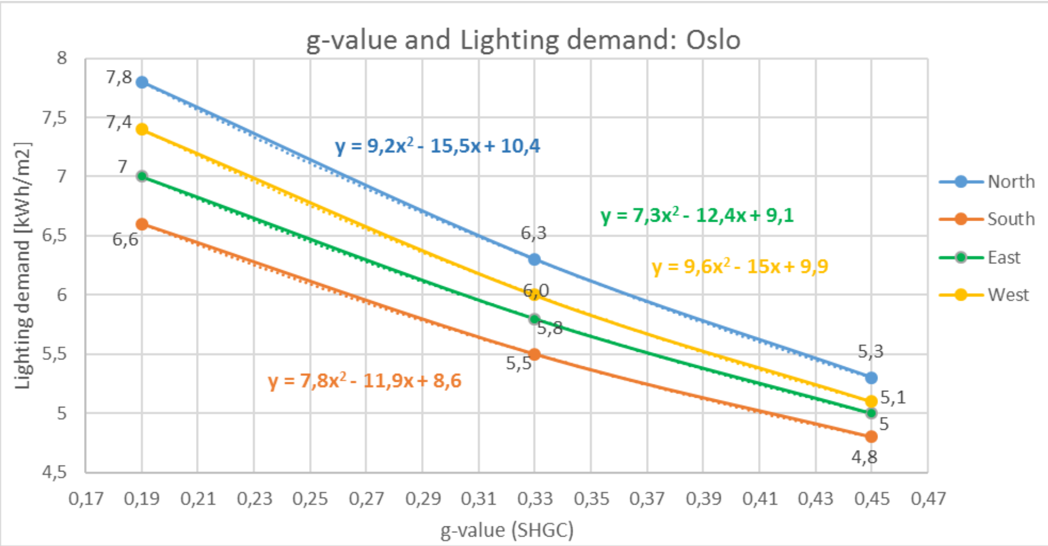

Figure 6.3.10 Relationship between g-value and lighting demand in Oslo.

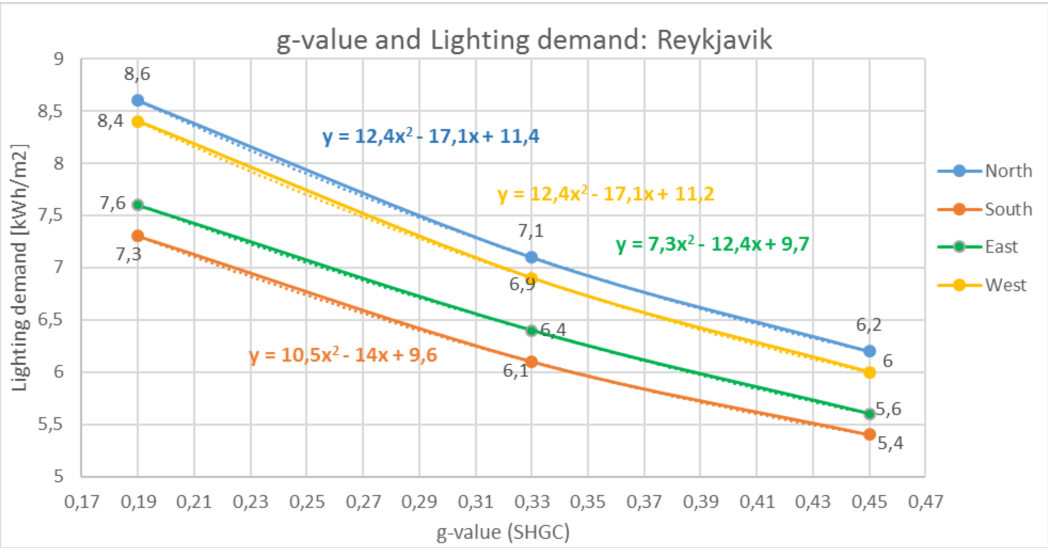

Figure 6.3.11 Relationship between g-value and lighting demand in Reykjavik.

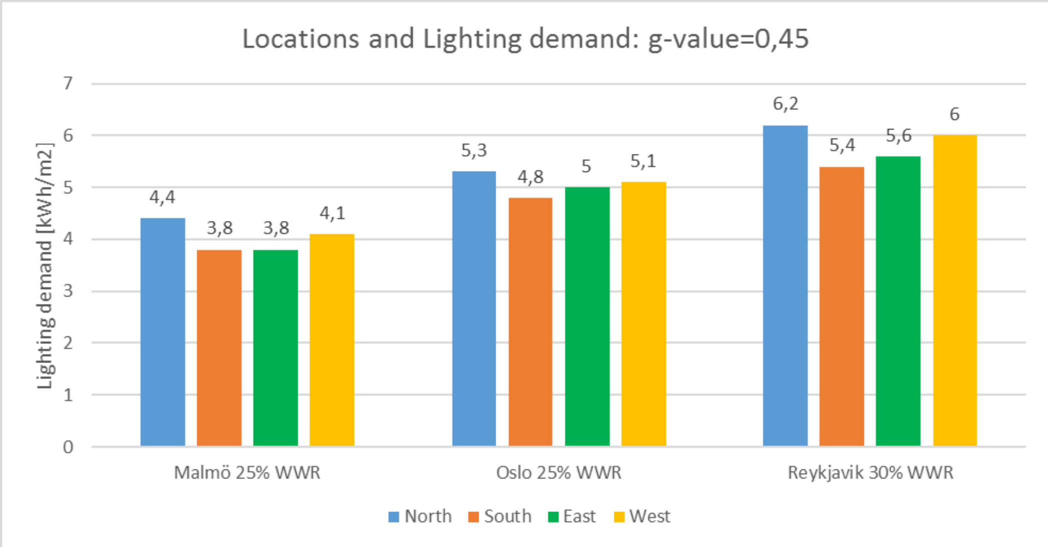

Figure 6.3.12 Location comparison – lighting demand and g-value.

Figure 6.3.9 – 6.3.11 indicate that the lighting demand decreases with increasing g-value, more specific increasing T_{vis}. Reason for this is due to increase in daylight admission through glazing. The lighting demand reduces more when g-value is increased from 0.19 to 0.45 than the increase of WWR from 20% to 30%. The lighting demand is always lowest for the highest g-value, i.e. 0.45, in each façade. The highest lighting demand is in the north façade and the lowest in the south at each location, this is due to the south façade has higher annual solar radiation intensity than the north. The east and west façade lie between the north and south. In accordance with WWR evaluations, between the east and west façade, east has more annual daylight admission, but the west has more annual solar heat load. The more annual daylight admission in the east façade explains why it always has lower lighting demand than the west. All four façades at each location decreases nearly equal amount. The gap between the highest and lowest lighting demand reduces with increasing g-value.

When lighting demand reduction is desired, increasing g-value in north façade should be the first proposal since it has the largest reduction. Alternatively, increasing g-value is the optimal solution. In this case, g-value of 0.45 obtains the lowest lighting demand. Ultimately, when lighting demand decrease is desired, increasing g-value is more effective than increasing WWR. Figure 6.3.12 indicates that the lighting demand at each orientation increases with increasing latitude due to decrease in magnitude and duration of the sunlight. Malmö has the lowest lighting demand and Reykjavik the highest.

6.4 Impact of g-value on IEQ

June, July and August are used for thermal comfort summer evaluation. December, January and February are used for thermal comfort winter evaluation. Second order regression characterizes the relationship between g-value range of 0.15 – 0.45 and IEQ.

Relationship of g-value and Thermal comfort summer

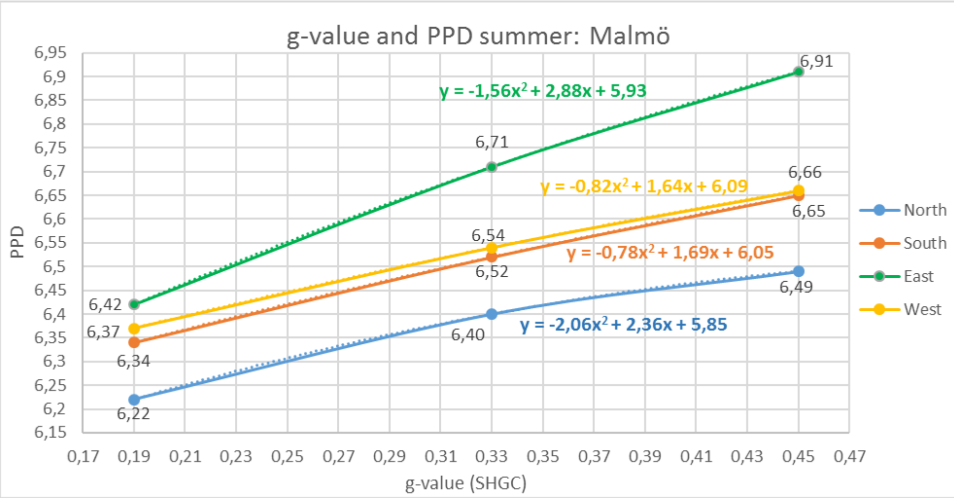

Figure 6.4.1 Relationship between g-value and thermal comfort summer in Malmö.

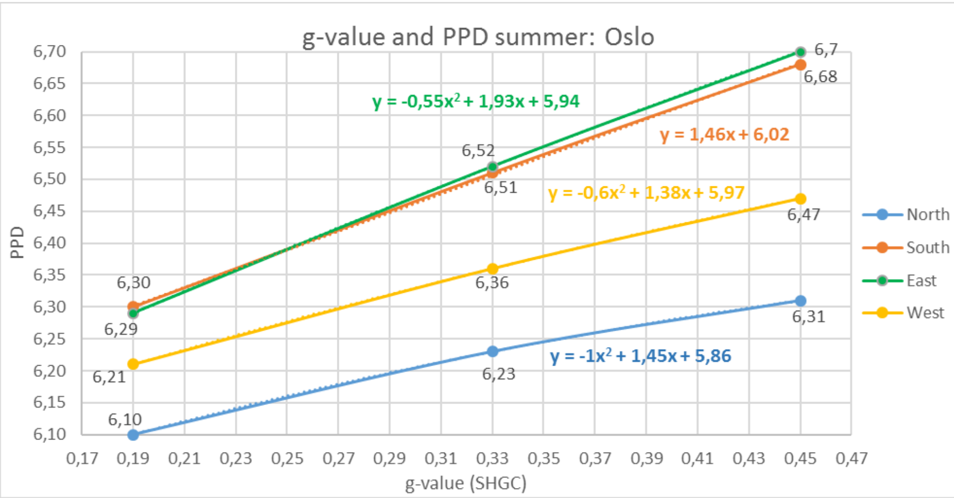

Figure 6.4.2 Relationship between g-value and thermal comfort summer in Oslo.

