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Good daylighting and low energy use in multi-family dwellings

Good daylighting and low energy use in multi-family dwellings:

MKB Greenhouse, Malmö

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E2B2

Förord

E2B2 Forskning och innovation för energieffektivt byggande och boende är ett program där akademi och näringsliv samverkar för att utveckla ny kunskap, teknik, produkter och tjänster.

I Sverige står bebyggelsen för cirka 35 procent av energianvändningen och det är en samhällsutmaning att åstadkomma verklig energieffektivisering så att vi ska kunna nå våra nationella mål inom klimat och miljö. I E2B2 bidrar vi till energieffektivisering inom byggande och boende på flera sätt. Vi säkerställer långsiktig kompetensförsörjning i form av kunniga människor. Vi bygger ny kunskap i form av nyskapande forskningsprojekt. Vi utvecklar teknik, produkter och tjänster och vi visar att de fungerar i verkligheten.

I programmet samverkar över 200 byggentreprenörer, fastighetsbolag, materialleverantörer, installationsleverantörer, energiföretag, teknikkonsulter, arkitekter etcetera med akademi, institut och andra experter. Tillsammans skapar vi nytta av den kunskap som tas fram i programmet.
Innovative solutions for good daylighting and low energy use in multi-family dwellings är ett av projekten som har genomförts i programmet med hjälp av statligt stöd från Energimyndigheten. Det har letts av Marie-Claude Dubois och Frida Persson Boonkaew och har genomförts i samverkan med ARQ stiftelse och Lunds universitet.

Den främsta målsättningen med detta projekt har varit att analysera och utveckla innovativa lösningar i bostäder för att både uppnå bra dagsljus och låg energianvändning. I projektet har det också ingått att validera ett energisimuleringsverktyg som används mycket i praktiken samt undersöka hur de boende uppfattar dagsljuset i lägenheterna. Fastigheten Greenhouse, som har ingått i studien, är ett flerfamiljshus som ägs av MKB Fastighets AB och är certifierat enligt Miljöbyggnad Guld och Passivhus Feby.

Stockholm, 15 september 2017

Anne Grete Hestnes,

Ordförande i E2B2
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Sammanfattning

Energieffektiva byggnader kräver välisolerade, lufttäta fasader med små och mellanstora fönster med lite värmeförluster genom klimatskalet och bra utnyttjande av passiv solvärme. I certifieringssystemen Miljöbyggnad, LEED och BREEAM ställs krav på såväl dagsljus som energi. För att uppnå krav på dagsljus vill man ha fönster som är tillräckligt stora och släpper in tillräckligt dagsljus. Att förena båda dagsljus- och energimålsättningar kan vara mycket svårt för projektörer. Ofta leder det till att man bortser från dagsljusfaktorkriteriet och prioriterar energikraven, vilket kan påverka dem som vistas i huset på ett negativt sätt eftersom dagsljus är viktigt för välbefinnandet.

Den främsta målsättningen med detta projekt har varit att analysera och utveckla innovativa lösningar i bostäder för att både uppnå bra dagsljus och låg energianvändning. I projektet har det också ingått att validera ett energisimuleringsverktyg som används mycket i praktiken samt undersöka hur de boende uppfattar dagsljuset i lägenheterna. Studien analyserade fastigheten Greenhouse, vilket är ett innovativt flerfamiljshus som är certifierade Miljöbyggnad Guld och Passivhus Feby. Greenhouse ägs av MKB Fastigheter AB.

Studien visade att simuleringarna har en rimlig noggrannhet jämfört med uppmätta värden. Studien visade också att genom att ha en mix av stora och mindre fönster och placera dem på ett sätt som tydligt tar hänsyn till dagsljus och passivsolvärme kan både krav på dagsljus och energi uppnås. Simuleringar visade att potentialen för energieffektivering (lägre årligt värmebehov) genom optimering av fönsterstorlek och placering är olika för olika orienteringar (ungefär ±4 kWh/m^{2}år på norr fasaden, ±2.5 kWh/m^{2}år på öst och väst, och ±4,5 kWh/m^{2}år på söder). Det behövs då även utvändiga solskydd för att undvika att det blir för varmt framförallt under vår, sommar och höst. En tredje resultat var att inglasade balkonger minskade dagsljuset med minst 50 procent i angränsande rum. Inglasade balkonger bör därför placeras intill rum som inte behöver dagsljus som korridor och badrum. I fastigheten som undersöktes uppfylldes de högsta kraven på dagsljus. Trots det upplevde hälften av de boende inte lägenheterna som speciellt ljusa, utan snarare neutrala eller mörka.

Nyckelord: Dagsljus, energianvändning, flerbostadshus, bostäder, mätningar, simuleringar, enkäter, certifiering, byggnadsregler

Summary

Energy-efficient buildings require well-insulated, airtight facades with small to medium-sized windows that have small heat losses while allowing good utilization of passive solar heat gains. Environmental certification systems such as Miljöbyggnad, LEED and BREEAM contain daylight and energy requirements. To meet the daylight requirements, windows need to be sufficiently large to allow sufficient daylighting. Combining both daylight and energy goals can be difficult for projectors. Most often, the daylight factor criterion is ignored and priority is given to the energy requirements, which may negatively affect building inhabitants since daylighting is important for well-being.

The main objective of this project was to analyze and develop innovative solutions in multi-family dwellings that achieve good daylighting and low energy use. The project also included a validation of an energy simulation tool widely used in practice and an investigation about how residents perceive daylighting in their apartments. The study analyzed the Greenhouse building, an innovative multi-family building which is certified according to Miljöbyggnad Gold and Passive House Feby. Greenhouse is owned by MKB Fastigheter AB.

