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Modern insulation requirements change the rules of architectural design in low-energy homes

Lies Vanhoutteghem*, Svend Svendsen

Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118, DK-2800 Kgs. Lyngby, Denmark

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In the design of very well-insulated homes, there is a need for a more nuanced design that takes into account winter and summer conditions. In this paper, we compare a traditional design for a typical Danish single-family house with large glazing areas oriented towards the south and smaller glazing areas towards the north, and a design with an even window distribution where the glazing-to-floor ratio is the same for each room. We found that the use of solar gains through south-oriented windows is not as important as is traditionally believed because, in well-insulated homes, space heating demand is not reduced much by having larger south-facing windows. Furthermore, we found that there is a g-value above which the additional solar gains through south-oriented windows do not help reduce space heating demand, and it becomes important to use solar shading or glazing with solar-control coating as a cheaper alternative to reduce overheating. Maximum window sizes from an overheating perspective were identified that are larger than the optimal window sizes for space heating demand. However, we show that the difference in space heating demand with optimal window size and with larger window sizes is small, so it is up to the building owner to decide whether or not he wants larger glazing areas to allow for more daylight. And windows can be positioned in the façade with considerable architectural freedom. However, we do recommend an even distribution of the glazing-to-floor ratio, because this generally provides an improved thermal indoor environment in south-oriented rooms and will ensure a better daylight level especially in north-oriented rooms. We also show that the optimal window size is influenced by thermal zone configuration and that there is a need for models in which a difference is made between zones with direct and with non-direct solar gains.

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1. Introduction

The tightening of energy requirements strengthens the focus on the design of buildings with low energy consumption. In Denmark, as in the rest of the European Union, building energy consumption represents between 30 and 40 per cent of the total energy consumption [1]. According to the recast of the Energy Performance of Buildings Directive [2], all new buildings should be designed and constructed to have 'nearly zero' energy consumption by 2020. To comply with the principles of the Energy Performance of Buildings Directive, the Danish government agreed on a reduction of energy consumption in new buildings by at least 25% in 2010, 2015 and 2020, giving a total reduction of the energy consumption of new buildings of at least 75% in 2020 compared to 2006 levels [3]. To follow up on policy, architects, engineers and builders need to consider how future new buildings are to be designed and built. Moreover, they will also face the challenge of designing better performing buildings at minimal extra cost compared to new buildings today.

Passive solar design is often considered a central issue in the design of low-energy buildings because utilization of solar heat through the windows is, when properly oriented, a free way of reducing heating and cooling demand. On the other hand, windows are often seen as the weakest part of the building envelope because their overall heat transfer coefficient is larger than that of the other building envelope components. As such, window orientation, size, configuration and the thermal performance of the individual window components can greatly affect the energy use in buildings, which means it is important to select the right window design from the early stages of the design process.

Various studies have tackled the subject of selecting appropriate window size [4–6] and thermal performance of window types [7,8] in residential buildings in different locations. With regard to the

* Corresponding author. Tel.: +45 4525 1855.
E-mail addresses: lieva@byg.dtu.dk, l.vanhoutteghem@gmail.com (L. Vanhoutteghem).

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energy needed for heating, these studies showed that orienting the largest glazing area to the south gives the best performance. Moreover, the overall energy needed for heating decreases with an increase in window size to the south. From a heating perspective, south-facing windows should therefore be as large as possible. Gasparella et al. [8] concluded, however, that savings on heating demand obtained from increasing the glazing area facing south are much less than the increase in cooling demand. Instead, solar transmittance appeared to be more important for heating and cooling demand. Persson et al. [9] showed that to reduce the risk of overheating and the energy needed for cooling in passive houses located in Sweden, there is an optimal size for windows facing south that is smaller than normally used. In contrast to previous studies, they also found that the size of energy-efficient windows in passive houses has no major effect on the heating demand during the winter and concluded that it would be possible to reorient the houses differently without losing too much energy. Furthermore, they suggested that instead of the traditional way of building passive houses, it should be possible to enlarge the glazing area in north-facing rooms. Findings by Morrissey et al. [10] tend to concur with this result. From a comparison of homes designed in accordance with current energy efficiency standards and future improved energy standards, they showed that more energy-efficient homes are less susceptible to effects of orientation. A study by Hassouneh et al. [7] also showed that if energy-efficient windows are used, flexibility in the choice of glazed area and orientation increases.