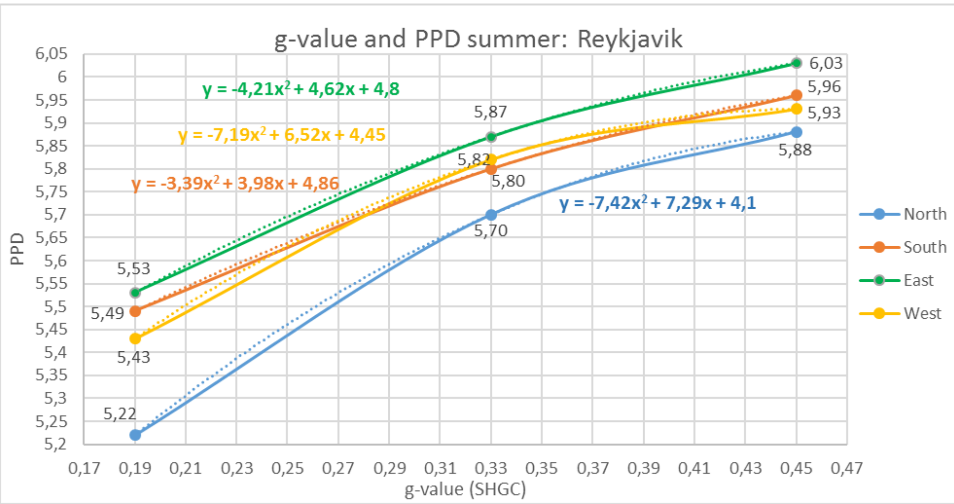

Figure 6.4.3 Relation between g-value and thermal comfort summer in Reykjavik.

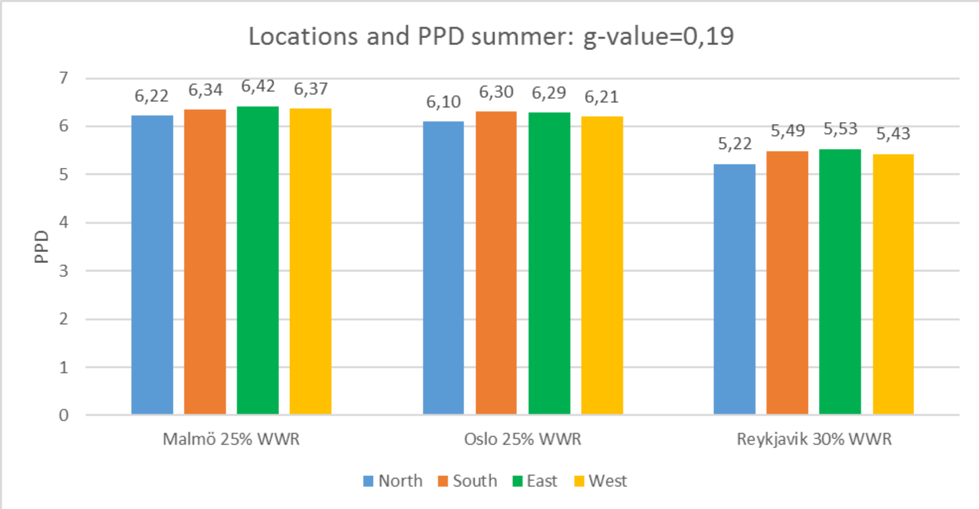

Figure 6.4.4 Location comparison – thermal comfort summer and g-value.

Unlike the WWR and summer PPD evaluation where summer PPD decreased with increasing WWR in Reykjavik. Here, Figure 6.4.1 – 6.4.3 indicate that the summer PPD increases with increasing g-value at all locations, independent of orientation. Reason for summer PPD increase with increasing g-value is due to during warm summer climate, the transmission heat loss through glazing is held at a constant rate by the constant WWR. While the amount of solar heat gain increases. This raises the room temperature and PPD gets higher, so it becomes worse. The summer PPD is always highest for the highest g-value in each façade, i.e. g-value of 0.45. The lowest summer PPD is always in the north façade at each location. This is because of the limited solar heat gain. All façades concave downward. The summer PPD increases the most in the north façade in Reykjavik. While the increase is the most in the east façade in Malmö and Oslo.

When summer PPD reduction is desired, reducing g-value should be proposed, in this case, g-value of 0.19 obtains the lowest summer PPD. Summer PPD does not change dramatically by g-value variations. Figure 6.4.4 indicates that the summer PPD decreases with increasing latitude in each orientation due to lowering outdoor temperature and solar radiation intensity. Malmö has the highest summer PPD and Reykjavik the lowest.

Relationship of g-value and Thermal comfort winter

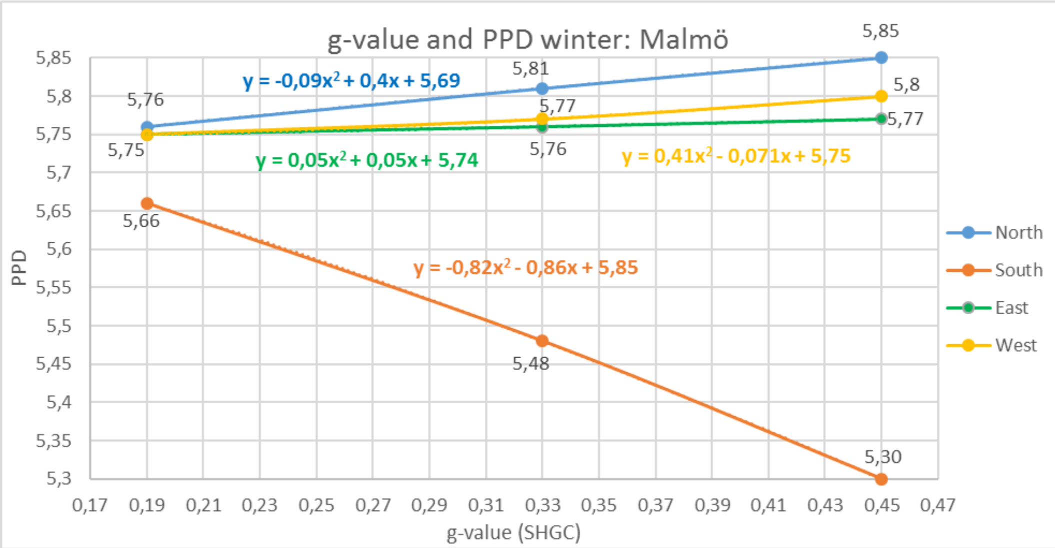

Figure 6.4.5 Relationship between g-value and thermal comfort winter in Malmö.

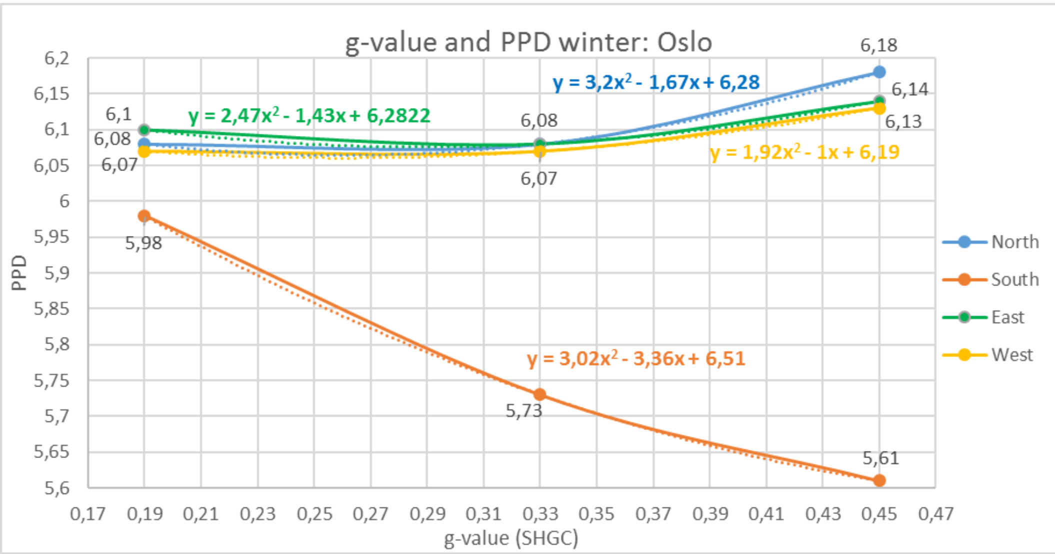

Figure 6.4.6 Relationship between g-value and thermal comfort winter in Oslo.

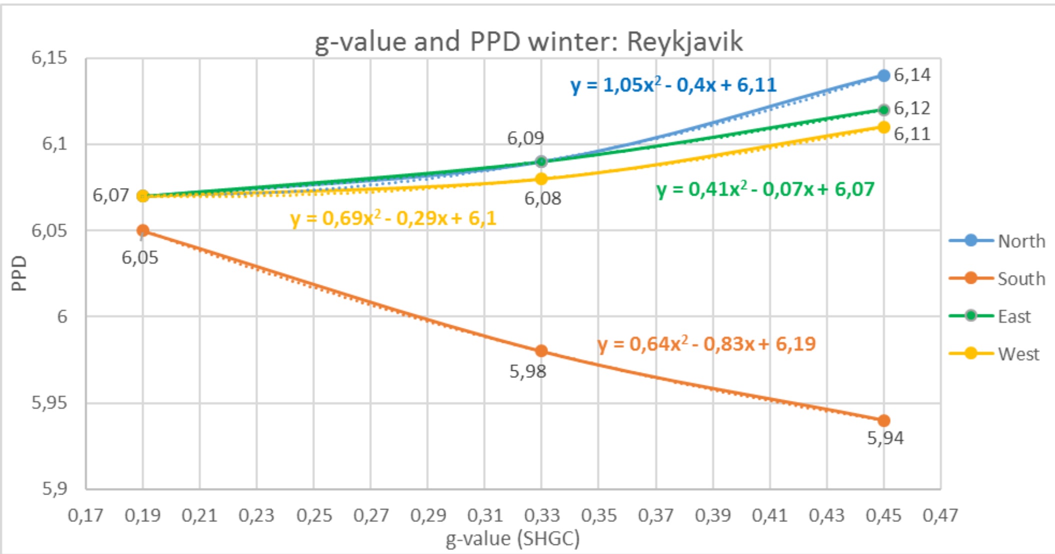

Figure 6.4.7 Relationship between g-value and thermal comfort winter in Reykjavik.