The study showed that the simulations have a reasonable accuracy compared to measured values. The study also showed that by having a mix of large and smaller windows and placing them in a way that clearly takes into account daylighting and passive solar heat gains, both daylight and energy requirements can be achieved. The potential for energy conservation (i.e. lower heating demand) through optimization of window size and position is different for different orientations (i.e. approximately ±4 kWh/m^2yr for north, ±2.5 kWh/m^2yr for east and west, and ±4,5 kWh/m^2yr for south). The study also indicated that large windows require external sun protection to prevent overheating, especially during spring, summer and autumn. A third result was that glazed balconies reduced daylight by at least 50 percent in adjacent rooms. Glazed balconies could therefore be placed next to rooms that do not require daylight such as corridors and bathrooms. In the property investigated, the highest standards of daylight were met. Despite this, half of the residents did not experience the apartments as particularly bright, but rather neutral or dark.

Keyword: Daylighting, energy use, multi-family housing, dwellings, measurements, simulations, subjective evaluations, certification, regulations

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1 Introduction

Environmental certification systems such as LEED, BREEAM and MiljöByggnad are currently strong drivers in the Swedish building sector. One of the most important credits in Miljöbyggnad is the energy use credit, which only addresses energy use for operation of the building. Energy use for operation is strongly affected by facade and window design. Windows in particular have a significant effect on operation energy since they typically lose 5-10 times more energy to the outside than a well-insulated wall. On the other hand, windows allow solar radiation inside the building, which can be either positive or negative on the overall energy balance.

Window design is thus a carefully controlled aspect of low energy building design. In general, the smaller the windows, the easier it is to reach the energy use and solar heat gain credits in Miljöbyggnad. On the other hand, a building with small windows is a building that does not support its inhabitants since daylighting and a connection to the outside have been shown to positively correlate with health and well-being.

1.1 Research objectives

This research project pursued three separate objectives. The first objective was to analyze and develop innovative solutions and guidelines for multi-family housing with good daylighting and low energy use thereby solving the conflict between energy and daylighting credits in certification systems. The second objective was to validate the simulation tools normally used in the practice of a large architectural office. The third objective was to verify the adequacy of the current minimum daylight factor requirement level in relation to assessment by building inhabitants, see figure 1.

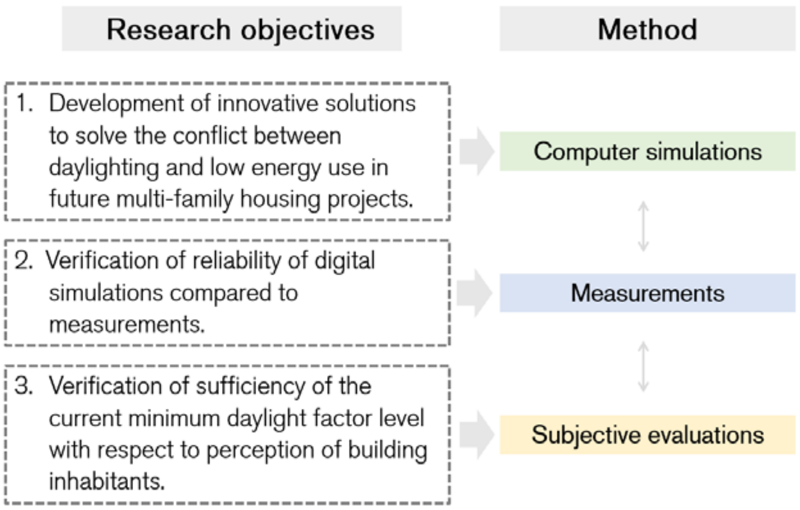


Figure 1 Research objectives in relation to research methods.

2 Method

These research objectives were met through an in-depth study of daylighting and energy use of a new innovative multi-family building. The study involved advanced computer simulations, in situ measurements as well as subjective evaluations by the building inhabitants as described in figure 1.

2.1 Context: Greenhouse in the eco-city Augustenborg

The studied object is Greenhouse, a residential building located in a part of Malmö called Ekostaden Augustenborg (Latitude 55°N, longitude 13°E), see figure 2.

Figure 2 View of Greenhouse in its context, source MKB Fastigheter (2016).

Greenhouse, designed by Jaenecke Arkitekter was finished in 2016 and consists of both a fourteen-story building referred to as 'Höghuset' (high house) in this report, and a lower building called 'Låghuset' (low house). Höghuset includes 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, which is divided in two parts, a glazed and an open part.

Each floor of Höghuset consists of three apartments, typically distributed as shown in figure 3, and oriented in three cardinal directions, i.e. South (S), East (E) or West (W). The larger three-room apartments have balconies oriented to the South. A typical layout of a West-oriented apartment is presented in figure 3 (right). Note that the two lower floors of Höghuset are slightly different as they house student apartments, so they were not studied in this project.

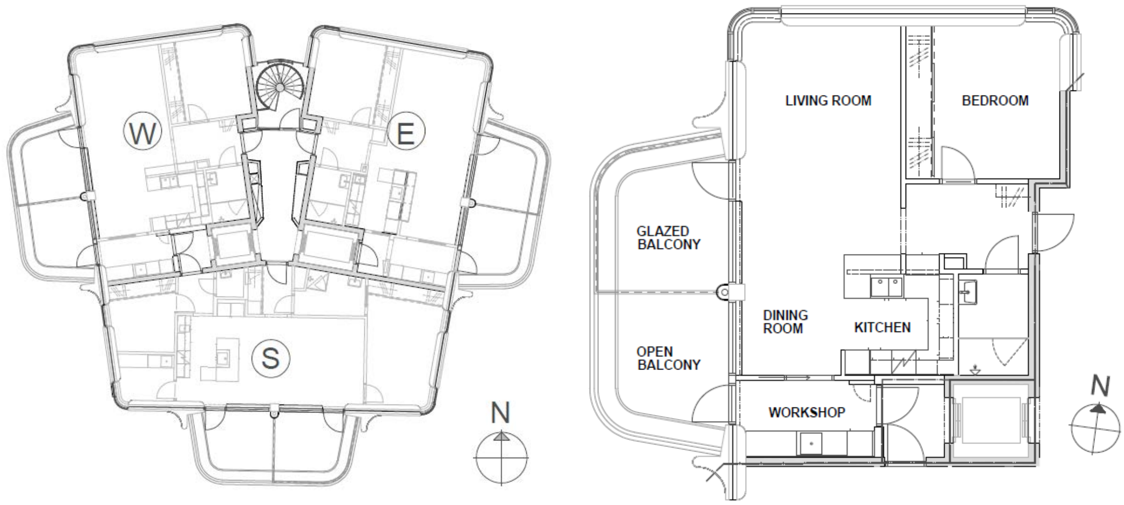


Figure 3 Typical floor of Höghuset showing the three apartments oriented to the West (W), East (E), and South (S).

