DAYLIGHTING IN ENVIROMENTALLY CERTIFIED BUILDINGS

Subjective and objective assessment of MKB Greenhouse, Malmö, Sweden

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Lund University

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

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Abstract

What could be considered an adequate level of daylight in buildings has become a debated question in the Swedish building industry. The current daylight requirements are often found difficult to meet in practice, especially in combination with other requirements regarding energy use. Outdated daylight requirements in the national building code combined with limited knowledge about the subjective impression of daylight in residential buildings are two issues that form the bottleneck around the question of daylight and energy in buildings. Daylight is of great importance to our health and well-being. It is thus important to identify an adequate daylight level while defining an appropriate expression of this level through relevant daylight metrics in building codes and certification systems. This study focuses on the tenants' subjective impression of the daylight conditions in the apartments of MKB Greenhouse, Malmö, Sweden. The goal of this study is to link the subjective impression of daylight to objectively measured and simulated data. This study contributes to knowledge in the field that will help to determine suitable daylight conditions in future energy efficient multi-family dwellings. Self-administered questionnaires are used to collect information about the subjective impression of daylight in Greenhouse. Physical measurements are carried out and existing daylight simulations are further analyzed and discussed in relation to both measurements and subjective assessments. The subjective assessments show that the respondents have a clear preference for daylighting and that their perception of daylight level is affected by other parameters than the daylight factor alone. The objective assessment shows that the daylight factor (DF_p) varies between 0.8-1.2% in the main living spaces of the apartments. Linking the objective results to the subjective ones, the results of this study is that the objective daylight level does not correspond to the expected level of subjective satisfaction. The final conclusion is thus that a lower threshold than the current ($DF_p \geq 1.2\%$) is not recommended.

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Executive summary

What could be considered an adequate level of daylight in buildings has become a debated question in the Swedish building industry. The use of environmental certification systems, especially the Swedish "Miljöbyggnad" is one reason for the higher priority of daylighting. This has drawn attention to the daylight requirements in the national building code, BBR. These are often found difficult to meet in practice, especially in combination with building requirements regarding energy use. The challenge of meeting daylight and energy requirements simultaneously has to do with the contradicting nature of these two aspects; the daylight requirement is easily met with large windows and clear glass, while the energy requirement tends to prioritize smaller window areas and coated glass. The challenge is bound to become even greater in the near future, with energy efficiency highly prioritized in the EU and daylight access tending to decrease in many areas due to urban densification and area maximization. The requirements on daylight in BBR are outdated and in need of both modernization and clarification. The ongoing debate amongst professionals concerns what could be considered realistic and appropriate requirements. This includes one very important aspect; securing the well-being and satisfaction of the building occupants. Knowledge of the subjective impression of daylight is limited and one problem is the missing link between objective daylight conditions and subjective perception.

Daylight is of great importance to the health and well-being of human beings. Regular exposure to both light and darkness is important for the control of many bodily processes and normal electric lighting is not comparable to daylight when it comes to providing optimal or sufficient conditions for this. Considering that people of industrialized countries spend 85-90% of the time indoors, adequate daylight levels indoors is crucial for securing sufficient and appropriate light exposure.

This study presents the subjective impression of daylight in an energy-efficient multifamily building in Malmö, Sweden. The building, "Greenhouse", is designed to meet the daylight requirements of Miljöbyggnad, which are based on the daylight regulations in BBR. The goal is to link the subjective impression of daylight to objectively measured and simulated data. The initiative to the study comes from a larger project entitled "Innovative solutions for good daylighting and low energy consumption in multifamily buildings", funded by the foundation for Architecture and Research (ARQ) and the Swedish Energy Agency. The project is a cooperation between the housing company MKB, Lund University (LTH) and White Architects. Staff involved in the project have contributed with the objective part of this study.

The study involved self-administered questionnaires to building inhabitants, on-site measurements under overcast sky conditions, and advanced light simulations. The questionnaires were only distributed during the winter season, when daylighting is scarce in Sweden. A total of 30 questionnaires, out of 41 distributed, were returned and analyzed.

Results show that the objective daylight level (0.8-1.2%) does not correspond to the expected level of subjective satisfaction. It is also clear that daylighting is preferred over electric lighting. A selection of the main conclusions, regarding the daylight level, are presented below.

Main conclusions

- The objective assessment indicates that the main living spaces of Greenhouse have a daylight level in the range between 0.8-1.2% DF_p.
- Although the general satisfaction with daylighting was high, a significant portion of respondents did not find daylight levels to be fully satisfying in all rooms. This suggests that lower threshold for DF might not be desirable in future environmental certification systems or in the building code. The debated question of the daylight threshold in BBR (1% DF_p) being set too high is consequently not supported by the subjective assessment.
- A higher daylight level is prioritized in the kitchen, while lower prioritized in the bedroom. This supports the suggestion of working towards a more flexible way of expressing the daylight requirements in BBR with differentiation according to room and usage. It also suggests that architectural plans should be reconsidered in Sweden, taking work tasks and screen use into account. This would yield different solutions, where the kitchen might be placed closer to the building façade and not in the core as is usually the case at the moment. Main living rooms might find a preferable location somewhat further away from the building facade, where nuisance from direct sunlight or high light levels would not be felt as strongly when using screen equipment. In this case for instance, a better architectural plan would have consisted of inverting living room and kitchen.
- The respondents' subjective perception of daylight level is affected by other parameters than the daylight factor alone; the results strongly suggest that daylight distribution and direct sunlight may also affect the assessment. In general more even distribution yields higher assessment for daylight levels. The study thus confirms that the daylight factor is not a sufficient indicator of daylighting quality and should perhaps be supplemented by other simple indicators such as uniformity (min/average) and perhaps climate-based values that take into consideration direct sunlight. This is the case for other certification systems such as BREEAM and LEED, which include either/or uniformity and spatial daylight autonomy.

This project was limited in time and budget and therefore some major limitations are to be kept in mind:

- The subjective assessments only cover the winter period. The conclusions may be different if the building was surveyed during a whole year;
- The measurements were carried out to assess daylight factors, requiring simultaneously measured interior and exterior illuminances collected under overcast sky conditions. Long term monitoring may result in more information and different conclusions.

The project is ongoing, with plans of further questionnaire investigations as well as a more detailed statistical analysis of the results. It is the hope of the author that this first study has contributed to knowledge that will be useful for determining suitable daylight conditions in future energy-efficient multi-family dwellings.

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Abbreviations

General:

BBR	Boverkets byggregler
BRE	Building research establishment
BREEAM	BRE environmental assessment method
BREEAM-SE	BREEAM, svensk tillämpning
CEN	Comité Européen de normalisation (European Committee for Standardization)
CIE	Commission Internationale de l'Eclairage (International Commission on Illumination)
EPBD	Energy Performance of Buildings Directive
FEBY	Forum för energieffektiva byggnader
ipRGC	Intrinsically photosensitive retinal ganglion cell
LEED	Leadership in energy and environmental design
MKB	Malmö kommunala bostads
NCC	Nordic construction company
NZEBs	Nearly zero-energy buildings
PEAB	Paulsson entreprenad aktiebolag
SAD	Seasonal affective disorder
SBUF	Svenska byggbranschens utvecklingsfond
SGBC	Sweden Green Building Council

Daylight:

ARQ	The foundation for architecture and research
ASE	Annual sunlight exposure (hours)
CBDM	Climate-based daylight modelling
DDM	Dynamic daylight metrics
D_T	Target daylight factor (%)
D_{TM}	Minimum target daylight factor (%)
DA	Daylight autonomy (%)
DF	Daylight factor (%)

DF_a	Average daylight factor (%)
DF_{MB}	DF_p positioned according to Miljöbyggnad (%)
DF_{median}	Median daylight factor (%)
DF_p	Point daylight factor (%)
DGP	Daylight glare probability (%)
E_{ext}	External illuminance (on a horizontal surface) (lux)
E_{int}	Internal illuminance (lux)
ERC	Externally reflected component
$E_{v, d, med}$	Median external diffuse illuminance (lux)
IRC	Internally reflected component
sDA	Spatial daylight autonomy (%)
SC	Sky component
UDI	Useful daylight illuminance (%)

Definitions

Annual Sunlight Exposure (ASE): The number of hours per year at a given point where direct sun is incident on the surface.

CIE Standard Overcast Sky: A CIE mathematically defined standard sky, where the sun is fully obscured and there is no indication of its position (Tregenza & Wilson, 2011) Alternatively, the meteorological condition of clouds completely obscuring all of the sky, which is characterized by the luminance at the zenith is three times brighter than at the horizon (DeKay & Brown, 2001).

Climate-based Daylight Modelling (CBDM): The prediction of various radiant or luminous quantities (e.g. irradiance, illuminance, radiance and luminance) using sun and sky conditions that are derived from standardized annual meteorological datasets

Closed Question: A question with a predefined set of answers the respondent can choose from.

Daylight: Natural light from the sun and sky.

Daylighting: The illumination of buildings by natural light.

Daylight Autonomy (DA): The percentage of the time-in-use that a certain user-defined lux threshold is reached through the use of just daylight.

Daylight Factor (DF): The ratio of the illuminance at a point on a given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the simultaneously measured illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, excluding the contribution of direct sunlight to both illuminances (CEN-TC169, 2015).

Daylight Glare Probability (DGP): A glare prediction index. A function of the vertical eye illuminance, the glare source luminance, its solid angle and its position index (Wienold & Christoffersen, 2006).

Illuminance: Photometric quantity describing the total luminous flux incident on a point or sensor from all directions of the half sphere. Illuminance is measured in lux, where one lux is one lumen per square meter.

Illuminance Uniformity (Uo): The ratio between the minimum and the average illuminance in a space or on a desk surface.

Luminance: Photometric measure of the luminous intensity per unit area of light travelling in a given direction. Luminance is measured in candelas per square meter, where one candela is one lumen per steradian.

Main living space: The open-plan space consisting of kitchen, dining room and living room.

Median external diffuse Illuminance ($E_{v,d,med}$): The illuminance produced by skylight on a horizontal surface of the Earth achieved for half of the daylight hours (2190 hours) in the year (CEN-TC169, 2015)

Minimum target Daylight Factor (D_{TM}): The minimum daylight factor allowed for a given area (i.e. sensor point) in order to satisfy the criterion for daylight provision over the entire space (CEN-TC169, 2015)

Nearly zero-energy building (NZEB): Buildings with very high energy performance and where the required amount of energy mostly comes from renewable energy sources (European Commission, 2017).

Respondent: The individual answering the questionnaire.

Spatial Daylight Autonomy (sDA): A standard requiring 50% of the occupied hours during a year to be adequately daylit.

Self-administered questionnaire: A questionnaire designed to be completed without intervention or support from an interviewer.

Target Daylight Factor (D_T): The daylight factor value that needs to be achieved across a specified fraction of a given area (i.e. sensor points across a grid) in order to satisfy the criterion for daylight provision (CEN-TC169, 2015).

Useful Daylight Illuminance (UDI): The fraction of the time in a year when indoor horizontal daylight illuminance at a given point falls in a given range (Nabil & Mardaljevic, 2005).

1 Introduction

Light is very important for human beings and probably plays a more significant role for health and well-being than what is recognized by most people. Some of our bodily processes, like sleep patterns, feeling of alertness, mood and physical strength, are controlled by biological clocks which in turn depend on regular exposure to both light and darkness each day (Foster, 2011). How these biological clocks react to light exposure depends on factors like the timing of the exposure, the spectrum (or "color") of the light and the duration of the exposure (Foster, 2011; Schierz & Vandahl, 2008). The most natural type of light we can be exposed to is daylight, representing the conditions and qualities we have evolved in and which our bodily processes are adapted to. How we react to other types of light sources, the ones we have created ourselves, with other qualities and with different timing compared to natures' rhythm of light and dark, is something that is more uncertain. Research indicates that we ought to be careful in following other light and dark patterns than those we have evolved in. As an example, light exposure during night has been identified as a possible reason for an increased risk for breast cancer among night-shift workers (Hansen, 2001; Schernhammer et al., 2001; Stevens, 2002 via Christoffersen, 2011). Despite having identified light as something that is of great importance to our health and well-being, it is still unknown what could be considered an adequate daily dose of light or darkness (Veitch & Galasiu, 2012).

A significant part of the natural light available outdoors is blocked by the building envelope, which depends on the design of the building. Considering that many of us spend up to 90% of our time indoors (Jenkins, Phillips, Mullberg, & Hui, 1992; Kotlík B & Mikešová, 2008; Klepeis et al., 2001; Schweizer et al., 2007), our exposure to natural light is significantly influenced by the building(s) we spend our time in. If well designed, a building can more or less be illuminated by natural light alone during daytime, which is referred to as "daylighting". Daylighting can also be used in combination with electric lighting, where a significant part of the ambient lighting comes from natural light while task lighting is handled by electric light sources.

The past years, providing new buildings with an "adequate" level of daylight has become a more prioritized question in Sweden through the increased use of environmental certification systems. Parallel to the increased interest for daylight, energy-efficiency has also increased in popularity, becoming a highly prioritized question, both through environmental certification systems and through an EU-demand of nearly zero-energy buildings (NZEBs) by 2021. Unfortunately, measures for improved energy standards are often in contradiction with measures for achieving good daylight levels in a building. The contradicting nature of these two aspects, in combination with rather unclear regulations about daylight, often result in the energy-aspect being prioritized at the cost of daylight. This is unfortunate, both considering the positive health-benefits of daylight and the fact that daylighting can actually save energy use. Prioritizing both aspects is possible, but often more challenging.

New energy-efficient multi-family buildings are often designed based on an environmental certification system such as Miljöbyggnad, BREEAM or LEED. In many cases, this includes specific requirements on the daylight conditions, which in combination with the energy requirements can be very challenging in the design process due to the contradicting nature of these two aspects. The daylight requirement is easily met with large windows and clear glass, while the energy requirement tends to prioritize smaller window areas and coated glass. In addition, the current trend of increased urban density and area maximization is bound to lead to decreased daylight access, which in combination with the EU-requirement of NZEBs by 2021 might make it even more difficult to meet and even maintain the daylight requirements in the future. These trends, in combination with a pressured building industry due to a housing shortage, have generated a debate amongst professionals concerning the appropriate and realistic daylighting level to secure well-being and satisfaction. It has also been pointed out that the current daylight regulations were developed before the computer age and are therefore in urgent need of modernization.

At the moment, there appears to be a gap in knowledge regarding the human subjective impression of daylight, which is valuable information towards a definition of what could be considered “healthy” daylight conditions. Feedback from tenants in combination with verification of simulated daylight conditions are needed to link real conditions to the tenants’ subjective impressions of these conditions. In order to bridge this gap, a project in collaboration with the housing company MKB and their recently built rental property, Greenhouse Augustenborg, was initiated. Greenhouse is a low-energy multifamily building which was designed to meet a combination of the requirements of a Swedish passive house according to FEBY 12 and “Miljöbyggnad”, level gold. The project consists of two parts, where the first part consists of verifying the simulated daylight levels by physical measurements while the second part focuses on collecting the tenants’ subjective impressions of daylight conditions through questionnaires.

1.1 Research Objective

This study focuses on the tenants’ subjective impressions of daylight conditions in the apartments of MKB Greenhouse. The goal of the study is to link the subjective impression of the daylight conditions to objectively measured and simulated data. This study will contribute to knowledge in this field, which will allow to determine suitable daylight conditions in future energy-efficient multi-family dwellings.

The research questions at the heart of the research process are formulated below:

- What are the tenants’ subjective impressions of the current daylight conditions in MKB Greenhouse? Are there any identifiable pattern(s)?
- Is it possible to identify a generally acceptable minimum daylight factor threshold that indicates well-being and satisfied tenants? In the affirmative, how does this correspond to the threshold required in the certification system(s) used?
- Are there any other identifiable patterns between the tenant’s subjective impressions and daylighting conditions?
- Besides the daylight factor, what other significant parameters are affecting the subjective impressions of daylight (uniformity, view, etc.)?

1.2 Research hypotheses

Based on the information found in the literature, as summarized in the background chapter, and on subjective information collected during on-site measurements, the following research hypotheses are made:

- The daylight level in MKB Greenhouse will be judged sufficient.
- The tenants' perception of daylight level is affected by uniformity. For example, the bedroom will be perceived as darker due to the higher contrast, while in reality it is brighter at the measurement point.
- The occupants are more interested in sufficient daylight levels in the kitchen and less concerned with high daylight levels in the bedroom.

1.3 Scope

This study focuses on the subjective impressions of daylight conditions in the residential apartments of Greenhouse Augustenborg, as reported by the tenants through self-administered questionnaires. The study is limited to the population of Greenhouse Augustenborg, requesting only one reply per household, which means that the size of the study is restricted to a maximum of approximately 40 responses.

The initiative to the study comes from a larger project entitled "Innovative solutions for good daylighting and low energy consumption in multifamily buildings", funded by the foundation for Architecture and Research (ARQ) and the Swedish Energy Agency. The project, led by Marie-Claude Dubois (White Architects), is a cooperation between the housing company owning Greenhouse, MKB, Lund University (LTH) and White Architects. This work consisted of three main tasks, as summarized below:

- Designing the questionnaire and presenting both a Swedish and an English version;
- Distributing and collecting the questionnaires;
- Comparing the data collected with the measured and simulated data;
- Analyzing and summarizing the results.

This study is limited to distributing the questionnaires during the winter season and the subjective impressions of the daylight conditions thus only refer to this condition.

The full project also includes physical measurements and simulations of daylight. While taking part in the work with the physical measurements, the results from the simulations (Angeraini, 2017; Bournas & Haav, 2016) have been provided here without direct contribution. The self-administered questionnaires is the main focus, but results from measurements and simulations are included in order to link the subjective impressions to actual conditions and to what was expected of the design.

1.4 Structure of thesis

The first chapter of this thesis presents relevant background information, necessary for understanding what lies behind the initiative to this study. This includes the subject of what makes daylight so important and its value for human beings. It also introduces the matter of subjective perception. The subchapter about metrics focuses on the metric mostly discussed in the Swedish daylight debate and another subchapter presents the Swedish regulations of daylight, both in the building code and in three commonly used environmental certification systems. The subchapter of Swedish daylight regulation also includes the subject of why and how the current regulations need to change. A review of similar projects is also made as well as a review of the design and use of self-administered questionnaires as social research method. The background chapter is followed by a methodology chapter, describing the studied object and the methods behind the self-administered questionnaire, the physical measurements and the simulations. A results chapter presents the most valuable results, followed by the two chapters containing discussion and conclusions.

1.5 Background

1.5.1 The importance of daylight

Daylight has a natural variation in brightness and intensity and carries information about the world outside; about the time of day, the weather and the season. According to Tregenza and Wilson (2011), most of us prefer to work and live in daylit environments, which might be connected to the fact that our senses are stimulated by change and not by constant conditions. Visual information is not only needed for the activities we are involved in, but for evolutionary biological information needs. As pointed out by Lam (1992), satisfying our need for biological information, "environmental clues" (weather, time of day, enclosure etc.), might even be more important to us than satisfying our visual needs for activities. We need these clues in order to know how to behave, what to expect and how to react. Consciously and unconsciously we seek information about the environment and Lam (1992) also expresses that we react negatively to environments which do not offer such clues.

Our most obvious use of light is that it makes it possible for us to see. But light also affects us in other, "non-visual ways", and as expressed by Veitch and Galasiu (2012), our health and well-being relies on regular exposure to both light and darkness each day. The non-visual effects of light control the timing of our biological clocks, or "circadian rhythms" but also our performance and feeling of alertness (Foster, 2011; Schierz & Vandahl, 2008). Through the advance of research, more has been learnt about how light affects us and insufficient daily light exposure has been recognized as a health issue in industrialized countries (CIE, 2004/2009 via Veitch & Galasiu, 2012).

We spend 85-90% of our time indoors (Jenkins, Phillips, Mullberg, & Hui, 1992; Kotlík B & Mikešová, 2008; Klepeis et al., 2001; Schweizer et al., 2007) and as expressed by Christoffersen (2011), this means low exposure to daylight for many of us. In addition to this, the northern latitude of Sweden means that daylight is only available for a few hours per day during the winter months and the intensity of the light during the winter is low. Working daytime hours, daylight is available while being indoors and the little time spent outdoors occurs during the dark period of the day, before sunrise or after sunset. Swedes' exposure to daylight varies significantly depending on the season (Adamsson, Laike, & Morita, 2016) and low exposure to daylight among indoor workers has been related to sleep problems, mental fatigue and an overall lowered health perception (Lowden et al. 2013). While it is still unknown what could be considered a "healthy" daily light dose (Veitch & Galasiu, 2012), Tregenza and Wilson (2011) pointed out that the design of buildings has an impact on our access to daylight considering the extensive time many of us spend indoors.

The introduction of electric lighting makes it possible to live an active life independent of nature's cycle of lightness and darkness. Electric lighting has reduced our exposure to natural light, increased our exposure to light after sunset and altered the timing of the circadian clock (Wright et al., 2013). Research indicates that our health is affected by not following nature's rhythm of a "biological day" (Foster, 2011). As will be discussed below, the effect of light depends on a number of factors, such as e.g. the timing and intensity of light, our response to normal electric lighting, which is not similar to our response to natural light, etc. (Foster, 2011). The light intensity most of us receive indoors through electric lighting is not comparable to the intensity of daylight (Foster, 2011). Even on an overcast day in Sweden (10 000 lux), daylight is 20-50 times brighter than normal office lighting (200-500 lux).

Electric lighting techniques are advancing and in some cases it is quite obvious that new knowledge about how light affects us is somehow implemented. Special light sources used for "light therapy" are a popular method used for curing seasonal affective disorder (SAD), but a Swedish review of different studies could neither confirm nor reject the efficiency of this treatment for treating SAD (Pettersson, 2008). Dynamic light sources according to specific lighting schemes is another method which is believed to have positive effects on shift-workers in terms of adapting to the working-hours (Lowden & Åkerstedt, 2012). One similar way of bringing our knowledge about the biological effects of light into practice is suggested by Figueiro (2013) through the use and development of modern lighting sources in combination with specific lighting schemes. According to this suggestion, schemes and lighting sources should be based on the available knowledge about the conditions needed for maintaining our circadian rhythm while satisfying our visual needs. Schierz and Vandahl (2008) expressed reservations about such use of electric light to improve health.

1.5.1.1 Well-being and health

Researchers have discovered a photoreceptor system in the eye, which is separate from the system used for vision. Located in the retina, this system consists of a specialized type of ganglion cells, which are directly sensitive to light and communicate with parts of the brain involved in regulating the circadian rhythms, but also other physical processes like the feeling of alertness (Foster, 2011). These "intrinsically photosensitive retinal ganglion cells (ipRGCs)" were discovered in 2002 by (Berson, Dunn, & Takao, 2002 via Veitch & Galasiu, 2012) and since then research has advanced rapidly in understanding how light affects humans biologically, independent from the visual realm.

The ipRGCs play an important role in the regulation of the circadian rhythms (Figueiro, 2013). Many of our physiological processes follow circadian rhythms (Veitch & Galasiu, 2012), which in turn are coordinated by a "master clock" controlled by a structure at the base of the brain (Foster, 2011; Figueiro, 2013). This structure acts as a control center and receives signals, most importantly through light, about when to prepare for sleep and when to wake up and prepare for activity (Boubekri, Shishegar, & Khama, 2016). Our circadian rhythm is naturally slightly longer than nature's 24 hour rhythm of light and dark (Czeisler et al., 1999) and needs daily resetting to stay aligned to the real day-night cycle (Foster, 2011), a process which is called entrainment (Boubekri, Shishegar, & Khama, 2016). Low light levels or darkness in the evening signals production of a sleep hormone called melatonin and exposure to light in the morning signals production of two hormones important for energy and activity levels, i.e. serotonin and cortisol (Boubekri, Shishegar, & Khama, 2016). These hormones are important for the entrainment of the circadian rhythm, and light plays an important role in regulating them.

The effect of light is influenced by the spectrum (the color of the light), timing of the light exposure, duration, pattern and history of the exposure (Schierz & Vandahl, 2008; Foster, 2011). The ipRGCs, that are involved in regulating the circadian rhythm, respond better to blue light (which refers to spectrum), and do not respond to brief exposure (which refers to duration) of light the same way our vision does (Foster, 2011). For a healthy, active person, the production of the sleep hormone has a peak in the middle of the night (Veitch & Galasiu, 2012), but exposure to light at night, particularly blue light, can change this pattern and disturb the timing of the circadian rhythm (Foster, 2011). Depending on the timing of light exposure, the circadian rhythm can be either delayed or advanced (Foster, 2011). The higher the light exposure during daytime, the lower this sensitivity of the circadian system to light exposure during night (which refers to history) (Figueiro, 2013). In other words, a person who lives or works outside during the day will not be as influenced by light exposure at night as a person who lives or works indoors all day.

Inadequate light exposure, or light exposure with inappropriate timing compared to nature's rhythm, will thus affect the circadian rhythm and in turn disrupt the sleep-wake pattern, which is so essential to good health and well-being. The consequence may be a reduction of performance and metabolic functions affecting mood, social skills, concentration, memory, inducing fatigue, depression and weight gain (Foster, 2011). As mentioned earlier, long-term effects of a disturbed circadian rhythm are also suspected to have a connection to an increased risk for cancer. Research also indicates that there is a connection between disturbed circadian rhythm, sleep and the immune system (Foster, 2011; Irwin, 2002; Irwin et al., 1996), increasing the risk for diseases and viral infections (Foster, 2011). A disturbed circadian rhythm can also cause a well-known form of depression, most often referred to as SAD (Boubekri, Shishegar, & Khama, 2016). The most common form of the condition occurs during the dark winter season, with symptoms like oversleeping, mood changes, lack of energy and over-eating (Tregenza & Wilson, 2011; Christoffersen, 2011) and is more common at northern latitudes where daylight is very limited during the winter months (Boubekri, Shishegar, & Khama, 2016; Christoffersen, 2011).

In addition to the effect that light exposure has on regulating the circadian rhythm, light also has other alerting effects (Veitch & Galasiu, 2012; Foster, 2011; Schierz & Vandahl, 2008) which activate parts of the brain involved in alertness, cognition, memory and mood (Foster, 2011). Increased light exposure during daytime, especially blue light in the morning, has showed positive effects on the ability to learn and process information. These are key features in school environments, which have been found to have an impact on students' performance (Shishegar & Boubekri, 2016).

Another important health aspect of light, sunlight to be more specific, is for the production of vitamin D in our bodies. Due to the fact that the type of radiation needed for the production of vitamin D, UVB-radiation, is absorbed by ordinary window glass (Wacker & Holick, 2013), this effect cannot occur indoors since the skin must be directly exposed to UVB radiation. Clothing and sunscreen also block the UVB-radiation needed for the production of vitamin D (Webb, 2006). This means, that it is important for humans to go outside, independently of the amount of daylight or sunlight received indoors. Vitamin D is needed to maintain a healthy skeleton, but has also been linked to positive regulatory effects on the immune system, preventing influenza and for preventing or mitigating cancer and autoimmune diseases (Engelsen, 2010). Vitamin D deficiency, which is prevalent in Nordic countries, is known for causing rickets, but has also been associated with a number of other health issues (Wacker & Holick, 2013).

1.5.1.2 Visual needs

Moving from discussing the non-visual aspects, light obviously also affects vison, which indirectly affects health since poor vision might be detrimental to proper function of the human being. Appropriate light levels and distribution are needed for the activities or tasks to carry out. A good luminous environment has been summarized and expressed by Lam (1992) using the following words:

"We are comfortable when we are free to focus our attention on what we want or need to see, when the information we seek is clearly visible and confirms our desires and our expectations, and when the background does not compete for our attention in a distracting way."

While good lighting conditions create visual comfort and good visual performance, inappropriate conditions cause discomfort, headache, glare and disorientation. (Rogers & Tillberg, 2015). The amount of light needed (illuminance) to perform visual tasks depends on the task and the environment where it is performed. Some typical values of required illuminance are presented in table 1 (VELUX, 2014).

Table 1- Typical illuminance levels for different types of visual tasks

100 lux	Tasks in movement, casual seeing with low detailing
300 lux	Tasks which are moderately easy
500 lux	Tasks which are moderately difficult, color judgement may be required
1000 lux	Tasks which are very difficult, high detailing required

According to Mardaljevic and Christoffersen (2017), an illuminance below 100 lux has a high probability of people switching electric lighting on, while an illuminance at 300 lux is considered sufficient for most building users.

Visual needs also depend on age and general health. With age, most people, even those with healthy vision, have higher visual needs compared to younger people (Schneck & Haegerstrom-Portnoy, 2003). Due to these age-related changes of the lens, an older person often needs two or three times the illuminance of a younger person with healthy vision to perform the same visual task (Littlefair, 2015). These changes also lead to a need of higher task contrasts, more glare protection, increased time for adapting to varying light conditions and an increased glare recovery-time (Schneck & Haegerstrom-Portnoy, 2003). Similar problems, especially a need for higher illuminances and an increased glare-sensitivity, are common for people with visual impairments (Littlefair, 2015).

Daylight through windows provides two visual functions; a view out and illumination. According to Tregenza and Wilson (2011), there is some evidence that daylight might be more effective in providing visual performance than electric lighting. The fact that daylight has perfect color rendering qualities and does not flicker is mentioned by Rogers and Tillberg (2015). Electric lighting does not provide a view out and most people prefer the natural variation of daylight and its connection to the world outside over the possibly flickering electric lighting (Rogers & Tillberg, 2015; Tregenza & Wilson, 2011).

1.5.1.3 Perception of daylight and visual preferences

As expressed by Tregenza and Wilson (2011), every single person has a unique perception of daylight. What one "sees", depends on each person's individual experiences and expectations, on physical factors, like noise and heat, on the social environment and the frame of mind, motivation and interest in what the person is doing.

According to Veitch and Galasiu (2012), research has shown that most people prefer to have windows or skylights in the main living spaces, which is probably connected to the fact that windows make a room appear more spacious and reduces the feeling of enclosure. For the same reason, windows are less appreciated in bathrooms, where a higher degree of privacy and enclosure is usually desirable.