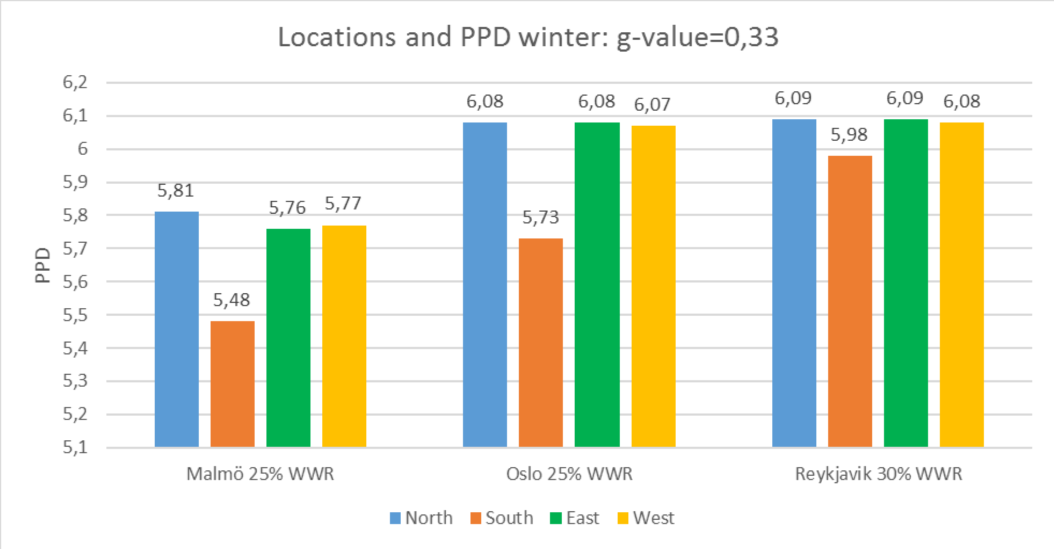

Figure 6.4.8 Location comparison – thermal comfort winter and g-value.

Figure 6.4.5 – 6.4.7 indicate that the winter PPD merely shows any increase with increasing g-value in the north, east and west façade at each location. Meanwhile the winter PPD decreases with increasing g-value in the south façade. Figure 2.6 showed that the solar radiation intensity is the strongest in the south during winter in Stockholm. This explains why the south façade is the only façade that has decreasing winter PPD at each location during cold winter. Higher g-value allows more solar heat gain through glazing, thus the solar heat gain overpowers the constant high transmission heat loss through glazing by a constant WWR, meanwhile the room temperature increases and the winter PPD drops. The winter PPD is always the highest for the highest g-value, except in the south façade, at each location. The g-value of 0.45 obtains the highest winter PPD, except in the south façade, where g-value of 0.19 obtains the highest PPD. Although PPD in the south facade decreases with increasing g-value, it can't compensate the winter PPD increase when WWR in increased from 20% to 30%. Like WWR evaluation showed, that the lowest and best winter PPD is always in the south façade, while the other three façades lie closely together.

When winter PPD reduction is desired, reducing g-value in the north, west and east façade should not be recommended, instead increasing g-value in the south façade should be the only solution. It is safe to say that winter PPD is not heavily influenced by g-value variations. Figure 6.4.8 indicates that the winter PPD increases in each orientation with increasing latitude due to colder winter climate, i.e. lowering outdoor temperature and solar radiation intensity. The north, east and west façade in Oslo and Reykjavik have similar winter PPD values since these two locations share similar winter climate.

Relationship of g-value and Daylight factor

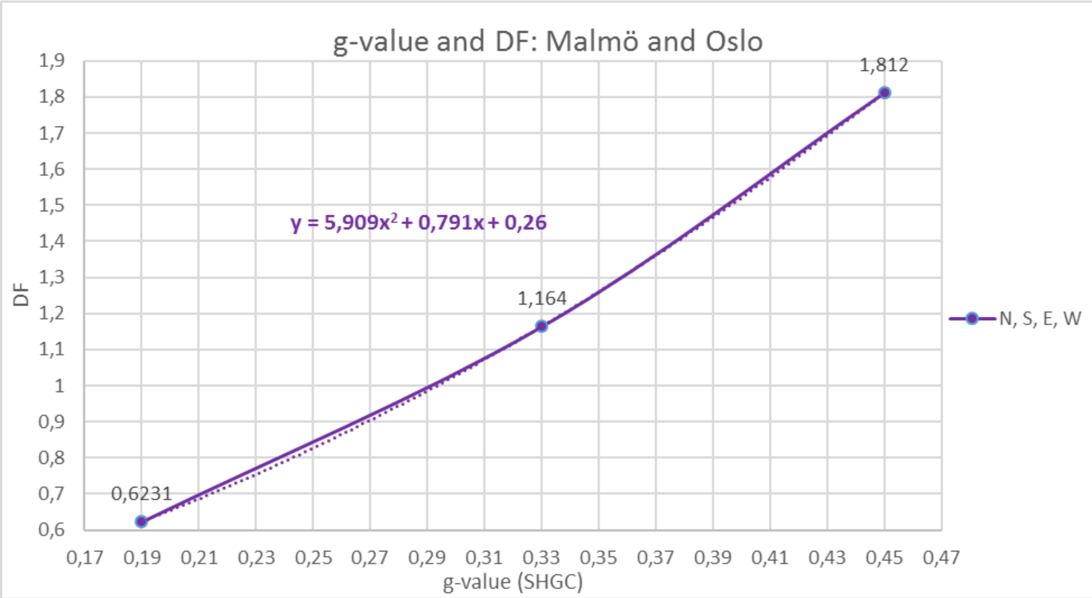

Figure 6.4.9 Relationship between g-value and daylight factor in Malmö and Oslo.

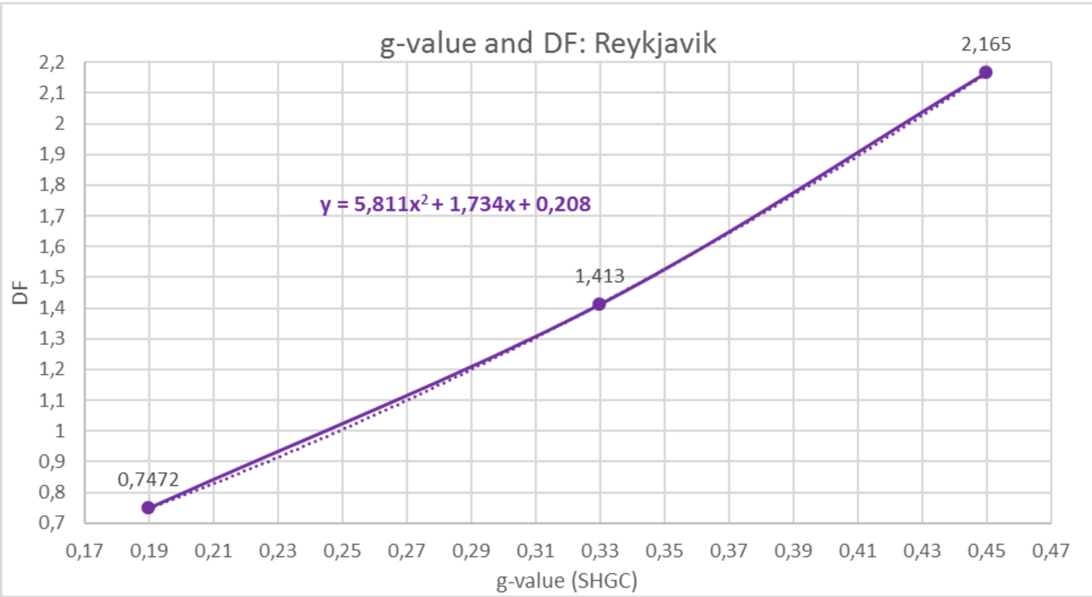

Figure 6.4.10 Relationship between g-value and daylight factor in Reykjavik.

Daylight factor increases with increasing g-value. This is because higher g-value tend to have higher T_{vis} which allows more daylight admission through glazing. Daylight factor is independent of orientation and location. Here, g-value of 0.45 obtains the highest and best daylight factor. Malmö and Oslo has a constant WWR of 25%, while Reykjavik has a constant WWR of 30%. The DF increases not as fast as it did when WWR is increased from 20% to 30%, but the g-value of 0.45 (with a constant WWR of 25% and 30%) obtains a higher DF of 1.812 and 2.165. Increasing WWR is more effective than increasing g-value when it comes to DF improvement.

6.5 Scores

Table 6.1 shows the scoring results from WWR evaluation in Malmö. It indicates that the smallest WWR of 20% receives the highest ED score in each orientation. In contrast, the largest WWR of 30% receives the highest IEQ score in each orientation. After combination, the middle size WWR of 25% receives the highest total score in each orientation.

Table 6.2 shows the scoring results from g-value evaluation in Malmö. It indicates that glazing with the highest g-value of 0.45 receives the highest IEQ score in each orientation. As for ED score, the highest g-value receives the highest ED score in the north and west facade. But g-value of 0.33 receives the highest ED score in the south and east facades. After combination, the highest g-value receives the highest total score.

In conclusion, the middle size glazing of 25% WWR with the highest g-value of 0.45 is an excellent choice to secure low ED and good IEQ in an office building in Malmö.

Table 6.1 Malmö WWR evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Malmö	No	North	20% WWR	18	14	32
			25% WWR	17	17	**34**
			30% WWR	16	18	34
		South	20% WWR	21	16	37
			25% WWR	21	18	**39**
			30% WWR	19	19	38
		East	20% WWR	18	14	32
			25% WWR	18	15	**33**
			30% WWR	16	16	32
		West	20% WWR	16	15	31
			25% WWR	15	16	**31**
			30% WWR	13	18	31

Table 6.2 Malmö g-value evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Malmö	No	North	0.19	13	14	27
			0.33	17	17	34
			0.45	19	19	**38**
		South	0.19	18	14	32
			0.33	21	18	39
			0.45	20	21	**41**
		East	0.19	17	13	30
			0.33	18	15	33
			0.45	17	17	**34**
		West	0.19	14	13	27
			0.33	15	16	31
			0.45	16	18	**34**

Table 6.3 shows the scoring results from WWR evaluation in Oslo. It indicates that the smallest WWR of 20% receives the highest ED score in each orientation. In contrast, the largest WWR of 30% receives the highest IEQ score in each orientation. After combination, the middle size WWR of 25% receives the highest total score in each orientation.

