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Simulation of indoor environment in low energy housing

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SUMMARY
The aim of this study was to assess whether low energy consumption in dwellings imposes problems by deteriorating the indoor environment. Several indoor environment parameters were correlated with the energy consumption of low energy houses. One house from a village of low energy houses in Denmark was selected and sensitivity analyses were conducted for the importance of occupancy, ventilation, window opening, and heat recovery efficiency. In particular occupancy and venting played significant roles for the indoor environment and energy consumption. It was also shown that with passive measures, but also with the installation of a chiller, a comfortable thermal indoor environment could be achieved with only a minor increase in the energy consumption.

KEYWORDS
Architecture and design, building controls and automation, energy performance, HVAC systems, occupant/user control.

1 INTRODUCTION

With the large share of society's energy consumption that takes place in buildings (40% throughout Europe), it is clear that optimization of buildings' energy performance can provide a significant step towards a more sustainable society (Tommerup et al. 2007; Karlsson & Moshfegh, 2006). The issue of reducing energy consumption in buildings becomes more complicated when also the indoor environment is to be considered. Since the time people spend in all types of indoor environments amounts to almost 90%, designers should not forget that a comfortable and healthy indoor environment is as important as the optimization of the buildings' energy performance (ISIAQ-CIB TG42, 2004).

The aim of the study was to investigate if low energy houses in Denmark comply with the requirements to the indoor environment, i.e. to assess if design for low energy consumption compromises the indoor environment. Also, it was studied how different behavioral and system parameters affect the indoor environment and energy consumption of such houses.

2 MATERIALS/METHODS

An evaluation project had been performed in a settlement of low-energy detached houses called "Fremtidens Parcelhuse" (Detached Houses of Tomorrow) in Denmark (Kristensen et al. 2009). The evaluation consisted of a questionnaire survey among occupants in 28 of the houses and physical measurements in 9 of the houses.

One of the dwellings of the "Fremtidens Parcelhuse" project was selected for a simulation study. Selection criteria were measured and calculated energy consumption and indoor environment of the house. The selected house had an area of 170 m^2 and consisted of three bedrooms, an office, two bathrooms, a kitchen-dining room, a living room, a small entrance and a utilities-storage room. The layout of the house can be seen in Figure 1. The house was equipped with a floor heating system to provide the necessary heat indoors and with a ventilation system to provide clean air to the occupants and to support the heating system to heat up the space. At the design stage, the annual energy consumption of the house had been evaluated with the Danish simulation program BE06, which is the standard tool used to check if the design energy consumption comply with the requirements in the building regulations. BE06 gave results on the energy used for space heating, ventilation and domestic hot water, in total amounting to 55 kWh/m^2. However, the observed energy consumption of the house was 75 kWh/m^2. Since the calculated and observed energy consumption differed the energy consumption was simulated by a sophisticated indoor environment and energy software, IDA-ICE 4.0 (IDA-ICE 4.0, 2009). The simulations would run for a whole year, using climate data from Copenhagen, close to the village and with similar climate conditions.

Furthermore, one very important aspect of the current study was a sensitivity analysis in which the influence on the indoor environment and energy consumption of varying several behavioral and building specific parameters was studied.

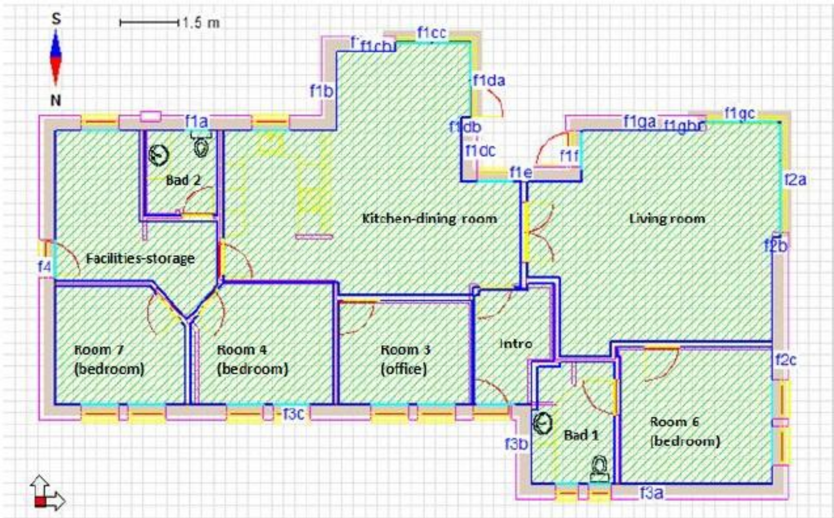

Figure 1: Layout of the house investigated with IDA-ICE 4.

