Daylight and thermal comfort in a residential passive house

-A simulations study based on environmental classification systems

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Abstract

Construction of passive houses has increased in recent years. The aim of passive houses has traditionally been energy efficiency, which means that the indoor climate faces a risk of being overlooked as these two objectives sometimes contradict each other. One conflict that usually arises is the one between daylight, heating demand and thermal comfort during summer. As the use of environmental classification systems increases, indoor climate conditions are emphasized. This requires careful planning and a wider perspective in order to achieve both energy efficiency and a satisfying indoor climate.

This paper investigates how indoor climate and energy usage is affected by the choice of windows and shading devices in a residential passive house. This is particularly interesting since cooling systems rarely are available in Scandinavia to manage overheating during summers, and daylight quality is seldom investigated in residential houses.

Possible solutions to these contradicting demands were obtained by simulations of NCC's passive house “Kuben”. Among the tested solutions are different types of glass, paints, inclination of window niches, window sizes, and internal and external shading devices. The results of these simulations were compared with the Swedish passive house criteria and Miljöbyggnad, a growing Swedish environmental classification system based on 15 so-called indicators. Six of these are affected by the window and shading, and are included in this paper. Different solutions were developed where Kuben remains being a passive house while achieving the highest grade in Miljöbyggnad for the studied indicators.

This paper shows that by choosing window glass with a higher light transmission, more daylight and reduced energy usage can be achieved. Increasing the window area will have the same affect. Both these actions increase the need of shading, where external awnings provided the most effective solution. Optionally, the building can meet the requirements by increasing the roof overhang and by adding internal solar shading.

The results emphasize that all window properties should be considered at an early stage to ensure a good final result. It is important to consider the effect of the window properties’ on the need for solar shading.

Keywords: windows, shading, g-value, solar heat load, Miljöbyggnad, environmental classification systems, passive house, daylight, daylight factor, solar radiation.

Introduction

In recent years buildings using passive house technology have become more and more common. The main purpose of these buildings is to reduce the heating demand by utilizing 'free' energy from internal gains and the sun, and minimizing heat losses. The two objectives are contradictory in terms of window-glass area since windows insulate less than a solid wall, thus the glass area needs to be minimized to keep transmission losses low. Optimizing the window area and the window-to-floor area ratio is therefore essential in low-energy housing.

The window area also affect indoor climate in different ways; natural light indoors contribute to wellbeing, but large windows can also cause problems due to thermal radiation from warm or cold glass surfaces or from causing over-temperatures during the summer. It is therefore very important to evaluate the indoor climate by performing simulations for this type of highly insulated buildings.

Office buildings, with high internal loads during the day due to large glass areas and large internal gains, have been the subject of several studies. This is mostly because of the additional cost for cooling and the lowered productivity of employees if indoor climate requirements are not sufficiently met. Residential buildings however, have been somewhat neglected in studies, but are not necessarily less interesting. The energy consumption during 2010 for heating and hot water in residential housing in Sweden was 63.4 TWh [Energimyndigheten, 2011] compared to 22.4 TWh for non-residential buildings, not including industry. Thus the need for energy optimization is great in this area, as well as preventing possible problems from having a poor indoor climate where people live and sleep.

The need for a well-balanced amount of windows has been stressed by most environmental classification systems including "Miljöbyggnad", a growing Swedish environmental classification system [SGBC, 2012].

This article is based on a Master of Science thesis with the same title. Further results, as well as a more detailed methodology, are available in that publication [Heier & Österbring, 2012].

Objective

The purpose of this paper is to show how both low energy usage and a good indoor climate can be attained in a residential passive house, mainly relating to the properties of windows and shading devices. The objective is to provide the building industry with tools and general recommendations when designing very low-energy buildings.

Method

The evaluation was done by simulating different cases of window setups in a building. This includes: shading of windows, blinds, glass properties (e.g. reflecting films) and glass areas. All these parameters were studied with regard to indoor climate and energy. The basis of these simulations was an existing passive house, the performance of which was assessed by comparison to six of the 15 indicators in Miljöbyggnad, a Swedish environmental classification system for buildings. The target level to meet for this project is gold, which is the highest possible grade in the Miljöbyggnad standard. The building must continue to meet passive house requirements throughout the process. [Sveriges centrum för nollenergihus, 2012].