Table 6.4 shows the scoring results from g-value evaluation in Oslo. It indicates that the highest g-value of 0.45 receives the highest ED and IEQ score.

In conclusion, the middle size glazing of 25% WWR with the highest g-value of 0.45 is an excellent choice for low ED and good IEQ in an office building in Oslo.

Table 6.3 Oslo WWR evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Oslo	No	North	20% WWR	14	15	29
			25% WWR	14	17	**31**
			30% WWR	12	18	30
		South	20% WWR	16	15	31
			25% WWR	15	17	**32**
			30% WWR	13	18	31
		East	20% WWR	15	13	28
			25% WWR	13	15	**28**
			30% WWR	11	16	27
		West	20% WWR	14	14	28
			25% WWR	12	16	**28**
			30% WWR	11	17	28

Table 6.4 Oslo g-value evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Oslo	No	North	0.19	10	13	23
			0.33	14	17	31
			0.45	15	18	**33**
		South	0.19	15	12	27
			0.33	15	17	32
			0.45	15	19	**34**
		East	0.19	12	11	23
			0.33	13	15	28
			0.45	13	16	**29**
		West	0.19	11	13	24
			0.33	12	16	28
			0.45	13	17	**30**

Table 6.5 shows the scoring results from WWR evaluation in Reykjavik. It indicates that the biggest WWR of 30% receives the lowest ED score but the highest IEQ score in each orientation. The smallest glazing of 20% receives the best score for ED in each location. Unlike WWR evaluation in Malmö and Oslo, after combination, the largest WWR of 30% receives the highest total score in Reykjavik. This is the reason for using the constant 30% WWR for g-value evaluation in Reykjavik.

Table 6.6 shows the scoring results from g-value evaluation in Reykjavik. It indicates that the highest g-value of 0.45 receives the highest ED and IEQ score in each orientation.

In conclusion, the largest glazing of 30% WWR with the highest g-value of 0.45 is an excellent choice for low ED and good IEQ in an office building in Reykjavik.

Table 6.5 Reykjavik WWR evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Reykjavik	No	North	20% WWR	14	17	31
			25% WWR	14	20	34
			30% WWR	13	21	**34**
		South	20% WWR	20	18	38
			25% WWR	20	20	40
			30% WWR	19	21	**40**
		East	20% WWR	16	18	34
			25% WWR	16	19	35
			30% WWR	15	20	**35**
		West	20% WWR	16	18	34
			25% WWR	15	19	34
			30% WWR	14	21	**35**

Table 6.6 Reykjavik g-value evaluation score table. High scores are in red colour.

Location	External shading object	Orientation	Glazing parameter	ED score	IEQ score	Total score
Reykjavik	No	North	0.19	10	19	29
			0.33	13	21	34
			0.45	15	22	**37**
		South	0.19	14	17	31
			0.33	19	21	40
			0.45	20	22	**42**
		East	0.19	11	17	28
			0.33	15	20	35
			0.45	16	21	**37**
		West	0.19	10	17	27
			0.33	14	21	35
			0.45	15	21	**36**

6.6 External shading object

WWR and g-value evaluations with external shading object were done in IDA ICE for Malmö with 20% WWR and g-value of 0.33. These two examples illustrate the difference in ED and IEQ between with and without external shading object. Further evaluations were not conducted for other WWR and g-values, nor other locations.

Figure 6.6.1 indicates that thermal comfort summer and winter does not change much after placing the external shading object (ESO) in each façade. The DF decreases equal amount after ESO placement in each façade. The heating demand is always higher after ESO placement, due to ESO blocking the solar heat gain needed to counteract on the transmission heat loss through glazing. The largest heating demand difference is in the south façade and the smallest in the north. The east and west façade show little change in heating demand. The cooling demand is always lower after ESO placement, due to less solar heat gain. The smallest change is in the north façade, while south and east façades show about 1/3 reduction, and west façade 1/2 reduction. The lighting demand is always higher after ESO placement, due to less daylight admission. The lighting demand increases roughly about 1.5 – 2 kWh/m^2 in each façade. Figure 6.6.2 indicates that overall, g-value evaluations with external shading object share similar behaviour as WWR evaluations indicated in Figure 6.6.1.

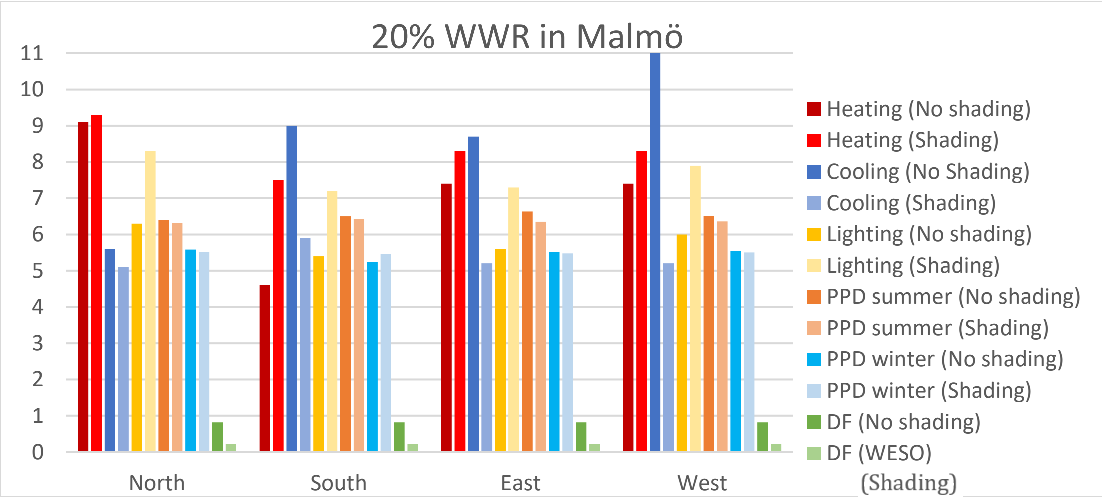

Figure 6.6.1 Comparison between with and without synthetic external shading object for 20% WWR in Malmö.

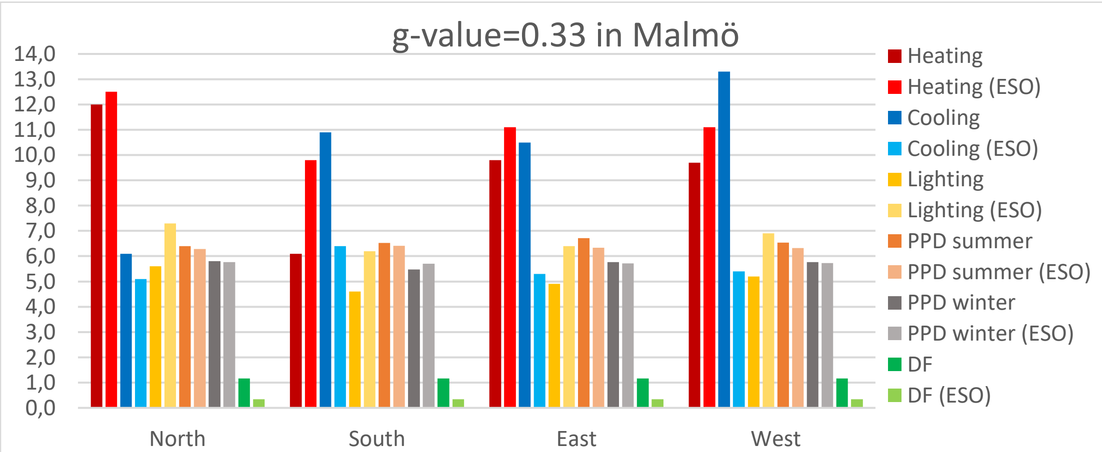

Figure 6.6.2 Comparison between with and without synthetic external shading object for g-value of 0.33 in Malmö.

6.7 Summary of observations

When WWR increases, both transmission heat loss and solar heat gain increases. When the glazing transmission heat loss overpowers the solar heat gain with increasing WWR, the heating demand increases, the winter PPD gets worse in all locations and the summer PPD gets better in Reykjavik. While the transmission heat loss is held at a fixed rate with a constant WWR, the solar heat gain overpowers the transmission heat loss with increasing g-value, so the heating demand decreases, the cooling demand increases and the summer PPD gets worse in Malmö and Oslo.

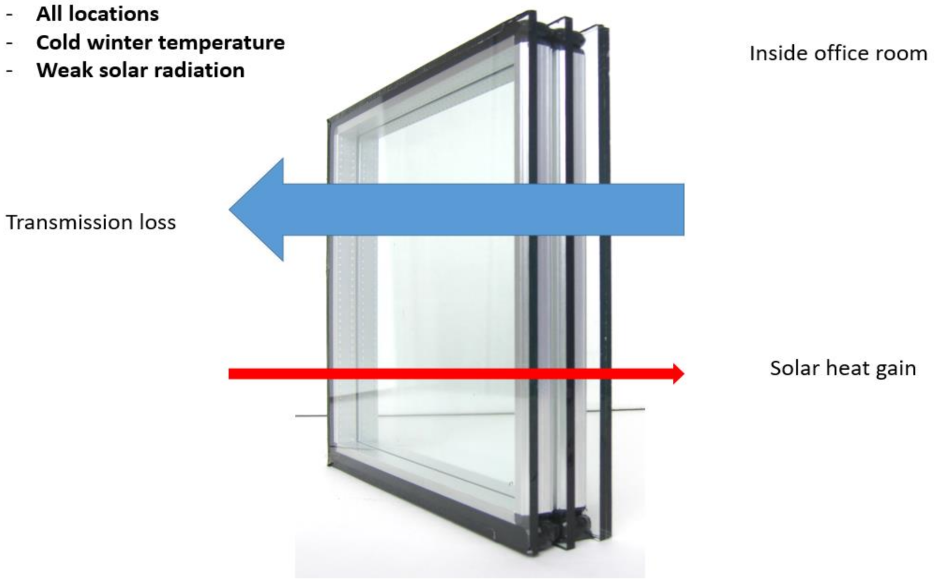

Figure 6.7.1 Winter climate at the three Nordic countries has lower outdoor temperature than the room temperature and a limited solar heat load. So, the glazing transmission heat loss overpowers the solar heat gain.