2.2 Measurements

Physical daylight measurements with lux meters were performed in five apartments of Höghuset during the end of September and beginning of October 2016. Three types of measurements were collected namely daylight factors according to a grid, point daylight factors (DFp) according to the Miljöbyggnad definition, and the surface reflectance of walls and floors.

The interior and exterior illuminance was measured simultaneously under overcast sky conditions using a Hagner EC-1 and E4-X illuminance meters respectively. The light detectors used are made of Sillicon photodiode V_λ-filtered and cosine corrected with accuracy higher than ±3% (±1 in last digit) (Hagner, 2016). All instruments were calibrated prior to the measurements against 'Standard light A' by Hagner, Stockholm. The reference used was MTt6P03331-K01, traceable to SP Technical Research Institute of Sweden and secondary reference 52132. The calibration accuracy was ±3%.

2.3 Simulations

The simulation work was divided in two parts, where one part concerned the effect of sunspace and balcony on daylighting in the adjacent living spaces and the second part focused on the effect of fenestration size and position on daylighting, energy use and overheating, see figure 4.

Advanced daylight and energy simulation tools were used including the programs Rhinoceros, Grasshopper, Honeybee, Ladybug, Octopus, Radiance, DIVA for Rhino, DAYSIM, and EnergyPlus in a complex iterative loop described in Appendix A. More details about the simulations can be found in Bournas & Haav (2016) and Angeraini (2017).

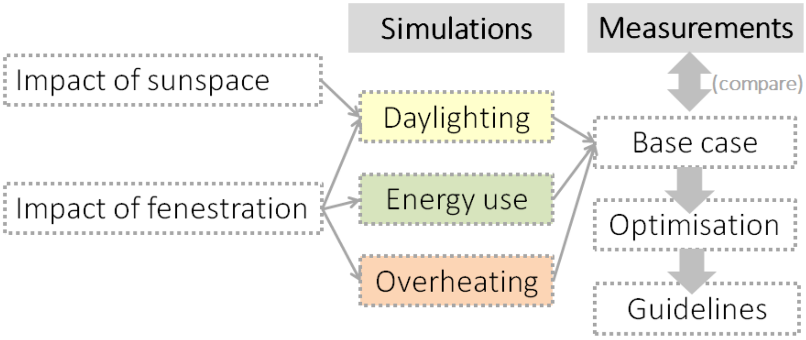


Figure 4 Diagram explaining the overall simulation sequence.

2.4 Subjective evaluations

A self-administered questionnaire was developed with closed questions about the following topics:
1) general satisfaction with the apartment;
2) daylight level;
3) daylight distribution;
4) direct sunlight;
5) view through windows;
6) physical environment;
7) personal information.

The questionnaire was distributed to all tenants of Greenhouse during the late part of December 2016 and collected during January 2017. A slightly compressed version of the questionnaire as received by the tenants (English version only; Swedish was also provided) can be found in Appendix B. More details about the subjective evaluations are provided in Levin (2017).

3 Results

3.1 Measurements

Figure 5 shows the average (DFave), median (DFmedian) and point daylight factor (DFp) values obtained for the main living space of the 4th and 11-12th floor apartments on East, West and South orientations. The South apartment on the 11th floor was not studied by simulations and this data is thus absent in the graph.

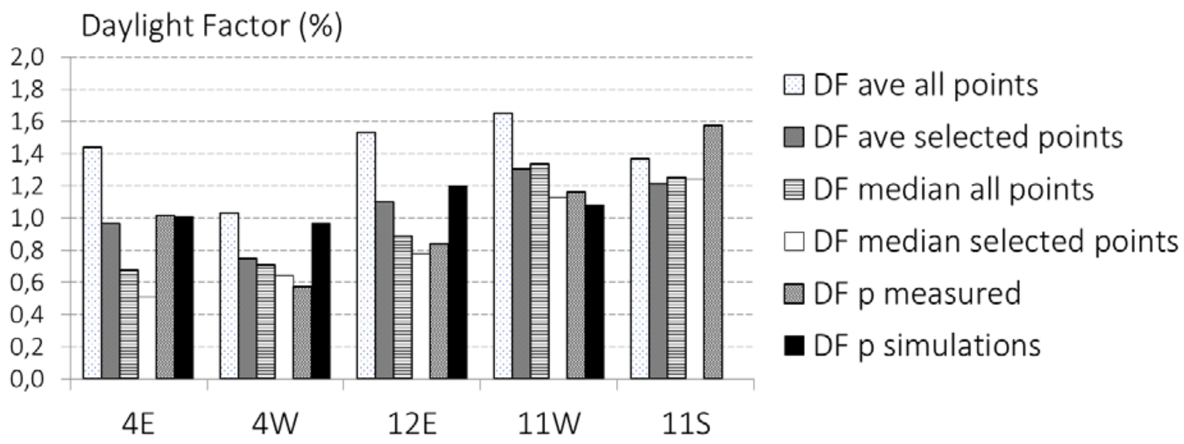


Figure 5 Average (DF ave), median (DF median) and point daylight factor (DF p) values for the 4th and 11-12th apartments on East, West and South orientations in the main living spaces.

As seen in figure 5, measurements show the highest DFp for the main living space for apartment 11W while simulations show the highest DFp for apartment 12E. The difference between simulated and measured result for the 4W apartment can be explained by the large amounts of plants in the glazed balcony during measurements in this specific case. There is however no obvious explanation for the difference between measured and simulated DFp in apartment 12E (0.84% compared to 1.2%), except for the fact that the weather conditions were unstable during the day of measurements, as fact well noted by the measuring staff. However, note that measured and simulated values correspond remarkably well for apartments 4E and 11W.