Calculations and simulations were carried out using several programs including IDA ICE 4.21 for energy and indoor climate, Parasol v6.6 for calculation of solar shading and VELUX Daylight Visualizer 2.6 for daylight simulations. A passive house outside of Kungsbacka developed by NCC was studied. It is part of the currently largest passive house development in Sweden (2012) at Vallda-Heberg. The object is a one-family home of 140 m^2 called Kuben (the cube), see Figure 1.

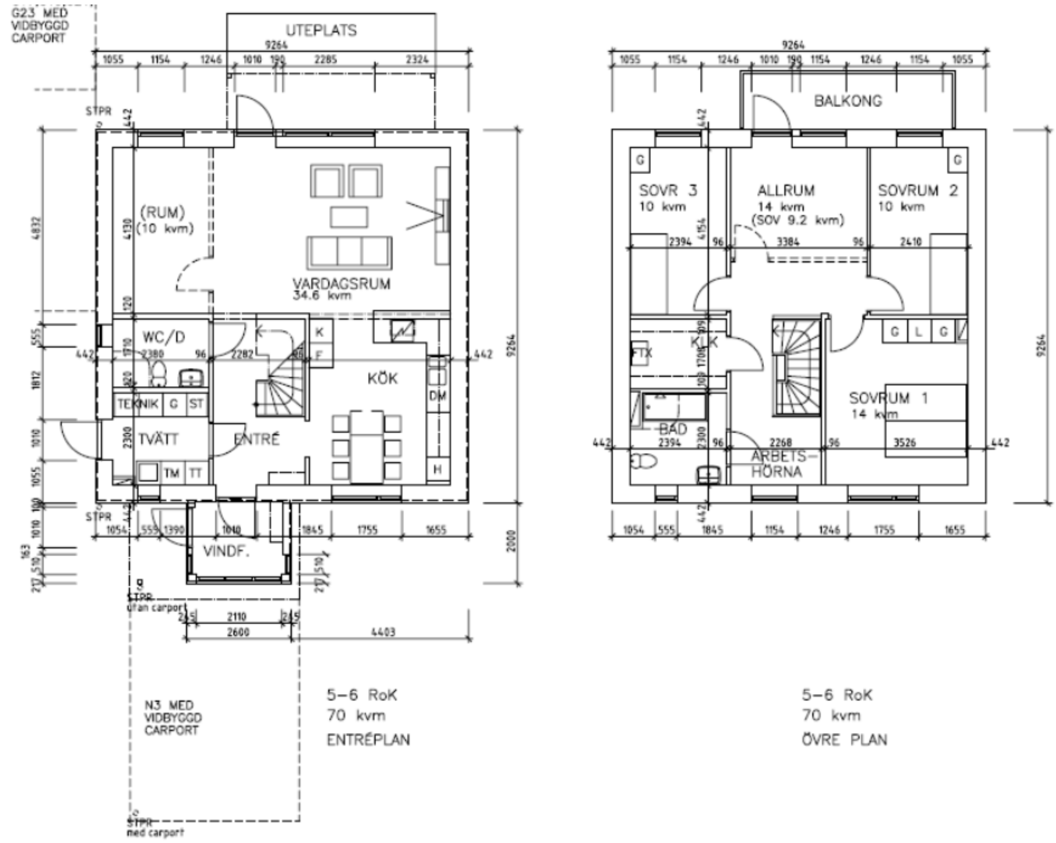

Figure 1: **Floor plans (in Swedish) of Kuben, a total of 140m². The 1st floor is on the left. [NCC, 2012].**

The six indicators from Miljöbyggnad assessed in this report are: Energy demand, Installed power, Solar heat load, Thermal climate; winter and summer, and Daylight. The procedure used in this study was an iterative process: to identify the most critical indicator, suggest a solution for that indicator and then repeat the process until the demands for all indicators were reached.

Calculations were done according to methods recommended by Miljöbyggnad. The worst rooms regarding solar heat load were found by simulations in IDA ICE and occur on the second floor in the two small bedrooms and the living room, all facing south. ParaSol models were then developed for these rooms to find the g-value. Daylight factor was discovered to be insufficient for most rooms.