Between the east and west façade, each has its own distinct characteristics. The west façade has more annual solar heat load therefore higher cooling demand, and the east façade has less solar heat load to compensate the transmission heat loss through glazing which leads to higher heating demand. The east facade has higher summer solar heat load than the west during June, July and August, therefore higher summer PPD. The east façade has more annual daylight admission than the west, which leads to lower annual lighting demand. By adding the heating, cooling and lighting demands, shows that east and west façade are the two most energy consuming facades.

The WWR and g-value evaluations with heating demand, cooling demand and winter PPD confirm the significance of south façade receiving the highest annual solar heat load of all facades and the insignificance of the north façade receiving the lowest. For instance, by increasing g-value in the south façade, it allows the strong solar radiation to pass through, thus decreasing the heating demand. Whereas the weak solar radiation in the north façade does not make any significant impact when g-value is increased.

When latitude increases, the recognition of lower outdoor temperature and lower solar radiation intensity explains the increase and decrease in each ED and IEQ element. As long WWR and g-value are constant at different locations, when orientation increases in latitude, the winter PPD, heating and lighting demand increases, while the cooling demand and summer PPD decreases.

By understanding the rule of transmission heat loss against solar heat gain, the east and west façade characteristics, the significance of solar radiation in the south façade and the insignificance in the north, it is now clear how to achieve the desirable ED and IEQ by adjusting the WWR and g-value.

- When the heating demand reduction is desired, decreasing WWR in north facade should be the first choice. Alternatively, lowering WWR is the optimal solution. It is more effective to decrease the WWR (by merely 10%) rather than using high performance glazing with high g-value in the north, east and west façade, but in the south façade, the g-value is more effective.
- When the cooling demand reduction is desired, decreasing WWR or g-value in the south or west façade should be the first choices. Alternatively, lowering WWR or g-value is the optimal solution. High performance glazing with high g-value has negative effect on energy saving due to high cooling demand.
- When the lighting demand reduction is desired, increasing WWR should be proposed, independent of façade orientation. But, increasing g-value is more effective. Increasing g-value in the north façade should be the first proposal.
- When the summer PPD reduction is desired, reducing WWR in Malmö and Oslo should be proposed, but increasing WWR in Reykjavik. Reducing g-value could also be proposed, independent of location.
- When the winter PPD reduction is desired, reducing WWR in the north, west and east façade should be proposed. Increasing g-value should only be applied in the south façade.
- When the daylight factor increase is desired, increasing WWR and g-value are the optimal solutions. Increasing WWR is more effective.

6.8 Discussion

The problem of choosing limited range of WWR is it represents very limited range of regression analysis, making it difficult to choose the accurate regression type to predict for higher WWR values. But this range was chosen for a reason, which was to fulfil the minimum ED and IEQ requirements according to NS 3701 and Miljöbyggnad.

The evaluations indicated that the east façade has less cooling demand than the west because of lower solar heat gain. But, the east façade has lower lighting demand than the west because of higher daylight admission. The reason why solar heat gain does not go hand in hand with daylight admission through glazing is because the different characteristic of g-value and T_{vis}. The g-value hinders the direct solar radiation passing through glazing, whereas T_{vis} hinders the visible daylight.

The highest cooling demand is in the south façade in Oslo. This complies with the evaluations from WWR and heating demand, which suggested that the south façade receives the most annual solar heat load at each location. Malmö and Reykjavik deviate from this rule, where their highest cooling demand in in the west façade.

The summer and winter PPD does not change much by the impact of WWR and g-value. One explanation could be that the indoor climate is monitored by the adequate ventilation system. Perhaps other thermal comfort factors could be added to offset the ED of the score table, for example by adding the thermal comfort level of glare.

7 Conclusion

After completing the study of glazing parameters' impacts on the ED and IEQ, many interesting discoveries were found; the rule of glazing transmission heat loss against solar heat gain, the east and west façade characteristics, the significance of solar radiation in the south façade and the insignificance of solar radiation in the north façade.

Understanding these discoveries is crucial, because they give an insight of how WWR and g-value affect the ED and IEQ elements of an office building in the Nordic climate. In other words, these discoveries clarify the reason why the examined ED and IEQ elements react in a certain way by WWR and g-value variations. However, the main guideline is that these discoveries all rely on the climate condition, that is the outdoor air temperature and the solar radiation intensity. As these two climate factors depend on the location, orientation and time-period. Eventually, these two climate factors can be manipulated with WWR and g-value variations to receive the desirable ED and IEQ.

The score table results indicated that with the minor deviation of the west façade in Reykjavik, overall, the middle size glazing of 25% WWR and the highest g-value of 0.45 is an excellent choice to achieve low ED and good IEQ for the study case. This gives the impression that by limiting the WWR to a minimum value and by applying high performance glazing with high g-value should be the optimum guideline when designing an office building with low ED and healthy IEQ in the Nordic countries.

8 Future research

Figure below is an imaginable programme tool that could be developed in the future. This programme sums up the evaluation process and gives a quicker visual interpretation of the results. The functioning is based on inserting the glazing parameters, for example of WWR and g-values, into the programme, then the programme calculates and shows the glazing performance results in terms of ED and IEQ given by its value and score.

By using the façade design tool, it is possible to find the window design with the lowest ED and best IEQ for an office perimeter zone in Sweden, Norway and Iceland. Finding the optimal design is a process and there is not one clear answer. It depends on the fixed conditions of the design and other assumptions made by the design team.

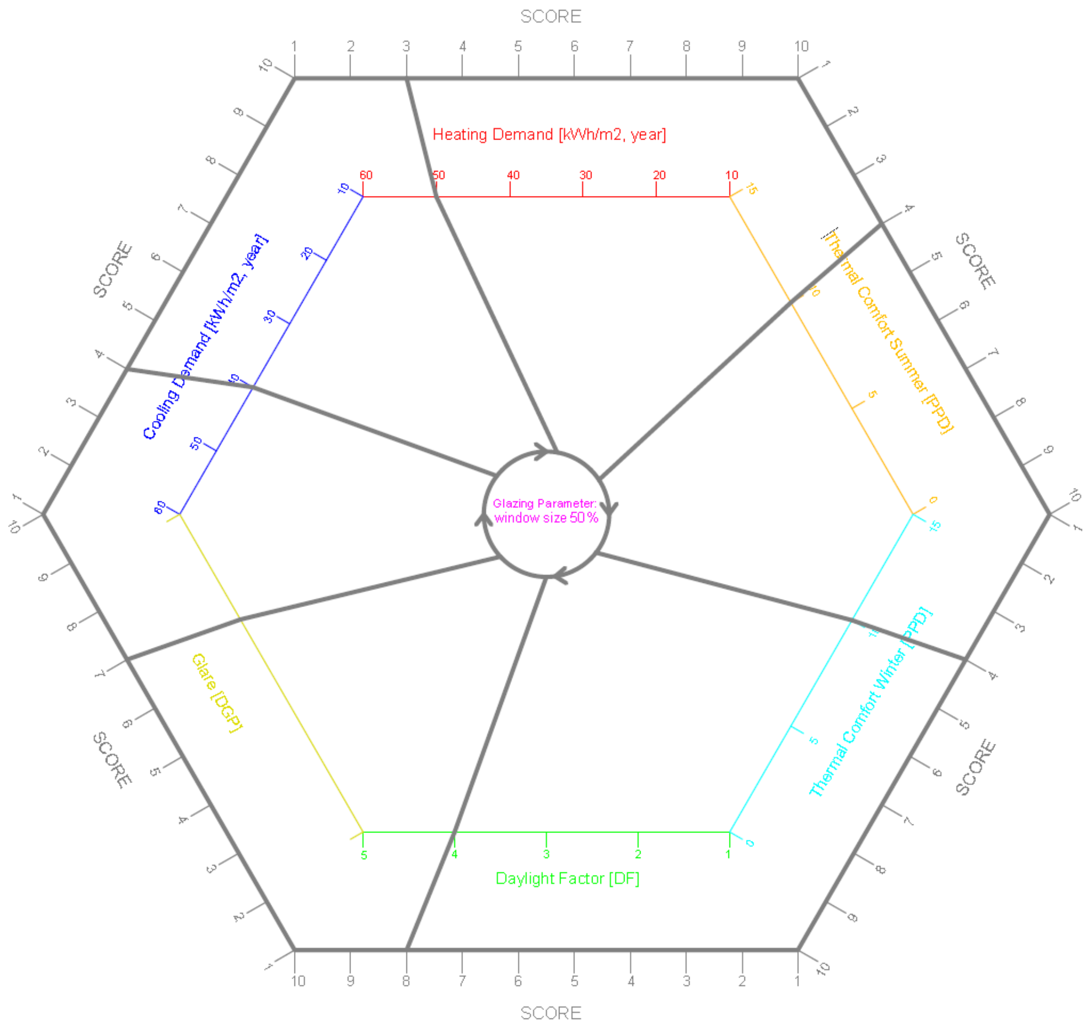

Figure 8.1 A preliminary drawing of the evaluation tool to evaluate the glazing performance in terms of ED and IEQ.

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Appendix A – Higher WWR evaluations

Unlike g-value range, 20 – 30% WWR range is quite limited. A regression type used for 20 – 30% WWR evaluation might fit perfectly within this range, but when predicting for higher WWR, the same regression type is far from being accurate. Further evaluations had to be conducted with higher WWR values in order to determine the most accurate regression type within the 20 – 30% WWR range, but also for more precise evaluation results for WWR values higher than 30%. In addition, the deviations for each ED and IEQ evaluations were calculated.

WWR of 50% and 70% were used for higher WWR evaluations for each ED and IEQ element. This is in accordance with the study on design guidance for offices in Minneapolis, where WWR range of 10 – 60% were examined. Figure A.1 shows the size difference of the study case's glazing for 30%, 50% and 70% WWR.

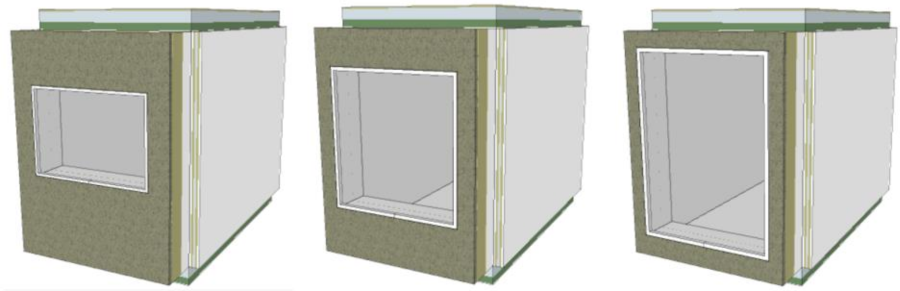


Figure A.1 Study case with 30% WWR and two higher WWR of 50% and 70%.