How much daylight is needed varies according to surveys between different groups of people, and it is likely that the preference for a specific daylight quantity is connected to the function of the building, its architectural nature and the cultural background of the person (Tregenza & Wilson, 2011). According to Tregenza and Wilson (2011), occupants of very high density residential blocks of Hong Kong have been found to be satisfied with lower daylight levels than the occupants of social housing in Western Europe and people in modern expensive areas have been found to expect more of both daylight level and view out than people in lower-cost areas.

Too much daylight can cause glare and visual discomfort, a problem which is likely to be more common among elderly and vision impaired people as mentioned earlier. As pointed out by Veitch and Galasiu (2012), most research about visual discomfort caused by too much light from windows has been done in office settings assuming a middle-aged person with healthy vision, which cannot be applied to residential environments and which does not take into consideration how light is perceived by an old or vision-impaired person. The subject of discomfort from light through windows has not been investigated for residential buildings and even for offices there is a gap in research when it comes to how discomfort caused by daylight, sunlight and windows is perceived by different age groups (Veitch & Galasiu, 2012).

Research from office settings suggests that the sensation of glare and level of discomfort is also affected by variables not related to lighting, such as the task involved (Veitch & Galasiu, 2012) or how interesting is the scene outside (the glare source) (Galasiu & Veitch, 2006; Tuaycharoen, 2011). For example, most people experience less discomfort with a nice view of the landscape or interesting tv-screen, than when looking at less interesting scenes with the same brightness and luminance pattern (Tregenza & Wilson, 2011; Tuaycharoen & Tregenza, 2007; Tuaycharoen & Tregenza, 2005). Somehow, what is uncomfortable is sometimes still perceived as acceptable, due to compensatory mechanisms (Veitch & Galasiu, 2012).

According to Veitch and Galasiu (2012), there is still much to be learnt about discomfort in residential settings and about the experience of discomfort. In their literature review they found that studies of daytime residential light levels in the USA (Bakker, Iofel, & Lachs, 2004) and the Netherlands (Aarts & Westerlaken, 2005) show that home-dwelling elderly often rate their light levels as adequate, even when they are much lower than what is recommended for good visual performance. They also point out that the reason for this would be interesting to know, especially since studies have shown that increased light levels in the homes of elderly has a positive effect on life quality (Brunnström et al., 2004). Veitch and Galasiu (2012) also claimed that daylighting needs to be combined with better understanding of the activities and visual needs in residential settings. Meeting both non-visual and visual needs simultaneously is a challenge and will not be guaranteed by the mere presence of daylight through a window.

1.5.1.4 Energy efficiency

According to Veitch and Galasiu (2012), daylight is the most energy-efficient light source during daytime and the most energy-efficient way of providing the light exposure needed for health and well-being. However, for it to be a sustainable and energy-efficient method of delivering light inside buildings, understanding of how it affects other aspects is necessary. Daylighting, energy-efficiency and thermal comfort are three closely related aspects of sustainable building. Daylighting requires good planning with appropriately placed and sized windows, suitable orientation and wise choices of solar control. If these things are not carefully planned, there is a risk of negative effects on both energy efficiency and thermal comfort, as well as on the visual comfort of the occupants. As an example, if the solar shadings are used throughout the day due to failed planning of the daylighting (or the solar shading control system), unnecessary energy is lost through windows that are not used, while electric lighting needs to be switched on.

A well designed daylit building has potential for saving energy through daylight utilization, i.e. the replacement of electric light by daylight. For commercial buildings, the saving potential is in the range between 20-60% (VELUX, 2014). Residential buildings have not been studied to the same extent and there is less understanding and knowledge about the daily activities and preferences for light in dwellings (Veitch & Galasiu, 2012). According to Danish statistics from 2005, electric lighting uses 15-17% of the total electricity use of residential buildings (Logadóttir et al., 2013). Just like in the Swedish energy regulations, this energy consumption is excluded from the Danish national energy requirements.

Studying the saving potential in dwellings requires assumptions of a user profile for how the light is switched on and off, which in turn requires good understanding of how and when the occupants use their homes. A study from 2012 showed that the need for electric lighting was reduced between 16-20% by introducing a skylight in a single-family house (VELUX, 2014). The results included eight different European locations and different orientations of the house. In line with these results, daylight utilization in a single family house located in Stockholm was found to reduce the need for electric lighting by 23-42% in another study (Du, Hellström, & Dubois, 2014).

As mentioned above, in Sweden, the required level of energy efficiency in buildings in the current building code does not include the occupants' use of electricity. For residential buildings, this means that electricity for lighting and other household equipment lies outside the energy regulations. This has been criticized for not encouraging and rewarding sustainable behavior and for risking missing out on significant energy saving opportunities (Rogers & Tillberg, 2015). According to a recent article (Lundgren, 2016), this also has consequences for the design of buildings, leading to limited design choices without necessarily resulting in optimized energy efficiency. As pointed out by Lundgren (2016), the current building code has made windows generally undesirable from (a limited) energy point of view. By excluding the occupants' electricity use for lighting in the energy section, one very positive energy aspect of window glass is ignored, which is offering free daylight that could reduce the need for electric lighting. While the architect might want to optimize the size of the window glass to provide good daylighting according to section 6.3 (Light, within section 6: hygien, health and environment), the consultant responsible for the energy efficiency focuses on the regulations in section 9 (energy management) and might want to minimize window sizes to limit solar heat gains and heat losses[1]. The current building code has made daylighting and energy efficiency two conflicting aspects, where the energy aspect is more likely to be prioritized since there is a requirement on verification of energy efficiency but not daylight.

1.5.2 Daylighting, definitions and metrics

The amount, or level, of daylight outside depends on the solar elevation and the sky conditions and varies according to location, season, time of day and weather (VELUX, 2014). These variations are exemplified for the location of Denmark in table 2 (Christoffersen, 2006). To put these numbers in relation to something known, the interior illumination by electric light in our homes and workplaces is typically around 200 lux and rarely exceeds 400-500 lux (Foster, 2011).

Table 2- External horizontal illuminance levels for the location of Denmark

Sky condition	Season	Horizontal illuminance [lux]
Overcast	winter	5 000
Overcast	summer	30 000
Clear sky, direct sunlight	winter	25 000
Clear sky, direct sunlight	summer	90 000
Blue sky, no sunlight	winter	3 500
Blue sky, no sunlight	summer	12 000

As expressed by Boubekri (2016), buildings act as a filter of daylight. The level of available daylight inside buildings depends on the orientation, building site characteristics, façade and roof characteristics, size and positioning of windows, window glazing properties, shading system, geometry and reflectance of interior surfaces (VELUX, 2014).

There are three components of interior daylight (VELUX, 2014); direct sunlight, diffuse skylight and reflected light. Direct sunlight is very intense, directional and has constant

[1] Larger glazed areas with low u-values are not as critical considering heat losses as increased glazed areas with higher u-values.

movement. When the direct sunlight is scattered by the atmosphere and clouds, it creates the second component of daylight called diffuse skylight. This light is very soft and has a much lower intensity. Both direct light and diffuse skylight are reflected by the ground and surrounding environment, which defines the third component of daylight i.e. reflected light.

The amount of reflected light depends on the surface reflectance properties of the surroundings. Reflected light from the ground often contributes to 15%, or more, of the total amount of daylight on the façade of a building and in high density areas, reflected light can even be the main supplier of daylight inside buildings (VELUX, 2014).

Daylight is generally measured using the so-called daylight metrics, which are quantities derived from directly measurable physical values such as luminance or illuminance. Daylight metrics allow assessing either the quantity or quality of available daylight and/or visual comfort inside buildings, and some metrics address both aspects. Daylight metrics can be simplified methods of static conditions such as the daylight factor or more advanced dynamic methods called dynamic daylight metrics (DDM). DDM require advanced computer simulations (Rogers & Tillberg, 2015), often referred to as Climate-Based Daylight Modelling (CBDM) (Mardaljevic J. , 2006). Qualitative metrics may be used to predict the probability of glare, for instance. One popular metric is the “Daylight Glare Probability” (DGP), which is more complex compared to quantifying metrics (Rogers & Tillberg, 2015).

The main focus of this subchapter is the quantifying and static metric called daylight factor (DF), due to its popularity and significant role in the debate surrounding the Swedish daylight requirements.

A daylight factor can be described as the ratio of the interior daylight illuminance on a given surface to the simultaneously measured illuminance from an unobstructed overcast sky, expressed as a percentage. Unless otherwise stated, an overcast sky with a luminance distribution according to the CIE Standard Overcast sky is used (Tregenza & Wilson, 2011). The CIE Overcast sky is the same for every location in the world, and has a constant luminance distribution where the sky at the zenith is about three times brighter than at the horizon (Rogers & Tillberg, 2015) The DF can be described by equation 1:

$$DF = \frac{E_{Int}}{E_{Ext}} \cdot 100 \quad [\%] \tag{1}$$

Where E_{int} is the internal illuminance (lux) and E_{ext} the external illuminance (lux).

The internal illuminance, E_{int}, consists of three components; the sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC), as illustrated in figure 1.

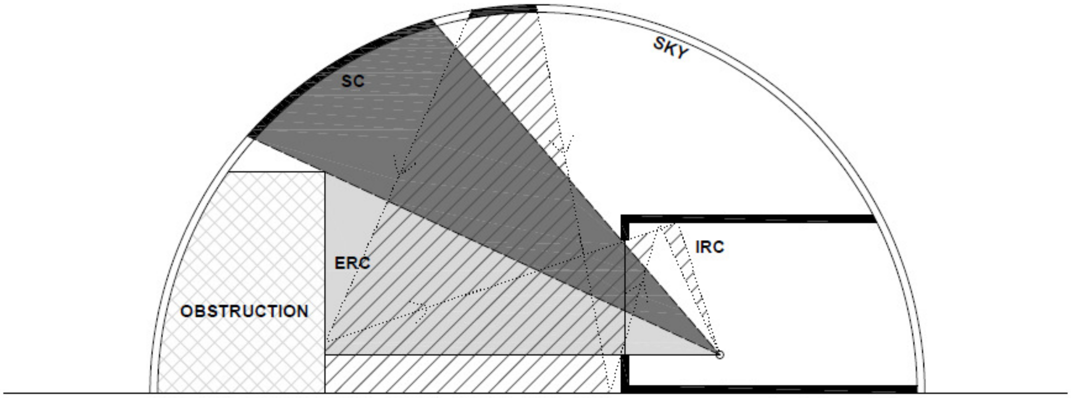

Figure 1- Principle sketch of the three components of internal illuminance; the sky component (SC), externally reflected component (ERC) and internally reflected component (IRC).

According to Tregenza and Wilson (2011), the DF has a history that starts somewhere around the 1930s before the use of computers and other advanced techniques. The basic idea was a method which quantifies daylight as the ratio between interior and exterior illuminance. Some simplifying assumptions were applied to the method; the sky is overcast with a simple luminance distribution, there is no sunlight, all interior and exterior surfaces act as diffuse reflectors and the room is empty (Tregenza & Wilson, 2011).

Reinhart (2006) claimed that the concept of daylight factors was used even earlier, in the beginning of the 1900s, with the main use to support a law called "rights for light" in the UK, which was based on an old Roman law. Considering this historical use, it has been suggested that the daylight factor was not developed to be used as an indicator for good daylighting design (Reinhart, Mardaljevic, & Rogers, 2006), which often is the application of the metric today.

Even though more advanced techniques have enabled the use of other metrics, the DF is still at this point frequently used in both official standards and codes of practice (Tregenza & Wilson, 2011; Mardaljevic, Heschong, & Lee, 2009), mostly due to its simplicity rather than its precision or reliability.

The DF can be expressed as either a point-value i.e.measured at a specific point, DF_p or as an average value over a surface DF_a. Comparing these two, the DF_p says less about the overall appearance of a room than the DF_a (Tregenza & Wilson, 2011). Daylight factors can be calculated either by hand, by use of various formulas, or by computer simulation. Physical measurements can also be used to determine the DF as the ratio between the simultaneously measured interior and exterior illuminance during overcast sky conditions. But this is very time consuming and also expensive, due to the need for optical instruments.

The DF is affected by several building design features such as geometry, surrounding environment and various surface properties (Reinhart, Mardaljevic, & Rogers, 2006). But a number of external circumstances like orientation, location, season, time of day and direct sunlight are excluded (Rogers & Tillberg, 2015) and these simplifications lead to significant limitations of the DF (Love & Navvab, 1994; Nabil & Mardaljevic, 2005; Mardaljevic, Heschong, & Lee, 2009) in its capacity to describe real world phenomena.

Despite its limitations, DF_a can be useful as an indicator of the daylight quantity (under overcast weather conditions) at early design stages (Tregenza & Wilson, 2011). Table 3 presents some key thresholds of the DF_a, which at early design stages can provide a hint of the environmental performance and balance between daylight and need for electric lighting (Tregenza & Wilson, 2011)

Table 3 - Key thresholds for assessing the light conditions at early design stages by use of the average daylight factor (daylight from side windows)

DF_a	Rooms without electric lighting	Rooms with daytime electric lighting
1%	Gloomy appearance, harsh contrast with view out	Electric lighting may mask daylight variation
2%	Areas distant from windows may seem underlit	Appearance of daylit room even if electric lighting is the main task illumination
5%	The room looks brightly daylit. Visual and thermal discomfort may occur with large window areas	Electric lighting rarely needed
10%	The character of a semi-outdoor space, such as a conservatory. Visual and thermal conditions may be unsuitable for office-type tasks.	

Putting these numbers into the context of a standard overcast sky in Northern Europe (10 000 lux); 1% DF=100 lux, 2%=200 lux, 5%=500 lux and 10%=1000 lux. As mentioned earlier, 300 lux is considered a sufficient illuminance level for most building users and tasks, while illuminances above 500 lux should be avoided where people work mainly with computers. The thresholds suggested by Tregenza and Wilson in table 3 correspond quite well to this. They also correspond quite well to practical experience from working with daylight in Sweden, according to Dubois (2016).

But the frequent use (Nabil & Mardaljevic, 2005; Mardaljevic, Heschong, & Lee, 2009) of the DF as a metric for stating requirements on daylight, used in building codes and standards, is criticized (Nabil & Mardaljevic, 2005; Mardaljevic, Heschong, & Lee, 2009; Cantin & Dubois, 2011; Mardaljevic, Christoffersen, & Raynham, 2013). This is connected to the fact that other more sophisticated metrics are available today. Many of these simplifications have to do with the use of the CIE Standard Overcast Sky, which excludes circumstances that in reality play a significant role for the amount of available daylight in a building (Mardaljevic, Heschong, & Lee, 2009; Nabil & Mardaljevic, 2005; Tregenza & Wilson, 2011).

The sky is never constant in reality, and the specific pattern of the CIE Standard Overcast Sky rarely occurs, not even in climates with mainly overcast conditions (Tregenza & Wilson, 2011; Mardaljevic, Heschong, & Lee, 2009). Real skies vary both in luminance distribution and in the total amount of light that penetrates the cloudy atmosphere (Tregenza &

Wilson, 2011). Orientation can be mentioned as one factor that also plays a role in reality; the same amount of daylight is not received through a north and south orientated window (Mardaljevic, Heschong, & Lee, 2009), not even under overcast conditions (Tregenza & Wilson, 2011). The sky spectral power distribution also changes constantly throughout the day and it is different for different parts of the sky, which means that daylight on different orientations will have different colors.

Another limiting aspect in the use of DF is that it only considers horizontal illuminance and does not consider any other aspects of daylight quality (Cantin & Dubois, 2011). Other indicators of daylight quality have been recognized, for instance luminance distribution, glare, directionality of light, color rendering, color appearance and flicker (Swedish Standards Institute (SIS), 2011)

Metrics which have been suggested as more accurate predictors of daylight availability, are the metrics calculated using climate-based daylight modelling (CBDM) (Mardaljevic J. , 2006; Mardaljevic, Christoffersen, & Raynham, 2013). These metrics include realistic climate conditions as obtained from climate data files, with the effect of both the sun and the sky, and are calculated by the use of specific dynamic simulation programs (Mardaljevic J. , 2006).

The most popular CBDM metrics at the moment are the Useful Daylight Illuminance (UDI), the Daylight Autonomy (DA), the Spatial Daylight Autonomy (sDA) (Rogers & Tillberg, 2015; Mardaljevic, Christoffersen, & Raynham, 2013) and the Annual Sunlight Exposure (ASE). CBDM has been used for over a decade, but is still not the recommended method in most building codes and standards (Mardaljevic, Christoffersen, & Raynham, 2013). Calculating CBDM metrics require special simulation tools, but also a certain degree of knowledge, time and understanding and are normally not an option for non-experts (Rogers & Tillberg, 2015).

1.5.3 Regulations for daylighting in Sweden

Daylight in buildings is mainly regulated in the building regulations (BBR) by the National Board of Housing, Building and Planning, “Boverket”. BBR includes both mandatory provisions (“föreskrifter”) and general recommendations (“allmänna råd”). The general recommendations state how the binding mandatory provision can or should be fullfilled, by presenting a method for showing that the requirement is met. This is however just a recommendation and other methods can be used, provided that it can be demonstrated that the binding regulation (mandatory provision) is still met (Boverket, 2016).

The regulations for daylighting in BBR stems from the oil-crisis in the late seventies, resulting in restrictions regarding window areas and introduction of a minimum accepted daylight level as expressed by a 1% DF_p (Rogers & Tillberg, 2015), where the point for measurement is located 1 m from the darkest lateral wall, half way in the room.

1.5.3.1 The Swedish building code, BBR

The requirements regarding daylight in BBR include three aspects; daylight (BBR23), sunlight (BBR21) and a view out (BBR23).

The binding regulation regarding daylighting, for any room used more than occasionally, is that the design and orientation of the room should offer *good access to direct daylight.* This mandatory provision is followed by a general recommendation, suggesting a simplified method of window-to-floor area ratio of 10% for showing that the regulation is met. The method is standardized according to SS 91 42 01, where certain conditions for when the method is valid are specified. These conditions regard the size of the room, window glazing, geometry and positioning and sky exposure angle, which are greatly limited. Following this simplified method corresponds to a DF_p of approximately 1%, according to BBR. If the conditions for using this method are not met, an alternative method is recommended. The alternative method is described in a separate document, "Räkna med dagsljus" (Löfberg, 1987), where the DF_p is calculated using formulas in three steps (to calculate the three parts SC, ERC and IRC).

A general recommendation is also presented for providing a view out, with a minimum of one window in any room used more than occasionally. The window should be positioned in a way that makes it possible to follow the course of the day and seasonal changes and skylights are not considered suitable to fulfill this requirement. Access to direct sunlight is regulated by a mandatory provision, saying that at least one room, where people spend longer periods of time, should have access to direct sunlight.

1.5.3.2 Daylight in environmental certification systems

The use of environmental certification systems has grown in popularity in Sweden over the past years, with Miljöbyggnad, BREEAM-SE and LEED being regularly used on the Swedish market (SGBC, 2016). These systems all include daylight as an environmental indicator, but compulsory requirements for daylighting are only found in the Swedish system Miljöbyggnad. According to Rogers and Tillberg (2015), these environmental certification systems, Miljöbyggnad in particular, are at the heart of the current debate about the national daylight requirements.

One significant difference between Miljöbyggnad and the two international systems BREEAM and LEED has already been mentioned; Miljöbyggnad has daylight as a compulsory requirement for certification, while it is an optional credit in BREEAM and LEED. This means that a building can be certified according to BREEAM or LEED without fulfilling the daylight requirements. The systems also have different requirements on daylight, which are briefly discussed in the following section.
In the Swedish building sector, all three environmental certification systems, Miljöbyggnad, LEED and BREEAM, are used and they are managed by the Swedish organization for sustainable building, "Sweden Green Building Council" (SGBC, 2016).

Miljöbyggnad
The most spread environmental certification system in Sweden is Miljöbyggnad (SGBC, 2016). Miljöbyggnad, originally called "Miljöklassad byggnad" originates from a government financed initiative called "Bygga-Bo-Dialogen" and was developed in cooperation between scientists and 27 companies (Johansson & Hedin, 2011). When Bygga-Bo-Dialogen ended in 2009/2010, a non-profit organization took over the responsibility for the system (Johansson & Hedin, 2011). The name was changed to "Miljöbyggnad" when SGBC took over the responsibility for developing and administrating the system.

Miljöbyggnad has three certification levels (SGBC, 2016); BRONZE, SILVER and GOLD. Daylight is one of the aspects included in indoor environment and to achieve the different levels of certification, a point daylight factor[2] (according to the standard SS 91 42 01) in each room needs to meet the requirements presented in table 4 (SGBC, 2016):

Table 4- Miljöbyggnad certification levels and their requirements on the daylight factor, DF_{MB}

Certification level	**Required DF_{MB}**	**Comment**
BRONZE	> 1 %	
SILVER	≥ 1.2 %	
GOLD	≥ 1.2 %	Computer simulated + questionnaires

The first level of certification, BRONZE, corresponds to the regulations in BBR. If the BBR requirements are met, the building automatically obtains the BRONZE level points, for daylighting only. The BRONZE level is marketed as a guarantee of the building actually fulfilling the authorities' minimum requirements (SGBC, 2016). In order to obtain the last level of certification, GOLD, computer simulation showing that the DF is met is required. A GOLD certification also requires a passed questionnaire result from the tenants, where at least 80% find the quality of daylight acceptable or better (SGBC, 2016)

Around 870 Swedish buildings have been certified according to Miljöbyggnad by the end of 2016, with SILVER as the most popular certification level (SGBC, 2016).

BREEAM

BREEAM (BRE Environmental Assessment Method) is a certification system from the United Kingdom, developed and administrated by BRE (Building Research Establishment). It has been on the market in different versions since 1990 and is the most spread international environmental certification system in Europe. SGBC has adapted BREEAM to Swedish conditions and since 2013 it is this version, BREEAM-SE, that is used in Sweden. The system covers significantly more aspects than Miljöbyggnad (SGBC, 2016).

When it comes to daylighting, BREEAM-SE has two options for fulfilling the requirement. One is by using a climate-based dynamic indicator, with a minimum average illuminance level of 200 lux during 2650 hours of the year. The other alternative is by achieving a minimum average daylight factor of 2.1-4.4% depending on certification level, number of floors, type of building and latitude (SGBC, 2016). In addition to this, there are requirements regarding either uniformity or a minimum DF, with an alternative possibility to fulfill specific requirements for room depth and a view out (SGBC, 2016).

The registered number of Swedish BREEAM-certified buildings in 2016 is close to 400 (BRE, 2016).

[2] DF_{MB}: A DF_p specifically positioned according to Miljöbyggnads requirements

LEED
The LEED^{TM} Green Building Rating System was developed in the USA by the non-profit organization the U.S. Green Building Council. The system has been on the market in different versions since 1999, is the most spread internationally and covers more aspects than any other environmental certification system (SGBC, 2016).

Fulfilling daylight requirements is one way of collecting certification credits in LEED, but the daylight credit is not compulsory. The requirements for daylighting has varied significantly between different versions of LEED (Rogers & Tillberg, 2015). In the latest version 4.0 “Spatial Daylight Autonomy” (sDA) and “Annual Sunlight Exposure” (ASE) are used (USGBC, 2016), which are dynamic and climate-based indicators. Two other options are available, one by simulating illuminance levels, meeting a specific range for a certain amount of hours on two specified calendar days, and the other by physical measurements of the illuminance level, also for a certain amount of hours and on two different occasions (USGBC, 2016).

The number of Swedish LEED-certified buildings was close to 200 by the end of 2016, with an additional 80 in the registration process. (USGBC, 2016)

Why certify a building?
The three leading construction companies of Sweden, Peab, Skanska and NCC (Sveriges Byggindustrier, 2016), all use certification systems with requirements for daylighting as strategies for sustainability. Peab uses the Swedish “Miljöbyggnad” as standard for residential buildings (Peab, 2016), while NCC mainly uses BREEAM (NCC, 2016). Skanska accepts a variety of certification systems, Miljöbyggnad, BREEAM and LEED among these (Skanska, 2016). While Peab and Skanska mainly market the use of these certification systems as part of sustainable thinking, NCC adds that the certification of a building also has a positive impact on the market and rental value.

Rogers and Tillberg (2015) claim that there is no research showing how good daylighting affects the economic value of a building. According to them, the factors included in these economical assessments do not make it possible to distinguish the specific effect of “environmental” or “green” features. And to their knowledge, no studies on the economic effect of good daylighting has been carried out on the Swedish market and very few internationally.

According to a report by the World Green Building Council (2013), studies around the world have indicated positive economic benefits of “green” buildings. Among these benefits, this report lists a higher attraction of tenants and higher rents and sales prices.

1.5.3.3 Challenges and need for change

The construction industry's organization for research and development (SBUF) recently published a report about the Swedish daylight regulations and the need for change (Rogers & Tillberg, 2015). The report is written as a pre-study with the goal to propose a modernized version of the daylight requirement in BBR, making it a realistic and attainable standard for practical use in the building industry. A significant part of this subchapter will refer to this report.

As mentioned earlier, there is currently a vivid debate about the Swedish regulations for daylighting and according to the authors of the SBUF report, the use of environmental certification systems, especially Miljöbyggnad, has significantly contributed to fueling this debate. The daylight requirements in Miljöbyggnad are based on the BBR requirements for daylighting. According to Rogers (2016), the daylight requirements are considered the most difficult to achieve within Miljöbyggnad, which has put SGBC, the organization responsible for Miljöbyggnad, under great pressure from the building industry. Some professionals have even suggested abandoning the daylighting requirements altogether since it is nearly impossible to achieve in dense urban environments.

Experts have been consulted and claim that it is the outdated and vague chapter about daylighting in BBR, which is at the origin of the frustration in the industry (Rogers & Tillberg, 2015; Dubois, 2016). The DF_p based method, devised before the computer age is found difficult to apply in practice and insufficient to appropriately describe the daylight conditions in a room. In addition, the fact that all rooms used more than occasionally must comply is vividly criticized as this puts great restrictions on urban densification. Some experts have expressed the opinion that more flexibility should be allowed in the system by allowing some rooms like e.g. bedrooms to have lower daylight levels.

According to a historical review by Rogers and Tillberg (2015), the daylight regulations in BBR more or less remained the same between 1993 and 2014, when the chapter was updated and clarified. Despite this rather recent revision of the chapter, it is considered outdated and in need of reformulation. The introduction of environmental certification systems has been mentioned as one part of this “sudden” interest in the matter. A number of other contributing factors will be discussed below, starting with briefly describing the current situation in the building industry.

There is a housing shortage in Sweden at the moment, which by different instances is expressed using the following numbers:

- The government (2016) aims for 250 000 new dwellings by 2020;
- Boverket (2016) estimates a need for 440 000 new dwellings by 2020;
- and 710 000 by 2025.

In addition to the housing shortage, there is also a need for extensive refurbishment of the existing building stock during the coming decades and the challenge of meeting the Energy Performance of Buildings Directive (EPBD) after the 31st of December 2020 (Energimyndigheten, 2015). The combination of a housing shortage and new energy standards creates a great pressure on the building industry, which could explain the interest for clear and realistic daylight regulations.

Stockholm is one example of this trend of urban densification. Stockholm is the fastest growing city in Europe, and is estimated to increase its population by 11% by 2020 (DN, 2015). The city of Stockholm presents a clear strategy of urban densification, mainly in the central parts of the city, as a way to handle the increasing population (Stockholms stad, 2016). Strategies of city densification can also be found in the current “översiktsplan” (overview plan) of e.g. Malmö and Gothenburg.

According to Rogers (2016), meeting a DF_p of 1% is difficult to achieve in dense parts of the cities, but also in new built suburbs. He claims that in these dense areas, many buildings have a significant number of occupied rooms below the required level, often with as little as one third of the required daylighting. A study of ten recent buildings in Stockholm showed that if the whole building is considered, only one or two of the buildings had a compliant daylight credit (Höstmad, 2015). A more recent investigation with nearly 16000 rooms in existing Swedish multi-family buildings indicated that only 8% of the existing stock may comply to the current regulation (Dubois et al., 2017).

The second trend significantly affecting daylight negatively, according to Rogers and Tillberg (2015), is area maximization. In their report, area maximization is explained as an effect of increasing land prices and building costs. In order to get as much rentable or sellable area out of the production as possible, the use of exterior corridors and/or large glazed balconies are common strategies. Another common strategy is stretching the building plan to the very end of the property border, even though this may not be appropriate due to nearby obstacles or buildings.

The third trend mentioned to have an impact on daylighting in the report by Rogers and Tillberg (2015) is energy optimization, which often applies measures with a negative effect on daylighting. Examples of these are thicker walls, smaller glazed areas, increased room-depths, use of low-emissivity coatings, etc.

The report by Rogers and Tillberg includes a number of recommendations on how to improve the current daylight regulations in BBR (SBUF 12996, 2015):

- The simplified method "glazing to floor area" can be kept, but the limitations of the method need to be clarified.
- Replace the old point-daylight factor with measuring the average daylight factor of the room.
- The regulations need to allow other, more advanced methods, as options of how to show that the requirements are met.
- Boverket needs to investigate if measurements can be used to show that the requirements are met. And if so, write a method description of this.
- The current requirement of 1% DF_p might be too high and needs to be investigated.
- The required DF_p should be based on the function of the building and room.
- There is a need for a separate document with guidelines and standard values to use for calculating the daylight.

The final recommendations thus suggest that there is a possibility that the current threshold of 1% DF_p is set too high. This is not fully in line with the report as whole, where daylighting is promoted and "good" daylight access is discussed to be represented by a much higher threshold. More recent research has however yielded different conclusions of these original recommendations (Dubois, 2016). The following recommendations have been reformulated:

- The simplified method "glazing to floor area" needs to be excluded completely from the daylight chapter in BBR (earlier suggested to be kept but clarified).
- Instead of replacing the old DF_p with a DF_a, the median value, DF_{median} is considered to be more representative[3] and will be the new recommendation.
- Alternately, an area weighted DF_{median} at apartment level could be considered as it is more intuitive for architects.
- The current required level of 1% DF_p is no longer considered set too high since this recent research has shown that lowering this DF_p to e.g. 0,8% would not significantly increase the level of compliance. However, the requirement should be more flexible. Adopting an area based method at apartment level may solve this problem. These new recommendations have at the time of writing this thesis not yet been published but they were presented publicly at a Symposium in Berlin in May 2017.