No specific shading is used for energy calculations at this stage; instead of simulating complex movable shading systems for all windows a generic reduction factor of 0.71 was multiplied to the windows' g-value, in compliance with SVEBY calculation standard. For other indicators where the g-value is of major importance, such as solar heat load and thermal comfort in summer, actual window properties are used.

Thermal climate summer can be calculated in two ways; solar heat load (SVL) or predicted percentage dissatisfied (PPD). The PPD-method is very sensitive to input data. Solar heat load does not have the same possibility of being manipulated and was chosen instead for all calculations and comparisons of thermal climate summer. This topic is further developed in the discussion chapter.

Results

In the first part of this section the original building, as constructed, is compared to the demands set by Miljöbyggnad and the current passive house standard FEBY 12 [Sveriges centrum för nollenergihus, 2012].

In the second part, results from the different proposed modifications to the building are presented. These results will show the effects on the affected indicators. Some of the modifications affect many indicators but not to a significant degree; for example were the changes in PPD for the winter case not large enough to be of interest. These are however still included in summaries.

In this paper, both the terms *heating demand* and *energy demand* are used. These are not the same; the heating demand is the required energy to maintain a sufficient temperature during the heating season, and the energy demand is a buildings total energy usage calculated according to Swedish building regulation [Boverket, 2011]. The reason for using both definitions is to achieve a comparable number. To find the annual energy demand the following factors are added to the annual heating demand of Kuben:

- Ventilation losses : 633 kWh, which is 4.51 kWh/m²
- Forced ventilation in kitchen fan (100l/s): 285 kWh, which is 2.03 kWh/m²
- Hot water heating: 20 kWh/m²
- Pumps: An additional 1% of total energy demand
  [SVEBY, 2009]

Performance of original design

Miljöbyggnad's demands are compared to the conditions in the, for each respective indicator, most exposed living space. Simplified calculations were carried out to determine which rooms require in-depth analysis, and only these results are presented. Note that the definition omits hallways, bathrooms and similar spaces as residents only stay briefly in these spaces. [SGBC, 2012]

As can be seen in Table 1, the most critical indicator is daylight factor, the ratio between illuminance levels outside and inside for an overcast sky. Thermal climate summer and solar heat load must also be improved. Following the set procedure, changes affecting daylight will be implemented first.

Table 1: **All criteria and results of the original building design. Daylight factor is furthest from the required value.**

	Bronze	Silver	Gold	Passive-house	Result	Miljöbyggnad grade
Energy demand [kWh/m²]	≤90	≤67.5	≤58.5	≤55	49.9	Gold
Installed power [W/m²]	≤60	≤40	≤25	≤17	15.7	Gold
Solar heat load [W/m²]	≤38	≤29	≤18	-	19.9	Silver
Thermal climate winter, PDD [%]	≤20	≤15	≤10	-	8.1	Gold
Thermal climate summer, SVF [-]	<0.048	<0.036	<0.025	≤0.036	0.025	Gold
Daylight [%]	≥1.0	≥1.2	≥1.2	-	0.8	Fail

Daylight

The room with lowest daylight factor is bedroom 2 on the 2nd floor. Twelve options affecting the daylight factor have been investigated. Most of these also affect other indicators, which were simulated again in order to find the new results. The following options were investigated:

- Inclining the window niche, with three different angles: 10°, 20°, and 30°
- Changing the light transmittance of the glass, testing four additional glass types with different combinations of light transmittance and g-value
- Changing the reflectance of surface materials, with two additional reflectance cases
- Increasing glass area in three steps: 10%, 20%, and 30%

Only one of the measures tested, increasing the glass area by 30%, managed to reach the target level of 1.2%. Thus, a number of measures from the list above are generally needed to fulfill the daylight criteria. Combinations of the listed setups were therefore simulated to see if these would reach the demand. The criteria was reached for several of the combinations, four of these are presented in Table 2 and given new case notations. These notations will be used in the report from now on. The cases results are compared to the criteria for passive houses and the GOLD level for Miljöbyggnad in Table 3. As can be seen, while daylight has improved, there are other factors that have deteriorated. Note that for some proposed changes, annual heating demand decreases.