<u>Heating demand and WWR:</u>

WWR and heating demand relationship (see Figure 6.1.1 – 6.1.3) indicates that all facades at each location has a linear behaviour for the WWR range of 20 – 30%. So, one façade test example is sufficient for higher WWR estimation. The east façade in Malmö was chosen (Figure 6.1.1), which had a linear function of $y = 46x - 1{,}8$. This function is plotted for the heating demand estimation for the WWR range of 10 – 90% in Figure A.2. To check the reliability of this linear function, two additional evaluations were conducted. One for 50% WWR and the other for 70% WWR, as they are presented by the two red dots in Figure A.2. These two evaluation results had a 2% and 3% deviation from the linear function from the 20 – 30% WWR and heating demand evaluation in east façade in Malmö. This is very accurate indeed, so in conclusion linear regression is the most accurate regression type to demonstrate the WWR and heating demand relationship within the range of 20 – 30% WWR and higher than 30% WWR. The linear function is now set with 3% deviation.

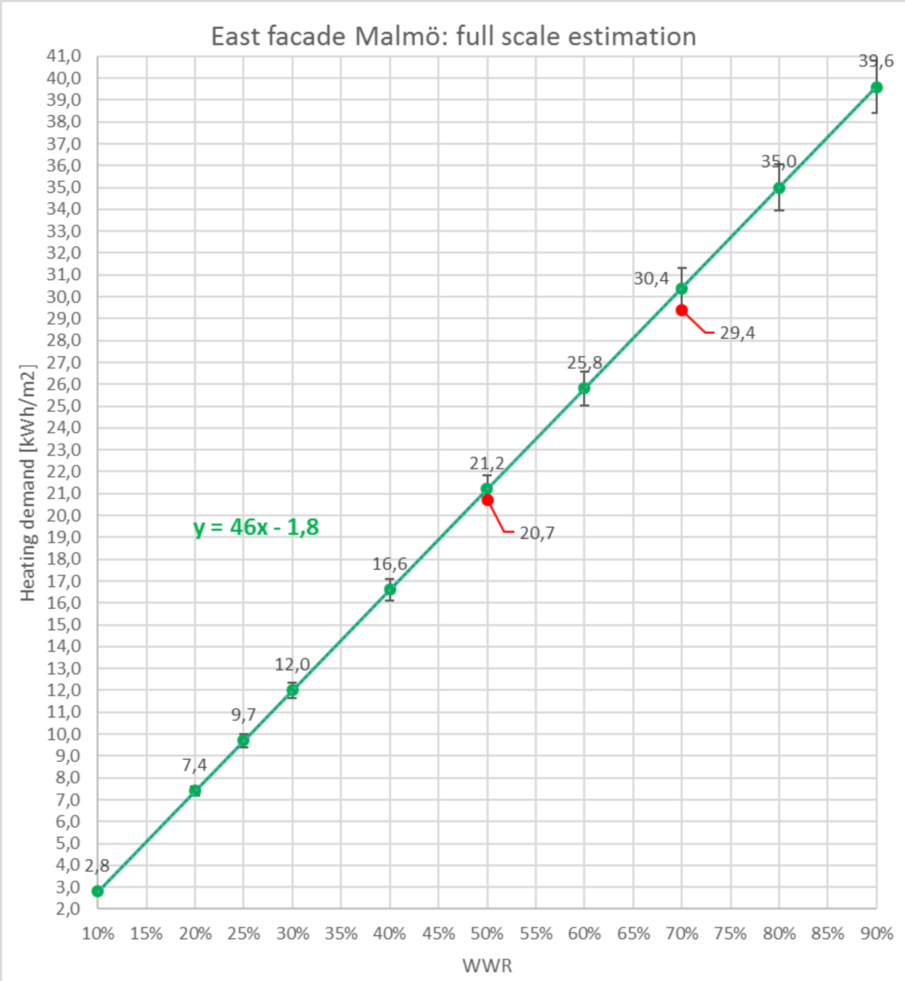


Figure A.2 Relation between heating demand and higher WWR in the east façade in Malmö. Investigation on regression type and observation of deviation.

Cooling demand and WWR:

Again, the task is to find the most accurate regression type and compute the deviation percentage. Figure 6.1.5 – 6.1.7 indicate that except for the east façade in Reykjavik, all the WWR and cooling demand relationships in each façade at all locations have a linear behaviour, therefore one test example is sufficient. The south façade in Oslo was chosen, which had a linear function of y = 52x (Figure 6.1.6). This function is plotted in Figure A.3 and shows the estimation for WWR range of 10 – 90%. To check the reliability and accuracy of this linear regression for higher WWR values, two additional evaluations were conducted, one for 50% and the other for 70% WWR, as they are presented by the two red dots in Figure A.3. The outcome was that the results from these two evaluations had about 8.3% and 13.1% deviation from the linear function. In conclusion, linear regression is reliable for the WWR and cooling demand relationship. Furthermore, power regression was also checked, but it had a higher deviation percentage for 50% and 70% WWR evaluations. Even though linear regression for Reykjavik in the east façade has a large deviation, up to 91%, it is still the most accurate regression type (Figure A.4).

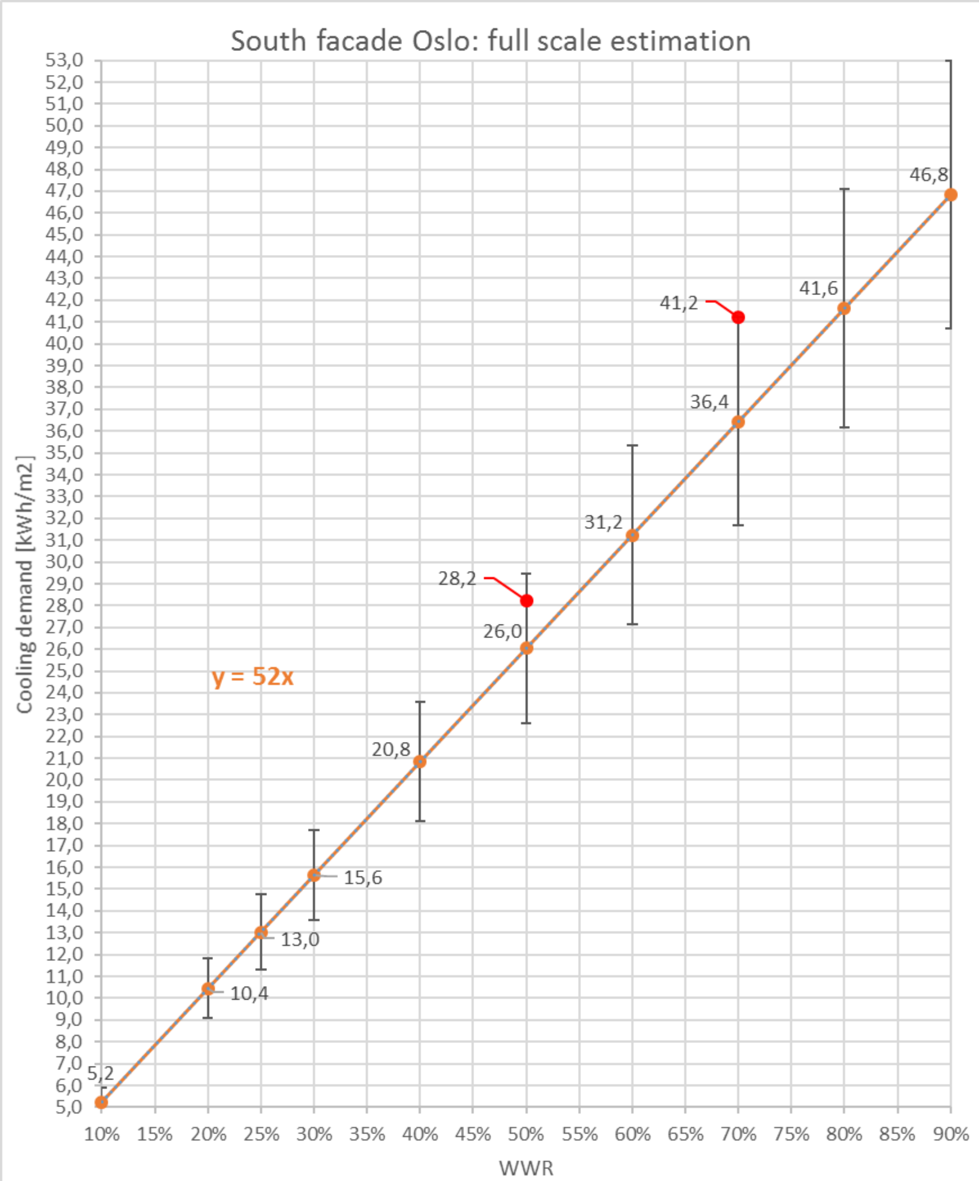


Figure A.3 Relation between the cooling demand and higher WWR in south façade in Oslo. Investigation on regression type and observation of deviation.

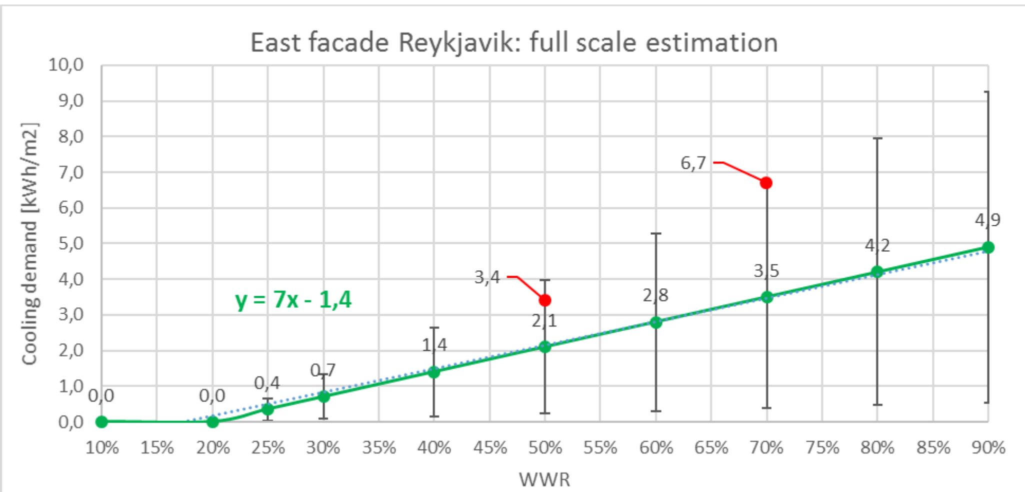


Figure A.4 Relation between the cooling demand and higher WWR in east façade in Reykjavik. Investigation on regression type and observation of deviation.