Overall, the simulation results show a reasonably high correlation with the measurements results considering the large amount of error sources in the daylight measurements (variable sky distribution, interior finishes, presence of furniture in addition to 'normal' measurement errors, e.g. error on sensors, position of points, height of points, shading of the measurement equipment by staff, obstacles etc.). Note that for the simulations, a normal error of ±20% has been noted by other researchers (Reinhart, 2017).

Finally, it is worth noting that the three simulated DFp are below the requirement for Miljöbyggnad Gold, which can be explained by a different interpretation of the position of the measurement point for DFp in relation to the facade. A consequence of this is that daylighting in the existing rooms is slightly lower than anticipated within the boundaries of the heated building envelope.

3.2 Simulations

3.2.1 Effect of glazed sunspace

In order to investigate the effect of the addition of sunspace and balcony on the daylight conditions in the living areas, two sections were produced showing the DF transversally across the room for each orientation, see figure 6.

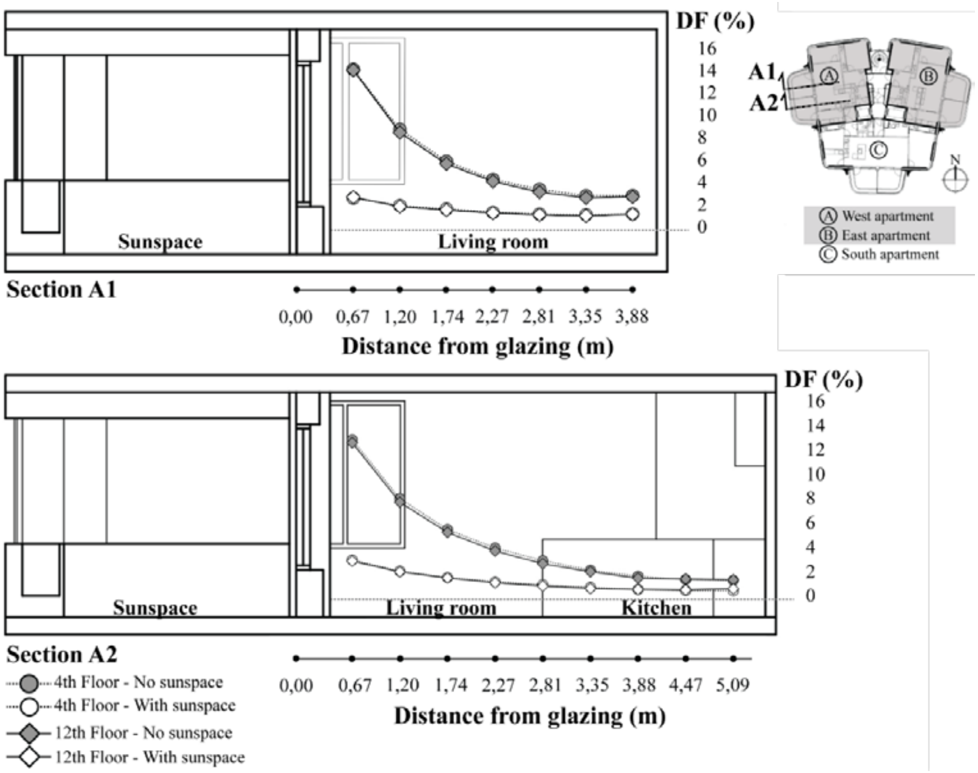


Figure 6 West apartment section and DF points.

Figure 6 shows how the daylight factor at each point dropped when the sunspace and balcony were added to the building in the living room facing West. The same trend was observed for the East facing apartments on 4th and 12th floor, see Angeraini (2017) for all results. Figure 6 shows that the biggest drop was found in the areas closest to the windows where the DF was reduced by 75-80% on both floors. Looking at Section A2, which shows the living room and kitchen, the DF values at the back of the room (kitchen area) did not exhibit an extreme drop compared to the areas near the windows. This is explained by the fact that the areas closest to the windows receive more light from the zenith, which is then blocked by the balcony and sunspace, whereas areas in the back of the room receive more light from the horizon and from the internally reflected light component, which is less affected by the balcony and sunspace. This trend happened on both lower and higher apartments. However, daylight uniformity (i.e. minimum to average DF) in the studied space increased when the sunspace and balcony were added, which may contribute to reduce contrast and improve visual comfort. Detailed results can be found in Angeraini (2017).

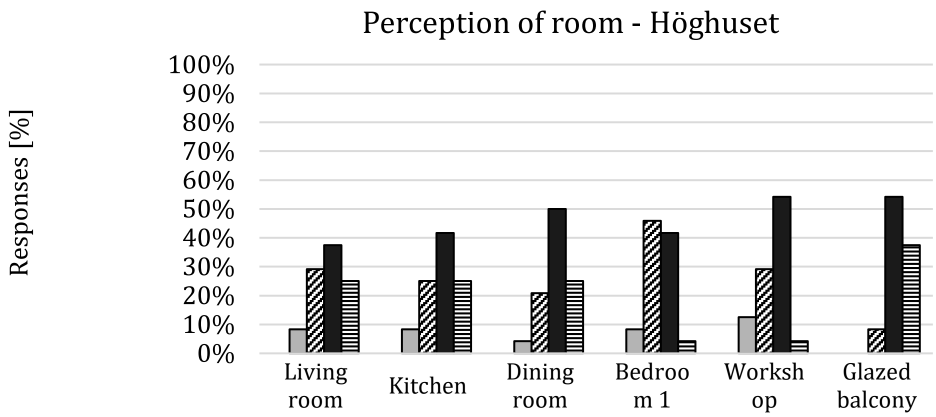
3.2.2 *Effect of fenestration*

The effect of fenestration design (size, position, etc.) was studied in detail using optimization techniques and genetic algorithms; see Bournas & Haav (2016) for methodological details. One important result concerns the optimal window-to-wall (WWR) ratios. Table 1 presents an overview of the best performing cases in terms of low energy use and best daylighting for each orientation. It is shown that there are a higher number of possible design solutions for North facing windows, with optimal WWR ratios between 10-50%. These optimal solutions either minimize heating or maximize daylighting or both. For the East and West orientations, the optimum WWR approximately ranges from 40-50 %. On the South, the highest WWR of 78 % returned the lowest energy use and best daylighting. This is because on the South side, large windows also bring passive solar gains that compensate for the additional heat losses through the window. However, in this case, overheating occurs with large windows and it is essential to provide efficient solar shading devices.