Table 2: **Simplification into case notation for four working solutions. The original building is included for reference.**

Description	Case notation
U_{glass} /LT 0.5/57	(Original building)
U_{glass}/LT 0.6/71, window niche inclined 30 degrees & 90% surface reflectance	A
U_{glass} /LT 0.6/71 & 10% increase in window size	B
U_{glas} /LT 0.6/71 & 30% increase in window size	C
U_{glass} /LT 0.5/57 & 30% increase in window size	D

Table 3: **Comparison of working solutions for daylight with the other parameters and the criteria set by both the Passive House standard and Miljöbyggnad level gold. The solar heat load is too high for all solutions.**

Parameter	Daylight [%]	Energy [kWh/m²]	Installed power [W/m²]	Solar heat load [W/m²]	Thermal climate winter, PPD [%]	Thermal climate summer, SVF [-]
Gold level	≥1.2	≤58.5	≤25	≤18	≤10	<0.025
Passive house	-	≤55	≤17	-	-	≤0.036
Original	0.8	49.9	15.7	19.9	8.12	0.025
A	1.2	49.5	16.2	26.8	8.14	0.034
B	1.2	49.4	16.3	30.0	8.15	0.038
C	1.5	50.1	16.8	38.2	8.18	0.048
D	1.2	50.9	16.4	27.6	8.15	0.035

As can be seen in Table 3, the next parameters to be focused on are solar heat load and thermal comfort during the summer. The formulae used for calculating these two numbers (solar heat load and SVF) are identical except for a numerical factor. A consequence of this is that as long as the demand on solar heat load is fulfilled, thermal climate summer will also be satisfactory. The four solutions referenced as A-D will therefore be further developed with regard to solar heat load in the following section.

Solar heat load and thermal comfort

The four different solutions that complied with daylight criteria are adapted in an effort to make the solar heat load reach adequate levels.

The g-value for the windows on the 2nd floor is 0.22, which includes the glass' g-value of 0.36 and a roof overhang of 63 cm. This means that 22% of the sun's radiated energy is transferred into the room. As a reference, the required g-value is calculated to 0.2 for the upstairs living room to reach a solar heat load below 18 W/m², for the original building's window to floor ratio. The solution of increasing glass areas to comply with the daylight indicator will require a reduction in g-value. Note that generic g-values for shading devices, for example found in tables in SVEBY, are not enough to determine if the shading device is able to fulfill the solar heat load demand. In general, simulation of the shading device in combination with the actual window is needed.

Movable shading does not affect the daylight factor, since residents are assumed to remove movable shading when required in order to increase light. This makes movable shading a suitable choice since the most difficult requirement to reach is daylight. For annual heating demand simulations the generic shading coefficient of 0.71 advocated by SVEBY, is replaced by calculated values from ParaSol.

For annual heating demand, simulating with a reasonable control system is of importance. The shadings will be drawn when the solar radiation reaches 100 W/m² on the external window surface.

18 shading devices were simulated for each of the four cases in table 2, in total 72 different setups:

- 2 types of external awnings with 4 angles each; 30°, 45°, 60° and closed
- 2 types of internal blinds (venetian blinds), with 0° or 80° slat angles

- 3 different internal roller-blinds
- 3 types of fixed roof overhang including the original construction