3 RESULTS

The “Fremtidens Parcelhuse” project

The observed primary energy consumption in the nine houses adjusted for degree days, indoor temperature and residents' use of hot water was higher than predicted at the design stage. On average it was 31% above the calculated energy frame by the software used by the stakeholders (BE06), and 13% above the requirement for low energy class 2 according to the current Danish Building Regulations, BR 10, which is 37.1 kWh/m^2 (DEACA, 2010). However, wide variation was observed and one house consumed twice as much energy as calculated, whereas another house had a normalized energy consumption that was only ⅔ of the one calculated. Altogether, seven of the eight surveyed houses had an energy consumption that exceeded what was expected from the calculations made at the design stage and six of the nine houses even consumed more energy than specified in the building regulations.

According to the questionnaire survey (Kristensen et al, 2009), 68% of the occupants expressed that they feel that it is too hot during the summer period. This was the most prevalent complaint among the indoor parameters in focus. Moreover, measurements in the houses provided more solid evidence that overheating should be seriously addressed.

The selected house

The energy consumption that was calculated with the IDA-ICE 4 software was 63.4 kWh/m^2, closer to actual (measured) consumption that was observed in the house. The results from IDA-ICE 4 regarding the thermal indoor environment were compared with the measurement results and provided a clear indication that overheating was a major problem. Maximum operative temperatures reached 30°C in all rooms and in many cases even exceeded this temperature. The room with the most serious overheating problems (maximum operative temperature 31.8°C) was the living room. In April, June, July and August the operative temperatures exceeded by far the maximum desired temperature of 26°C. During a hot day in July (July 15th) it could be seen that temperatures exceeded 30°C and never fell below 27.5°C. A duration diagram of indoor temperatures in the living room showed that for almost 1000 hours the operative temperature was higher than 26°C.

Sensitivity analysis

The effect of occupancy, overheating solutions, window opening, ventilation rate and effectiveness of the heat exchanger and finally infiltration rate on energy consumption and indoor environment was investigated and the main conclusions are provided in the next paragraphs.

Occupancy

The occupancy pattern in the basic model in BE06 was a rough assumption commonly used in conducting building energy calculations in Denmark. Occupants were assumed to be present at all times yielding a constant internal load of 1.5 W/m^2. By assuming a metabolic rate of 1 met, the house should have around 2.5 occupants. This was modeled for the purpose of creating an identical model in the advanced simulation program IDA-ICE 4 as in the simpler BE06, but at this point the occupancy was revised to be more realistic. According to the updated model, the house had four occupants and each occupant had some basic “habits”, i.e. each occupant conducted specific functions every day in specific rooms of the house. Apart from the more realistic model, two more extreme models were created; one with only two occupants in the house and one with four occupants staying inside the house all day. Figure 2 shows that with high internal loads, the space heating demand and the total energy consumption were reduced. With two occupants present, the space heating demand increased.

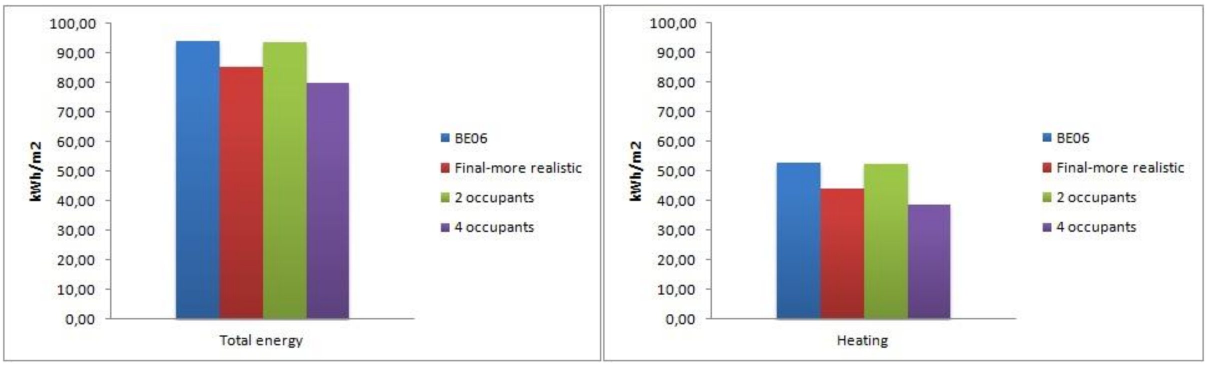

Figure 2: Sensitivity analysis for occupancy. Total energy consumption (a). Space heating demand (b).