Lighting demand and WWR:

The power regression is the most accurate regression type describing the relationship between the WWR and lighting demand for 20 – 30% WWR and higher WWR values. It has 7% deviation for 50% WWR and 15% for 70% WWR.

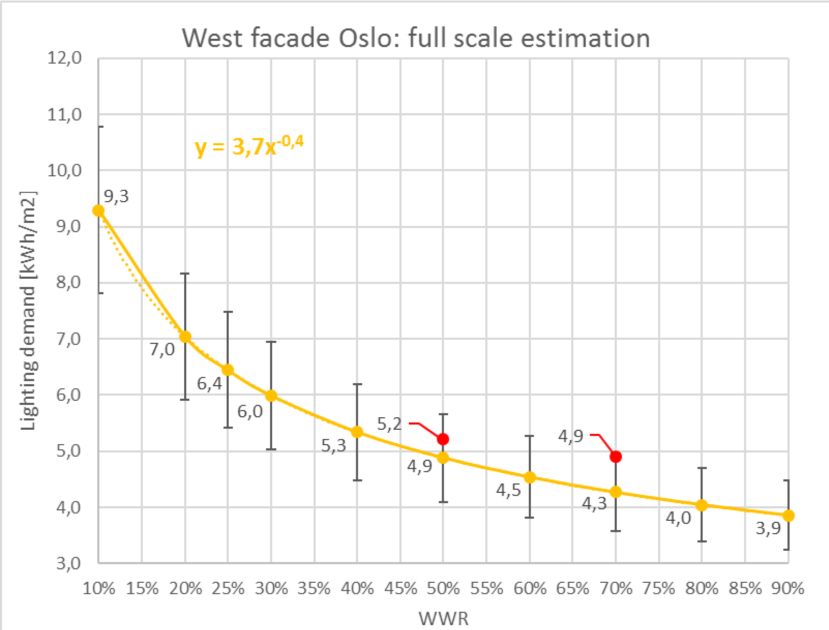


Figure A.5 Relation between the lighting demand and higher WWR in west façade in Oslo. Investigation on regression type and observation of deviation.

Thermal comfort summer and WWR:

When PPD increases with increasing WWR, the exponential regression is the most accurate regression type for the WWR and thermal comfort summer relationship. It has a minimum deviation percentage of 6.5%.

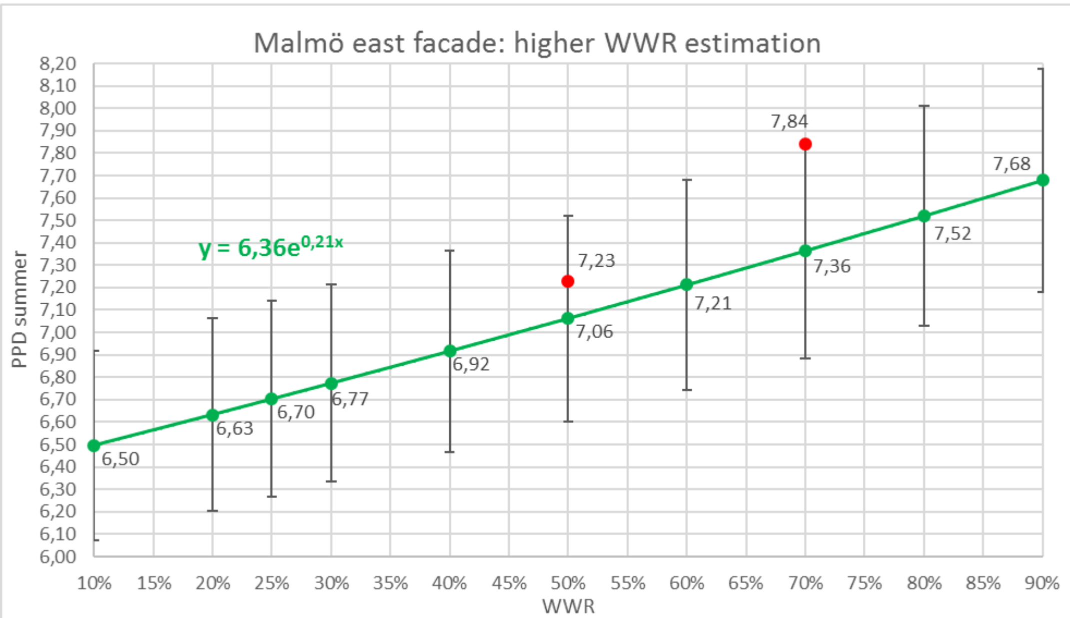


Figure A.6 Relation between the thermal comfort summer and higher WWR in Malmö in the east façade. Investigation on regression type and observation of deviation.

When PPD decreases with increasing WWR, the power regression is the most accurate regression type for the WWR and thermal comfort summer relationship. It has a minimum deviation percentage of 1%.

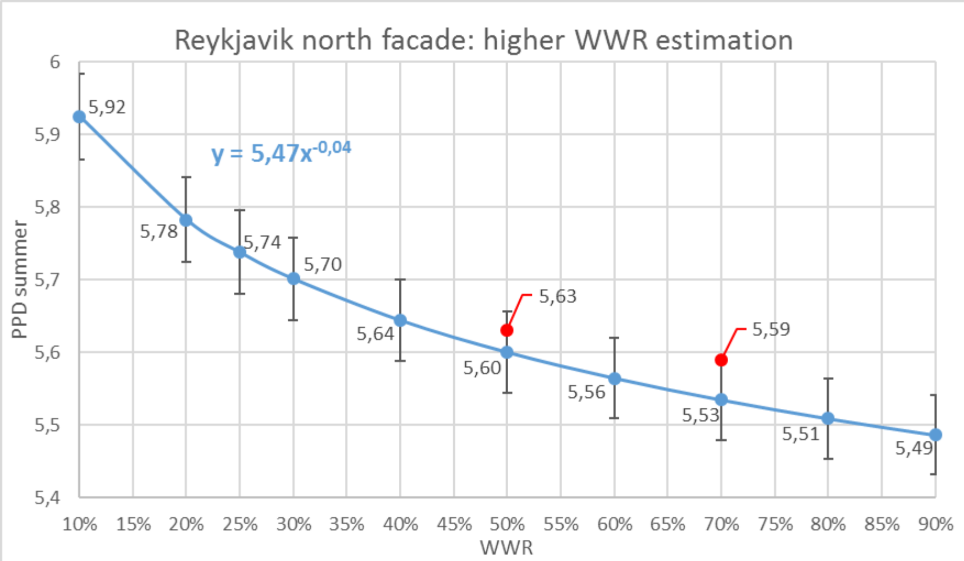


Figure A.7 Relation between the thermal comfort summer and higher WWR in Reykjavik in the north façade. Investigation on regression type and observation of deviation.

Thermal comfort winter and WWR:

The thermal comfort winter and WWR relationship is best described by the power regression. It has a minimum deviation percentage of 3%.

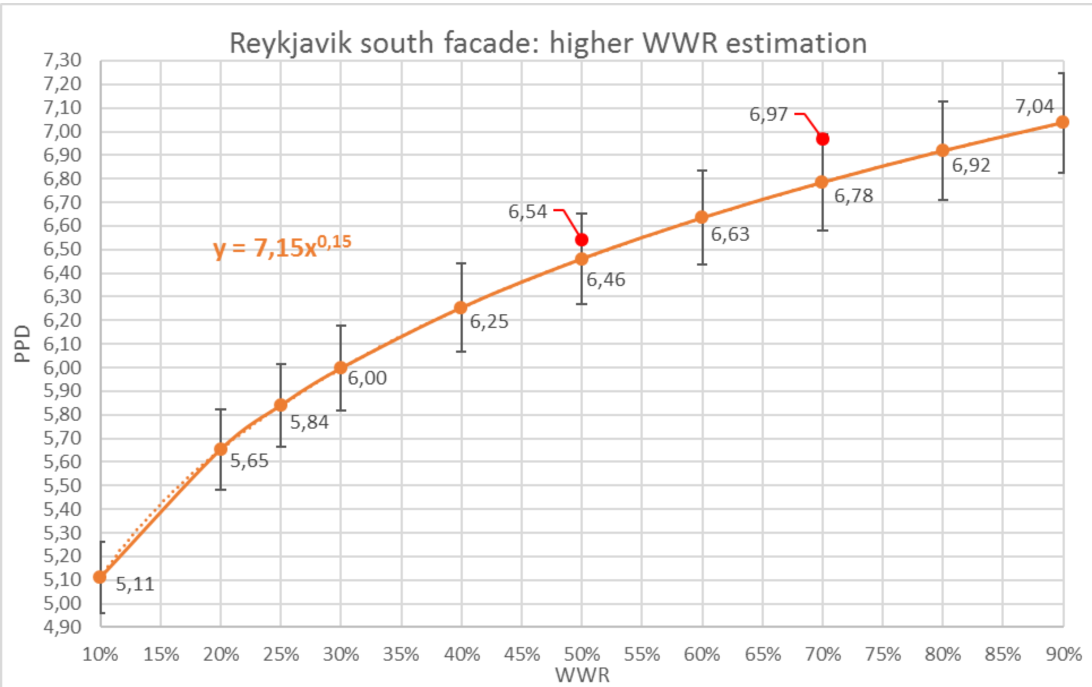


Figure A.8 Relation between the thermal comfort winter and higher WWR in Reykjavik in the south façade. Investigation on regression type and observation of deviation.

Daylight factor and WWR:

The daylight factor and WWR relationship is best described by the logarithmic regression. It has a minimum deviation percentage of 11%.