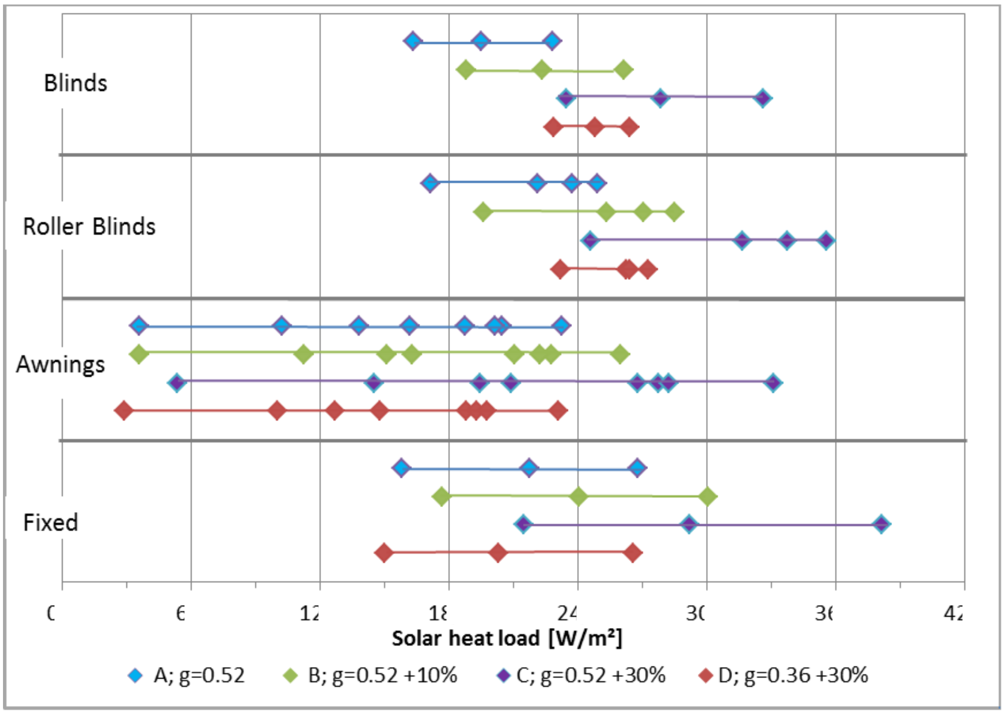

Figure 2: The simulated SVL-values for the different shading devices, depending on case. Every point represents one tested setup. The solutions with lowest resulting values have been used for complete simulations.

In Figure 2, which shows solar heat load for different shading devices, the differences between the cases become more apparent. A larger span among the cases for internal shadings can be seen, as window size becomes a major factor. The g-value of the window highly influences the obtainable g-values when including internal shading devices; as both the range and minimum are highly affected.

Three of the 15 non-fixed shading devices were chosen since at least one of the cases A-D, by only using this solution, reached a solar heat load below 18 W/m². They are also the solutions with the lowest solar heat load in each category of shading devices. Therefore, the three setups correspond to the points furthest to the left in Figure 3 below, for each type respectively.

The simulation results shows that closed awnings is a very efficient way to the lower solar heat load. For internal shadings the annual heating demand decreases which is caused by the generic shading factor of 0.71 being replaced with the actual g-value and influenced by a control system.

In order to improve the fixed shadings that did not reach desired levels, combinations of fixed and moveable shadings are certainly possible. Only case C, where the fixed shading was extended to cover a 30˚ angle from the base of the window, met the daylight demands. Thus, this is the only model further developed into combinations with other shading devices. The following three additions to case C, presented in Table 4, were simulated. All have a 30˚-covering overhang:

Table 4: **Results on indicators with combined systems of fixed shading and internal devices.**

Shading setup	g-value system [-]	Solar heat load [W/m²]	Annual heating demand [kWh]
C, overhang & blind	0.153	17.9	3150
C, overhang & roller-blind 1	0.145	17.0	3170
C, overhang & roller-blind 2	0.173	20.2	3100

Two of these modifications are able to comply with the indicator for solar heat load. Noteworthy is that the annual heating demand decreases. The reason is, as previously, due to the generic shading coefficient being replaced with more optimized solutions.