An interesting example of the difference between the use of the DF_a and the DF_{median} is found in an article by Mardaljevic and Christoffersen (2017) and according to the authors the DF_{median} is a more stable and faithful indicator for describing daylight conditions in a room.

The current requirements for daylighting in BBR have also been criticized for not having an upper limit, which can lead to the impression of the more daylight the better (Rogers & Tillberg, 2015; Dubois, 2016). As presented in table 3, there is a threshold above which daylight may create overlighting and glare problems in addition to resulting in higher energy use. Any maximum level has however not at this point been explicitly stated in the expert recommendations.

The need for new daylight standards is not only debated in Sweden, but also internationally by both researchers and practitioners (Mardaljevic & Christoffersen, 2017). A Technical Committee, CEN/TC 169 "Light and lighting", has supported work towards a new daylight standard for CEN-countries (CEN-TC169, 2015). As part of this work, one proposal was presented by Mardaljevic and Christoffersen (2017), suggesting "*moving from the use of relative values based on a single sky to the use of annual occurrence of absolute values, determined from climatic data*". The aim of the authors' proposal is to have a standard based on climatic files, but also to have it formulated in a way that reduces the risk of conscious or unconscious misinterpretation. It is also estimated to have the advantage of being easy to implement with respect to the tools and knowledge of today, and to be a step towards CBDM. The proposal is expressed using the following words:

"To demonstrate compliance with the standard, it is necessary to show that a target illuminance E_T is achieved across a percentage of the relevant floor area A_P for a percentage of the year Y_P. Internal illuminances are derived from annual data for diffuse horizontal illuminance appropriate to the location of the building/space under evaluation."

[3] (Mardaljevic & Christoffersen, 2017; Mardaljevic, Christoffersen, & Raynham, 2013; Mardaljevic J. , 2013)

The work prepared by the Technical Committee CEN/TC 169 “Light and lighting” lead to a CEN-Enquiry (CEN-TC169, 2015), with recommendations including daylight provision, view out, exposure to sunlight and protection from glare. For a daylit room to meet the recommended minimum level of daylight provision, it is expressed that:

- An illuminance level of 300 lx should be exceeded over 50% of the space for more than half of the daylight hours in the year.
- An illuminance level of 100 lx should be exceeded over 100% of the space for more than half of the daylight hours in the year.

Recommendations are also made for a space considered to be medium or highly daylit, here suggesting 500 and 750 lx respectively instead of the minimum 300 lx.

These recommendations are also expressed in terms of daylight factors by a reverse calculation method explained in the standard. Converted to daylight factors, it results for Stockholm in a minimum target daylight factor, D_{TM}, of 0.8% over the whole space, which ensures that at least half of the daylit hours in a year give more than 100 lux in the whole space. In addition to this, half of the area should meet a target daylight factor, D_T of more than 2.5% during half of the daylit hours in a year, which ensures that 300 lux will be obtained in half of the space and half of the time

The target daylight factor, D_T, is calculated using the *median external diffuse illuminance, $E_{v, d, med}$*, for the location. $E_{v, d, med}$ is defined as the illuminance produced by skylight on a horizontal surface on the Earth achieved for half of the daylight hours (2190 hours) in the year. For Stockholm this value is 12100 lx. An example of how D_T is calculated for an illuminance level of 300 lux in Stockholm is illustrated in equation 2:

$$D_T = \frac{300}{12100} \cdot 100 \quad [\%] \tag{2}$$

Daylight factors are calculated over a reference plane 0.85 meters above the floor and for a grid and area as specified in the standard.

This brief review of the international work with new daylight standards suggests a similar type of debate about outdated daylight requirements internationally. The reason for the Swedish daylight requirements not keeping up with the development of newer techniques and methods for evaluating daylight, or for not having discovered the problems of meeting the requirements in dense part of cities earlier, seems to be a rather complex question. Boverket themselves gave a brief explanation of the situation through Estlander (2014) during a conference, which is summarized below.

Daylight has not been a prioritized question at Boverket for a long period of time and the question was brought to their attention by daylight experts wanting a meeting about daylight around 2014. Boverket do not have experts themselves, and are depending on external experts in different fields when working with regulations and general advice. These days, even the number of architects employed at Boverket is insufficient. Boverket explains the fact that daylight has had a low priority partly by referring to the problem of what BBR by law can and cannot regulate. Boverket works for the Swedish social Board, with a main focus not on the buildings but on the citizens. They write regulations and general advice on subjects that are specified in “Plan- och Bygglagen” (PBL), the Swedish planning and building Act. The question of daylight is mainly handled in a paragraph about hygiene, health and environment, and it is specified that a matter must be of “unacceptable risk” for Boverket to be able to regulate it. According to Boverket daylight is more of a psychosocial matter and question of health over longer timespans than what in most cases can be considered an “unacceptable risk”. Boverket therefore finds the topic of daylighting a difficult subject falling somewhere in-between what they by law can and cannot regulate. It has recently also come to Boverket’s attention that the standard SS 91 42 01 that they use as a general advice for daylight, has expired and needs to be either updated, replaced by another standard or simply removed. If removed, Boverket would have to write the information as a general advice directly in BBR. This would also mean that they would have to take full responsibility in the matter, which they do not have the competence for. (Estlander, 2014)

1.5.4 Review of results from similar projects

As expressed by Veitch and Galasiu (2012), it is still unknown what could be considered an adequate daily dose of light or darkness. The question of what would be a reasonable daylight level to use as a minimum level needs to be investigated, and one way of collecting information in the subject is to actually ask people how they feel about the daylight conditions in their homes. The subjective perception of daylight in residential settings has not to the authors’ knowledge been studied to any larger extent internationally and even less nationally.

Sweden and the other Nordic countries have a climate with long and dark winters, not comparable to other European countries or other parts of the world. The architecture is dominated by low-rise buildings and the cities are less dense than in many other parts of the world. The few international studies that have been found are located in parts of the world with conditions very different from the Swedish ones, which makes it difficult to assess whether the research findings would be similar in Sweden.

One study was recently carried out in Hong Kong (Xue, Mak , & Cheung, 2014), which investigated the effect of daylighting and human behavior on luminous comfort in residential buildings. A total of 340 questionnaires were distributed, collected and statistically analyzed. Satisfaction with daylighting was found to affect the degree of luminous comfort the most and external obstructions had the largest impact of the physical factors. Among the behavior related factors, the use of electric lighting affected the luminous comfort the most. Extensive use of electric lighting was found an indicator of poor daylighting conditions and lower luminous comfort. They also found that 90% of the respondents were mostly concerned about the daylighting performance of their living room. The six factors most affecting the occupants’ satisfaction with daylighting were perception of uniformity, thermal discomfort, external obstruction, solar access hours in summer, expected sunlight hours in winter and orientation. No statistical difference between genders was found, but older people tended to be more satisfied with their luminous environment.

In another study, the perception of uniformity was pointed out as an important factor for assessing daylighting quality among researchers, a result found through a questionnaire survey (Galasiu & Reinhart, 2008). The questionnaire was directed to professionals in the field of sustainable building and daylighting. Among the respondents, 28 were researchers and a majority of them reported that they used daylight uniformity as an indicator of the overall quality of their daylighting design. Only two other criteria were additionally listed as significant by the researchers; avoidance of glare and energy savings.

Another recent study of residential settings in Hong Kong (Xue et al., 2015) investigated the effect of sun shadings and balconies on luminous comfort. The analyzed questionnaires indicated a positive effect on glare-related issues, but a negative effect on the illuminance uniformity. It was also noticed that the residences with a balcony tended to use internal shadings and electric lighting more, which was linked to dissatisfaction with privacy.

The question of what metric to use in residential daylighting design was raised by Xue, Mak & Huang (2016) for typical Hong Kong residences. Statistical analysis of a questionnaire survey in combination with climate-based simulations was used as method. The study showed that the static metric uniformity is determinant of luminous comfort; low uniformity indicates lower luminous comfort. The dynamic metric average DA_{300} also showed a correlation with luminous comfort, with the conclusion that these two metrics could be a useful combination in daylighting design.

1.5.5 The use and design of self-administered questionnaires

The main part of the information in this chapter is a summary of the information in chapter four and five of a book by Bryman & Teevan (2005) on research methods in social sciences. This section is relevant for the methodology used in the present thesis

Research interviews exist in a variety of forms, but when dealing with *survey research,* two forms are mainly used; the *structured interview* and the *self-administered questionnaire.* The structured interview is a method of standardizing both the way to ask questions and the recording of answers, with the aim of reducing errors due to variation in the questions and accurate processing of answers. The interviewers read out the questions exactly the way they are printed and in the order they are written. The questions are normally very specific and with a fixed set of answers to choose from, also referred to as *closed questions.* Compared to *open questions*, where the respondent answers in his/her own words, the closed questions have both advantages and disadvantages. The main advantages are the easy processing of answers, the good comparability of answers and the quick and easy way of answering. The disadvantages are mainly the fact that there is a risk of missing out on spontaneous and unexpected answers, in addition to the fact that respondents might find it difficult to identify themselves with the suggested answers.

A common method for carrying out a structured interview without the actual interviewer being present in the room is the "*self-administered questionnaire*". The questionnaire can be delivered and collected in a number of ways, where mailed questionnaires are one of the most common methods used. The mailed questionnaire has a number of advantages compared to the structured interview with an interviewer, but it also has some disadvantages discussed below.
On the positive side, the self-administered questionnaire is cheaper, quicker, easier to administer and finally less sensitive to "interviewer effects", which has to do with the presence of an actual interviewer and the use of different interviewers. The disadvantages are mostly

related to the fact that the questionnaire is self-administered. The absence of an actual interviewer means that there is no possibility to explain things that are difficult or unclear to the respondent, which might lead to the respondent skipping the question or filling an inaccurate answer. There is also the risk of the respondents losing interest in answering questions that are not obvious to them and not completing the questionnaire at all. To avoid the problem of "response fatigue", questionnaires have to be kept as short as possible, which limits the amount of possible questions to ask and also the length and complexity of the question. For the same reason, questionnaires are normally restricted to using mainly closed questions with fixed answer sets, since people in general do not want to write a lot. There is also the problem of not being able to control the order in which the respondent answered the questionnaire, or who actually answered for that matter. Another disadvantage is the risk of not getting responses from people with limited language skills or literacy. The loss of spontaneous and unexpected answers can be mentioned as another disadvantage for questionnaires using mostly closed questions. One solution to this can be to simply add an "other" category with the possibility to leave further details. Another solution is to perform a pretest, where frequently noticed "other"-replies are listed as answering alternatives in the final test.

To summarize, if the questionnaire is not well designed, there is an increased risk of incomplete questionnaires, mistakes and a lower response rate. A well-designed questionnaire on the other hand has advantages in terms of cost and time that are difficult to compete with if the research topic can be studied using closed questions and fixed answer sets.

1.5.5.1 Designing a questionnaire

The following subchapter summarizes the most important things to think about when designing a questionnaire, which is a summary of the information presented by Bryman & Teevan (2005).

Information and language

A questionnaire needs to be preceded by an information letter providing relevant information about the project and clear instructions on how to fill the questionnaire, using a plain and simple language. Clear instructions include specifying how to mark the answer and how many answering alternatives are allowed. Relevant information to include apart from actual instructions are for example to present the research project and explain why it is important, make the identity of the person/organization contacting the respondent clear, clarify who is responsible for the research, leave contact information in case of questions, mention research funding, explain how the respondent was chosen, explain how the information will be handled, state confidentiality and/or anonymization etc. It is also important to end the questionnaire by actually thanking the respondents for their participation.

Questions and answers

There are many things to think about when designing the questions and answers in a questionnaire. To start with, it is important to keep the respondent interested and focused and avoid causing a feeling of confusion, irritation or fatigue. It is recommended to use a plain and simple language, to avoid technical terms and abbreviations, to avoid long questions or asking about things that the respondent cannot know or cannot remember. A rule of thumb is not to ask about things further back in time than one month. It is important to make sure that there is one and only one answering alternative that fits each respondent. Answering alternatives should neither overlap nor have gaps leaving any category or interval out. It is also of importance to match the question and answers, in other words to make sure that the answers fit the phrasing of the question and vice versa.

When designing questions and answers, one should consider the problem of different interpretation among respondents and avoid words and expressions that have different meaning to different individuals. One rule is to avoid ambiguous terms by using a more specific or clarifying language with less or no room for individual interpretation. An example is the use of "often" or "sometimes", which could easily be replaced by an actual time interval. Another example is the use of strong expressions like "hate" or "love", which can be used generously by one individual and very restrictively by another. If one respondent's interpretation of "hate" equals another respondent's interpretation of "dislike" the evaluation of the questionnaire will be meaningless.

The questionnaire should be designed from a "neutral" point of view, not trying to lead the respondent in any direction. Questions should not be expressed in a leading manner and the answer set needs to be balanced. A balanced answer set is achieved by using one "neutral" answer and the same amount of negative as positive answers.

It is also important to review every question in terms of its relevance for the research topic and to make as good use of every question as possible. Questions that are very general may not be of much use for the research and thus rephrasing them to be more specific might be more useful. It is also important to make as much use of the answers as possible. Instead of offering a yes/no alternative, there could be more research value in a more varied set of answers. One should also carefully consider using the "Don't know"-answer before offering this option. Questions (and answers) that are double-barreled or questions that actually ask about more than one thing should be avoided, since evaluating the meaning of the answer is difficult. Last but not least, questions should not include negatives ("not" etc.), due to the risk of missing the word and ending up with an inaccurate response.

Order of questions

A strategic and logical order of the questions is important in order to secure the respondents' interest and attention. Therefore, early questions should be directly related to the research topic and questions likely to be obvious and easy to answer should precede more difficult questions. Questions about personal information should not be asked at the beginning of the questionnaire due to the risk of people inquiring about their relevance to the research topic. Questions that are of more sensitive or embarrassing character should be saved for later parts of the questionnaire, but not be left for the very end. Questions of the same topic are preferably grouped together and different topics arranged in a logical order. Within a group of questions the questions of more general character should precede more specific questions. (Bryman & Teevan, 2005)

Another strategy in the order between general and specific questions can be useful if wanting the respondent to have reflected on the specific questions before taking a stand in the more general context. This can be useful to reveal the respondents' sincere opinion or in matters where the specific questions might be useful to give the respondent the opportunity to reflect on the subject before answering a more general and maybe complex question. (Langlet & Wärneröd, 1993)

Testing the questionnaire
Finally, in order to discover mistakes in the design of the questionnaire, it is important to have it tested by a smaller group of people before sending it to the intended sample of respondents. (Bhattacherjee, 2012; Bryman & Teevan, 2005)

2 Methodology

This study includes collecting information about the subjective impression of daylight conditions in the apartments of Greenhouse Augustenborg, and studying simulated and measured data of daylight factors in four sample apartments of Greenhouse to compare these values with the subjective assessments. The following subchapters describe the studied object and the method used for the self-administered questionnaire and the physical measurements.

2.1 Greenhouse Augustenborg

The studied object is Greenhouse, a residential building located in a part of Malmö called Ekostaden Augustenborg. A view of Ekostaden, with the "tower" of Greenhouse in the middle, is presented in figure 2.

Figure 2- A view of Greenhouse and the surrounding buildings of Ekostaden Augustenborg (Image MKB Fastighet)

Greenhouse is owned by MKB, the largest housing company in Malmö (MKB, 2016), and is part of their work on developing new sustainable building concepts. The building has been environmentally certified according to both Miljöbyggnad Gold and the FEBY12 passive house standard. There has also been additional focus on offering sustainable lifestyle choices, including urban gardening and bicycle transportation. The information presented about Greenhouse in this sub-chapter focuses on features relevant for daylighting only.

The combination of certification according to both Miljöbyggnad Gold and FEBY12 makes Greenhouse an interesting object for this specific study, which focuses on daylight requirements in energy efficient buildings. Miljöbyggnad Gold includes specific requirements for daylighting while the passive house standard requires an energy efficient building. Another reason for studying Greenhouse is the cooperation between researchers, MKB and the tenants. The tenants have been selected by MKB to have an interest in the concept of Greenhouse, a sustainable lifestyle and urban gardening, and have signed a contract which obliges them to take part in any research related to this concept. To summarize, the choice of object means that the subjective impression of daylighting is collected from an energy efficient building designed to have daylighting conditions that are more generous than the current requirements in BBR. The information is collected from tenants with an interest in sustainability and who have formally agreed to take part in related research.

Greenhouse, designed by Jaenecke Arkitekter, was finished in 2016 and consists of both a fourteen-storey building, “Höghuset”, and a lower building, “Låghuset”, which both can be seen in figure 3. An underground garage and old laundry building create a connecting garden space between the two parts.

Figure 3 - A street view (rendered image) of Greenhouse showing the lower part of Höghuset, the connecting laundry-building and Låghuset. (Image MKB Fastighet)

Höghuset includes a total of 32 apartments, most of them with two rooms and kitchen and some with three rooms and kitchen. These apartments are called “odlingslägenheter” (apartments for gardening), since they include a 20 m^2 balcony for cultivation as well as a potting workshop. The large balconies are divided in two parts, one glazed and one open, to offer different climatic conditions. Both parts are surrounded by 40 cm wide planting beds and a specific workshop for planting and storing the necessary equipment is located in direct contact with both balcony and elevator. A view (rendered) from one of the balconies is presented in figure 4.

Figure 4- An architecture rendered view of the large balconies of Höghuset. (Image Jaenecke Arkitekter)

The apartments are oriented in three different directions, with the balcony directed to either the south, east or west. The shape of the building was designed with the aim of maximizing the direct exposure to sunlight on the balconies. Each floor consists of three apartments, typically distributed according to figure 5. The two lower floors of Höghuset are slightly different as they house student apartments.

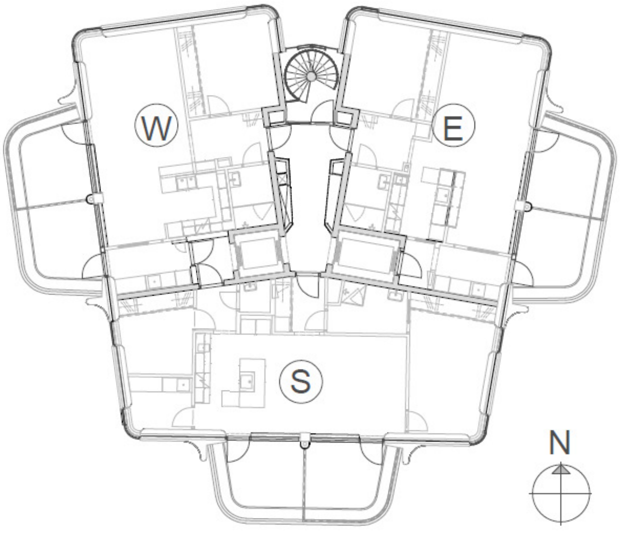

Figure 5- A typical floor of Höghuset showing the three apartments oriented to the west (W), south (S) or east (E)

Large windows and a glazed door connect the balconies with the open main living space (kitchen, dining room and living room). The smaller two-room apartments have their balconies oriented to the east or west and typically only have additional windows in the rounded corner of the living room and bedroom. A typical layout of a western apartment is illustrated in figure 6. The larger three-room apartments have balconies oriented to the south. The master bedroom has one corner window towards southeast and one window towards east, the smaller bedroom one window to the west and the workshop one corner window to southwest.

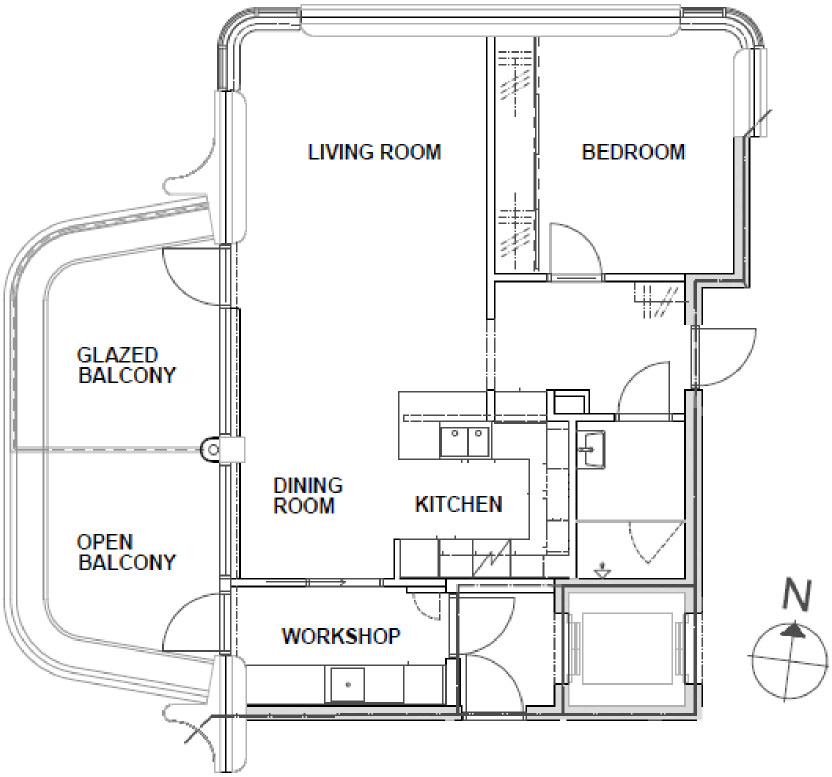

Figure 6 – A typical layout of a western apartment (Höghuset).

Låghuset includes a total of twelve maisonette apartments, a smaller part with four rooms and kitchen and the rest with five rooms and kitchen. The apartments are either located on the second to third floor or on the fourth to fifth floor, offering the lower apartments an outdoor ground-terrace and the upper apartments a roof terrace. The apartments are accessed through exterior corridors on the northwest side of the building and the glazed surfaces are typically oriented to northwest and southeast. An example of one upper and lower floor is presented in figure 7 and an example of the layout of an apartment is shown in figure 8.

Figure 7- Floor plans of the upper six maisonette apartments of Låghuset. The highlighted apartment is presented more detailed in figure 8.

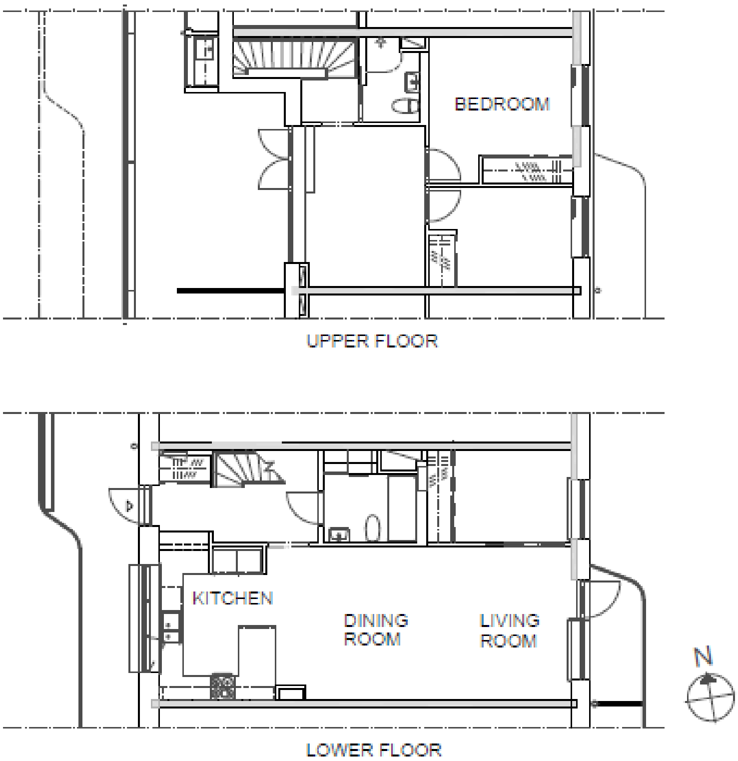

Figure 8 – An example of the layout of an apartment of Låghuset. Only the rooms that were included in the questionnaire are written on each plan.

All apartments have large open living spaces stretching from the northwest to southeast, with an open balcony to the southeast. The lower apartments also have a southeast balcony on the upper floor, in one of the bedrooms. Apart from the large open living space (kitchen, dining room and living room), the apartments have three or four bedrooms. In some cases, the fourth bedroom is replaced by a smaller extra living space, two bathrooms and a separate entrance room with staircases. The ground floor of Låghuset houses a kindergarten.

2.2 Subjective assessment

A partly developed, self-administered questionnaire with closed questions was the starting point of this study. This first draft of the questionnaire, designed by members of the research team, included seven chapters presented in the following order; general satisfaction with the apartment, daylight level, daylight distribution, direct sunlight, view through windows, physical environment and personal information. At this point five tenants had also been selected and contacted to make appointments regarding physical measurements of daylight in their apartments. The research team also decided to distribute the questionnaire during the autumn/winter of 2016/2017.

The study progressed with a literature study of designing questionnaires and revising the questionnaire accordingly. This was followed by testing the questionnaire on respondents in two steps before handing out the final version of the questionnaire to the tenants of Greenhouse. These steps will be described in the following sub-chapters and are also illustrated in figure 9:

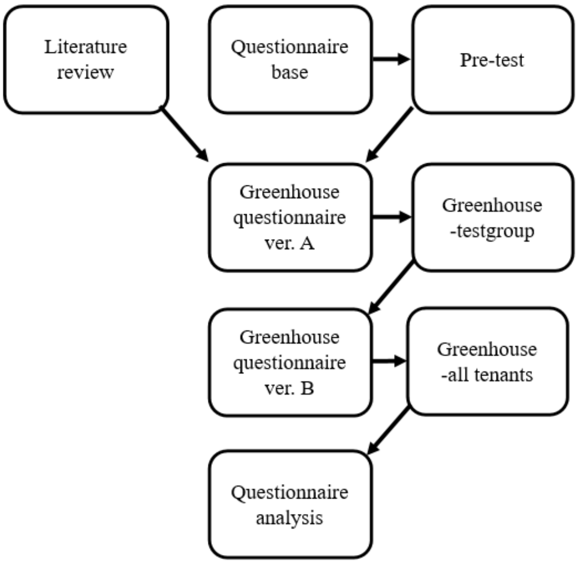

Figure 9- Workflow of the subjective assessment

2.2.1 Pre-test

An unrevised version of the questionnaire was sent by e-mail to a number of family members and friends, with various age, sex and background, in order to collect valuable information about how the questions were interpreted, time for answering, need for additional information, etc. Five questionnaires were distributed and collected, with the following useful feedbacks:

- Complementary information in the introduction text is necessary (for instance, respondents answered the questionnaire from work and not from their homes).
- The layout of the introduction text needed to be clearer and respondents' information more noticeable (for instance, information about time, date and apartment number was omitted by several respondents).
- Some questions needed to be rephrased and clarified to avoid misinterpretation.
- Some questions were missing important answering alternatives.
- No specific issues with understanding the language and terms were reported.
- The answering time was reported to vary between 20-30 minutes, the longer times reported by those being distracted or who would have preferred a questionnaire in Swedish.
- A question for recognizing night-shift workers needed to be added to the questionnaire.

Some examples of the notes taken from analyzing the pre-tests are presented in Appendix A.

2.2.2 Implementation of literature study and pre-test

The questionnaire was revised according to the knowledge learnt from the literature study and the pre-test. The language was generally simplified to be as clear and informal as possible, avoiding difficult and/or unnecessary words. The introduction text was supplemented with more and clearer instructions and the general layout of the questionnaire was improved. The order of the questions was slightly changed, with the chapter of general satisfaction moved from the very beginning to a later chapter, to give the respondents an opportunity to reflect on the specific subject before answering generally. Each question was reviewed and when necessary revised to meet the following recommendations:

- Use simple and plain language, avoid negative expressions;
- Clarify how the respondent should answer;
- Only ask about one thing at a time;
- Match question and set of answers;
- Make sure no answering alternative was omitted;
- Use balanced and neutral answering sets;
- Make sure answer alternatives provide useful information and that they are not ambiguous and sensitive for personal interpretation;
- Make good use of the research and do not include questions that are not useful or omit questions that could contribute with useful information.

Based on these recommendations, a number of questions and/or answering alternatives were rephrased and two additional questions about time of use of some rooms were added.

2.2.3 Testing the designed questionnaire

The questionnaire was subsequently handed out to a small group of five tenants where daylight was physically measured, as a final test of the questionnaire before distribution to the rest of the tenants. MKB handled the practical distribution and collecting of the questionnaires and an English version of the questionnaire was offered to those preferring this.

The introduction letter informed the respondents about the purpose of the questionnaire and instructed them to let the answers reflect on their general perception of daylight during this season of the year (autumn/winter). They were also instructed to be at home when filling the questionnaire and to answer during daylight with electric lighting preferably switched off. Each respondent should also specify the time and date they filled the questionnaire and what apartment number he or she had. The respondents were also instructed to return the questionnaire in the mailbox at the local MKB office two weeks later. These four responses are included in the results, due to the rather small number of respondents available. Three of the questionnaires were returned on time and apart from indicating a need for clearer instructions about the apartment number, no need for further revision was identified.

A new section was however added to the questionnaire before locking the final version. This section included three questions about activities, daylight as only light source when performing different activities and the respondents' preference for and reflection about daylighting versus electric lighting. Background research revealed a lack of knowledge in this type of information and it was found both interesting and useful to include these questions in this study.

2.2.4 Final questionnaire

The final version of the questionnaire was distributed during the late part of December and collected during January. It was handed out to all tenants of Greenhouse, except the students on the lower floors of Höghuset and the five tenants who answered during November.

A compressed overview of the final questionnaire is found in table 5. Note that this version is not identical to the distributed version of the questionnaire, which can be found in Appendix B.

Table 5 – A compressed summary of the questionnaire.

IMPORTANT, READ THIS BEFORE!

Questionnaire about daylighting in Greenhouse

Dear tenant,
This questionnaire is part of a research project about daylighting and energy in Greenhouse entitled "Conditions for daylighting in environmentally certified buildings – example from the Greenhouse Augustenborg". This project is funded by the Swedish Energy Agency (grant #39682-1) and ARQ (grant #4:2105).