Examining table 1, one can see that all designs involve windows with the highest possible head height, at 2,55 m. This independent variable affects the daylight penetration in the room. Moreover, the optimum windows have a shape that tends to be square, in other words, the height-to-width ratio of these windows is close to 1,0.

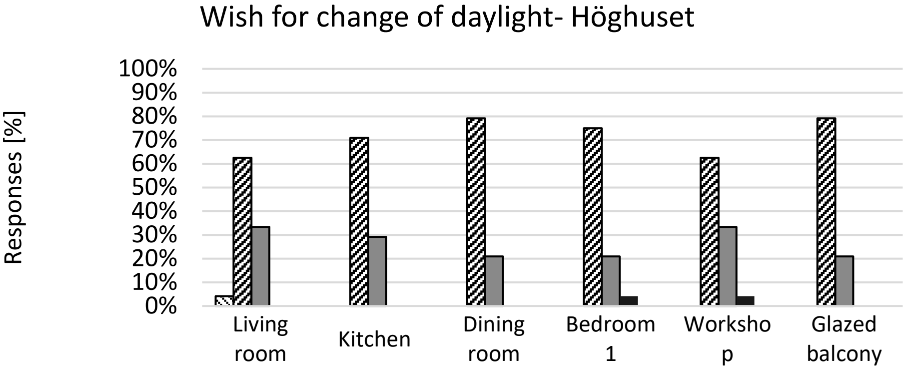
3.3 Subjective evaluations

The full results on the subjective evaluations are published in Levin (2017). One specific question concerned the experience of daylight level in the apartment, see figure 7. As seen in figure 7, no respondent reported perceiving any room as very dark and only a small part (4-13%) reported perceiving dark conditions. A majority of the respondents found the main living spaces, workshop and glazed balcony to be in the range 'bright-very bright', while the bedroom was perceived as 'neither dark nor bright' by the majority of respondents. Notable is however the significant part of the respondents (25-54%) who perceived the interior 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 the Swedish building regulations. Figure 8 also shows the results for the question concerning desirable change in daylight level. This figure show that despite the bright interior, a significant portion of respondents wished more daylight in their apartment.



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



	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 8 Höghuset - Responses to question 1b: 'How would you wish to change the daylight in the following rooms?'

Table 1 Optimal fenestration designs in order to maximize DA50lx and minimize annual heating demand of the bedroom for each orientation.

WWR	Orientation			
	NORTH	EAST	WEST	SOUTH
10% - 20%	WWR=10%, 10%, 10%, 16%, 16%			
20% - 30%	23%, 23%			
30% - 40%	32%, 32%, 39%, 39%	39%		
40% - 50%	47%	42%, 42%, 47%	42%, 47%	
50% - 60%		52%	52%, 52%	
60% - 70%	62%	62%		
>70%			78%	78%

4 Conclusions

4.1 Measurements

The results of *in situ* measurements in four apartments of Greenhouse were compared to results obtained from the simulation program. The measurements indicated that the main living spaces of Greenhouse have a DFp in the range between 0.8-1.2 %. The DFp measured and simulated was lower than the projected value due to a different interpretation about the position of the measurement point. One conclusion is thus that this aspect needs to be more clearly defined in future formulations of the Swedish building regulations and certification system Miljöbyggnad. Overall, the measurements and simulations returned reasonably close values given the large amount of possible error sources involved in both measurements and simulations. An important conclusion is thus that the simulation program used is reliable.

4.2 Simulations

4.2.1 Sunspace and balcony

The simulations showed that adding the actual sunspace (3,4 m deep and 3,8 m long) and balcony (3,4 m deep and 3,8 m long) on the apartment building reduced daylight levels in the adjacent living spaces by at least 50% under overcast sky conditions. The geometry of the sunspace and balcony was found to be the most important factor affecting daylighting in the adjacent spaces. Increasing the depth and length of the sunspace reduced the amount of daylight received in the adjacent spaces, which lead to an increase in the electrical lighting consumption, where the length was a more critical factor than the depth of the balcony and sunspace.

Designing sunspace with the least depth and the shortest length is recommended in view of the results of this study. One recommendation to architects is therefore to place sunspace and balcony adjacent to opaque parts of the building envelope.

4.2.2 Fenestration

The study showed that the objectives of heating and daylighting are in conflict with each other on all orientations except for the South orientation. The potential for energy conservation (i.e. lower heating demand) through optimization of window size and position is different for different orientations (i.e. approximately ±4 kWh/m^2yr for north, ±2.5 kWh/m^2yr for east and west, and ±4,5 kWh/m^2yr for south). Note that this potential only regards heating energy use.

On a South orientation, WWR should be maximized, if heating and daylighting are the objectives of optimization. The drawback is a high increase in the operative temperature, hence, exterior solar shading should be added to control overheating. On East and West orientations, the optimum WWR range, for the optimization of heating and daylighting was 40-50 %. North windows should be square-shaped and placed high on the façade to optimize daylighting and thermal energy. A WWR of 34 % was optimum on the North for satisfactory daylight levels, low heating demand and no overheating. The North orientation is probably preferable for a bedroom, as the necessary illuminance can be achieved by diffuse irradiation only and the overheating time is minimized.

The importance of passive solar gains on the South orientation to reduce heating demand and contribute to daylighting is clearly outlined in this study. The use of a balcony affects both heating and daylighting levels negatively and thus one recommendation to architects is that sunspaces and balconies should be adjacent to the opaque parts of the building envelope as far as possible, i.e. adjacent to corridors, toilets, storage, and the like.