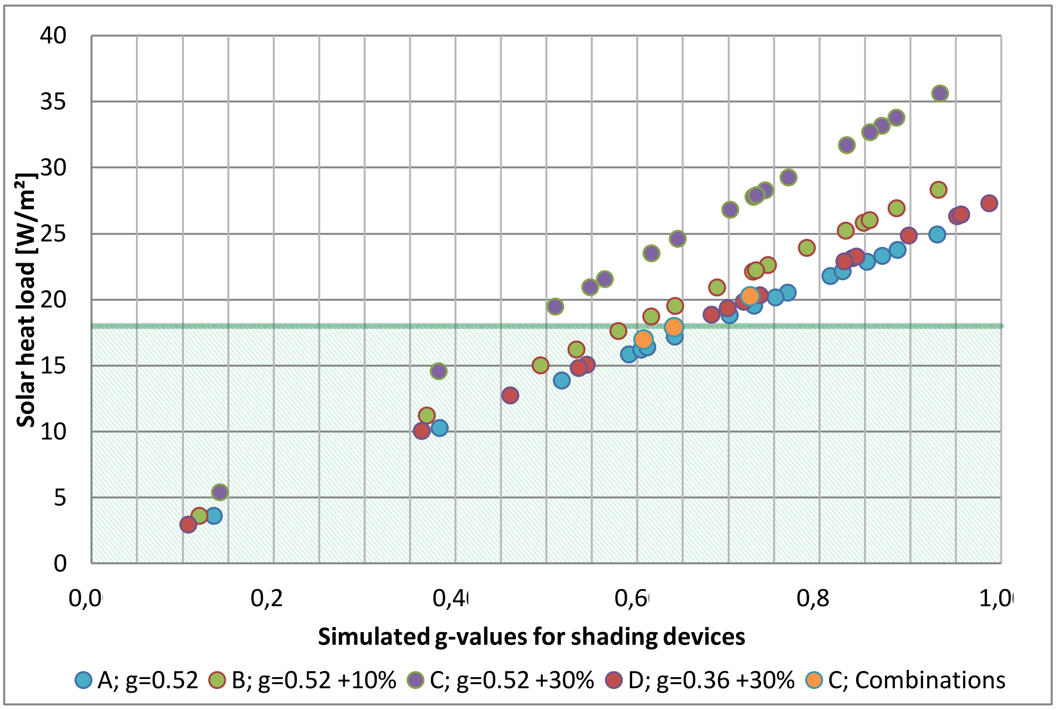

Figure 3: **All simulated cases of shading systems, depending on case. Points in the green area reach the demand of SVL less than 18 W/m².**

Figure 3 shows all the different simulated shadings and which g-values they provide for the different cases. Two different angles of awnings are clearly visible around 0.1 and 0.4 g-value. Higher g-values are obtained for fixed shading, roller blinds and blinds. Points in the green area marks solutions reaching below 18W/m², so several solutions provide sufficient shading to meet the requirements. Only a few of these comply with daylight requirements as most fixed shadings fail to allow light into the building.

To summarize the results, some of the different working solutions will be presented. Increasing window size and/or increasing LT-value enable the building to comply with daylight demands, and the increased solar heat load from those changes can be handled by different shading options.

- If external moveable shading (in this case, awnings) is chosen, any of the four cases will present a working solution
- If internal shading devices are to be used only case A presents a working solution. Case A has a higher reflecting wall paint and the window niches are inclined

- If the roof overhang is extended, case C also presents working solutions combined with internal shading

Final results for these solutions are presented in Table 5 below. The first part contains the requirements and the results of the original building design, the middle part the solutions comprising internal shading devices, and the final one shows the different cases with a closed awning.

Table 5: **Summary of working solutions made up by combinations with different internal shading and external awnings, and their results for all assessed indicators. Different means of comparison are included at the top.**

Parameter	Daylight [%]	Solar heat load [W/m²]	Energy [kWh/m²]	Installed power [W/m²]	Thermal climate winter, PPD [%]	Thermal climate summer, SVF[-]
Miljöbyggnad, level Gold	≥1.2	≤18	≤58.5	≤25	≤10	<0.025
Passive house	-	-	≤55	≤17	-	≤0.036
Original	0.8	19.9	49.9	15.7	8.12	0.025
A & blind	1.2	17.2	48.8	16.2	8.14	0.021
A & roller blind	1.2	16.4	48.9	16.2	8.14	0.020
C & extended overhang + blind	1.4	17.9	49.5	16.8	8.18	0.022
C & extended overhand + roller blind	1.4	17.0	49.6	16.8	8.18	0.021
A & awnings	1.2	3.6	51.0	16.2	8.14	0.005
B & awnings	1.2	3.6	51.0	16.3	8.15	0.005
C & awnings	1.5	5.4	51.7	16.8	8.18	0.007
D & awnings	1.2	2.9	51.8	16.4	8.15	0.004

There are several possible solutions all of which consist of movable, mostly external, shading devices. It can be concluded that it is certainly possible to both follow passive house standards and achieve a high environmental classification, which is a way to ensure good buildings.