For the indoor environment, the results were opposite. For the extreme scenario of four occupants always being present, the IAQ and the indoor thermal environment were significantly deteriorated; the maximum operative temperature reached almost 33°C, the CO_2 concentration in general was above 1200 ppm and in the most problematic room, it exceeded 2300 ppm.

Dealing with overheating

Several solutions to reduce the overheating problems were studied. These included installation of external blinds, introduction of a strategy for controlled window opening in the most problematic areas (kitchen and living room) and finally the installation of a chiller so the underfloor heating system could serve also for underfloor cooling during hot summer days. A combination of the abovementioned solutions provided conditions in which the operative temperatures indoors never exceeded 25.3°C with an increase in the final energy consumption of only 3.1 kWh/m^2.

Window opening

In a Scandinavian climate, window opening may often cause increased building energy consumption and indoor environment complaints due to draught. A very common case where occupants open their bedroom window every morning and also in the afternoon when they return home, was simulated. In this case, energy consumption was significantly increased (11%), mainly due to increased heating demand during the morning venting so that indoor temperatures would return to normal as soon as possible. Furthermore, indoor environment was deteriorated since indoor operative temperatures where significantly lower than 20°C and in some cases they reached 13°C.

Ventilation rate and effectiveness (Eff) of the heat exchanger

The ventilation rate was set to 0.33 l/s per m^2 from the Danish Building Regulations and in the BE06 model. One scenario with 0.43 l/s per m^2 and one with 0.23 l/s per m^2 were chosen for the sensitivity analysis. At the same time, the heat exchanger efficiency was varied in the range from 0.7 to 0.9. Altogether, nine scenarios were simulated and the resulting annual total energy consumption for each scenario is shown in Figure 3.

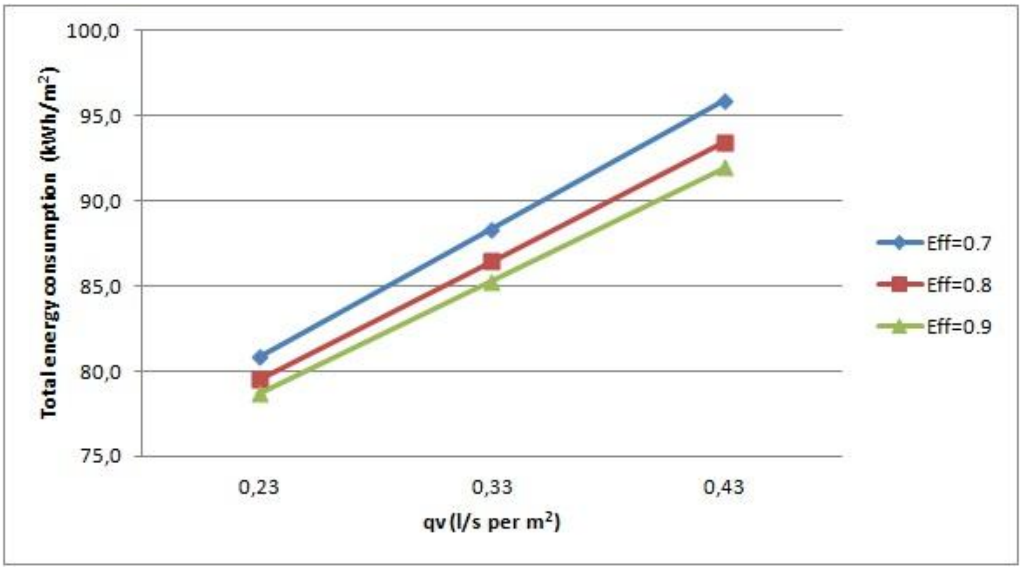

Figure 3: Sensitivity analysis of the total energy consumption with different ventilation rates (qv) and heat exchanger's efficiency (Eff).