In this project, we want to evaluate the daylighting conditions in your apartment. Daylighting plays a central role in guaranteeing a healthy living environment and reducing energy consumption. You will receive two identical questionnaires at different times of the year. Each questionnaire takes about 30 minutes to answer.

The questionnaire is composed of eight parts. Please take time to answer each question as honestly and thoughtfully as possible. The answers should be based on the average daylight levels that you experience ***at this time of the year****. As the questionnaire focuses on natural light it is important that you follow the instructions below:*

- ***Be at home*** *when answering the questionnaire*
- *Answer the questionnaire* ***during daytime***
- ***Switch off electrical lighting*** *(if possible)*

In addition, "bedroom 1" in the questionnaire refers to the main bedroom in the apartment. Rooms that are not listed can be specified and described in the category "other room". Please select only ONE answer unless otherwise stated.

Your opinion is important, so we would very much appreciate your feedback. Answers are kept confidential and will become anonymous when computerized.

Please fill in your apartment number, the date and time before filling the questionnaire.

Apartment number: 705 - _ _ _ - 01

Date: ________________________________ Time: __________________________

Please leave your filled questionnaire in the postbox at MKB's office (Augustenborgsgatan 3), all pages stapled together or placed in an envelope, <u>the 1st of January 2017 AT THE LATEST!</u>

Before you start, here are some useful definitions to help you answer the questionnaire:

- *"Daylight" refers to light penetrating through windows including sunlight and diffuse or reflected light.*
- *"Sunlight" refers to direct light from the sun. Direct light and sunlight are synonymous.*
- *"Daylight level" refers to the amount of daylight.*

PART 1: DAYLIGHT LEVEL

1a. How would you describe daylight in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Very dark	Dark	Neither dark nor bright	Bright	Very Bright	I don't know

1b. How would you wish to change daylight in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Less daylight	No change	More daylight	Does not matter	I don't know

1c. Please rank the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room) according to your need for daylight:

Living room	Kitchen	Dining room	Bedroom 1	Work-shop	Glazed bal-cony	Other room

1d. Choose the description best corresponding to your experience of each room (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Glaring, so bright I have to close the curtains	Very awakening and refreshing, pleasant	Has just enough light for performing tasks	Rather dull and sad	Very dark and gloomy, unpleas-ant

PART 2: DAYLIGHT DISTRIBUTION

2a. How would you describe the distribution of daylight in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Very even	Even	Acceptable	Uneven	Very uneven	I don't know

2b. Do the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room) have any dark areas that are interrupting daily activities or making the space uncomfortable?

No	Yes, a few	Yes, many	I don't know

2c. Do the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room) have any bright areas that are interrupting daily activities or making the space uncomfortable?

No	Yes, a few	Yes, many	I don't know

PART 3: DIRECT SUNLIGHT

3a. Do you experience direct sunlight in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Not at all	A little	Moderately	Much	Very Much	I don't know

3b. How often do you use curtains, blinds or other sun shadings during daytime in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Never	A few times per week	1-2 h per day	3-4 h per day	More than 4 h per day	I don't know

3c. What is the main purpose when you use internal shading? Select ONE or SEVERAL alternatives for each room (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room) from the list below:

I have no shading	Prevent direct sunlight	Prevent diffuse light	For privacy	Prevent heat	To darken the room

PART 4: VIEW THROUGH WINDOWS

4a. How sufficient is the view through the windows in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Very poor	Poor	Acceptable	Generous	Very generous	I don't know

4b. How would you describe the view through the windows in the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

Very unpleasant	Unpleasant	Acceptable	Pleasant	Very pleasant	I don't know

PART 5: GENERAL SATISFACTION OF YOUR APARTMENT

5a. How would you describe your general satisfaction with the following aspects of your main living spaces (the main living spaces are the living room, kitchen and dining room):

Very dissatisfied	Somewhat dissatisfied	Moderate	Somewhat satisfied	Very satisfied	I don't know

5b. How would you describe your general satisfaction with the following aspects of the glazed balcony:

Very dissatisfied	Somewhat dissatisfied	Moderate	Somewhat satisfied	Very satisfied	I don't know

PART 6: ACTIVITIES AND REQUIREMENTS

6a. What activities are common in your home? Choose ONE or SEVERAL activities for each room (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room):

I use digital screens	I watch TV	Paperwork	Seated detailed work	Standing detailed work	Other activity	No particular activity

6b. How do you feel about daylight as the only light source when performing the following activities (digital screens, TV, paperwork, seated detailed work, standing detailed work, socializing, cleaning, meals, orientation):

Too little daylight	Slightly too little daylight	Enough daylight	Slightly too much daylight	Too much daylight	Don't know

6c. How do these statements match you (Not Correct, Partly Correct or Correct):

I don't take very much notice of daylight	Daylight is nice, but electric lighting suits me just as good
I prefer daylight to electric lighting	I am satisfied with the amount of daylight received outdoors

I need plenty of daylight indoors to feel good	I need plenty of daylight indoors for good vision
The activities I perform indoors often require blocking daylight out	I am sensitive to intense/bright daylight and often experience discomfort when exposed to intense/bright light

PART 7: PHYSICAL ENVIRONMENT

7a. Where were you while answering the questionnaire?

Next to the window	Roughly in the middle of the room	Further back in the room	Not in the room	Not at home

7b. How was the electric lighting when you answered the questionnaire?

All electric lighting was switched **off**	**Parts** of the electric lighting was switched **on**	**Most** of the electric lighting was switched **on**	I don't know

7c. How would you describe the sky conditions outside at the moment?

	1	2	3	4	5	6	7	
Sky fully covered with clouds	□	□	□	□	□	□	□	Completely clear sky (no clouds)

7d. What part(s) of the day do you normally use the following rooms (living room, kitchen, dining room, bedroom 1, workshop, glazed balcony, other room) during weekdays/7e "…weekends":

Most parts of the day	before 8:00	8:00-11:00	11:00-14:00	14:00-17:00	17:00-19:00	after 20:00	I use the room very little

PART 8: PERSONAL INFORMATION

8a. What is your age?

<19	19-29	30-39	40-49	50-59	60-69	>70

8b. What is your gender?

Male	Female	Other

8c. Do you use any visual aids (e.g. glasses, contact lenses, magnifying glass etc.)?

Yes, always	Yes, sometimes	No, never

8d. If you answered yes to the preceding question, please provide further details:

Shortsighted	Farsighted	Both shortsighted and farsighted	Bifocal lenses	Trifocal lenses	Progressive lenses

8e. Select the ONE alternative below that best corresponds to the type of work you have:

I work using a computer the majority of the time	I work using a computer sometimes	My work does not involve computers	My work is performed outdoors	I am retired	I do not work at the moment	I am a student

8f. Select ONE or SEVERAL alternatives below to describe your working hours:

I work during daytime	I work evenings	I work nightshifts	Not applicable

2.2.5 Analysis of questionnaires

The questionnaires were analyzed using the software Excel. After using the apartment number for identifying the position of the apartment (Höghus/Låghus, floor and orientation) and marking the specific tenant's contribution in a separate document, each questionnaire was given an identity number and handled anonymously in the Excel file. Floor position was entered with a code representing a specific section of the building to keep the responses of Höghuset anonymous. The data was entered with each questionnaire representing one row, and each question representing one column. The answering alternatives were coded by numbers and each specific answer entered as a number in each cell. The results are discussed in this thesis only with support from descriptive statistics but the research team plans to run more advanced statistical analysis on the data in the near future.

2.3 Objective assessment

2.3.1 Measurements

Physical daylight measurements[4] were performed in five apartments of Höghuset during the end of September and beginning of October 2016. The measurements were performed in collaboration with staff involved in the research project and were spread over a number of weeks due to measurements requiring overcast sky conditions in combination with the apartment being available. The apartments were chosen to represent different orientations and floors of the high building, as presented in table 6. Due to easier access to the west apartment on the 11th floor, this apartment was assessed instead of the west apartment on the 12th floor. Since simulations (Angeraini, 2017) have shown that at higher level the floor level does not really influence the results, results from 11th floor can replace results from the 12th floor. The south apartment on the 11th floor was also included due to easy access.

Table 6 - The five apartments used for measurements, including date and time

Apartment No.	Orientation	Floor	Day	Time
A1	East	4	2016-09-28	11-13
A2	West	4	2016-09-29	11-12
-	~~West~~	~~12~~	~~2016-10-25~~	~~11-12~~
A3	East	12	2016-10-07	11-12
A4	West	11	2016-09-29	13-14
A5	South	11	2016-10-06	11-13

The aim of the measurements was to compare the DF values with the simulated ones. Three types of measurements were performed; daylight factors according to a grid, point daylight factors according to Miljöbyggnad, DF_{MB}, and the surface reflectance of walls and floors. The surface reflectance was measured to compare to the surface reflectance used in the simulations and will not be described further here.

The interior and exterior illuminance were measured simultaneously under overcast sky conditions using a Hagner EC-1 and E4-X illuminance meters respectively.
The exterior illuminance was measured from the roof of Höghuset, to avoid influence from obstructing buildings. The interior illuminance was measured 0.8 meters above the floor, without obstructing the illuminance meter and with all electric lighting switched off. Values of interior and exterior illuminances were collected for points in a marked grid in each room, with the principle of collecting values from the centerline of each glazed portion on the façade and one line for each opaque portion in order to have a balance of bright and dark

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[4] See Dubois et al., (2017) for a more detailed description of the measurements.

points. The lines are illustrated in figure 10. The illuminance was measured starting 0.5 meters from the facade and continuing at 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 and 6.0 meters from the façade.

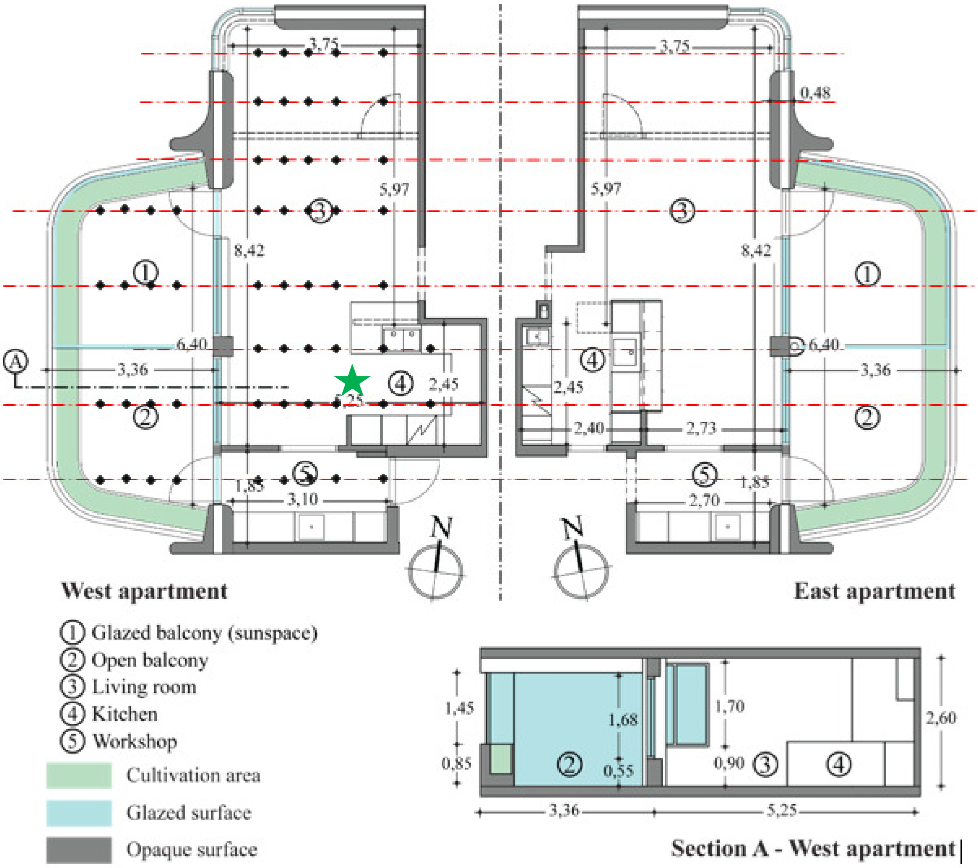


Figure 10- Lines for measurements of the internal illuminance. Values collected at points along the lines, starting 0.5 meters from the facade and continuing at 1.0, 1.5, 2.0, 3.0, 4.0, 5.0 and 6.0 meters from the façade. The measurement points are principally shown in the west apartment. The image is partly from Angeraini (2017).

The specific daylight factors according to Miljöbyggnad, DF_{MB}, were measured at one point in each room; 0.8 meters above the floor, 1.0 meter from the darkest sidewall and at half room depth. The position of this point in the main living spaces is principally marked with a green star in figure 10. The daylight factors were calculated using equation 1.

3 Results

3.1 Subjective assessment

3.1.1 The respondents

Of the 41 distributed questionnaires, a total of 30 completed questionnaires, representing 29 different households, were returned by the end of January. The distribution of respondents (house, orientation and floor) are presented in table 7 and 8.

Table 7- Distribution of respondents with respect to house type and position/orientation

	Number of distributed questionnaires	Number of collected questionnaires	Comment
Höghuset	**31**	**24**	23 households
West	11	8	
East	11	9	
South	9	7	
Låghuset	**10**	**6**	
Lower block	4	2	
Upper Block	6	4	1 corner apartment

Table 8- Distribution of respondents in Höghuset with respect to floor position

	Number of distributed questionnaires	Number of collected questionnaires
Höghuset		
Floor 4-6	8	7
Floor 7-9	9	5
Floor 10-14	14	11

As seen in table 7-8, the collected questionnaires of Höghuset cover the three orientations of the apartments quite evenly. A slightly lower representation of the floors 7-9 can be noticed, but the representation of floors can still be considered satisfying. However, for Låghuset the number of respondents is much lower but the number of households is also lower in this part of the project.

The distribution of the respondents' age and gender is presented in figure 11:

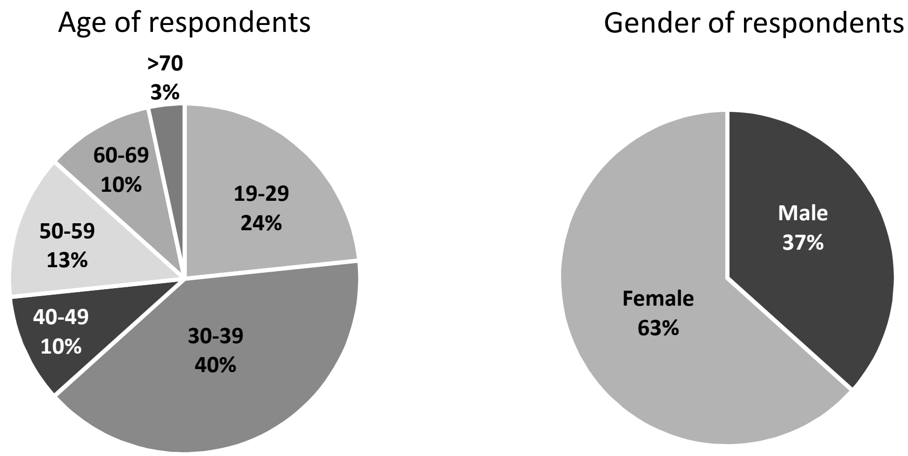


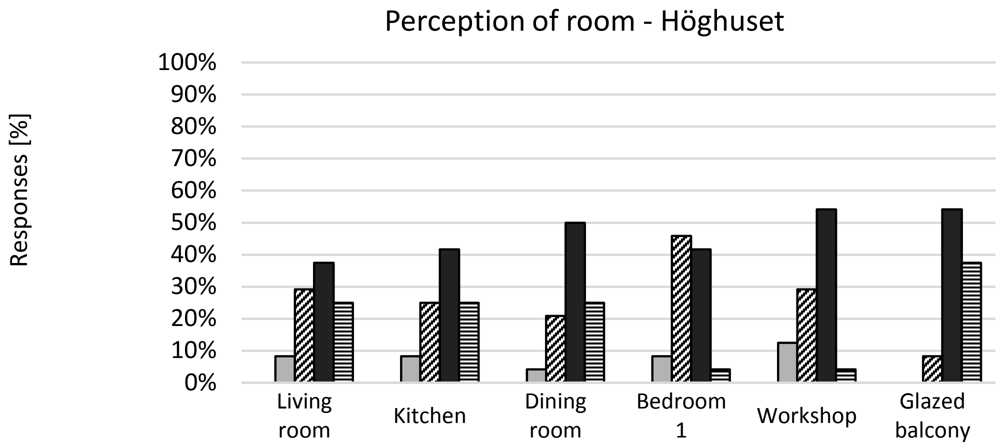
Figure 11- Age and gender distribution of the respondents

As can be seen in figure 11, the majority of respondents are women (63%). Looking at the age distribution, a majority of the respondents are between 19-39 years of age (64%). Other collected personal information about the respondents show that most of them have normal daytime jobs (71%) and only a small part work evenings (10%) or nightshifts (6%). Most of the respondents work using computers to some extent, with 27% reporting using computers a majority of the time, 33% sometimes while 20% were students. Judging from these results, a significant part of the respondents can be assumed to work in front of computers and during daytime. Only a small part of the respondents indicate other types of workdays, by reporting performing their work outdoors (3%), not working (3%) or retirement (10%).

The collected information about the respondents' visual health show that half of them never use any visual aids, while the other half either uses visual aids always (40%) or sometimes (10%). The dominating visual impairment is being shortsighted (79%).

3.1.2 Part 1 – daylight level

How would you describe the daylight?
The responses to this question are summarized in figure 12.



	Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony
Very dark	0%	0%	0%	0%	0%	0%
Dark	8%	8%	4%	8%	13%	0%
Neither dark nor bright	29%	25%	21%	46%	29%	8%
Bright	38%	42%	50%	42%	54%	54%
Very bright	25%	25%	25%	4%	4%	38%

Figure 12 - Höghuset - Responses to question 1a: How would you describe daylight in the following rooms?

As seen in figure 12, no respondent report perceiving any room as “very dark“ and only a small part (4-13%) report perceiving “dark“ conditions. A majority of the respondents find the main living spaces, workshop and glazed balcony to be in the range “bright-very bright”, while the bedroom is perceived as ”Neither dark nor bright” by the majority of respondents. Notable is however the significant part of the respondents (25-54%) who perceive the interior rooms as “dark-neither dark nor bright”, which is surprising considering that the daylight level in Greenhouse is designed to be more generous than the requirements in BBR.

Summaries of the responses from each apartment orientation is presented in figure 13-15, presenting the answers for "dark", "neither dark nor bright" and "bright-very bright" separately, in order to make the results a bit clearer.

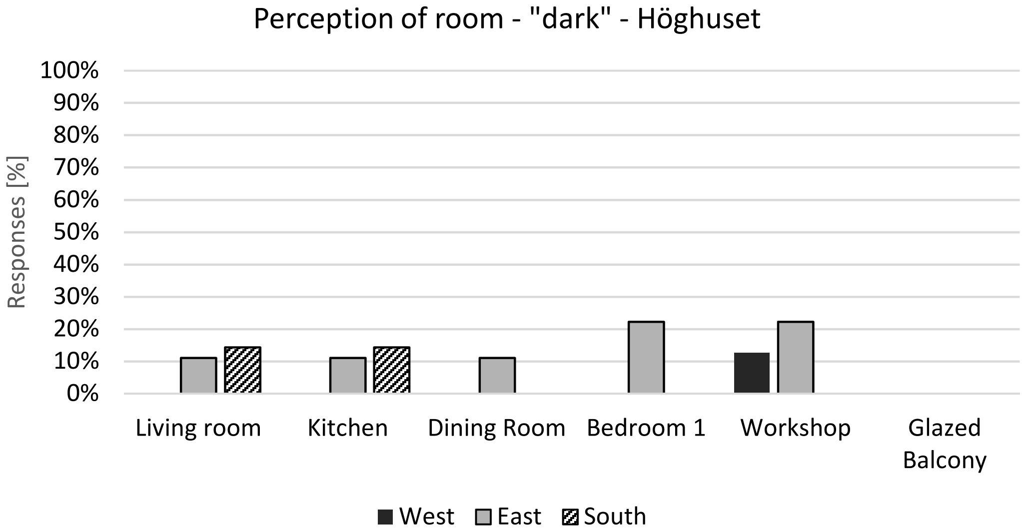


Figure 13 - Höghuset - Responses to question 1a: How would you describe daylight in the following rooms? Only answers of "dark" are presented in the figure and for each apartment orientation separately.

As seen in figure 13, "dark" perception is more frequent for east oriented apartments, with the highest scores for bedroom (22%) and workshop (22%).

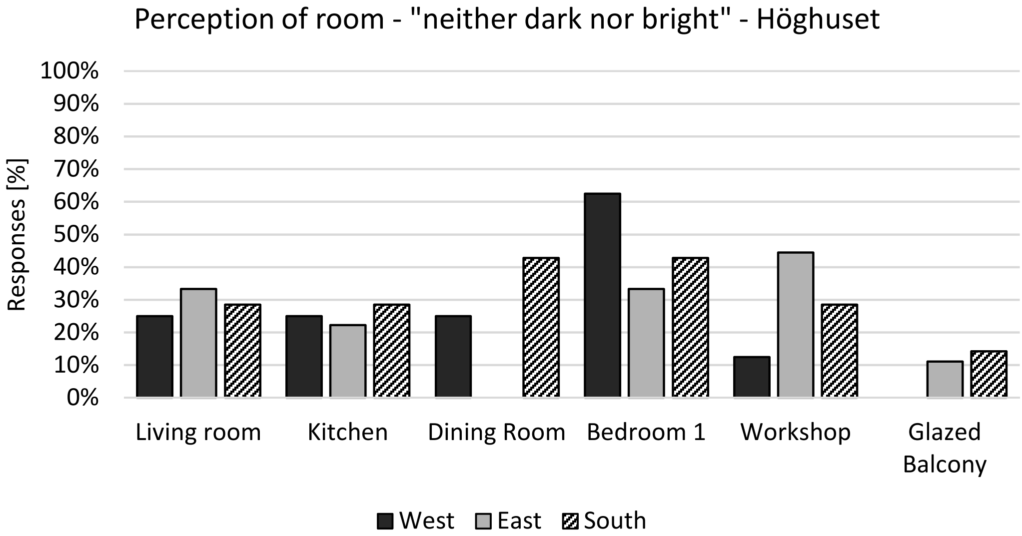


Figure 14 - Höghuset - Responses to question 1a: How would you describe daylight in the following rooms? Only answers of "neither dark nor bright" are presented in the figure and for each apartment orientation separately.

Perception of “neither dark nor bright”, as seen in figure 14, is rather equally distributed between the orientations in living room and kitchen, with scores between 22-33%. The dining room has significantly more responses coming from south oriented apartments (43%), and none at all from east ones. The bedroom has higher scores in all three orientations, the highest noted for west oriented apartments (63%). The workshop has highest scores for east oriented apartments (44%) followed by south ones (29%). The glazed balcony has low scores for “neither dark nor bright” in all three orientations.

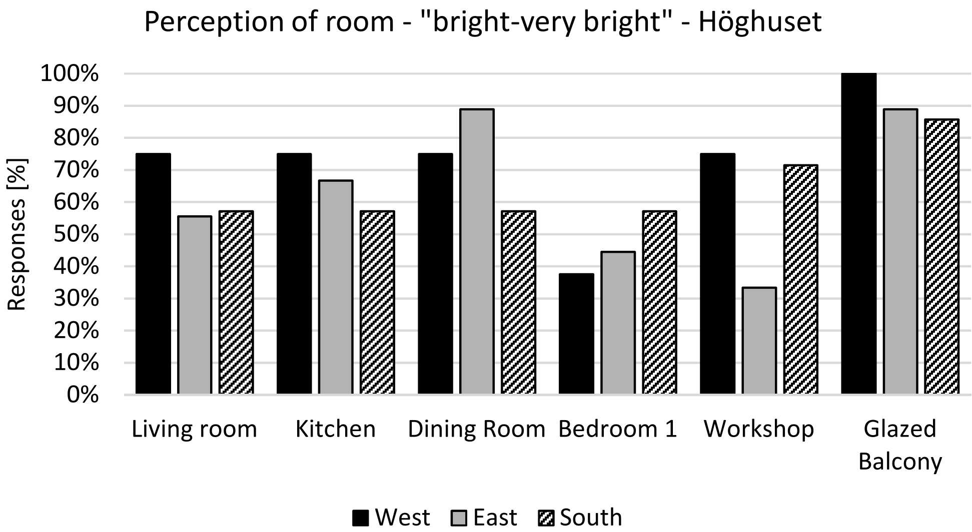


Figure 15- Höghuset - Responses to question 1a: How would you describe daylight in the following rooms? Only answers in the range between “bright” to “very bright” are presented in the figure and for each apartment orientation separately.

As seen in figure 15, the main living spaces (living room, kitchen and dining room) are perceived as “bright to very bright” by a majority of the respondents. West oriented living spaces are perceived as “bright-very bright” more frequently than the south oriented ones, which have one window less due to a different layout of the larger south apartments. The east oriented living spaces show a greater variation in the perception of the three parts of the open space (living room, kitchen and dining room), with a much brighter perception in the dining room.

The glazed balcony is also perceived as “bright to very bright” by most respondents, with west oriented balconies more frequently perceived as “bright-very bright” than the other orientations. The workshop is reported as “bright-very bright” by the majority of respondents of west and south oriented apartments, while only a third of the respondents in east oriented apartments report “bright to very bright” conditions.

In apartments with west or east orientation, the bedroom obtained lower responses for “bright-very bright” than the main living spaces of these apartments. The bedrooms of east oriented apartments show a greater variability in perception, with answers ranging from "dark" to "bright". The master bedroom of the south oriented apartments are perceived as "bright" or "very bright" to the same extent as the south living spaces.

The respondents' perception of daylight in Låghuset are presented in figure 16. The answer category "very dark" did not receive any score and it is therefore not presented in the graph. Answers for "bright" and "very bright" category are summarized in a single category to make it clearer.

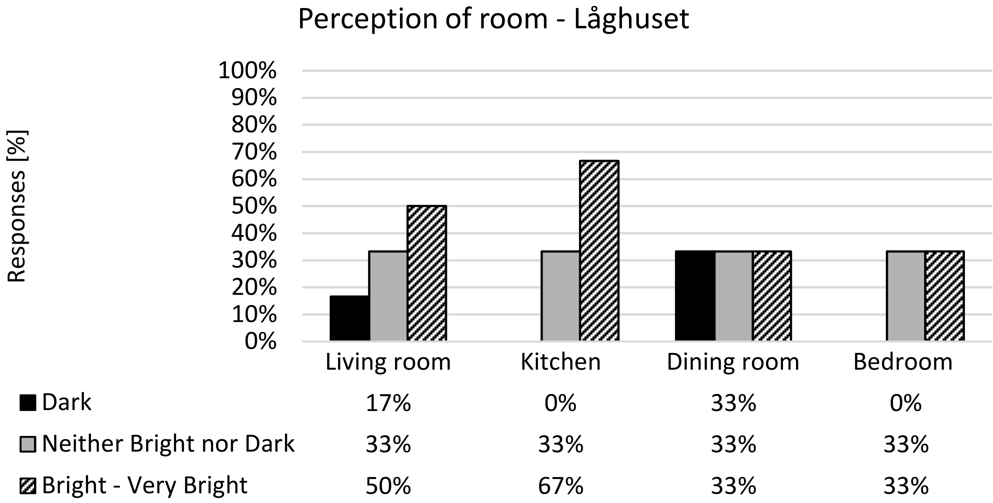
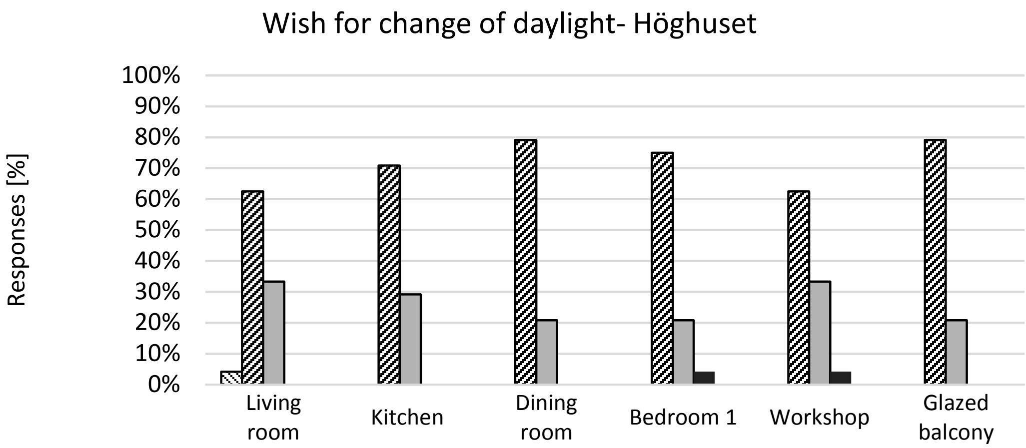


Figure 16- Låghuset - Responses to question 1a: How would you describe the daylight in the following rooms? Only represented answers are presented and answers of "Bright" and "very bright" have been summarized to one category.

As seen in figure 16, the main living spaces of Låghuset are perceived differently by the respondents. A majority of the respondents (67%) find the kitchen "bright to very bright", while the dining room have as many respondents finding the dining room "dark" (33%) as "neither bright nor dark" (33%) or "bright-very bright" (33%). The living room is perceived as "bright to very bright" by half of the respondents. The responses indicate that the main living spaces are perceived as brighter closer to the façade (kitchen, living room) and darker in the core of the room (dining room). This was also pointed out in a comment by one of the respondents. The master bedroom, with only four reported answers from the six questionnaires from Låghuset, is found "neither bright nor dark" to "bright" by the respondents.

How would you wish to change the daylight?

The respondents' wish for change of the daylight level (Höghuset) is presented in figure 17.



	Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony
Less daylight	4%	0%	0%	0%	0%	0%
No change	63%	71%	79%	75%	63%	79%
More daylight	33%	29%	21%	21%	33%	21%
Does not matter	0%	0%	0%	4%	4%	0%
Don't know	0%	0%	0%	0%	0%	0%

Figure 17- Responses to question 1b: "How would you wish to change the daylight in the following rooms?"

As seen in figure 17, a wish for more daylight in Höghuset is expressed by 21% for the dining room, bedroom and glazed balcony, by 29% for the kitchen and by 33% for the living room and workshop. The rest express that they do not wish for any change, with one exception where 4% (1 respondent) wanted less daylight in the living room.

Figure 18 shows the frequency of respondents wishing for more daylight in each of the three apartment orientations.

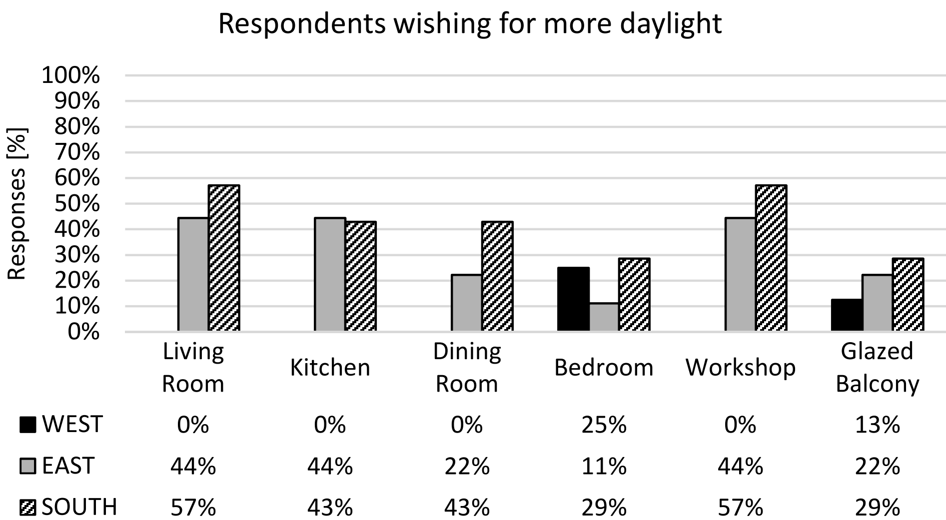
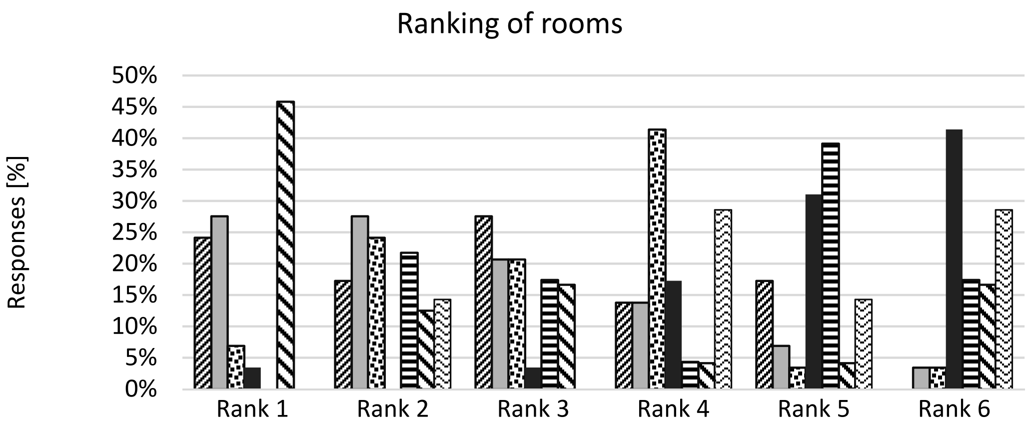


Figure 18 – Responses to question 1b (Höghuset):”How would you wish to change the daylight in the following rooms?”Only the respondents wishing for more daylight are presented, each apartment orientation separately.

As seen in figure 18, a wish for more daylight is less frequent among respondents living in apartments oriented towards west than towards east or south orientations. Respondents of south oriented apartments show the largest tendency of wishing for more daylight.

A wish for more daylight in Låghuset is expressed by 17% of respondents for the kitchen and 33% for the living and dining room. The rest of the respondents in Låghuset express no wish for change.

Rank the rooms 1-6 according to your need for daylight (1 is the highest need): A summary of the ranking made by the respondents is presented in figure 19. A higher need for daylight is represented by 1 and a lower need for daylight by 6.



	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
Living room	24%	17%	28%	14%	17%	0%
Kitchen	28%	28%	21%	14%	7%	3%
Dining room	7%	24%	21%	41%	3%	3%
Bedroom	3%	0%	3%	17%	31%	41%
W-shop	0%	22%	17%	4%	39%	17%
Glazed balc.	46%	13%	17%	4%	4%	17%
Other room	0%	14%	0%	29%	14%	29%

Figure 19: Responses to question 1c:"Please rank the following rooms according to your need for daylight (1 highest need, 6 lowest)".

As seen in figure 19, three rooms can be identified at a certain ranking more frequently than others. These are the glazed balcony at 1st place, the dining room at 4th place and the bedroom at 6th place. The other rooms are ranked by the respondents with greater variation. Figure 20 shows the same results, presented using three ranking intervals instead of six.

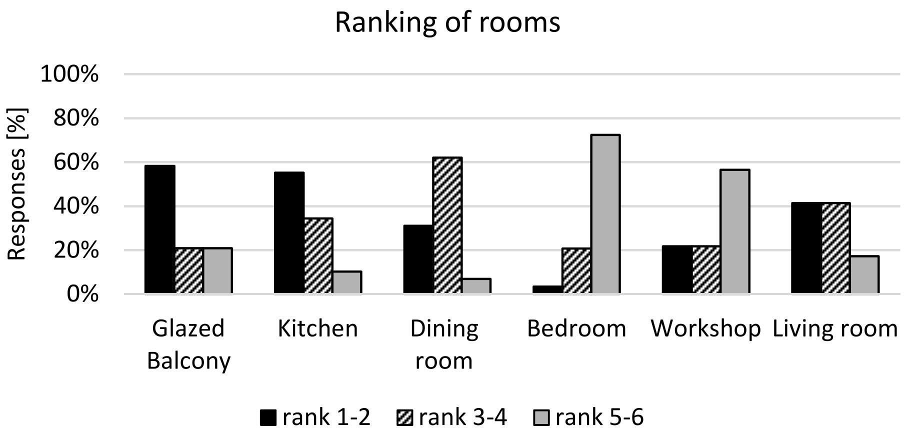


Figure 20 - Ranking of rooms according to need for daylight, presented using three intervals, (1 highest need, 6 lowest)

As can be seen in figure 20, the bedroom and workshop show a high frequency of being ranked to have a low need for daylight. A high share of respondents express a need for daylight in the glazed balcony and kitchen. The dining room is typically ranked in the middle, while the living room is split between a high and a medium need for daylight.

Choose the statement best corresponding to your experience of the room:
A summary of the respondents' choice of statement(s) for describing each room in Höghuset is presented in figure 21.

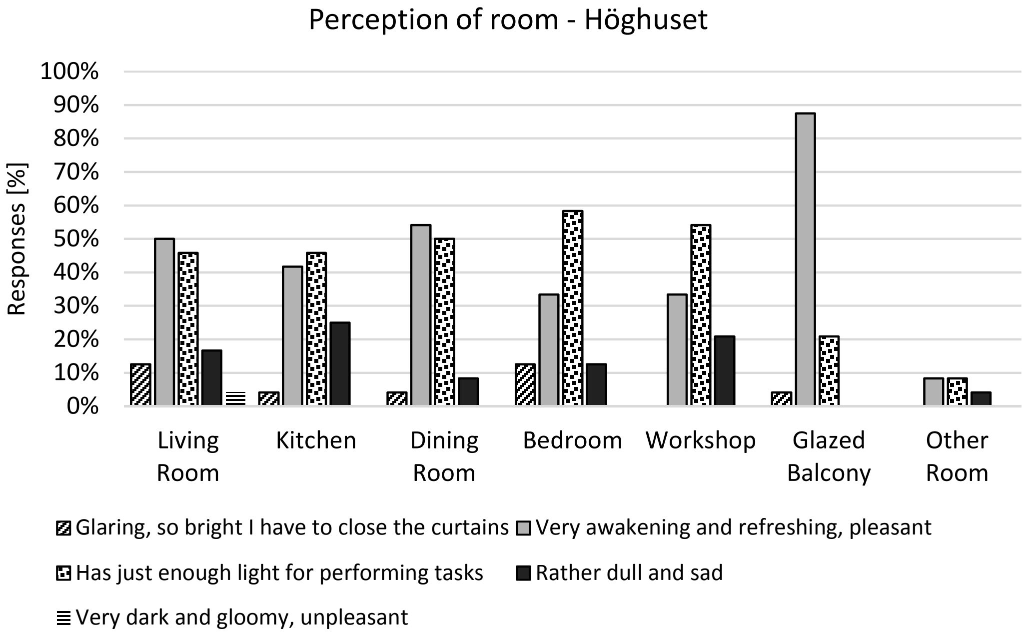


Figure 21- Responses to question 1d:"Choose the statement best corresponding to your experience of the room" (Höghuset).

Figure 21 shows quite similar results for the main living spaces (living room, kitchen and dining room), with 42-54% finding the space "very awakening and refreshing, pleasant" and 46-50% describing it as having "just enough light to perform tasks". The results are also similar for bedroom and workshop, with a majority of the respondents using the statement "has just enough light to perform tasks" for describing these rooms. Most respondents (88%) find the glazed balcony "very awakening and refreshing, pleasant". The highest use of the statement "rather dull and sad" is seen for the kitchen (25%) and the workshop (21%).

A review of the responses from each orientation reveals the following:

- Reports of perceiving a room as "glaring" are rare to non-existing for south oriented apartments and generally not above a maximum of 10% of west or east oriented apartments. The exceptions are living rooms (25%) of west apartments and bedrooms (22%) of east apartments.

- Reports of perceiving a room as “rather dull and sad” are almost non-existant for west oriented apartments. For east and south oriented apartments some respondents, ranging between 33-44%, find living room and kitchen “rather dull and sad”. The workshop is also perceived as “rather dull and sad” by 44% of the respondents in east oriented apartments.

- The use of the statement “very awakening and refreshing, pleasant” for describing a room has the highest frequency in the main living spaces of west oriented apartments (63-88%), followed by south apartments (57%). Rooms of east oriented apartments generally show a much lower use of this statement for describing the rooms (11-33%).

A summary of the respondents’ choice of statement(s) for describing each room in Låghuset is presented in figure 22.

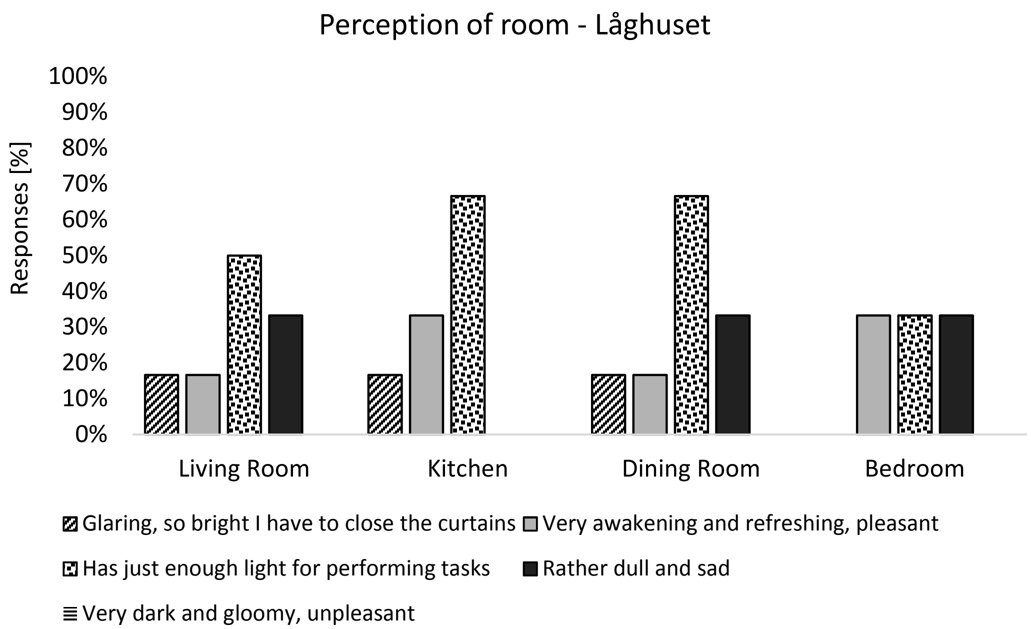


Figure 22 - Responses to question 1d:”Choose the statement best corresponding to your experience of the room”(Låghuset).

Figure 22 shows that a majority of the respondents of Låghuset describe the main living spaces by using the statement “has just enough light for performing tasks”. The remaining responses are mainly represented by use of the statement “rather dull and sad” (33%) for both the living- and dining room and “very awakening and refreshing, pleasant” for the kitchen (33%). This adds to previous results and indication of a darker core of the main living spaces and a kitchen which is perceived as brighter than the rest of the space. The descriptions of the bedroom are varied and show equal use of “rather dull and sad”, “has enough light for performing tasks” and “very awakening and refreshing, pleasant”.

SUMMARY PART 1 – DAYLIGHT LEVEL
Two different questions about the respondents' perception of the rooms were included in part one. The first question show that a surprisingly large part of the respondents (25-37%) perceive the main living spaces in the range "dark-neither dark nor bright". Bedrooms of west and east oriented apartments are perceived as darker than the living spaces of these apartments, which is also the case for workshops of east apartments. Differences between apartments of various orientations can be noticed; with respondents of western apartments more frequently using "bright" or "very bright" to describe the rooms (except the bedroom). The responses from Låghuset indicate that the kitchen is found to be "bright" or "very bright", while the core of the main living space (dining room and possibly parts of the living room) is perceived as darker.

The second question about the respondents' perception of the rooms does not indicate any significant problems with excessive levels of daylight in either Höghuset or Låghuset, but some problems are reported in the living room of west apartments and bedroom of east apartments. The second question reveals that a part of the respondents of east and south oriented apartments (Höghuset) perceive their living room and kitchen as "rather dull and sad" A significant part of the east apartment respondents (Höghuset) also perceive the workshop as "rather dull and sad", confirming the previous results. Again, rooms of western apartments tend to be perceived the brightest. The second question also confirms the previous findings in Låghuset, i.e. that parts of the respondents find the core of the main living spaces as darker, describing it as "rather dull and sad".

No respondents, with one exception, express the wish for less daylight in any room. A wish for more daylight is expressed by 21-33% and to a higher extent by respondents of east and south oriented apartments.

The kitchen (and glazed balcony) is often prioritized high in terms of need for the most daylight, while a medium need for daylight is typically expressed for the dining room and a lower need for daylight typically expressed for the bedroom.

3.1.3 Part 2 – daylight distribution

How would you describe the distribution of daylight?
A summary of the respondents' perception of the daylight distribution (Höghuset) is presented in figure 23.

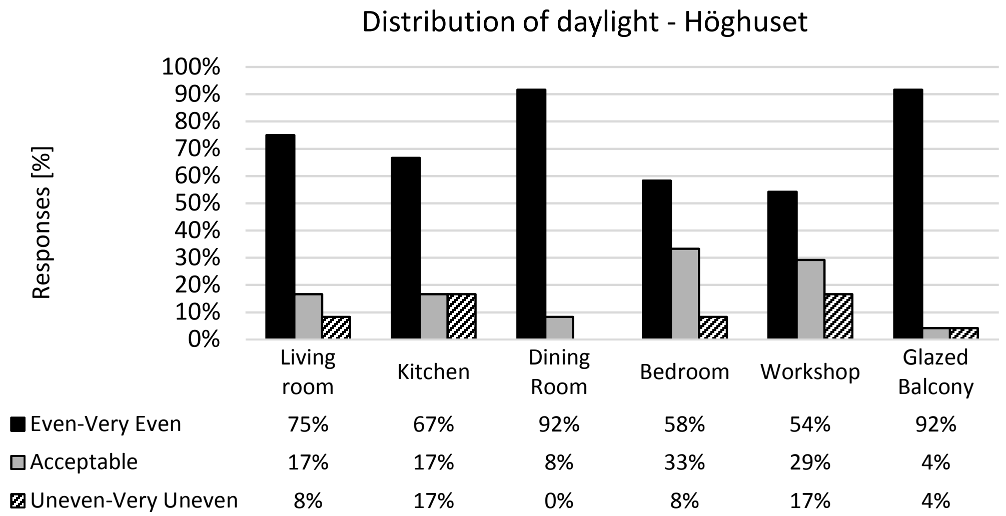


Figure 23- Responses to question 2a:"How would you describe the distribution of daylight in the following rooms?" (Höghuset)

As seen in figure 23, the results for dining room and glazed balcony are quite similar, with 92% describing the daylight distribution as "even" or "very even". This is also the main description of the daylight distribution in the living room and kitchen (75% and 67% respectively). The bedroom and workshop are also perceived as having an "even" to "very even" daylight distribution by the majority of respondents (58% and 54% respectively), but also have a significant part of the respondents describing it as "acceptable" (33% and 29% respectively). A summary of the responses describing the distribution as "even" or "very even", each apartment orientation summarized separately, is presented in figure 24.

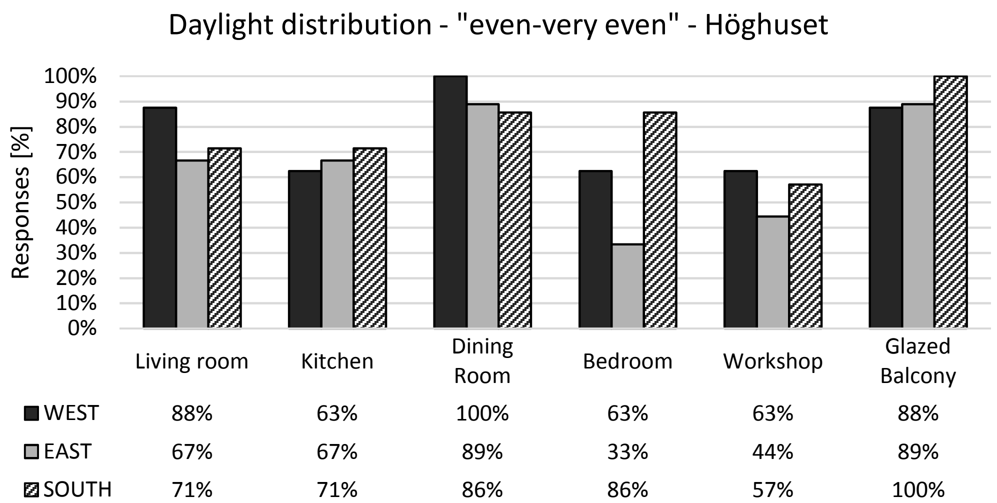
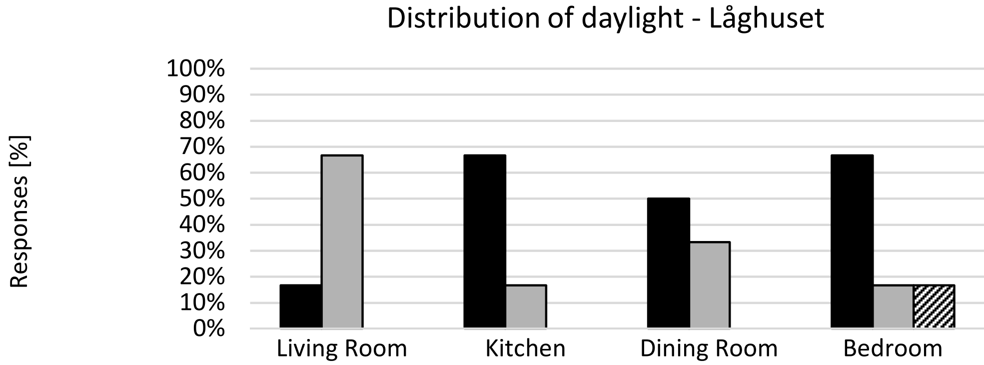


Figure 24- Responses to question 2a:"How would you describe the distribution of daylight in the following rooms?" (Höghuset). Only scores in the range "even-very even" presented.

As seen in figure 24, an "even" or "very even" distribution of daylight is reported rather equally comparing apartments of different orientations, except for bedrooms of east oriented apartments, where only 33% find the distribution "even-very even" compared to bedrooms of west (63%) and south (86%) oriented apartments. "Uneven" or "very uneven" (only reported for east apartment workshops) distributions are reported from mainly east oriented apartments (living room, kitchen, bedroom and workshop).

A summary of the respondents' perception of the daylight distribution (Låghuset) is presented in figure 25.



	Living Room	Kitchen	Dining Room	Bedroom
Even-Very Even	17%	67%	50%	67%
Acceptable	67%	17%	33%	17%
Uneven-Very Uneven	0%	0%	0%	17%

Figure 25 - Responses to question 2a:"How would you describe the distribution of daylight in the following rooms?"(Låghuset)

Figure 25 shows that a majority of the respondents (67%) find the daylight distribution of kitchen and bedroom in the range between "even to very even", while the majority (67%) describe the daylight distribution of the living room as "acceptable". The distribution of the dining room is described in the range between "even to very even" by a larger part (50%) and as "acceptable" by a smaller part (33%).

Do the following rooms have any dark areas that are interrupting daily activities or making the space uncomfortable?

A summary of the responses from Höghuset show that the only rooms where a noticeable number of respondents recognize any dark areas as disturbing are the kitchen (29%) and the Workshop (33%). The responses from Låghuset do not indicate any room with dark areas that are disturbing to the occupants (never more than one respondent recognizing "some" dark areas).

Summarizing the three apartment orientations of Höghuset separately, the fraction of respondents recognizing any disturbing dark areas are presented in figure 26. Only one respondent claims to be disturbed by "many" dark areas and the rest report being disturbed by "some" dark areas.

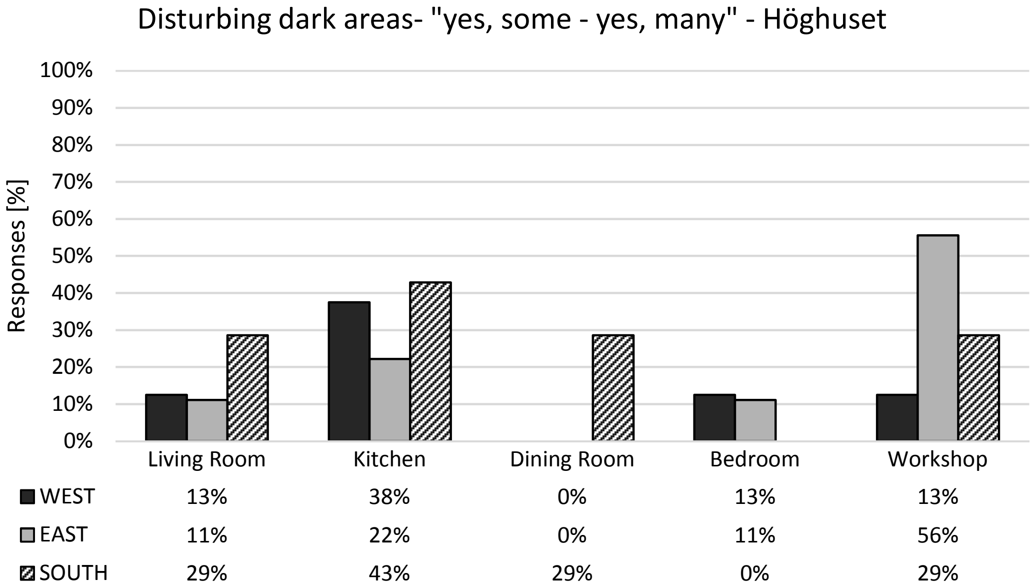


Figure 26 - Responses to question 2b:"Do the following rooms have any dark areas that are interrupting daily activities or making the space uncomfortable?"(Höghuset). Only answers of "yes, some" or "yes, many" are presented.

As seen in figure 26, disturbing dark areas of the main living spaces are recognized significantly less for east oriented apartments, while these have a significantly higher frequency of respondents recognizing dark disturbing areas of the workshop (56%). The kitchen is reported to have dark disturbing areas by 38% of the respondents living in west apartments and by 43% of the respondents living in south apartments.

Do the following rooms have any bright areas that are interrupting daily activities or making the space uncomfortable?

The analysis of the responses show that there are no rooms where a noticeable number of respondents recognize any bright areas as disturbing in either Höghuset or Låghuset. The living room of Höghuset is the only room with a small indication of disturbing bright areas, with 21% (5 respondents) reporting this. The results do not indicate any specific apartment orientation with higher or lower occurrence of bright disturbing areas in the living room. The one respondent reporting bright disturbing areas in Låghuset comments that this occurs when using a projector screen in the living room. Another respondent of a south apartment in Höghuset comments on having reported "some" disturbing bright areas in the main living spaces, but is pleased with the large windows and with not covering them with curtains and can therefore cope with "some" disturbing bright areas.

SUMMARY PART 2 – DAYLIGHT DISTRIBUTION

In general, the daylight distribution is mainly perceived as "even" in most rooms of both Höghuset and Låghuset. With only a few exceptions, the distribution is not considered below an "acceptable" level. The distribution is more frequently described as "acceptable" in the bedrooms and workshops of Höghuset and in the living and dining rooms of Låghuset. The living room of Låghuset is the only space where an "acceptable" distribution is reported by the majority. Perception of an "uneven" daylight distributions is almost non-existing in

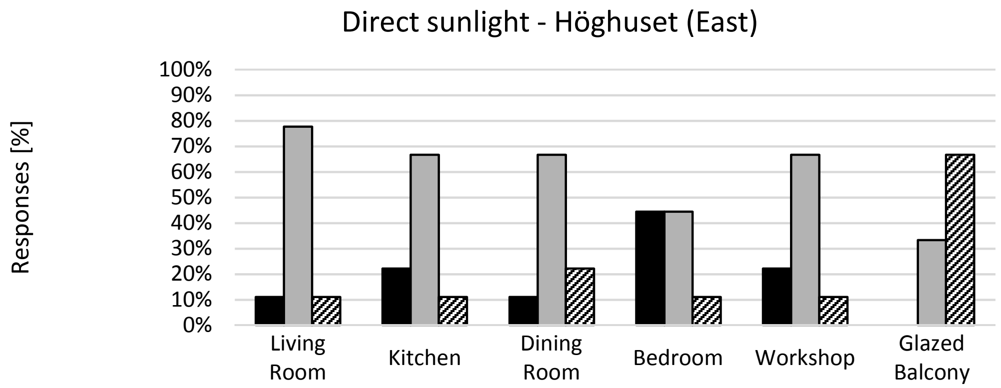
Låghuset and rather limited in Höghuset (4-17%). Notable however is that the reported "uneven" daylight distributions mainly come from east oriented apartments and represent 22-33% of the responses for some rooms.

Any significant problems with "dark disturbing areas" cannot be identified in either Höghuset or Låghuset. Some respondents of Höghuset recognize "dark" areas in the kitchen and/or the Workshop, the workshop is more frequently represented by respondents of east apartments and the kitchen more frequently by south and west respondents.

Neither can any significant problems with "bright disturbing areas" be identified in either Höghuset or Låghuset. Some respondents of Höghuset, various orientations, recognize disturbing "bright" areas in the living room.

3.1.4 Part 3 – direct sunlight

Do you experience direct sunlight in the following rooms?
A summary of the responses from the respondents of east oriented apartments of Höghuset is presented in figure 27.

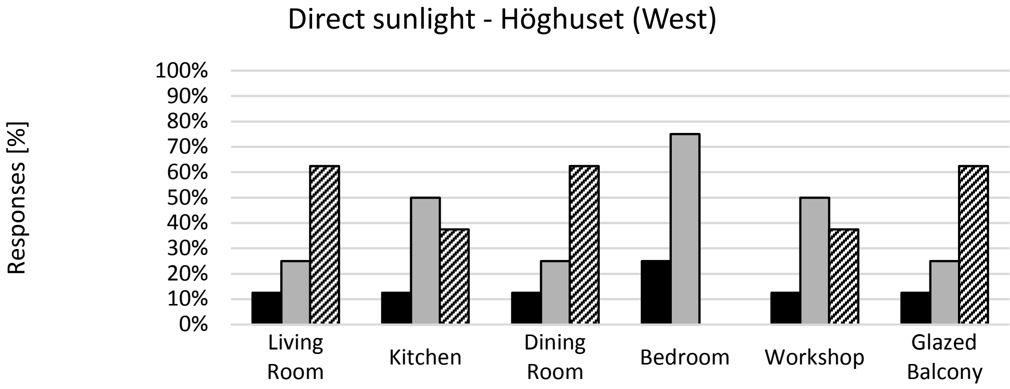


	Living Room	Kitchen	Dining Room	Bedroom	Workshop	Glazed Balcony
Not at all	11%	22%	11%	44%	22%	0%
A little-Moderately	78%	67%	67%	44%	67%	33%
Much-Very Much	11%	11%	22%	11%	11%	67%

Figure 27- Responses to question 3a (Höghuset, east apartments):"Do you experience direct sunlight in the following rooms?"

As shown in figure 27, the results for the main living spaces and workshop are quite similar, with a majority of the respondents reporting direct sunlight in the range between "a little-moderately". The glazed balcony is by a majority considered to have direct sunlight in the range between "much-very much". The bedroom is by most considered to have quite little direct sunlight, with 44% reporting "no direct light at all" and 44% reporting "a little-moderately". In general, the rooms of the east apartments are reported to have a "moderate" level of direct sunlight during winter.

A summary of the answers from the respondents of west oriented apartments of Höghuset is presented in figure 28.