Discussion

Several interesting thoughts have emerged during the course of this work. Firstly, window properties will be discussed, secondly shading devices and finally Miljöbyggnad and difficulties with how the indicators are simulated.

Window properties

Specifying window size and glass properties is a very complex issue due to the number of factors they affect. A common problem when trying to comply with environmental classification systems, such as Miljöbyggnad, is the contradicting demands. These demands lead to an optimization process that is iterative in nature, making it somewhat slow and almost impossible if features such as daylight are considered too late in the project. To set a glass area to use would be an over-simplification, and may lead to restrictions in choosing the most appropriate windows. The opposite is also true: specifying a type of window to find a required glass area, which may inhibit the building's figuration. It is essential that these parameters are evaluated early in the process to allow for optimization. Our working concept of focusing on one parameter at a time works reasonably well when considering revisions late in the project, but when designing from scratch a more holistic approach is preferable.

Our suggestion would be to start by deciding which level of demands the building should comply with. Step 2 would then be to look at installed power demands and calculate a required U_{mean}-value. This would have to include an estimation of ventilation and air-leakage losses. Step 3 would involve a basic window placement. A starting point for this step could be to use a glass to floor area ratio of 15%. Step 4 would require a daylight analysis of the building, which gives the required light transmission value for the windows. Several window options could then be suggested based on LT- and U-values, that is required to comply with the U_{mean}-demand. Step 5 is to use these different U-values to determine a required thickness for the other construction parts. At step 6, solar heat load is considered which determines what shading is required for the building.

Since the original building was quite far from reaching the goals set in the classification system, the **window to floor area ratio** chosen for the specified glass type can be questioned. The LT-values of the glass has to be considered when deciding these areas, or the experience of the completed building may deviate from the architect's vision.

The **window niche inclination** has a very small impact on the heating demand but provides a fair amount of additional daylight, but not necessarily in the point specified. Perhaps what this proposal accomplished best is to lessen the sensation of the thick walls.

A simple solution such as using wall paint with **higher reflectance** will improve daylight conditions moderately. This solution combined with carefully suitable windows considering not only the **U-value** but **also g- and LT-values** is needed if low glass to floor area ratios is to be maintained. Results also show that a higher U-value for the glass can be completely offset by an increased g-value when it comes to heating demand. This is highly dependent on orientation and cannot be used as a general rule when choosing windows. Careful considerations must however be done to avoid overheating.

Shading devices

With regard to daylight, moveable shading devices are always preferable, and can be more effective than fixed shading considering annual heating demand. The efficiency is very dependent on the way manual interactions with the shading device are simulated. Simulations of the control in this paper are based on solar intensity. The method of using solar intensity as a control for shading systems is not completely accurate as people need to be at home in order to use solar shading when no automation is present. For annual heating demand, results are on the safe side as the shading device is used more than it likely will be in the real building.

Among the simulated shading devices, several advantages and disadvantages can be found. **Awnings** are the most flexible due to the ability to control their angle from perpendicular to completely covering the window. Exterior shading devices have the advantage of absorbing and reflecting the incoming radiation on the outside of the building, making them more effective in general. A disadvantage of exterior shading devices is their exposed installation making them sensitive to strong winds and subject to heavy wear. This is the opposite of internal **blinds** and **roller-blinds**; they are less effective but the shading device is protected on the inside of the building.

Simulations in ParaSol produce g-values for each month, which can vary greatly depending on the shading device. The g-value chosen for annual heating demand calculations is the lowest g-value obtained, which is for July. Comparing g-values to SVEBY's generic shading coefficient shows that internal shading devices are overestimated in SVEBY, especially for glass with a low g-value. Once again this is not a major problem as it puts annual heating demand calculations on the safe side. For solar heat load calculations, using these values are however not on the safe side.

To reach solar heat load demands, either adjustable awnings or a combination of fixed and internal shadings can be used. A **combination** of awnings and internal shading presents the same effect. For glare reasons internal moveable shading should always be available even if external shading devices are present. Utilizing external shading devices to combat glare issues can have a negative impact on the heating demand. Large windows, or windows with a high g-value, may require external shading to reach sufficiently low g-values as internal shading devices may not be sufficient.