The simulations also indicated that the WWR ratio is not a sufficient predictor of energy use or daylighting performance. An energy and daylighting assessment requires the height-to-width window ratio and information about the window position, which significantly affects daylighting in the space. Overall, it was also found that the heating demand was not dramatically affected by the WWR, as the studied apartment had a very high insulation level.

Many more results, discussion and conclusions are presented in Bournas & Haav (2016) and should be consulted by the reader interested in this part of the research.

4.2.3 Subjective evaluations

Subjective evaluations were performed using a survey distributed to building inhabitants. The subjective evaluations showed that the respondents have a clear preference for daylighting over electric lighting. The satisfaction with the view was high for this building as a whole. Other aspects of the building were generally assessed as satisfying except perhaps for temperature and electric lighting.

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 DFp might not be desirable in future environmental certification systems or in the building code. The debated question of the daylight threshold in regulations (1 % DFp) being set too high is consequently not supported by the subjective assessment in this research. Note however that the questionnaires were only distributed during the winter season, when daylighting is scarce in Sweden. The main conclusions need to consider this major limitation.

A higher daylight level was prioritized in the kitchen, while a lower level would seem acceptable in the bedroom. This supports the suggestion of working towards a more flexible way of expressing the daylight requirements with a possibility of differentiation according to room and usage. It also suggests that architectural plans should be reconsidered taking work tasks (kitchen meal preparation) and screen use (living room) 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 closer to the building core, where nuisance from direct sunlight or high daylight levels would not be felt as strongly. In this case for instance, a better architectural solution would have consisted of inverting living room and kitchen. However, the solution of inverting kitchen and living room need to also be weighed against other important planning aspects such as e.g. location of plumbing close to toilets, functionality of the apartment layout, etc.

The respondents’ subjective perception of daylight level is affected by other parameters than the daylight factor alone. The results strongly suggest that daylight uniformity and direct sunlight may also affect the assessment. In general, more even daylight distribution yields higher assessment of daylight levels or brightness, which is in line with previous studies. The study thus confirms that the daylight factor should be supplemented with other indicators such as uniformity (min/average) and climate-based values. Note that uniformity and climate-based daylight metrics have recently been integrated into the certification systems BREEAM and LEED.

4.3 Design guidelines

The following points should serve as design guidelines for planners of multi-family dwellings:

- Avoid very large glazed balconies directly adjacent to the main living spaces as they will cut daylighting and passive solar gains significantly, which increases heating loads and reliance on electric lighting.
- Place glazed balconies adjacent to rooms that do not necessitate daylighting and passive solar gains (corridors, toilets, circulation, etc.). The access to the glazed balcony can still be from the main living spaces with a smart overall planning.
- Windows should have different sizes on different orientations.
- On a South façade, large, well-insulated windows (> 70 % WWR - window-to-wall ratio) perform best. They provide lower heating demand due to passive solar gains and good daylighting.
- On East and West facades, moderate window ratios (40-50 % WWR) perform best in terms of energy use and daylighting.
- On North facades, smaller i.e. 10-50 % WWR perform better as there are no passive solar gains on this façade.
- Windows, especially large ones on South, East and West facades, need to be protected by efficient (external) solar shading devices, either manually or mechanically controlled.
- Square windows generally perform better in terms of daylighting a space.
- Windows should preferably be placed further apart if there is more than one window in the same room in order to have a better daylight distribution. A better daylight distribution provides a higher brightness perception, and thus less reliance on electric lighting.
- Windows should be placed high up close to the ceiling line as they will then allow for a deeper daylight penetration.
- The kitchen is the room where the highest daylight levels should be provided while bedrooms could have lower daylight levels. This means that kitchen should be placed directly next to the façade and not close to the building core.
- Living spaces such as living rooms involve today screen based activities (TV, computer) so these spaces are sensitive to overlighting and glare and could thus be provided with more moderate daylight levels. Interior curtains or screens are needed for glare control.
- The minimum point daylight factor (DFp) of 1,0% should be considered as an absolute minimum. Lower values will probably result in dissatisfaction during the winter months.
- Supplement daylight assessments with assessment of daylight uniformity as well as climate-based daylight indicators (e.g. spatial daylight autonomy DA, useful daylight illuminance UDI, etc.), which provide information about direct sunlight.

4.4 Future research

Although the daylighting software used has been validated experimentally in many previous studies, it is still worthwhile to continue verifying the validity of the simulation engine used once in a while. Future research should continue to include some form of physical measurements to make sure that researchers and consultants involved in this field keep close contact with real world phenomena. Much learning was gained through the measurements in this project even though measurements were difficult to achieved and very time consuming.

The simulations emphasized the importance of passive solar heat gains for low energy use and good daylighting. However, this conclusion is based solely on energy simulations with a single computer program (Energyplus) so the results are entirely dependent on the assumptions made in programming the software. Note also that a single climate file was used, which may not represent the future projected climate conditions. In future research, it would be interesting to test this result using different simulation engines and different climate files and also verify whether it is true in reality with e.g. measurements in real buildings. Simulations with an energy-efficient, dynamic shading device should also be compared to a solution with fixed shading such as overhand or the like. Finally, simulations should also include the possibility for natural ventilation of the extra solar heat gains when necessary, which was not possible in the present case due to time limitations. In addition, it would be interesting to test (through simulation) some of the more encompassing solutions proposed such as inversion of kitchen and living room, moving of glazed balcony away from the living space windows to see how such solution would perform in terms of overall energy use, thermal comfort and daylighting.

Last but not least, the study indicated that not all building inhabitants in Greenhouse were fully satisfied with daylighting conditions in their apartment despite the fact that this building obtained the highest environmental certification level (Miljöbyggnad Gold). However, the questionnaire was distributed and collected during the darkest part of the year. Future research should also collect the inhabitants' perception of daylighting during other seasons such as summer, spring and autumn.