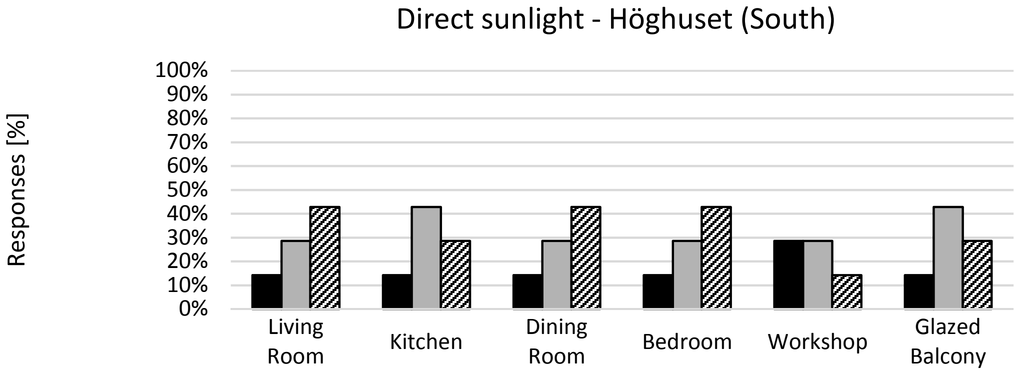


	Living Room	Kitchen	Dining Room	Bedroom	Workshop	Glazed Balcony
Not at all	13%	13%	13%	25%	13%	13%
A little-Moderately	25%	50%	25%	75%	50%	25%
Much-Very Much	63%	38%	63%	0%	38%	63%

Figure 28- Responses to question 3a (Höghuset, west apartments):"Do you experience direct sunlight in the following rooms?"

As shown in figure 28, the results are identical for living room, dining room and glazed balcony, with a majority (63%) of the respondents reporting direct sunlight in the range between "much-very much". Identical results are also obtained for the kitchen and workshop, with 50% reporting direct sunlight in the range between "a little-moderately" and 38% reporting "much-very much". The bedroom is found to have low levels of direct sunlight, with a majority (75%) reporting "a little-moderate" levels and the rest (25%) reporting "no sunlight at all". In general, the west oriented apartments are considered to have higher levels of direct sunlight in dining room and living room, lower levels in kitchen and workshop and the least in the bedroom. The results are very different when compared to the east facing apartments, most probably because occupancy and direct sunlight occur at the same time as people occupy their living space in the evening after work.

A summary of the answers from the respondents of the south oriented apartments of Höghuset is presented in figure 29.

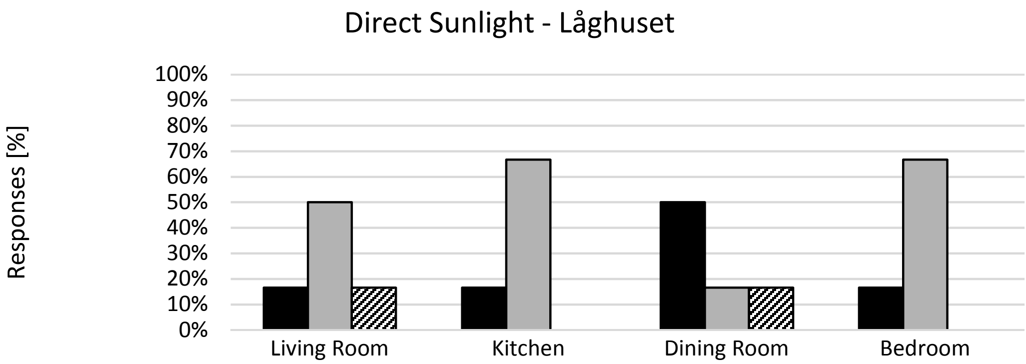


	Living Room	Kitchen	Dining Room	Bedroom	Workshop	Glazed Balcony
Not at all	14%	14%	14%	14%	29%	14%
A little-Moderately	29%	43%	29%	29%	29%	43%
Much-Very Much	43%	29%	43%	43%	14%	29%

Figure 29 - Responses to question 3a (Höghuset, south apartments):"Do you experience direct sunlight in the following rooms?"

As seen in figure 29, the results are identical for the living room, dining room and bedroom with 43% reporting "much-very much" direct sunlight, 29% reporting "a little-moderate" levels and 14% reporting "no direct sunlight at all". The kitchen and glazed balcony are perceived to have slightly less direct sunlight, and the workshop the least. In general, the kitchen and workshop are perceived to have less direct sunlight than the other rooms in the south apartments. Worth noting is also that the south master bedroom is reported to have more direct sunlight than in the bedroom of east or west apartments but the south facing bedroom also have more windows. The South glazed balcony is not reported to have as much direct sunlight as the west or east balconies.

A summary of the responses from the respondents of Låghuset is presented in figure 30.



	Living Room	Kitchen	Dining Room	Bedroom
Not at all	17%	17%	50%	17%
A little-Moderately	50%	67%	17%	67%
Much-Very Much	17%	0%	17%	0%

Figure 30- Responses to question 3a (Låghuset):"Do you experience direct sunlight in the following rooms?"

As shown in figure 30, most respondents report to experience “a little-moderate” amounts of direct sunlight in the living room (50%), kitchen (67%) and bedroom (67%). The dining room is perceived as having less direct sunlight, with 50% reporting “no direct sunlight at all”, which is hardly surprising as this space in located in the middle of the large room.

How often do you use curtains, blinds or other sun shadings during daytime?
All reported use of internal shadings is summarized for each apartment orientation in figure 31.

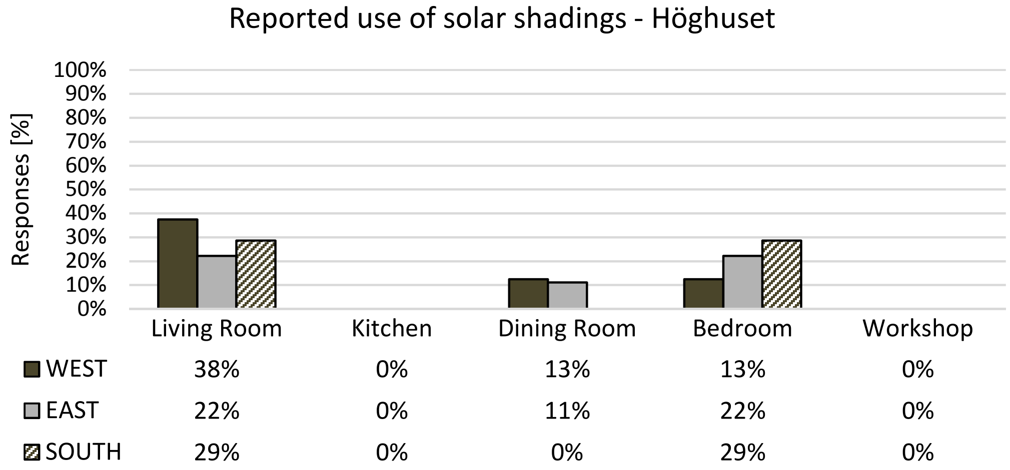


Figure 31 – Responses to question 3b (Höghuset):”How often do you use curtains, blinds or other sun shadings (during daytime) in the following rooms”? Each apartment orientation is presented separately.

A summary of the answers from the respondents of Höghuset indicate a low use of internal shadings during the winter. The only room with a significant use of internal shadings is the living room, where 21% of the respondents report using shadings “a couple of times a week” and 8% “a couple of hours every day” (not shown in figure 31). As seen in figure 31, the reported use of solar shadings is slightly higher in the living rooms of west oriented apartments than in east or south, which corresponds to previous indications of western living spaces having the most direct sunlight. Two respondents, who report no current use of shadings, comment that they want to install shadings in the future due to direct sunlight in the living room and dining room during mornings (east apartment) and in the living room (west apartment). Another respondent of an east apartment also comment on the apartment being very bright in the mornings and more “lagom” (acceptable) in the afternoon.

A majority of respondent of Låghuset report that they never use any internal shading devices. A daily use of 1-2 h is however reported by 33% of respondents in the kitchen and by 17% in the other parts of the main living space and master bedroom.

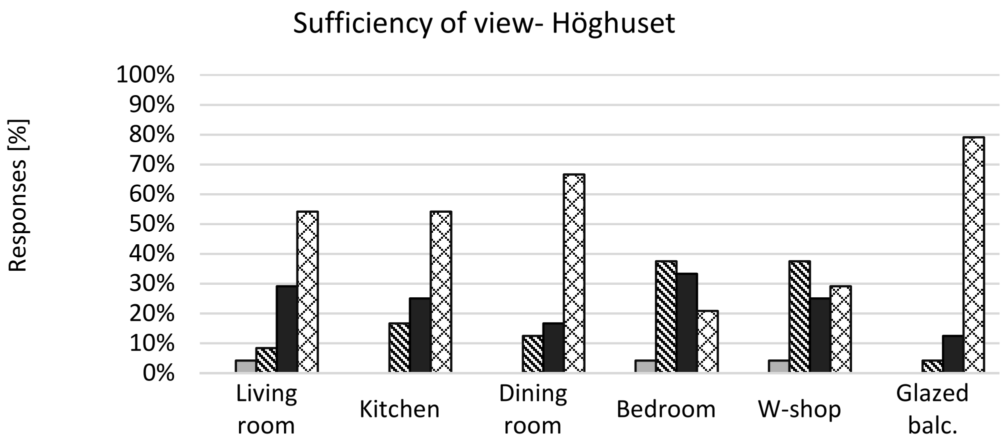
What is the main purpose when you use internal shading?
The respondents of Höghuset who report use of internal shadings in the living room all include “preventing direct sunlight” as a reason for the use. Some also add additional reasons, like “preventing diffuse light or heat”. In contrast, the answers for Låghuset indicate that “privacy” is the main reason for use of internal shadings during the winter.

SUMMARY PART 3 – DIRECT SUNLIGHT
The answers for Höghuset indicate that the west facing apartments are experienced as having the most direct sunlight in the main living spaces. The bedrooms of west and east oriented apartments are perceived as having less direct sunlight than the south apartments, while the south glazed balconies have less direct sunlight than the east and west facing balconies. The answers for Låghuset indicate a generally low-moderate level of direct sunlight, with significantly less direct sunlight in the dining room than in the other parts of the main living spaces.

The use of internal shadings is very low during the winter and the only room with a significant use of shading devices is the living room of Höghuset. Comparing the living rooms of differently oriented apartments, western apartments exhibit a slightly higher use of shading devices in the living room. This corresponds to previous indications of western living spaces perceived as having the most direct sunlight. The respondents of Höghuset who do report use of internal shading devices all include "preventing direct sunlight" as a reason for using the devices. In Låghuset, use of internal shadings during the winter is related to privacy.

3.1.5 Part 4 – view through windows

How sufficient is the view through the windows in the following rooms:
A summary of the answers from the respondents of Höghuset is presented in figure 32.

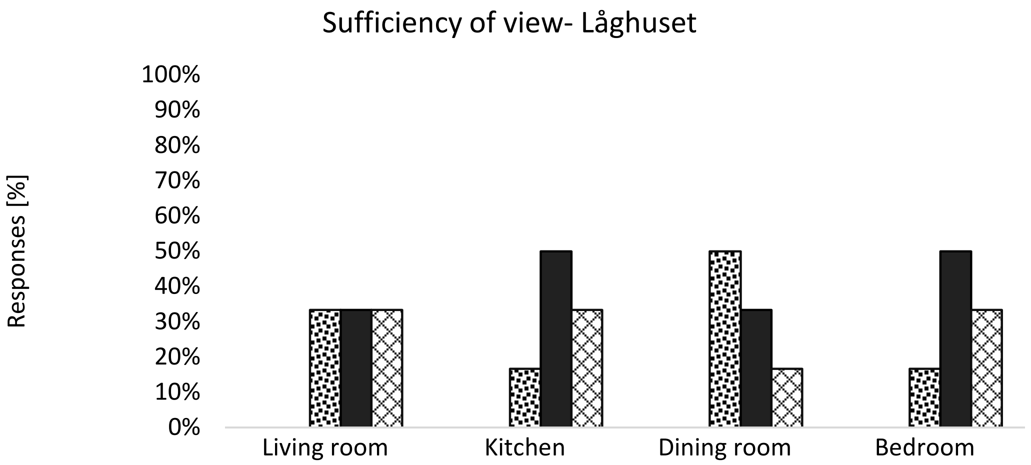


	Living room	Kitchen	Dining room	Bedroom	W-shop	Glazed balc.
Very Insufficient	0%	0%	0%	0%	0%	0%
Insufficient	4%	0%	0%	4%	4%	0%
Acceptable	8%	17%	13%	38%	38%	4%
Generous	29%	25%	17%	33%	25%	13%
Very Generous	54%	54%	67%	21%	29%	79%

Figure 32 – Responses to question 4a (Höghuset):"How sufficient is the view through the windows in the following rooms?"

As shown in figure 32, the majority of the respondents of Höghuset find the view from the main living spaces and glazed balcony "generous-very generous". A majority also describes the view from the bedroom (54%) and workshop (54%) in this range, but 38% also find the view from these rooms just "acceptable" or even "insufficient" (4%). Comparing different sections of Höghuset, all reports of the view being “insufficient” come from apartments of section B, floor 4-6, (section A lies outside the scope of this report). In the higher sections, no respondent described the view as any less than “acceptable”.

A summary of the answers from the respondents of Låghuset is presented in figure 33:

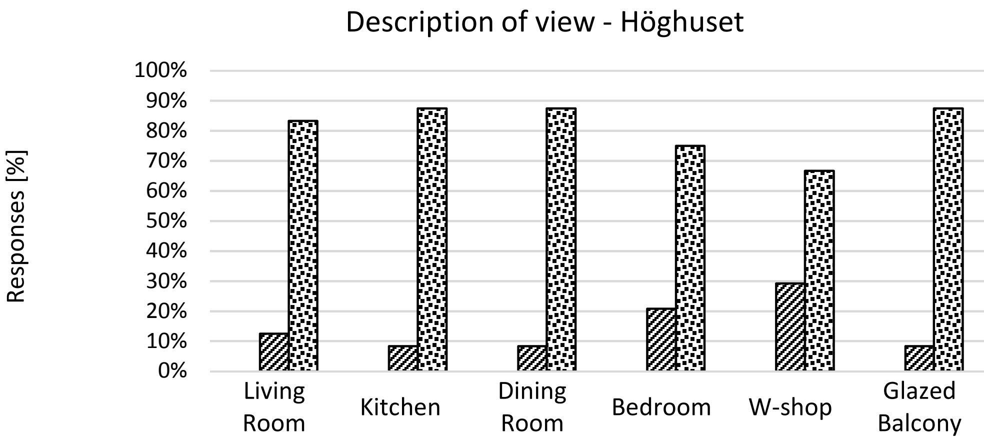


	Living room	Kitchen	Dining room	Bedroom
Very Insufficient	0%	0%	0%	0%
Insufficient	0%	0%	0%	0%
Acceptable	33%	17%	50%	17%
Generous	33%	50%	33%	50%
Very Generous	33%	33%	17%	33%

Figure 33 - Responses to question 4a (Låghuset):”How sufficient is the view through the windows in the following rooms?”

As shown in figure 33, the majority of respondents found the view from living room (67%), kitchen (83%) and bedroom (83%) to be in the range “generous-very generous”. The view from the dining room is reported as “generous-very generous” by fewer respondents (50%) and as “acceptable” view by the other 50%.

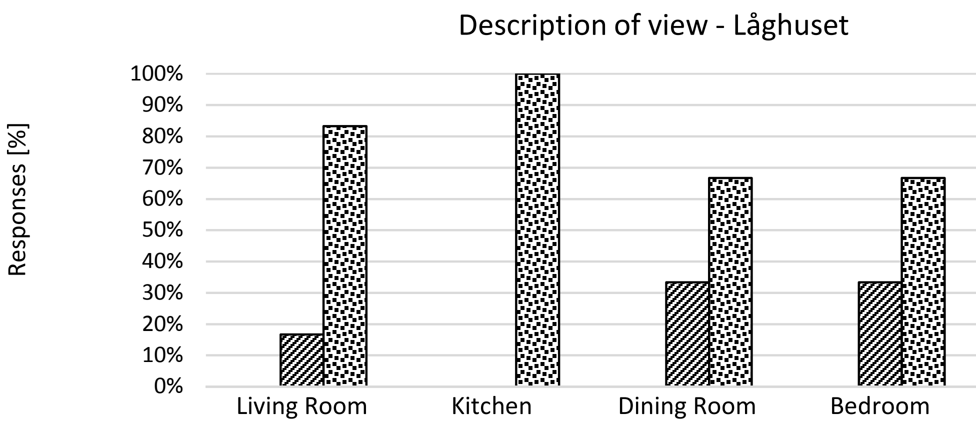
How would you describe the view through the windows in the following rooms?
A summary of the answers from respondents of Höghuset is presented in figure 34. Responses of “very unpleasant” and “unpleasant” are presented as one category and “pleasant” and “very pleasant” as one.



	Living Room	Kitchen	Dining Room	Bedroom	W-shop	Glazed Balcony
(Very) Unpleasant	0%	0%	0%	0%	0%	0%
Acceptable	13%	8%	8%	21%	29%	8%
(Very) Pleasant	83%	88%	88%	75%	67%	88%

Figure 34 – Responses to question 4b (Höghuset):"How would you describe the view through the windows in the following rooms?"

As shown in figure 34, more than 80% of the respondents find the view from the main living spaces and glazed balcony either "pleasant" or "very pleasant". The same description is given by the majority for bedroom (75%) and workshop (67%). No respondent assessed the view from any room less than "acceptable". The responses from Låghuset are quite similar, as shown in figure 35, with mainly positive descriptions of the view and never less than a description score as "acceptable".



	Living Room	Kitchen	Dining Room	Bedroom
(Very) Unpleasant	0%	0%	0%	0%
Acceptable	17%	0%	33%	33%
(Very) Pleasant	83%	100%	67%	67%

Figure 35 - Responses to question 4b (Låghuset):"How would you describe the view through the windows in the following rooms?"

SUMMARY PART 4 – VIEW FROM WINDOW
The view in most rooms of both Höghuset and Låghuset is perceived as “generous” or “very generous” by a majority of respondents. A higher occurrence of “acceptable” descriptions of the view is found in the bedrooms and workshops of Höghuset and in the dining room of Låghuset, which is hardly surprising since these rooms are located further in the core of the building. The view is mainly described using a positive expression, “pleasant” or “very pleasant” and no respondent describes the view from any room any less than “acceptable”.

3.1.6 Part 5 – general satisfaction with the apartment

How would you describe your general satisfaction with the following aspects of your main living spaces (living room, kitchen and dining room):
Figure 36 presents the answers regarding the general satisfaction of the main living spaces, as expressed by the respondents of Höghuset.

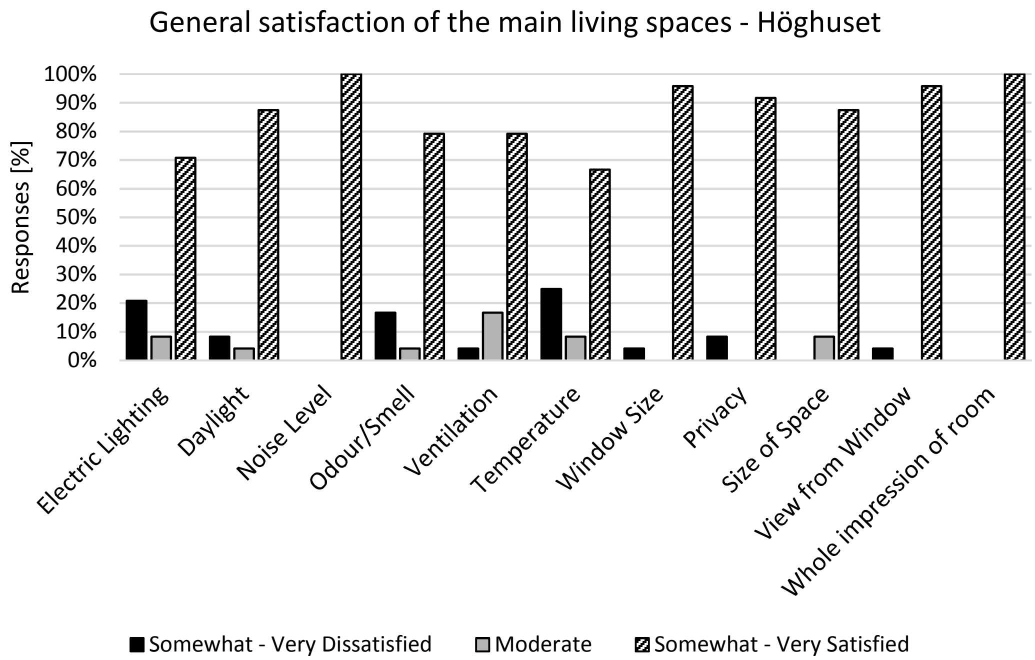


Figure 36 – Responses to question 5a (Höghuset):”How would you describe your general satisfaction with the following aspects of your main living spaces (living room, kitchen and dining room)?”

As shown in figure 36, for most categories, the assessment corresponds to “somewhat to very satisfied” for more than 80% of the respondents. The only categories with a lower amount of respondents answering in this range is electric lighting (71%) and temperature (67%). These two categories also have the largest percentage of respondents with an assessment in the range between “somewhat and very dissatisfied”, with electric lighting at 21% and temperature 25%.

Figure 37 presents the general satisfaction of the main living spaces, as expressed by the respondents of Låghuset.

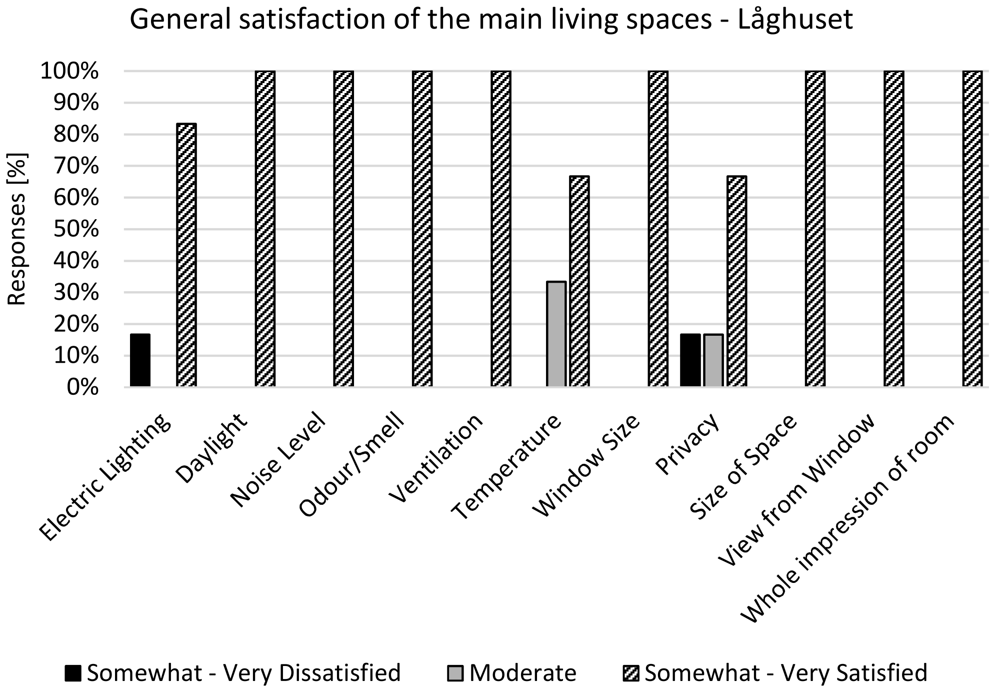


Figure 37 - Responses to question 5a (Låghuset):"How would you describe your general satisfaction with the following aspects of your main living spaces (living room, kitchen and dining room)?"

As shown in figure 37, the general satisfaction of the main living spaces is also high for Låghuset, for all categories except temperature and privacy, where the percentage of responses in the range between "somewhat-very satisfied" is lower (67%). Judging from the clarifying comments that are written by some of the respondents (both houses) who report a lower satisfaction with the temperature, the space is sometimes experienced as cold during the winter.

How would you describe your general satisfaction with the following aspects of the glazed balcony:

Figure 38 presents the general satisfaction regarding the glazed balcony for Höghuset.

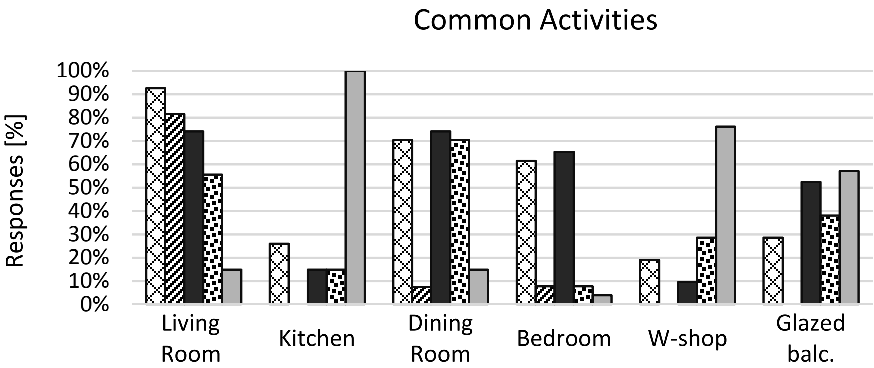
Figure 38 – Responses to question 5b (Höghuset):"How would you describe your general satisfaction with the following aspects of the glazed balcony?"

As shown in figure 38, most categories the majority of respondents (90%) assessed the glazed balcony as "somewhat to very satisfied". The two categories with slightly less positive assessments were temperature with 21% finding it "moderate" and 8% finding it "somewhat or very dissatisfying", and wind, with 17% finding it "moderate" and 13 % finding it "somewhat or very dissatisfying". Judging from the clarifying comments that are written by some of the respondents who report a lower satisfaction, the space is less insulated than expected.

SUMMARY PART 5 – GENERAL SATISFACTION OF THE APARTMENT
The general satisfaction of the main living spaces and the glazed balcony is high and a lower degree of satisfaction is only noticed, to a small extent, for temperature and electric lighting of the main living spaces and for temperature and wind protection of the glazed balcony. A lower degree of satisfaction with privacy can be identified among some of the respondents of Låghuset.

3.1.7 Part 6 – activities and requirements

What activities are common in your home?
Figure 39 presents a summary of the reported activities in each room. "Digital screens" refers to all digital screens other than TV, "paperwork" refers to both reading and writing different types of paper documents (newspaper, books, magazines, mail etc.), "seated detailed work" refers to activities like crafts, knitting, board games etc. and "standing detailed work" refers to activities like ironing, washing up, cooking etc.



	Living Room	Kitchen	Dining Room	Bedroom	W-shop	Glazed balc.
Use of dig. screens	93%	26%	70%	62%	19%	29%
Watch TV	81%	0%	7%	8%	0%	0%
Paperwork	74%	15%	74%	65%	10%	52%
Seated detailed work	56%	15%	70%	8%	29%	38%
Standing detailed work	15%	100%	15%	4%	76%	57%

Figure 39-The respondents' report of common activities in the different rooms of the apartment.

The following results can be summarized from figure 39:

- The use of "digital screens" (other than TV) are reported by a significant portion of respondents in the living room (93%), dining room (70%) and bedroom (62%), but this activity takes place to some extent in all rooms.
- 81% watch TV in the living room, which is more or less the only room where this activity takes place.
- "Paperwork" and paper reading mainly takes place in the living room (74%), dining room (74%), bedroom (65%) and also on the glazed balcony (52%).
- "Seated detailed work" mainly takes place in the living room (56%) and dining room (70%).
- "Standing detailed work" mainly takes place in the kitchen (100%), workshop (76%) and glazed balcony (57%).

How do you feel about daylight as only light source when performing the activities below:
Figure 40 presents how the respondents perceive daylight as only light source when performing a number of listed activities. The responses have been summarized in three categories, expressing insufficient, sufficient or excessive daylight levels for the particular activity.

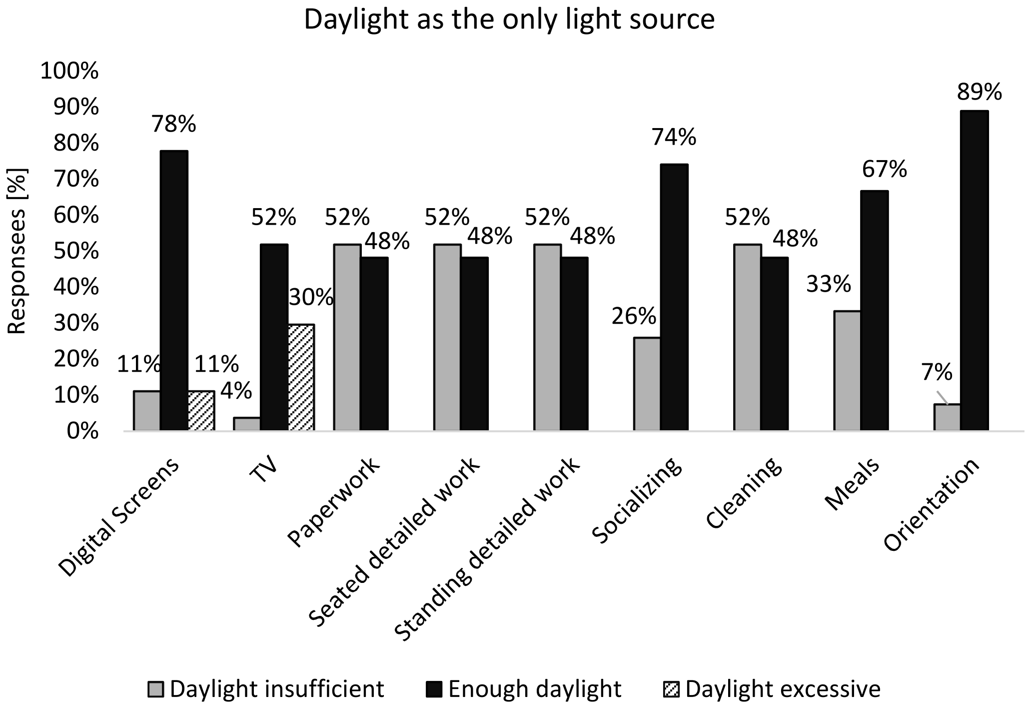


Figure 40 – Responses to question 6b:"How do you feel about daylight as the only light source when performing the activities below?" The responses have been summarized in three categories; insufficient, enough and excessive daylight.