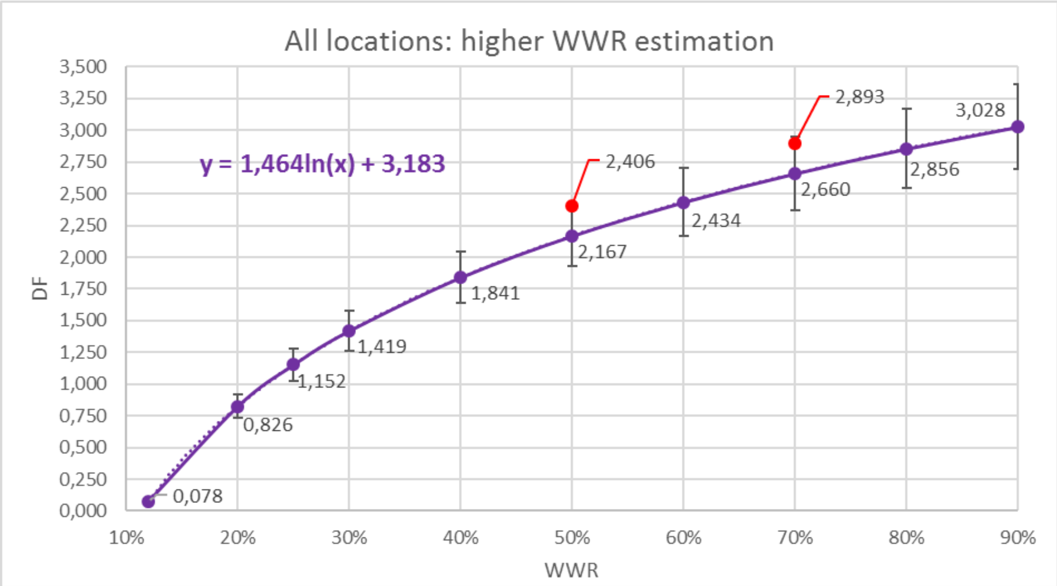


Figure A.9 *Relation between the daylight factor and higher WWR for all locations and orientations. Investigation on regression type and observation of deviation.*

Appendix B – IDA ICE Input data report

EQUA SIMULATION TECHNOLOGY GROUP		Input data Report	
Project		**Building**	
		Model floor area	9.8 m^2
Customer		Model volume	31.5 m^3
Created by	Bjartur Guangze Hu	Model ground area	0.0 m^2
Location	Oslo/Gardermoen_013840 (ASHRAE 2013)	Model envelope area	7.7 m^2
Climate file	Oslo/Fornebu_ASHRAE	Window/Envelope	25.0 %
Case	studycase_passivhus_noES_25%	Average U-value	0.3669 W/(m^2 K)
Simulated	24.5.2017 11:45:11	Envelope area per Volume	0.2439 m^2/m^3

Wind driven infiltration airflow rate 3.067 l/s at 50.000 Pa

Building envelope	Area [m^2]	U [W/(m^2 K)]	U*A [W/K]	% of total
Walls above ground	5.76	0.11	0.63	22.46
Walls below ground	0.00	0.00	0.00	0.00
Roof	0.00	0.00	0.00	0.00
Floor towards ground	0.00	0.00	0.00	0.00
Floor towards amb. air	0.00	0.00	0.00	0.00
Windows	1.92	1.08	2.06	73.24
Doors	0.00	0.00	0.00	0.00
Thermal bridges			0.12	4.29
Total	7.68	0.37	2.82	100.00

Thermal bridges	Area or Length	Avg. Heat conductivity	Total [W/K]
External wall / internal slab	4.80 m	0.004 W/(m K)	0.017
External wall / internal wall	6.40 m	0.004 W/(m K)	0.023
External wall / external wall	0.00 m	0.000 W/(K m)	0.000
External windows perimeter	5.60 m	0.014 W/(m K)	0.081
External doors perimeter	0.00 m	0.000 W/(K m)	0.000
Roof / external walls	0.00 m	0.000 W/(K m)	0.000
External slab / external walls	0.00 m	0.000 W/(K m)	0.000
Balcony floor / external walls	0.00 m	0.000 W/(K m)	0.000
External slab / Internal walls	0.00 m	0.000 W/(K m)	0.000
Roof / Internal walls	0.00 m	0.000 W/(K m)	0.000
External walls, inner corner	0.00 m	0.000 W/(K m)	0.000
Total envelope (incl. roof and ground)	7.68 m^2	0.000 W/(m^2 K)	0.000
Extra losses	-	-	0.000
Sum	-	-	0.121

Windows	Area [m^2]	U Glass [W/(m^2 K)]	U Frame [W/(m^2 K)]	U Total [W/(m^2 K)]	U*A [W/K]	Shading factor g
E	1.92	1.10	0.85	1.08	2.06	0.45
Total	1.92	1.10	0.85	1.08	2.06	0.45

Air handling unit	Pressure head supply/exhaust [Pa/Pa]	Fan efficiency supply/exhaust [-/-]	System SFP [kW/(m^3/s)]	Heat exchanger temp. ratio/min exhaust temp. [-/C]
AHU	600.00/400.00	0.65/0.65	0.92/0.62	0.87/1.00

DHW use	L/per occupant and day	No. of persons	Total, [l/s]
	0.000	1.000	0.000

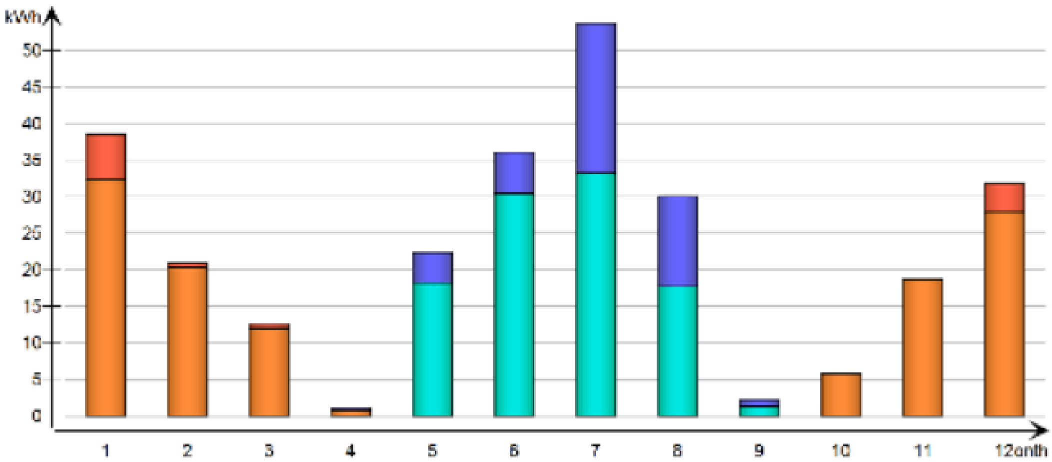
Appendix C – IDA ICE Systems Energy report

EQUA SIMULATION TECHNOLOGY GROUP		**Systems Energy**	
Project		**Building**	
		Model floor area	9.8 m^2
Customer		Model volume	31.5 m^3
Created by	Bjartur Guangze Hu	Model ground area	0.0 m^2
Location	Oslo/Gardermoen_013840 (ASHRAE 2013)	Model envelope area	7.7 m^2
Climate file	Oslo/Fornebu_ASHRAE	Window/Envelope	25.0 %
Case	studycase_passivhus_noES_25%	Average U-value	0.3669 W/(m^2 K)
Simulated	24.5.2017 11:45:11	Envelope area per Volume	0.2439 m^2/m^3

Used energy

kWh (sensible and latent)

Month	Zone heating	Zone cooling	AHU heating	AHU cooling	Dom. hot water
1	32.3	0.0	6.2	0.0	0.0
2	20.4	0.0	0.6	0.0	0.0
3	11.9	0.0	0.7	0.0	0.0
4	0.8	0.0	0.0	0.3	0.0
5	0.0	18.2	0.0	4.2	0.0
6	0.0	30.4	0.0	5.7	0.0
7	0.0	33.1	0.0	20.6	0.0
8	0.0	17.7	0.0	12.3	0.0
9	0.0	1.3	0.0	0.9	0.0
10	5.8	0.0	0.0	0.0	0.0
11	18.7	0.0	0.0	0.0	0.0
12	28.0	0.0	3.7	0.0	0.0
Total	117.9	100.8	11.2	44.1	0.0



Appendix D – IDA ICE Building's Energy report

EQUA SIMULATION TECHNOLOGY GROUP		Energy for "Zone"	
Project		**Building**	
		Model floor area	9.8 m^2
Customer		Model volume	31.5 m^3
Created by	Bjartur Guangze Hu	Model ground area	0.0 m^2
Location	Oslo/Gardermoen_013840 (ASHRAE 2013)	Model envelope area	7.7 m^2
Climate file	Oslo/Fornebu_ASHRAE	Window/Envelope	25.0 %
Case	studycase_passivhus_noES_25%	Average U-value	0.3669 W/(m^2 K)
Simulated	24.5.2017 11:45:11	Envelope area per Volume	0.2439 m^2/m^3

Energy for "Zone"

kWh (sensible only)

Month	Envelope & Thermal bridges	Internal Walls and Masses	Window & Solar	Mech. supply air	Infiltration & Openings	Occupants	Equipment	Lighting	Local heating units	Local cooling units	Net losses
1	-14.2	0.1	-33.5	-15.8	0.0	13.1	8.5	9.2	32.3	0.0	0.0
2	-11.1	0.2	-21.6	-15.8	0.0	13.1	8.5	6.3	20.4	0.0	0.0
3	-11.4	-0.8	-7.9	-18.6	0.0	14.2	9.3	3.1	11.9	0.0	0.0
4	-9.5	-1.9	8.2	-19.6	0.0	12.4	8.5	1.2	0.8	0.0	0.0
5	-7.3	-2.8	33.9	-24.5	0.0	10.7	8.1	0.2	0.0	-18.2	0.0
6	-3.3	0.6	40.9	-28.5	0.0	11.6	8.9	0.3	0.0	-30.4	0.0
7	-2.7	-0.0	43.9	-31.4	0.0	12.7	9.8	0.5	0.0	-32.8	0.0
8	-3.0	-0.0	27.5	-28.4	0.0	11.7	8.9	1.0	0.0	-17.7	0.0
9	-4.5	2.1	6.1	-26.8	0.0	12.8	9.3	2.3	0.0	-1.3	0.0
10	-7.2	1.3	-9.6	-19.4	0.0	14.2	9.3	5.3	5.8	0.0	0.0
11	-10.4	0.2	-23.9	-16.6	0.0	13.8	8.9	9.0	18.7	0.0	0.0
12	-12.6	0.3	-32.1	-15.9	0.0	13.1	8.5	10.4	28.0	0.0	0.0
Total	-97.2	-0.7	31.9	-261.5	0.0	153.2	106.6	48.8	117.9	-100.4	0.0
During heating (4695.0 h)	-66.5	14.2	-142.8	-100.3	0.0	80.8	52.6	42.9	117.9	0.0	0.0
During cooling (3256.0 h)	-18.2	-3.9	154.3	-128.4	0.0	52.8	40.5	3.3	0.0	-100.4	0.0
Rest of time	-12.5	-11.0	20.4	-32.8	0.0	19.6	13.5	2.6	0.0	0.0	0.0