Miljöbyggnad

The original building design has poor daylight compared to the demand stated in Miljöbyggnad. The way the daylight factor is measured affects to which degree solutions are helpful. Since the daylight factor quickly diminishes with increasing distance from the window, measuring the daylight factor at a point at half the room's depth, 1m from the darkest wall can be either beneficial or detrimental depending on the layout of the room. The comparable international environmental classification systems usually use an average daylight factor measured over the area of the room. To achieve Miljöbyggnad's desired daylight levels, several of the solutions had to be implemented simultaneously.

Daylight factor is a measure of quantity during the worst possible conditions. It does not measure the quality of light as too much light will lead to overheating and glare problems. Nor does it consider what happens during less cloudy weather. Cultural differences may play a role in describing what quality of daylight is. Considering the Nordic climate with limited light during winter, to maximize daylight may be the best solution for the residents' well-being.

There are two alternative options in Miljöbyggnad to assess thermal comfort during summer: PPD and solar heat load. One of the most influential factors affecting PPD is the inhabitants' habits regarding voluntary ventilation of the building which is very difficult to simulate accurately due to lack of statistics. The conclusion is that PPD is not a very effective measurement of summer indoor climate in residential buildings. PPD should only be used when cooling is available, as is intended.

The alternative method suggested by Miljöbyggnad, solar heat load, also lacks in some regards. It is based on the maximum solar heat load, which is dependent on whether the shading device is used or not. Assuming manual control, this places a high degree of responsibility on the inhabitants. Using the solar heat load as a measure of thermal comfort may lead to solutions promoting smaller window/floor area ratios, which have disadvantages mentioned in the previous section. Since thermal comfort depends on many factors, solar heat load alone is not an accurate measurement of thermal comfort, neither is indoor temperature. A complementary demand regarding indoor temperature in order to achieve the highest grade could be added in Miljöbyggnad, such as duration limits on over temperatures. We decided that, having these two choices for summer indoor climate, using solar heat load as a measure of thermal comfort was the more suitable for the building investigated.

Conclusions

First of all, it is certainly possible for passive houses to achieve the highest grade in the environmental classification system Miljöbyggnad. However, this requires careful planning and design. General guidelines to help during the early design stage are difficult to create; a direct result of the conflicting objectives of good building design. In this section, the paper's questions are answered and other important conclusions that were drawn along the way are presented.

- How does the choice of windows and solar shading affect the energy usage of a passive house?

The rise in energy usage due to a higher U-value of the window may be completely offset by an increased g-value due to greater solar radiation, but is highly dependent on orientation. An increase in U-value or increased window size will have a negative impact on installed power demands due to lowered mean U-value of the building envelope. All shading devices will have a negative impact on heating demand since solar gain is reduced. Using moveable shading devices could theoretically remove this effect but requires a high-performing control system. Fixed shading devices can be optimized to reduce this effect but only to a certain degree.

- How does the type of windows and solar shading affect the indoor climate conditions of a passive house?

Windows with low g-value limits may make internal shading inadequate to reach indoor climate conditions. Using moveable shading is always preferable when it comes to daylight. Large windows with a higher g-value may require external shading as it is more effective than internal shading. This should then be combined with internal shading in order to control glare.

- How can window to floor area-ratio be optimized with regard to energy and indoor climate conditions (including daylight)?

A starting point for window to floor area ratio should be about 15%. This is highly dependent on the glass used, the layout of the room and surroundings. In order to allow for deeper daylight penetration, windows should always be placed as high as possible on the wall. The suggested path below could be used instead of solely a ratio, as it is more adaptive.

- What factors or connections can be found to simplify decision making when planning windows (type, area, solar shading and orientation) in early stages of construction projects?

The process of determining window size, glass properties and shading devices is iterative in nature. By determining a suitable demand for installed power to be reached will place restrictions on the U_{mean}-value and thus narrows the window choice depending on how well insulated the building is. A daylight analysis should then be made to investigate required LT-values for the windows. When windows have been specified, solar heat load is investigated to specify the shading needed.

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