As seen in figure 40, the daylight level is not found to be higher than desired for any activity, with exception for the use of digital screens (11%) and watching TV (30%). However, the majority of respondents found the daylight level appropriate for these "digital" activities (screens 78% and TV 52%). Most respondents (89%) perceived the daylight level as "enough" for normal orientation and that it could work as only light source for this. The daylight level is reported "sufficient" by the majority for activities such as socializing (74%) and meals (67%). However, for activities with higher level of detailing, such as different types of paperwork or paper-reading, seated or standing detailed work and cleaning, only 48% find the daylight level "sufficient" as only light source and the rest report that it is slightly or even too low for these activities.

How do these statements match your opinion?

Figure 41 presents how well a number of statements regarding daylight in everyday life correspond to each respondent.

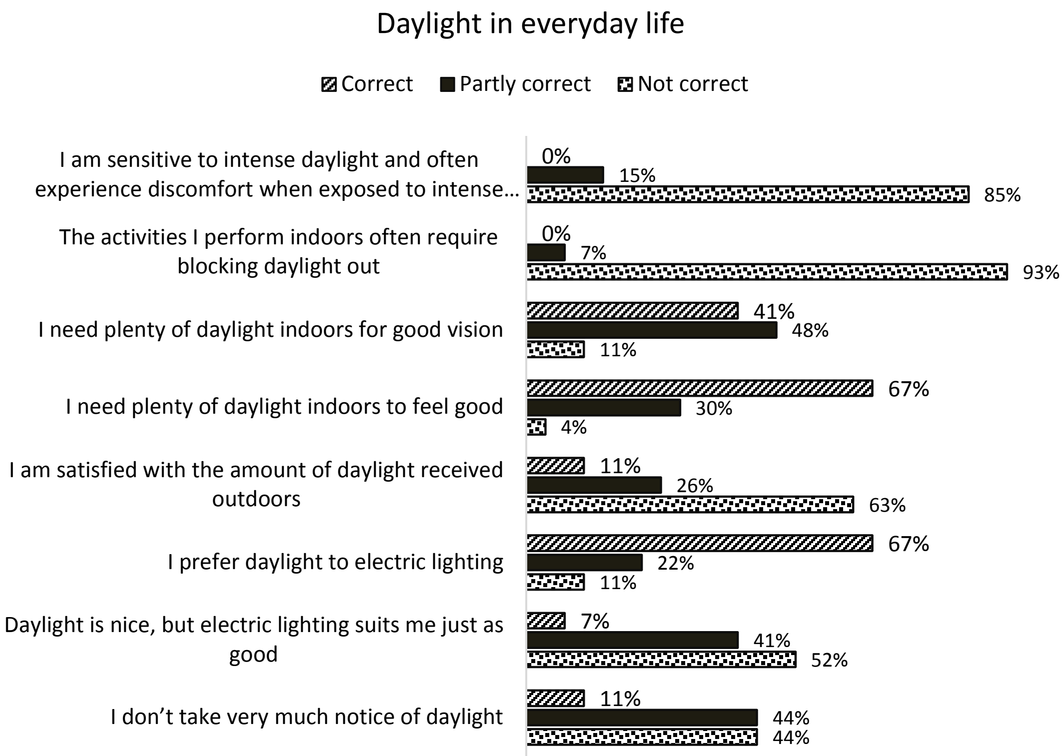


Figure 41 – Responses to question 6c:”How do these statements match you?”

The following can be summarized from figure 41:

- The respondents are generally not sensitive to intense daylight and only 15 % answer that they can experience discomfort to some extent when exposed to intense daylight.
- 93% claim that daylight does not interfere with daily activities and they do not need to shut daylight out.
- 41% need plenty of daylight indoors for good vision and 48% agree that this is important to some extent.
- 67% express that plenty of daylight indoors is important for them to feel good.
- 63% are not satisfied with the daylight they are exposed to outdoors.
- 67% express that they prefer daylighting over electric lighting.
- 52% express that electric lighting is an equivalent substitute to daylighting.
- 44% partly agree on not taking much notice of daylight while another 44% disagree on not taking much notice of daylight.

SUMMARY PART 6 – ACTIVITIES AND REQUIREMENTS
The eight statements about the respondents’ perception of and need for daylight reveal that daylight is generally not experienced to interfere with daily activities and most respondents do not experience any discomfort from intense daylight. A small number of respondents do however report that they to some extent are sensitive to intense daylight and may sometimes

experience discomfort when exposed to intense light levels. A majority of respondents claim that daylight is preferred over electric lighting, that the exposure outdoors is not satisfying (at this time of the year) and that plenty of daylight indoors is important for their well-being. A majority of respondents also agree that plenty of daylight indoors is important, or at least to some extent important, in terms of visual performance. The results thus indicate that the respondents have a preference for daylight and that they experience daylight as an important factor for well-being.

Daylight during this time of the year in Greenhouse is generally not considered "sufficient" as the only light source for activities with higher level of detail vision, while by the majority it is reported "sufficient" for more general activities which do not require any detail vision, like socializing, orienting and sharing meals. "Excessive" daylight is reported to a small degree and reports of this nature are connected to the use of digital screens, mainly when watching TV.

Activities with a higher need for detail vision are common in all rooms of the apartments, while the only activity where daylight is reported as "excessive" by a significant number of respondents, watching TV, almost exclusively takes place in the living room.

3.1.8 Part 7 – physical environment

The questions about the physical environment show that all respondents were, as requested, at home when filling the questionnaire and also managed to switch off all or most of the electric lighting.

A summary of the reported sky conditions at the time and day of filling the questionnaire is presented in figure 42:

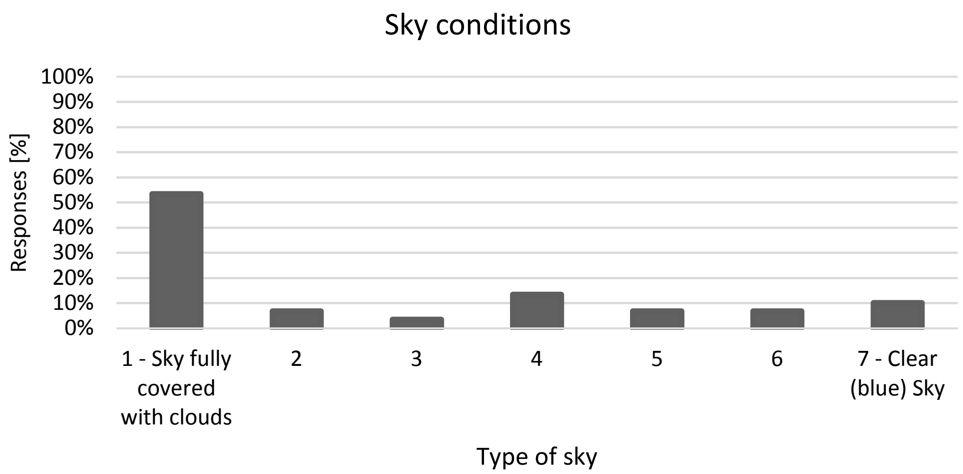


Figure 42 – Responses to question 7c:"How would you describe the sky conditions outside at the moment?"

As shown in figure 42, a fully, or to large extent, overcast sky is reported by a majority of respondents.

The respondents were also asked what hours of the day they normally use each room during weekdays and weekends respectively. Apart from different time intervals, the respondents had the option of selecting “I use the room most parts of the day”. Figure 43 shows the percentage of respondents who reported any use of the room during daytime, in the interval between 8 am and 5 pm. Note that the last time interval that was counted as “daytime”, 2-5 pm, also includes darkness at this time of the year in Malmö. Preferably this time should have been set to a maximum of 4 pm.

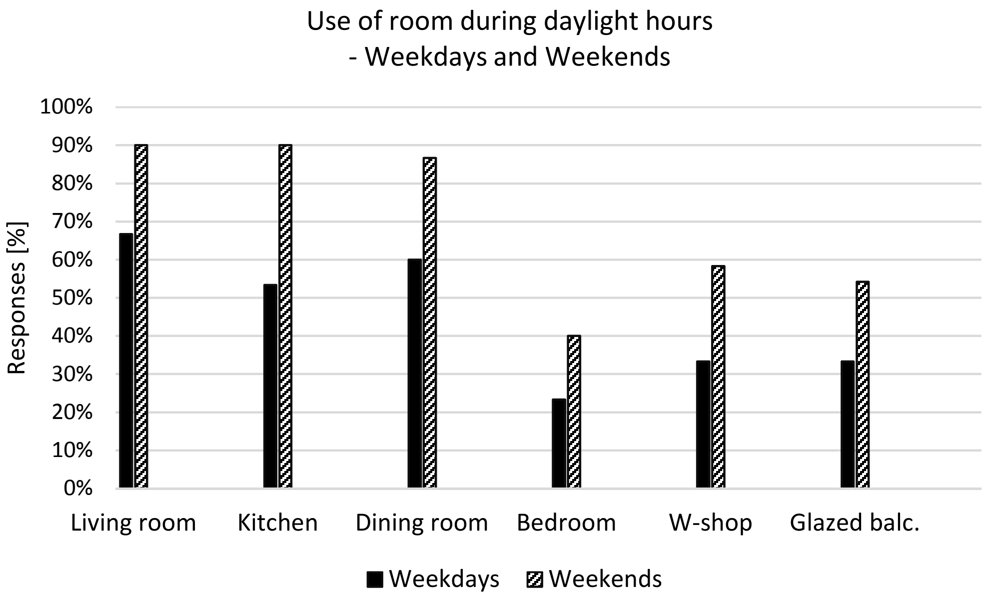


Figure 43 – Responses to question 7d-e:”What part(s) of the day do you normally use the following rooms during weekdays/weekends?” Only reported use during daylight hours is presented.

As can be seen in figure 43, the main living spaces are used during daylight by more than 50% of the respondents during weekdays and by close to 90% during weekends. The workshop and glazed balcony are used during daylight hours by 33% of the respondents during weekdays and by slightly more than 50% during weekends. As expected, the bedroom is not used to any great extent during daylight hours, with 23% reporting using it during daylight hours on weekdays and 40% on weekends.

3.2 Objective assessment

3.2.1 Daylight factor measurements

This chapter discusses the results from the physical measurements in the five apartments of Höghuset, presented in table 6. The presented daylight factors are expressed as average, medium, and/or point values according to Miljöbyggnad. The “selected” points are simply points taken every meter[5].

Glazed balcony
The results from measurements in the glazed balcony are presented in figure 44.

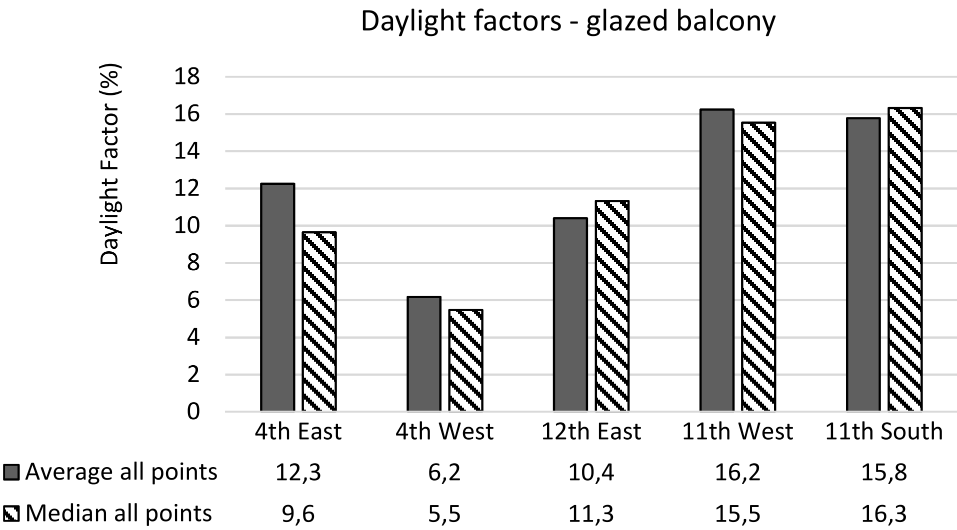
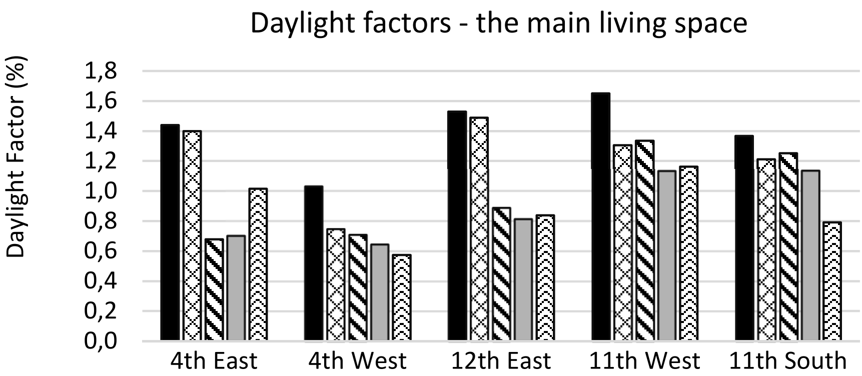


Figure 44- Average and median daylight factors in the glazed balconies of the five apartments

As shown in figure 44, the west apartment on the 4th floor, shows significantly lower daylight factors than the other apartments. This can be explained by an excessive amount of obstructing plants in the glazed balcony of this apartment, see figure 46. Apart from this, it can be noticed that the balconies with west or south orientations obtained higher daylight factors than the two east oriented ones.

Main living space
The results of measurements in the open-plan main living space (kitchen, dining room and living room) are presented in figure 45.

[5] Further details, see Dubois et al. (2017)



	4th East	4th West	12th East	11th West	11th South
Average all points	1,4	1,0	1,5	1,7	1,4
Average selected points	1,4	0,7	1,5	1,3	1,2
Median all points	0,7	0,7	0,9	1,3	1,3
Median selected points	0,7	0,6	0,8	1,1	1,1
DFmb	1,0	0,6	0,8	1,2	0,8

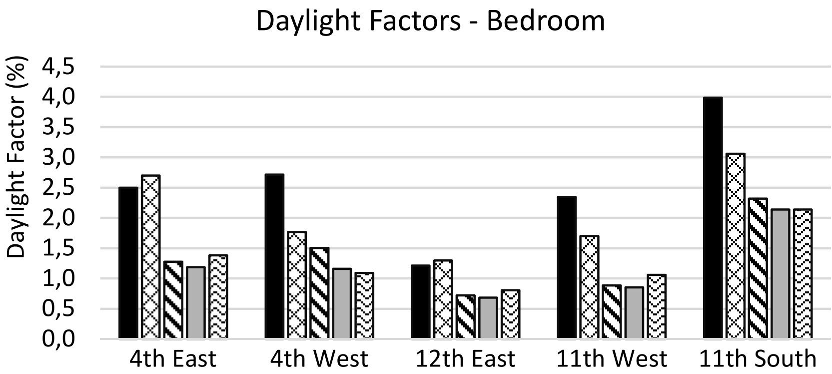
Figure 45 - Average, median and point daylight factors for the five apartments

As shown in figure 45, the median and average daylight factors are quite similar for the east apartments on the 4th and 12th floor. The west and south apartment located on the 11th floor show a tendency of higher values. Comparing the east and west apartments on the upper floors, the west apartment has higher daylight factors. The significantly lower daylight factors in the west apartment of floor 4 can be explained by the large amount of plants in the glazed balcony, see figure 46. Looking at the DF_{MB}, only one living room meets the required level for a Miljöbyggnad Gold certification (DF_{MB}=1.2%).

Figure 46 - The 4th floor west apartment with obstructing plants in the glazed balcony

Bedroom

The results from measurements in the bedroom are presented in figure 47.



	4th East	4th West	12th East	11th West	11th South
Average all points	2,5	2,7	1,2	2,3	4,0
Average selected points	2,7	1,8	1,3	1,7	3,1
Median all points	1,3	1,5	0,7	0,9	2,3
Median selected points	1,2	1,2	0,7	0,9	2,1
DFmb	1,4	1,1	0,8	1,1	2,1

Figure 47 - Average, median and point daylight factors in the bedrooms of the five apartments

As can be seen in figure 47, the results are similar for the east apartment (window pointing north-west) on the 4th floor and the west apartments (window pointing north-east) on the 4th and 11th floor. The 11th floor south apartment obtained significantly higher daylight factors, which can be explained by the larger sized room with two windows facing east and south-east respectively, see figure 48. The lower daylight factors obtained on the 12th floor east apartment can be explained by a dark curtain being left in front of the window during measurements, as seen in figure 49, which was overlooked by the measuring staff. Looking at the DF_{MB}, figure 47 indicates that all bedrooms, except, the 12th floor east apartment with the obstructing curtain, meet (or nearly meet) the required daylight factor for Miljöbyggnad Gold. Compared to the results from the living rooms, figure 45, the daylight factors obtained in the bedrooms were higher than in the main living space.

Figure 48 - The 2-window master bedroom of the 11th floor south apartment, photographed using a panorama setting to show the whole room.

Figure 49 - Obstructing curtain in the bedroom of the 12th floor east apartment overlooked by measuring staff.

Figure 50 shows how the daylight factor of the bedrooms varies when moving from the window to the back of the room.

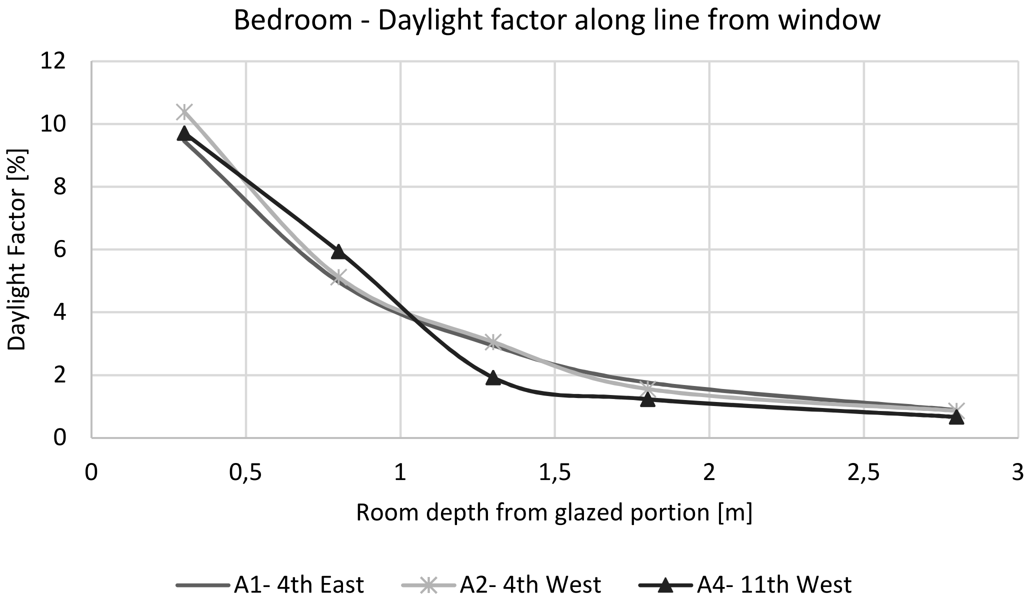


Figure 50- Variation of daylight factor from bedroom window to the back of the room

As can be seen in figure 50, there is a significant difference between the daylight factor close to the window and further back in the room, with most of the reduction within the first meter from the window. The back of the room obtained a daylight factor below 1%, while the area in front of the window obtained a daylight factor in the range between 5-10%. This causes a low illumination uniformity, which through calculations was shown to vary between 0.2-0.3.

3.2.2 Measurements compared to simulations

Figure 51 presents the measured DF_{MB} of the main living space compared to the simulated DF_{MB} for this space. An error bar is included for the simulation results, showing an error margin of $\pm$ 20%, as reported in the literature (Reinhart C. , 2017). The south apartment on the 11^{th} floor was not studied by simulations and is therefore not presented here.

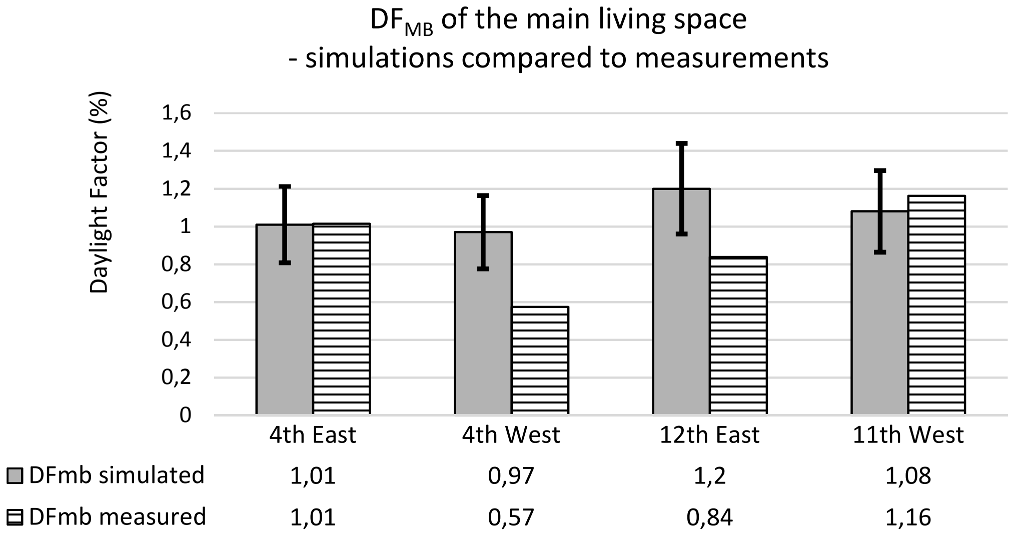


Figure 51 – Simulated and measured DF_{MB}. Error bars show a margin of 20%.

As seen in figure 51, measurements show the highest DF_{MB} for the main living space of the west oriented apartment on the 11th floor while simulations show the highest DF_{MB} for the east oriented apartment on the 12th floor. The difference between simulated and measured result for the 4th floor west apartment can be explained by the large amounts of plants in the glazed balcony during measurements. There is however no obvious explanation for the difference between measured and simulated DF_{MB} in the 12th floor east apartment (0.84% compared to 1.2%), except perhaps that the weather conditions were quite variable during the day of measurements. The measuring staff reported that they had to stop at some point because the sky changed from overcast to sunny with clouds with an atypical distribution. However, note that measured and simulated values correspond remarkably well for the 4th floor west apartment and 11th floor west apartment.

Overall, the measurements and simulations can be considered to correspond reasonably well considering the large amount of error sources in daylight measurements (sky distribution, interior finishes, presence of furniture and other measurement errors, e.g. sensors, position of points, height of points, shading of the measurement equipment, obstacles etc.) and the large error margin in daylight simulations (20%).

It is however also remarkable that the three simulated DF_{MB} are below the requirement for Miljöbyggnad Gold, which can be explained by a different interpretation of the position of the DF_{MB} point in relation to the façade. Apparently, in this case, the projecting team considered the limits of the glazed balcony as room limit when determining the half room depth, which moved the measuring point further away from the building core.

3.3 Subjective assessments compared to objective assessment

This chapter focuses on discussing the results from the subjective assessment in relation to the objective measurements in Höghuset. No measurement was performed in Låghuset and the response rate was quite small so this section only covers Höghuset.

Subjective indication: The main living space of west oriented apartments is brighter than the living space of east and south oriented apartments. The living space of south oriented apartments is perceived as darkest.

The main living spaces of western apartments are more frequently described as "bright-very bright"; they are perceived by no respondent as "dull, dark or sad" and no respondent has expressed the wish for more daylight. The main living spaces of east and south oriented apartments on the other hand show a higher percentage of respondents describing them as less bright and has a significant part of the respondents wishing for more daylight, especially in the south apartments.

The measured results, earlier presented in figure 45, are reviewed again and presented in figure 52, this time without including the results from the main living space with the excessive planting in the glazed balcony

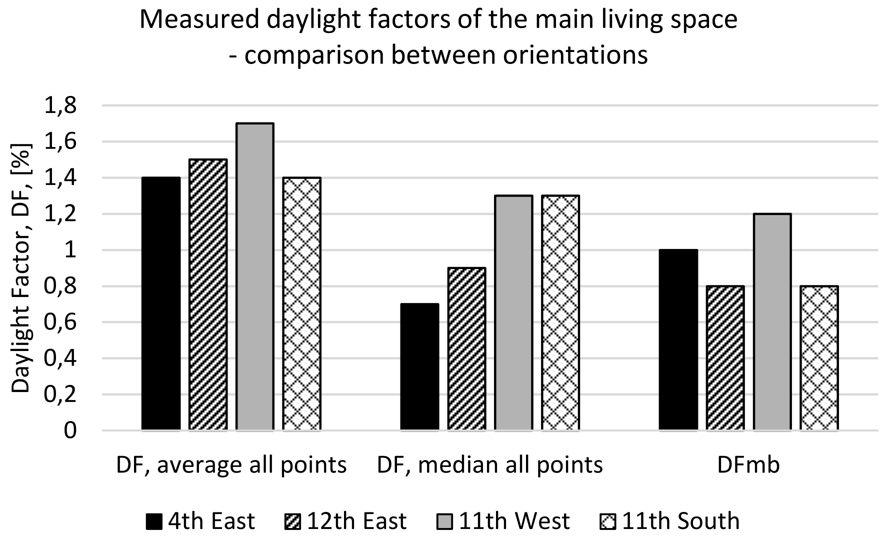
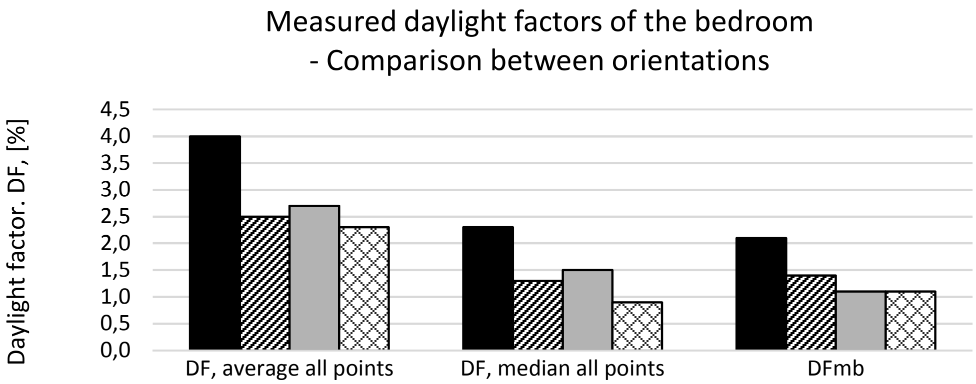


Figure 52 – Measured daylight factors of the main living spaces

Independent of which daylight factor is studied, the main living space of the west apartment did obtain higher daylight factor values than the east or south facing apartment. The measured average and point daylight factor in the west apartment is also higher than in the south, but the median daylight factors in the main living space of the west and south apartment are identical. The subjective impression is thus partly supported by the measurements. However, the difference between the daylight factors of the three orientations is not significant in terms of visual perception and it is likely that the respondents' perception is influenced by other aspects, e.g. evening sunlight in western apartments, which corresponds to the time of occupation for most people working during the day

Subjective indication: The main bedroom of south oriented apartments is brighter than the bedroom of east and west oriented apartments
The measured daylight factors were previously presented in figure 47, but a review of these results in figure 53 presents the difference even clearer (here the bedroom of A3 is excluded due to left curtain during the measurements).



	DF, average all points	DF, median all points	DFmb
11th South	4,0	2,3	2,1
4th East	2,5	1,3	1,4
4th West	2,7	1,5	1,1
11th West	2,3	0,9	1,1

Figure 53- Daylight factors in the bedroom, comparison between different apartment orientations

As seen in figure 53, both the average, median and point daylight factor are significantly higher in the master bedroom of south oriented apartments than in the other orientations. The subjective indication is thus supported by the results from measurements. The results of both measurements and subjective evaluation were anticipated since the bedroom of the south apartment has more windows and thus more daylight than the bedroom of east and west facing apartments.

Subjective indication: The bedroom of east and west oriented apartments is darker than the main living spaces of these apartments.
Figure 54 presents the daylight factors of the bedroom and main living space. Here the apartment with excessive planting in the glazed balcony and the apartment with the hanging curtains in the bedroom have been excluded in the comparison, leaving one western and one eastern apartment to review.

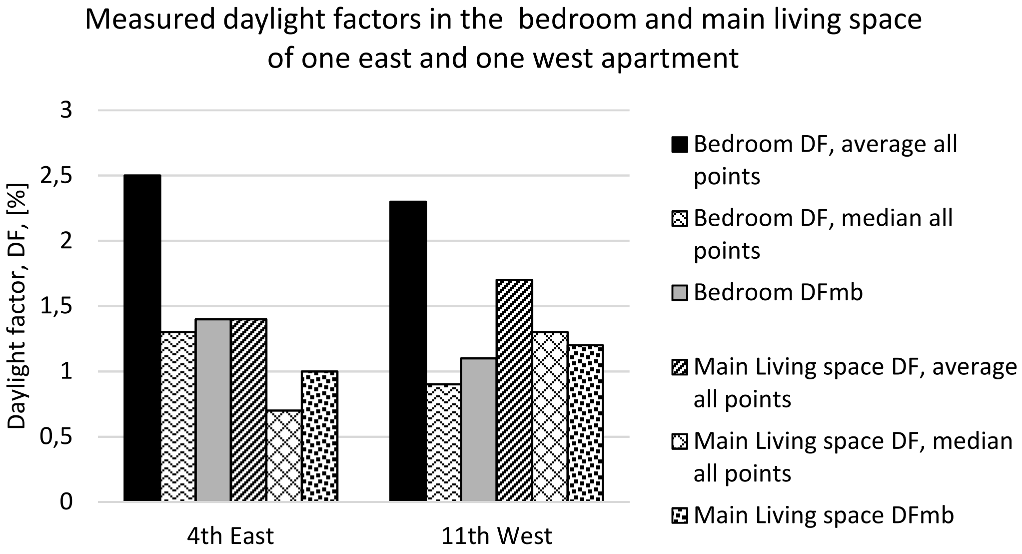


Figure 54 – Comparison between daylight factors in the bedroom and main living space (in one east and one west apartment).