Infiltration rate

During the evaluation project passive tracer gas measurements of air change rate were conducted in the investigated houses during two months (March and April 2009). In the selected house the measured air change rate was 0.78 h^{-1}. Since the infiltration rate constitutes a part of the air change rate, it was considered justified to change the infiltration rate so that its effect in energy consumption could be identified. The simulated infiltration rate was changed from 0.5 h^{-1} to 0.78 h^{-1} and it was shown that with the increased infiltration rate, the heating demand and thus the energy consumption was increased (Figure 3).

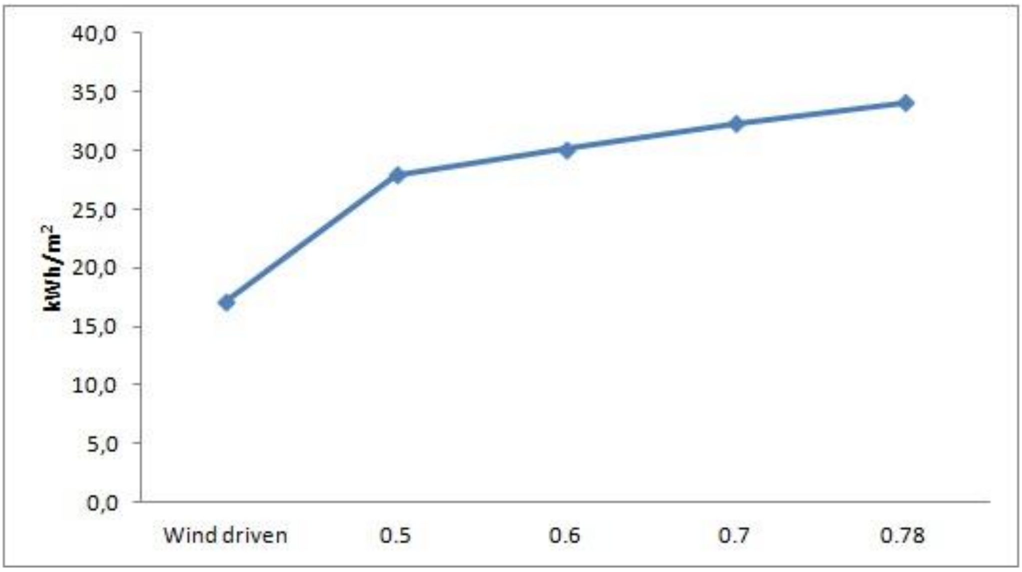

Figure 4: Energy consumption with different infiltration rates. Simulation only for March and April.

4 DISCUSSION

The house that was selected for the detailed analysis did not meet the requirements to low energy housing, since the reported consumption of energy for space heating, ventilation, cooling and domestic hot water was 63.4 kWh/ m^2 per year. According to the Danish Building Regulations the energy consumption should be lower than 37.1 kWh/ m^2 per year.

The observed complaints of overheating were supported by the results of the simulations; during hot summer days, the operative temperatures in some rooms exceeded 30°C. During these days the operative temperature was higher than 27.5°C, even during the night. The occupancy scheme that was suggested by the BE06 software was not considered realistic. For that reason, a sensitivity analysis considering occupancy was conducted. High occupancy reduced the energy consumption, mainly by decreasing the heating demand through higher internal heat gains, but on the other side also deteriorated the indoor environment due to higher operative temperatures, higher CO_2 concentration and higher relative humidity.

A solution to reduce overheating problems was the installation of external blinds in windows, window opening according to a specific strategy, and finally the installation of a chiller to support underfloor cooling when needed in situations with high internal heat gains. Mechanical cooling increased the total energy consumption by 3.6% securing at all times comfortable indoor thermal environment.

It was shown that with uncontrolled window opening the energy consumption significantly increased, mainly due to unnecessary heat loss from indoors to outdoors during the morning when outdoor temperatures were low. The heating demand increased and the thermal environment deteriorated by the lower operative temperatures. Increasing the ventilation rate led to higher energy consumption and increasing the efficiency of the heat exchanger resulted in lower energy consumption. Changing the infiltration rate from 0.5 h^{-1} to 0.78 h^{-1} almost doubled the total energy consumption. The indoor environment was also improved, but the vast increase of energy consumption was not desirable.

5 CONCLUSIONS

The simulations carried out in this study showed that behavioral or system parameters affected the energy consumption of low energy dwellings, so they did not comply with the requirements to low energy houses, even though they may be designed as such. The housing design mostly challenged the indoor environment with high temperatures during the summer, but this problem could be alleviated by reducing the solar irradiation with blinds and modifying the window opening behavior.

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