In the design of very well-insulated homes, the traditional guidelines of having larger windows to the south and smaller windows to the north, aimed at reducing heat loss on the north side while gaining as much solar heat as possible on the south, might therefore not be valid anymore. Instead, there is a need for a more nuanced window design that integrates both summer and winter conditions. Results from monitoring the thermal indoor environment in some of the first passive houses in Denmark [11,12] show overheating in some of the houses and the need to integrate natural ventilation and better solar control. A comparison also showed that houses designed with a more even window distribution (reduced area to the south and increased area in other orientations) were less subject to overheating [13].

To evaluate the selection of a particular window design and its influence on heating and cooling demand, attention should also be given to thermal zoning. Where the building parameters of different zones in a building vary, useful solar gains in each zone will also vary [14]. A study by O'Brien et al. [15] showed that thermal zoning has a significant effect not only on predicted energy performance and thermal comfort but also on optimal design selection, especially in solar homes because these are subjected to high levels of periodic solar heat gains in certain zones. O'Brien et al. suggest that a moderate level of detail should be applied to the issues of thermal zoning even in the early design stages. Yohanis et al. [14] suggest performing analysis of useful solar gains on a zone-by-zone basis to allow for differences in orientation, thermal mass, impact of adjacent zones, etc. However, in current building practice, single-family houses are often modelled as a single-zone. In Denmark, for instance, the program Be10, which is a one-zone model based on method 1 in EN13790 [35], is used to document the theoretical energy use in buildings before approval of construction [16]. This approach requires less model input and less simulation time, but can result in underestimation of energy use.

It can be concluded from the above-mentioned research papers that selecting a good window design is very difficult. The purpose of this research was to provide clear guidance in the design of very well-insulated homes early in the design process by investigating in more detail the choice of window size, type and orientation, and their influence on energy consumption and thermal indoor environment for two window designs: a traditional design with large south-oriented windows and smaller windows to the north, and a window design with a more even window distribution. We also extended the investigation to include three energy performance scenarios defined by the Danish building code: the current energy performance requirements for standard buildings class 2010, and the requirements for low-energy buildings class 2015 and 2020 [17]. Furthermore, we modelled various zone configurations to illustrate their importance in relation to the prediction of energy performance and thermal indoor environment.

2. The building

The building considered is a representation of the size and layout of a typical Danish single-family house. The house consists of one storey and has a heated floor area of 163 m^2, see Fig. 1.

In all scenarios, the external walls were modelled as brick and lightweight concrete cavity walls, the most common construction type in Danish single-family houses [19]. Starting with a design for the house that performs in accordance with the Danish building regulations today, upgrades in insulation thickness and window type were modelled to represent future energy performance requirements for low energy buildings in 2015 and 2020. The requirements are based on the introduction of an energy performance frame, see Table 1. New buildings should be designed so that their primary energy consumption does not exceed the energy performance frame, which includes primary energy use for heating, cooling, ventilation and domestic hot water in residential buildings.

The upgrades and thermal properties of walls, roof and floor are illustrated in Table 2.

In the original design of the house, the glazing area is equal to around 15% of the internal floor area, which is recommended in the Danish building regulations [17] for sufficient lighting conditions in residential buildings constructed in accordance with 2020 energy performance requirements. The glazing area oriented towards south accounts for 63% (15 m^2) of the total glazing area. The rest of the glazing area (9 m^2) is mainly oriented towards the north. If we consider a reference case with even window distribution where the glazing area is equal to 15% of the heated floor area in each room, the glazing area facing south will be reduced by 14%, whereas the glazing area facing north will be increased by 25%.

A constant ventilation rate of 0.5 air changes per hour with heat recovery rates of 80, 85 and 90% has been considered for the 2010, 2015 and 2020 energy performance scenarios, respectively. Infiltration was set to 0.05 h^{-1} through the whole year. To ensure a good thermal indoor environment, natural ventilation through open windows, indicated as venting, was set to 3 h^{-1}. This corresponds to the maximum air flow rate possible for single-sided natural ventilation by automated opening of windows [20]. Previous research [21,22,13] has shown that, in addition to venting, it is very important to integrate external solar shading early in the design to prevent the risk of overheating in very well-insulated homes, even though this is not usually done in northern Europe. Often alternatives, such as large overhangs and interior solar shading are used, but it has been demonstrated that these do not provide enough protection against overheating in very well-insulated homes [22,13]. Therefore, dynamically controlled external venetian blinds were applied, but only to south/west-facing windows of the house, on the assumption that, with a high venting rate, thermal zones with a north/east orientation will have a good thermal indoor environment. Design values for internal gains were implemented in accordance with standard practice in Denmark [20]. Internal gains were considered constant and were set to 3.5 W/m^2 for lighting and

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