As seen in figure 54, the daylight factors in the east apartment bedroom are higher than in the east apartment main living space. A similar result is found in the western apartment, if comparing the average DF. A comparison between the median or point DF of the western apartment does however not indicate any significant difference between the bedroom and main living space.

The comparison shows that if anything, the bedroom is objectively brighter than the main living space, which is contrary to the respondents' perception. This means that other factors have influenced the respondents' perception, resulting in the bedroom being perceived as darker than it actually is. One hypothesis is that the respondents' perception is influenced by the daylight distribution, which was more uneven in the bedroom due to the window position in the corner of the room.

Subjective indication: The workshop in east oriented apartments is dark, especially in comparison to the workshop of west oriented apartments.

Figure 55 presents the median and average DF in the workshop of different apartment orientations. Here the apartment with excessive planting in the glazed balcony is excluded (the workshop is adjacent to the glazed balcony). One east apartment is also excluded due to no available measurements for this specific workshop as the room was filled with furniture and it was impossible to walk in it. This leaves one east, one west and one south apartment to compare.

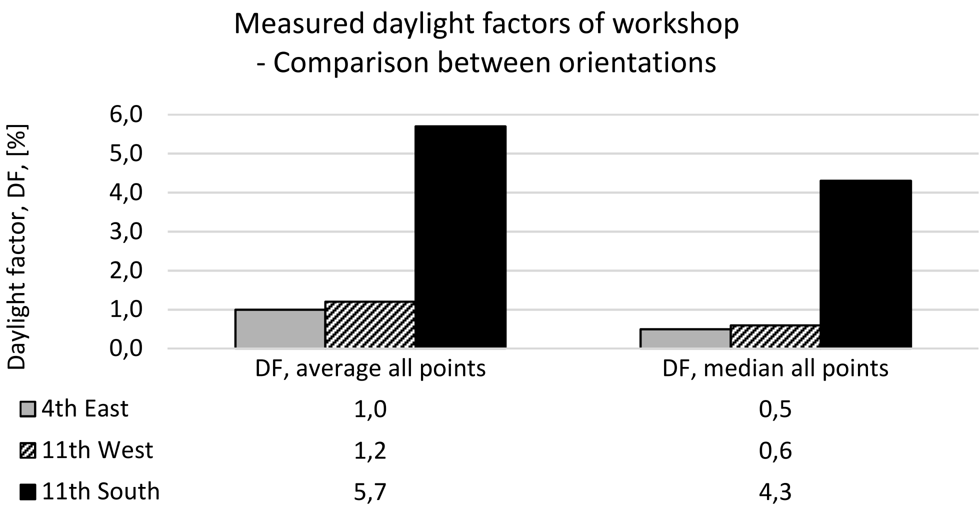


Figure 55 – Average and median DF of the workshop. Comparison between different apartment orientations.

As seen in figure 55, the workshop of the south oriented apartment had significantly higher daylight factors than for the east or west apartments. This can be explained by a completely different layout of the south apartments, with the south workshop having a corner window which is non-existent in the east and west apartments. Comparing the east and west workshop, they obtained similar daylight factors.

The measurements do not correspond to the difference between the subjective perception of workshops of east and west workshops, where some respondents of east apartments report a wish for more daylight in the workshop and to a higher extent describe it as “dull and sad”. Neither do they make sense of the subjective finding of respondents of south apartments wishing for more daylight in the workshop (57%), while respondents of west apartments do not. Clearly, other aspects are influencing the perception of daylight in the workshops. The measuring staff reported that this room was deeper and the daylight was thus more uneven in the east and west apartments.

4 Discussion

One objective of this study was to investigate the question regarding the minimum required DF threshold ($DF_p \geq 1.2\%$) in Miljöbyggnad by comparing measurements and simulations with the tenants’ subjective assessment. The analysis of the subjective assessment clearly points at two things that are interesting in the discussion of this question:

- The respondents have a clear preference for daylight; a majority of the respondents prefer daylight to electric lighting (67%) and express a need for plenty of daylight indoors in order to feel good (67%).

- The current daylight level is not perceived as too high; the respondents are not disturbed by excessive daylight levels and express no wish for less daylight. We should restate here however, that the study was carried out during the winter, which is the darkest part of the year in Malmö, Sweden. The results could be different for the summer period.

These results do not necessarily imply that a lower threshold would be unsatisfactory. The following results do however suggest this:

- The responses to the question about how the respondent would describe the daylight in each room show surprisingly high scores in the range "dark-neither dark nor bright", with 25-54% of the responses of Höghuset and 33-66% of Låghuset. This is a surprising result given the fact that the house was experienced generally as bright by the measuring staff compared to ordinary, non-certified buildings.
- The respondents' description of their experience of the main living spaces (kitchen, dining room and living room) show high scores for "just enough light to perform tasks", with 46-50% of the responses of Höghuset and 50-67% of the responses of Låghuset. The scores for "rather dull and sad" were also surprisingly high for some rooms, e.g. the kitchen of Höghuset (25%) and living room, dining room and bedroom of Låghuset (33%).
- As many as 21-33% of the respondents of Höghuset wish for **more** daylight, with the higher scores for the kitchen, living room and workshop. Låghuset showed high scores for the living room and dining room (33%).

Although the general satisfaction with the daylight in Greenhouse is high, the more specific questions about the daylight level show high scores for "neutral" expressions to describe the respondents' perception of daylight. Considering that the respondents express a clear preference for daylighting, the use of expressions like "neither dark nor bright" and "just enough light to perform tasks" do not indicate a full level of satisfaction. The daylight level was hypothesized to be judged sufficient, which is thus not completely shown in the subjective assessment.

As seen in the objective assessment, the main living spaces show daylight levels (DF_p) between 0.8-1.2%. Linking the objective assessment to the subjective, it is shown that with the current threshold (DF_p 1.2%) as a target, daylight levels are subjectively not fully satisfying. This suggests that the current threshold is at a minimum level already, at least in some rooms, which will be discussed further in the following section.

The subjective assessment points at a clear pattern in how daylighting is prioritized between the different spaces of the apartment. As hypothesized, daylight in the kitchen is prioritized higher than in the bedroom; the need for high light levels in the kitchen is easily explained by the type of activity (meal preparation) being performed there. In Greenhouse, a significant number of apartments have unfortunately higher daylight factors where daylighting is not prioritized (bedroom) and lower where found important (kitchen). Within the main living spaces, there is also a clear priority of daylighting in the kitchen compared to the living room, which is found to be sensitive to higher light levels due to the tenants often using this space for watching TV. This is an interesting lesson for architects; perhaps they should prioritize placing kitchens directly adjacent to facades and living rooms where TV watching takes place further in closer to the core of buildings. In the case of Greenhouse, an optimal planning of the space would be to have the lowest levels of daylight in the bedroom and the highest in the main living space, with more daylight in the kitchen and less in the living room. Since the need for daylighting is obviously not as high in every room of the apartment, it seems reasonable that this would also be expressed in the daylight requirements.

Another research objective was to analyze whether the subjective perception of daylight can be explained by objective findings. Here it is clear that the subjective results can only be explained to some extent by the objective results and that other aspects than variation in daylight factors are influencing the respondents' perception of daylight in a room. Results suggest that these aspects may be light distribution and direct sunlight coinciding with occupancy. This is based on the following observations:

- ***A room with higher daylight factor can be perceived as darker than one with lower daylight factor.*** This is the case in the eastern and western apartments of Höghuset, where the bedroom is often perceived as darker than the main living spaces. Objective findings do however show the opposite; the bedroom is significantly brighter than the main living spaces, but daylight distribution is more uneven in the bedroom compared to the main living spaces. Another example is the workshop of southern apartments (Höghuset), where the daylight factor is objectively very high but the subjective assessment show high scores for respondents wishing for more daylight. One hypothesis is that the workbench of this room is located in such a way that the occupants are self-shading when working with the plants, which may explain their complaints about insufficient daylight.

- ***Rooms with daylight factors that are perceptually equivalent can be perceived with great variation.*** An example of this is the workshop of eastern and western apartments, where a significant part of the eastern respondents express a wish for more daylight compared to none of the western, despite objectively similar daylight factors (figure 55). One explanation may be that the occupancy coincides with the direct sunlight for the west orientation.

The other aspects that are influencing the respondents' perception of daylight can only be discussed speculatively, since objective measurements other than the daylight factor lie outside the scope of this thesis. As hypothesized, some bedrooms are perceived darker compared to the objective values. Notable is that the bedrooms show a rather uneven distribution of daylight, as seen in figure 50. Some bedrooms had an illumination uniformity as low as 0.2-0.3. A low uniformity could be one contributing factor to the darker perception of the bedroom, which would be in line with previous research, where perception of uniformity has been found an important factor for assessing daylighting quality (Galasiu & Reinhart, 2008).

In order to draw any conclusions of what parameters are influencing the respondents' perception of daylight, the objective assessment would need to be expanded but this would require a continuous monitoring over a long period of time, entailing more sophisticated equipment. Further analysis of the subjective assessment, using statistical analysis methods, could also reveal patterns that were not discovered using descriptive statistics. This step is planned in the overall work plan of this research project.

When it comes to the objective assessment, simulated and measured daylight factors corresponded surprisingly well given the large amount of error sources in lighting measurements and the large error margin in daylight simulations (20%).

Finally, it needs to be pointed out that this study is not just any building or any group of people, but a modern building designed to have good daylight access and with tenants selected to have a special interest in environmental matters and "green" thinking. This might influence the results compared to other buildings and other groups of people. The respondents were also asked about daylight during the dark winter season, when the external daylight levels are low. This may have affected the results in either direction and the answers might have been different if the questionnaires were distributed at midsummer. Some respondents struggled with reflecting on the winter season as a whole and instead answered with regard to the conditions on that specific day. Assumable is that some respondents struggled with the opposite and possibly included their perception of the space during other seasons as well.

5 Conclusions

This thesis presented the results of subjective and objective assessment of daylight conditions in an environmentally certified building called MKB Greenhouse, located in Malmö, Sweden. This study involved questionnaires to building inhabitants, in situ measurements under overcast sky conditions, and advanced light simulations. The questionnaires were only distributed during the winter season, when daylighting is scarce in Sweden. The main conclusions from this study are stated below:

General conclusions:

- The respondents have a clear preference for daylighting over electric lighting.
- There is no indication of the respondents' subjective perception being influenced by dissatisfaction with other building aspects. The satisfaction with view and other building aspects is high, perhaps with a few exceptions; the view is less satisfactory for rooms located further in the core of the building and for rooms where the view is limited to one corner of the room, and the general satisfaction is slightly lower for temperature, electric lighting and privacy (maisonette apartments only).

Conclusions regarding measurements versus simulations:

- The measurements and simulations return reasonably close values.
- The measured DF_{MB} is lower than the required level of 1.2% due to a misunderstanding about the position of the measurement point during the design process. When accurately positioned, as in the objective part of this study, lower values of the DF_{MB} are thus obtained. This aspect needs to be more clearly specified in future reformulation of the certification system and buildings code.

Conclusions regarding daylight level:

- The objective assessment indicates that the main living spaces of Greenhouse have a daylight level in the range between 0.8-1.2% DF_p
- Although the general satisfaction with daylighting was high, a significant portion of respondents did not find daylight levels to be fully satisfying in all rooms. This suggests that lower threshold for DF might not be desirable in future environmental certification systems or in the building code. The debated question of the daylight threshold in BBR (1% DF_p) being set too high is consequently not supported by the subjective assessment.
- A higher daylight level is prioritized in the kitchen, while lower prioritized in the bedroom. This supports the suggestion of working towards a more flexible way of expressing the daylight requirements in BBR with differentiation according to room and usage. It also suggests that architectural plans should be reconsidered in Sweden, taking work tasks and screen use into account. This would yield different solutions, where the kitchen might be placed closer to the building façade and not in the core as is usually the case at the moment. Main living rooms might find a preferable location somewhat further away from the building facade, where nuisance from direct sunlight or high light levels would not be felt as strongly when using screen equipment. In this case for instance, a better architectural plan would have consisted of inverting living room and kitchen.
- The respondents' subjective perception of daylight level is affected by other parameters than the daylight factor alone; the results strongly suggest that daylight distribution and direct sunlight may also affect the assessment. In general more even distribution yields higher assessment for daylight levels. The study thus confirms that the daylight factor is not a sufficient indicator of daylighting quality and should perhaps be supplemented by other simple indicators such as uniformity (min/average) and perhaps climate-based values that take into consideration direct sunlight. This is the case for other certification systems such as BREEAM and LEED, which include either/or uniformity and spatial daylight autonomy.

This project was limited in time and budget and therefore some major limitations are to be kept in mind:

- The subjective assessments only cover the winter period. Different conclusions may be obtained if the building was surveyed during a whole year;
- The measurements only entailed the DF i.e. under overcast sky conditions. Long term monitoring may yield more information and different conclusions.

The project is ongoing and will entail further questionnaire investigations as well as a more detailed statistical analysis of the results. It is the hope of the author that this first study has contributed to knowledge that will allow to determine suitable daylight conditions in future energy-efficient multi-family dwellings.

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Appendices

Appendix A – Notes from pre-test of draft questionnaire

The five respondents, family members and friends, who participated in the testing of the first draft version of the questionnaire are presented in table I.

Table I - An overview of the respondents who participated in testing the first draft of the questionnaire

Respondent No.	Gender	Age	Background	Living
R1	Male	≈30	IT/Economist	Modern apartment
R2	Male	≈30	Mechanical Engineer	Older villa
R3	Female	≈35	Structural Engineer	Modern villa
R4	Female	≈55	Nurse	Modern apartment
R5	Male	≈50	Economist	Modern apartment

An overview of the respondents' understanding of the questionnaire and other information provided by the respondents is presented in table II.

Table II - A summary of the respondents' general understanding and other information provided by the respondents

Seem to have understood part?	R1	R2	R3	R4	R5
-Language	Yes	Yes	Yes	Most	Yes
-Questions	Yes	Yes	Yes	Most	Most
-Answers	Yes	Yes	Yes	Most	Most
Left comments?	No	Yes	Yes	Yes	No
Time for answering [minutes]?	20-30	20	20	20-30	20-30

The comments left by some of the respondents are summarized in table III:

Table III- A summary of the respondents' comments

Comments from respondents	Respondent
Q2b: Is missing an answering alternative for being satisfied with the current conditions.	R2, R3, R4
Q2b: The second part of the question, ranking the rooms based on need for daylight, is confusing.	R4
The questionnaire is designed for a specific apartment type, difficult to apply for houses	R2
I would have preferred a Swedish version of the questionnaire	R4
Q4b: Does the use of internal shadings refer to daytime only?	R4

A final summary of the outcome of the pre-test is presented in table IV:

Table IV- Final summary of outcome of pre-test

Summary of review of answers:

- Do we want respondents to be at home when answering? Clarify!
- Are respondents missing to fill out pre-page due to pre-test or due to not noticing?
- Q2b:The second part of the question (ranking) is easily omitted or misunderstood/interpreted differently.
- Q2b: Is missing an answer alternative for being satisfied (or wanting no change)
- Q4b: Clarify question with daytime use only.
- The question about physical conditions/electric lighting needs to be rephrased, R4 and R5 should have the same answers. Confusing set of answers?
- Nightshift workers (R4) needs to be identified.

Appendix B – Final questionnaire distributed in Greenhouse

Questionnaire about daylighting in Greenhouse

Dear tenant,
This questionnaire is part of a research project about daylighting and energy in Greenhouse entitled "Conditions for daylighting in environmentally certified buildings – example from the Greenhouse Augustenborg". This project is funded by the Swedish Energy Agency (grant #39682-1) and ARQ (grant #4:2105).

In this project, we want to evaluate the daylighting conditions in your apartment. Daylighting plays a central role in guaranteeing a healthy living environment and reducing energy consumption. You will receive two identical questionnaires at different times of the year. Each questionnaire takes about 30 minutes to answer.

The questionnaire is composed of eight parts. Please take time to answer each question as honestly and thoughtfully as possible. The answers should be based on the average daylight levels that you experience ***at this time of the year****. As the questionnaire focuses on natural light it is important that you follow the instructions below:*

- ***Be at home*** *when answering the questionnaire*
- *Answer the questionnaire* ***during daytime***
- ***Switch off electrical lighting*** *(if possible)*

In addition, "bedroom 1" in the questionnaire refers to the main bedroom in the apartment. Rooms that are not listed can be specified and described in the category "other room". Please select only ONE answer unless otherwise is stated.

Your opinion is important, so we would very much appreciate your feedback. Answers are kept confidential and will become anonymous when computerized.

Please fill in your apartment number, the date and time before filling the questionnaire.

Apartment number: 705 - _ _ _ - 01

Date: ___________________________________Time: ___________________________________

Please leave your filled questionnaire in the postbox at MKB's office (Augustenborgsgatan 3), all pages stapled together or placed in an envelope, the 1st of January 2017 AT THE LATEST!

Before you start, here are some useful definitions to help you answer the questionnaire:

- *"Daylight" refers to light penetrating through windows including sunlight and diffuse or reflected light.*
- *"Sunlight" refers to direct light from the sun. Direct light and sunlight are synonymous.*
- *"Daylight level" refers to the amount of daylight.*

PLEASE READ THE INFORMATION ON THE FRONT PAGE AND FILL IN YOUR APARTMENT NUMBER, THE DATE AND TIME BEFORE FILLING THE QUESTIONNAIRE!

PART 1: DAYLIGHT LEVEL

1a. How would you describe the daylight in the following rooms:

	Very dark	Dark	Neither dark nor bright	Bright	Very Bright	I don't know
Living room	□	□	□	□	□	□
Kitchen	□	□	□	□	□	□
Dining room	□	□	□	□	□	□
Bedroom 1	□	□	□	□	□	□
Workshop	□	□	□	□	□	□
Glazed balcony	□	□	□	□	□	□
Other room: ___________	□	□	□	□	□	□

1b. How would you wish to change the daylight in the following rooms:

	Less daylight	No change	More daylight	Does not matter	I don't know
Living room	□	□	□	□	□
Kitchen	□	□	□	□	□
Dining room	□	□	□	□	□
Bedroom 1	□	□	□	□	□
Workshop	□	□	□	□	□
Glazed balcony	□	□	□	□	□
Other room: ___________	□	□	□	□	□

1c. Please rank the following rooms according to your need for daylight (rank them by using the numbers 1-6, where 1 is highest need and 6 lowest, only use each number ONCE):

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony	Other room : _________
_______	_______	_______	_______	_______	_______	_______

1d. From the list on the left side, choose the letter best corresponding to your experience of the room:

- **A) Glaring, so bright I have to close the curtains**
- **B) Very awakening and refreshing, pleasant**
- **C) Has just enough light for performing tasks**
- **D) Rather dull and sad**
- **E) Very dark and gloomy, unpleasant**

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony	Other room : ________
_______	_______	_______	_______	_______	______	_______

Comments for PART 1 can be written here:

PART 2: DAYLIGHT DISTRIBUTION

2a. How would you describe the distribution of daylight in the following rooms:

	Very even	Even	Acceptable	Uneven	Very un-even	I don't know
Living room	□	□	□	□	□	□
Kitchen	□	□	□	□	□	□
Dining room	□	□	□	□	□	□
Bedroom 1	□	□	□	□	□	□
Workshop	□	□	□	□	□	□
Glazed balcony	□	□	□	□	□	□
Other room: ____________	□	□	□	□	□	□

2b. Do the following rooms have any <u>dark</u> areas that are interrupting daily activities or making the space uncomfortable?

	No	Yes, a few	Yes, many	I don't know
Living room	◻	◻	◻	◻
Kitchen	◻	◻	◻	◻
Dining room	◻	◻	◻	◻
Bedroom 1	◻	◻	◻	◻
Workshop	◻	◻	◻	◻
Glazed balcony	◻	◻	◻	◻
Other room: ____________	◻	◻	◻	◻

2c. Do the following rooms have any <u>bright</u> areas that are interrupting daily activities or making the space uncomfortable?

	No	Yes, a few	Yes, many	I don't know
Living room	◻	◻	◻	◻
Kitchen	◻	◻	◻	◻
Dining room	◻	◻	◻	◻
Bedroom 1	◻	◻	◻	◻
Workshop	◻	◻	◻	◻
Glazed balcony	◻	◻	◻	◻
Other room: ____________	◻	◻	◻	◻

<u>Comments for PART 2 can be written here:</u>

PART 3: DIRECT SUNLIGHT

3a. Do you experience direct sunlight in the following rooms:

	Not at all	A little	Moderately	Much	Very Much	I don't know
Living room	◻	◻	◻	◻	◻	◻
Kitchen	◻	◻	◻	◻	◻	◻
Dining room	◻	◻	◻	◻	◻	◻
Bedroom 1	◻	◻	◻	◻	◻	◻
Workshop	◻	◻	◻	◻	◻	◻
Open balcony	◻	◻	◻	◻	◻	◻
Glazed balcony	◻	◻	◻	◻	◻	◻
Other room: ____________	◻	◻	◻	◻	◻	◻

3b. How often do you use curtains, blinds or other sun shadings during daytime in the following rooms:

	Never	A few times per week	1-2 h per day	3-4 h per day	More than 4 h per day	I don't know
Living room	◻	◻	◻	◻	◻	◻
Kitchen	◻	◻	◻	◻	◻	◻
Dining room	◻	◻	◻	◻	◻	◻
Bedroom 1	◻	◻	◻	◻	◻	◻
Workshop	◻	◻	◻	◻	◻	◻
Glazed balcony	◻	◻	◻	◻	◻	◻
Other room: ____________	◻	◻	◻	◻	◻	◻

3c. What is the main purpose when you use internal shading? Select ONE or SEVERAL alternatives for each room from the list below:

A) I have no shading
B) Prevent direct sunlight
C) Prevent diffuse light
D) For privacy
E) Prevent heat
F) To darken the room

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony	Other room : _________
_______	_______	_______	_______	_______	_______	_______

Comments for PART 3 can be written here:

PART 4: VIEW THROUGH WINDOWS

4a. How sufficient is the view through the windows in the following rooms:

	Very poor	Poor	Acceptable	Generous	Very generous	I don’t know
Living room	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐
Dining room	☐	☐	☐	☐	☐	☐
Bedroom 1	☐	☐	☐	☐	☐	☐
Workshop	☐	☐	☐	☐	☐	☐
Glazed balcony	☐	☐	☐	☐	☐	☐
Other room: ____________	☐	☐	☐	☐	☐	☐

4b. How would you describe the view through the windows in the following rooms:

	Very unpleasant	Unpleasant	Acceptable	Pleasant	Very pleasant	I don’t know
Living room	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐
Dining room	☐	☐	☐	☐	☐	☐
Bedroom 1	☐	☐	☐	☐	☐	☐
Workshop	☐	☐	☐	☐	☐	☐
Glazed balcony	☐	☐	☐	☐	☐	☐
Other room: ____________	☐	☐	☐	☐	☐	☐

Comments for PART 4 can be written here

PART 5: GENERAL SATISFACTION OF YOUR APARTMENT

5a. How would you describe your general satisfaction with the following aspects of your main living spaces (the main living spaces are the living room, kitchen and dining room):

	Very dissatisfied	Somewhat dissatisfied	Moderate	Somewhat satisfied	Very satisfied	I don't know
Electric lighting	☐	☐	☐	☐	☐	☐
Daylight	☐	☐	☐	☐	☐	☐
Noise level	☐	☐	☐	☐	☐	☐
Odour/Smell	☐	☐	☐	☐	☐	☐
Ventilation	☐	☐	☐	☐	☐	☐
Temperature	☐	☐	☐	☐	☐	☐
Window size	☐	☐	☐	☐	☐	☐
Privacy	☐	☐	☐	☐	☐	☐
Size of space	☐	☐	☐	☐	☐	☐
View through windows	☐	☐	☐	☐	☐	☐
Whole impression of room	☐	☐	☐	☐	☐	☐

5b. How would you describe your general satisfaction with the following aspects of the glazed balcony:

	Very dissatisfied	Somewhat dissatisfied	Moderate	Somewhat satisfied	Very satisfied	I don't know
Size of space	☐	☐	☐	☐	☐	☐
Daylight	☐	☐	☐	☐	☐	☐
Temperature	☐	☐	☐	☐	☐	☐
Wind	☐	☐	☐	☐	☐	☐
Size of planting beds	☐	☐	☐	☐	☐	☐
Plants growth	☐	☐	☐	☐	☐	☐
Whole impression of balcony	☐	☐	☐	☐	☐	☐

Comments for PART 5 can be written here:

PART 6: ACTIVITIES AND REQUIREMENTS

6a. What activities are common in your home? Choose ONE or SEVERAL activities for each room below:

A) I use digital screens (computer, smartphone, other screens etc.)
B) I watch TV
C) Paperwork (reading newspaper/magazine/books, writing etc.)
D) Seated detailed work (crafts, knitting, board games etc.)
E) Standing detailed work (ironing, washing-up, cooking etc.)
F) Other activity: ____________________________________
G) No particular activity

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed balcony	Other room: __________
_______	_______	_______	_______	_______	_______	_______

6b. How do you feel about daylight as only light source when performing the activities below (see further explanation in the list above):

	Too little daylight	Slightly too little daylight	Enough daylight	Slightly too much daylight	Too much daylight	Don't know
Digital Screens	☐	☐	☐	☐	☐	☐
Watching TV	☐	☐	☐	☐	☐	☐
Paperwork	☐	☐	☐	☐	☐	☐
Seated detailed work	☐	☐	☐	☐	☐	☐
Standing detailed work	☐	☐	☐	☐	☐	☐
Socializing	☐	☐	☐	☐	☐	☐
Cleaning	☐	☐	☐	☐	☐	☐
Meals	☐	☐	☐	☐	☐	☐
Orientation	☐	☐	☐	☐	☐	☐
Other Activity: _____________	☐	☐	☐	☐	☐	☐

6c. How do these statements match you?

	Not correct	Partly correct	Correct
I don't take very much notice of daylight	☐	☐	☐
Daylight is nice, but electric lighting suits me just as good	☐	☐	☐
I prefer daylight to electric lighting	☐	☐	☐
I am satisfied with the amount of daylight received outdoors	☐	☐	☐
I need plenty of daylight indoors to feel good	☐	☐	☐
I need plenty of daylight indoors for good vision	☐	☐	☐
The activities I perform indoors often require blocking daylight out	☐	☐	☐
I am sensitive to intense/bright daylight and often experience discomfort when exposed to intense/bright light	☐	☐	☐

<u>Comments for PART 6 can be written here:</u>

PART 7: PHYSICAL ENVIRONMENT

7a. Where were you while answering the questionnaire?

	Next to the window	Roughly in the middle of the room	Further back in the room	Not in the room	Not at home
Living room	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐
Dining room	☐	☐	☐	☐	☐
Bedroom 1	☐	☐	☐	☐	☐
Workshop	☐	☐	☐	☐	☐
Glazed balcony	☐	☐	☐	☐	☐
Other room: ____________	☐	☐	☐	☐	☐

7b. How was the electric lighting when you answered the questionnaire?

	All electric lighting was switched **off**	**Parts** of the electric lighting was switched **on**	**Most** of the electric lighting was switched **on**	I don't know
Living room	□	□	□	□
Kitchen	□	□	□	□
Dining room	□	□	□	□
Bedroom 1	□	□	□	□
Workshop	□	□	□	□
Other room: __________	□	□	□	□

7c. How would you describe the sky conditions outside at the moment? Please select only <u>ONE</u> of the boxes on the scale below:

	1	2	3	4	5	6	7	
Sky fully covered with clouds	□	□	□	□	□	□	□	Completely clear sky (no clouds)

7d. What part(s) of the day do you normally use the following rooms during <u>weekdays</u>? Select <u>ONE</u> or <u>SEVERAL</u> alternatives below:

A) I use the room most parts of the day
B) Early morning, before 8:00
C) Late morning, 8:00-11:00
D) Midday, 11:00-14:00
E) Afternoon, 14:00-17:00
F) Evening, 17:00-19:00
G) Late evenings, after 20:00
H) I use the room very little

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed Balcony	Other room: __________
________	________	________	________	________	________	________

7e. What part(s) of the day do you normally use the following rooms during <u>weekends</u>? Select <u>ONE</u> or <u>SEVERAL</u> alternatives using the list above from question 7d:

Living room	Kitchen	Dining room	Bedroom 1	Workshop	Glazed Balcony	Other room: __________
_______	_______	_______	_______	_______	_______	_______

<u>Comments for PART 7 can be written here:</u>

PART 8: PERSONAL INFORMATION

The questions in this last part are for statistical purposes only. These answers will be kept confidential and the questionnaire will be anonymous when computerized.

8a. What is your age?

<19	19-29	30-39	40-49	50-59	60-69	>70
☐	☐	☐	☐	☐	☐	☐

8b. What is your gender?

Male	Female	Other
☐	☐	☐

8c. Do you use any visual aids (e.g. glasses, contact lenses, magnifying glass etc.)?

Yes, always	Yes, sometimes	No, never
☐	☐	☐

8d. If you answered yes to the preceding question, please provide further details by selecting ONE or SEVERAL alternatives below:

I am short-sighted	I am far-sighted	I am both short-sighted and far-sighted	I wear bifocal lenses	I wear trifocal lenses	I wear progressive lenses
☐	☐	☐	☐	☐	☐

8e. Select the ONE alternative below that best corresponds to the type of work you have:

I work using a computer the majority of the time	I work using a computer sometimes	My work does not involve computers	My work is performed outdoors	I am re-tired	I do not work at the moment	I am a student
☐	☐	☐	☐	☐	☐	☐

8f. Select ONE or SEVERAL alternatives below to describe your working hours:

I work during daytime	I work evenings	I work nightshifts	Not applicable
☐	☐	☐	☐

Please add any comment or information that you may find relevant here:

Thank you for your much appreciated contribution!

Do not hesitate to contact us for any question or additional information, see contact information on the last page.

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Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services