5 Publications

This project was made possible thanks to the dedicated work of graduate students enrolled in the international Master Programme Energy-efficient and Environmental Buildings, at LTH, Campus Helsingborg. A total of five students, who are also co-authoring this report, were involved in this project. This project resulted in the publication of four Masters Theses, available through Lund University Publication (LUP) website:
https://lup.lub.lu.se/student-papers/search/publication?sort=publicationstatus.desc&sort=year.desc

1. Angeraini S J (2017). Sunspace design parametrization based on daylight performance in a multi-storey residential building. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

2. Bournas I & Haav L (2016). Multi-objective Optimization of Fenestration Design in Residential spaces. The Case of MKB Greenhouse, Malmö, Sweden. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

3. Levin T (2017). Daylighting in environmentally certified buildings: Subjective and objective assessment of MKB Greenhouse, Malmö, Sweden. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

4. Shalaby M (2017). The Effect of Architectural Configurations on the Biological Light Response in Residential Buildings. Greenhouse project in Malmö. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

One conference article was also published:

Haav L, Bournas I, Angeraini S J (2016). Bi-objective optimization of fenestration using an evolutionary algorithm approach. *Int. Conf. PLEA 2016: Cities, Buildings, People: Towards Regenerative Environments,* Los Angeles, 11-13 July 2016.

6 References

Angeraini S J (2017). Sunspace design parametrization based on daylight performance in a multi-storey residential building. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

Bournas I & Haav L (2016). Multi-objective Optimization of Fenestration Design in Residential spaces. The Case of MKB Greenhouse, Malmö, Sweden. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

Hagner (2017). [Online] Available at: www.hagner.se [Accessed 23 May 2017].

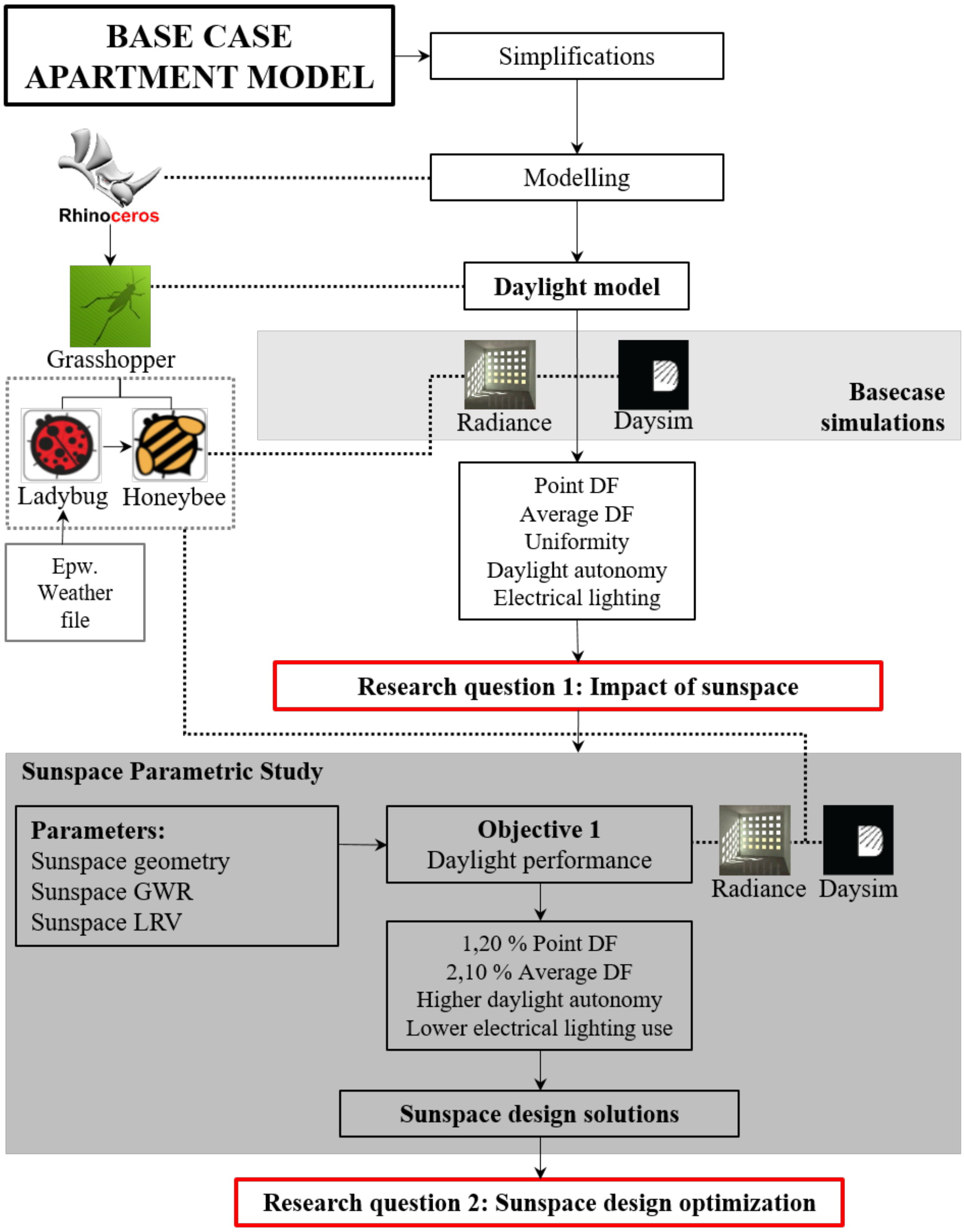
Levin T (2017). Daylighting in environmentally certified buildings: Subjective and objective assessment of MKB Greenhouse, Malmö, Sweden. Master's thesis, Lund University (LTH), Division of Energy and Building Design.

MKB Fastigheter AB (2016). Greenhouse. [Online] Available at: https://www.mkbfastighet.se/globalassets/nyproduktion/greenhouse/faktablad-gh-150224_eng.pdf [Accessed 23 May 2017].

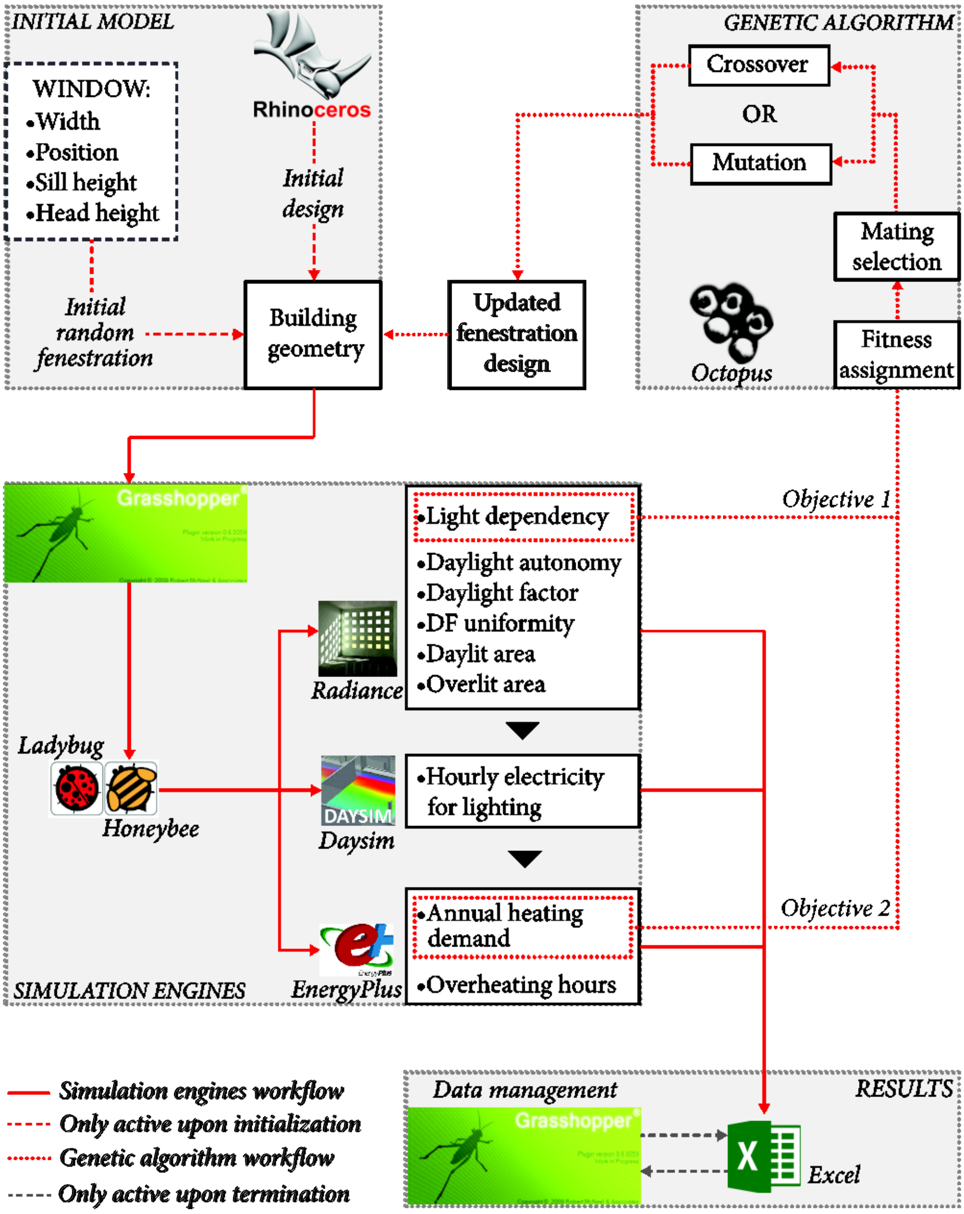
Reinhart C F (2017). IBPSA Webinar: Session-7: Daylight Performance Predictions by Christoph Reinhart, Thursday, Feb 23, 2017.

Appendix A

Simulation process for studying the effect of glazed balcony on daylighting.



Simulation process for studying the effect of fenestration on daylighting and energy use.



Appendix B

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 : __________
________	________	________	________	________	_______	________

<u>Comments for PART 1 can be written here:</u>

<u>PART 2: DAYLIGHT DISTRIBUTION</u>

2a. How would you describe the <u>distribution</u> of daylight in the following rooms:

	Very even	Even	Acceptable	Uneven	Very uneven	I don’t know
Living room	☐	☐	☐	☐	☐	☐
Kitchen	☐	☐	☐	☐	☐	☐
Dining room	☐	☐	☐	☐	☐	☐
Bedroom 1	☐	☐	☐	☐	☐	☐
Workshop	☐	☐	☐	☐	☐	☐
Glazed balcony	☐	☐	☐	☐	☐	☐
Other room: _____________	☐	☐	☐	☐	☐	☐

2b. Do the following rooms have any dark 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 bright 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: ____________	☐	☐	☐	☐

Comments for PART 2 can be written here:

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 <u>ONE</u> or <u>SEVERAL</u> 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 : ________
________	________	________	________	________	________	________

<u>Comments for PART 3 can be written here:</u>

<u>PART 4: VIEW THROUGH WINDOWS</u>

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 <u>glazed balcony:</u>

	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	☐	☐	☐	☐	☐	☐

<u>Comments for PART 5 can be written here:</u>

PART 6: ACTIVITIES AND REQUIREMENTS

6a. What activities are <u>common</u> 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 <u>only light source</u> 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 shortsighted	I am farsighted	I am both shortsighted and farsighted	I wear bifocal lenses	I wear trifocal lenses	I wear progressive lenses
☐	☐	☐	☐	☐	☐

8e. Select the <u>ONE</u> 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
☐	☐	☐	☐

<u>Please add any comment or information that you may find relevant here:</u>

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.

Runt 35 procent av all energi i Sverige används i bebyggelsen. I forskningsprogrammet E2B2 arbetar forskare och samhällsaktörer tillsammans för att ta fram kunskap och metoder för att effektivisera energianvändningen och utveckla byggandet och boendet i samhället. I den här rapporten kan du läsa om ett av projekten som ingår i programmet.

E2B2 genomförs i samverkan mellan IQ Samhällsbyggnad och Energimyndigheten åren 2013–2017. Läs mer på www.E2B2.se.

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