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Published in:
H V A C Magasinet

Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

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There has been a growing international focus on reducing the energy consumption in buildings. This study evaluates the energy performance and indoor environment of a plus-energy house located in Denmark. The studied house was a detached, single-family house, built for the Solar Decathlon Europe competition in 2012 by the Technical University of Denmark. Different parameters were investigated by means of simulations in order to improve the energy performance and the indoor environment of the house. Some of the investigated parameters were the orientation of the house, positioning and areas of the windows, thermal bridges, and infiltration

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Introduction

Decreasing the energy consumption in buildings will continue to be a vital part of achieving the goal of reducing the greenhouse gas emissions. As the buildings evolve to be more energy efficient, some undesired effects are also being encountered. A result of this evolution is an increase of thermal discomfort for the occupants due to factors such as overheating and poor indoor air quality.
There has been a growing international focus on reducing the energy consumption to reduce the impacts of global warming. The energy used in buildings represents 40% of the total energy consumption in Europe and, as a result, there has been an increasing interest towards zero- and plus-energy houses. The low energy houses have, as a result of the low infiltration, low U-values and often due to large glazing façades, a tendency to overheat resulting in discomfort for the occupants, Larsen (2011).
This study focuses on a plus-energy house, Fold, which was designed for an international student competition Solar Decathlon Europe 2012 by the students of Technical University of Denmark. Fold is a plus-energy house because it produces more energy than it consumes on a yearly basis, Kazanci et al. (2013), Kazanci et al. (2014). The house was located in Denmark and since September 2013, it has been used as a full-scale experimental facility where different heating, cooling and ventilation strategies had been tested. Various physical parameters were measured, as well as the energy production and consumption. Even though the house is classified as a plus-energy house due to the electricity production by the photovoltaic/thermal panels placed on the roof, there is potential for improvement regarding the energy consumption and indoor environment.
The main goal of this study is to provide improvement suggestions (i.e. lowered energy consumption and improved indoor environment) based on the parametric analyses, carried out with computer simula- ▷

This paper was presented at ROOMVENT 2014, 13th SCANVAC International Conference on Air Distribution in Rooms, Sao Paulo, Brazil.

Figure 1: The South façade (top) and the North façade (bottom).

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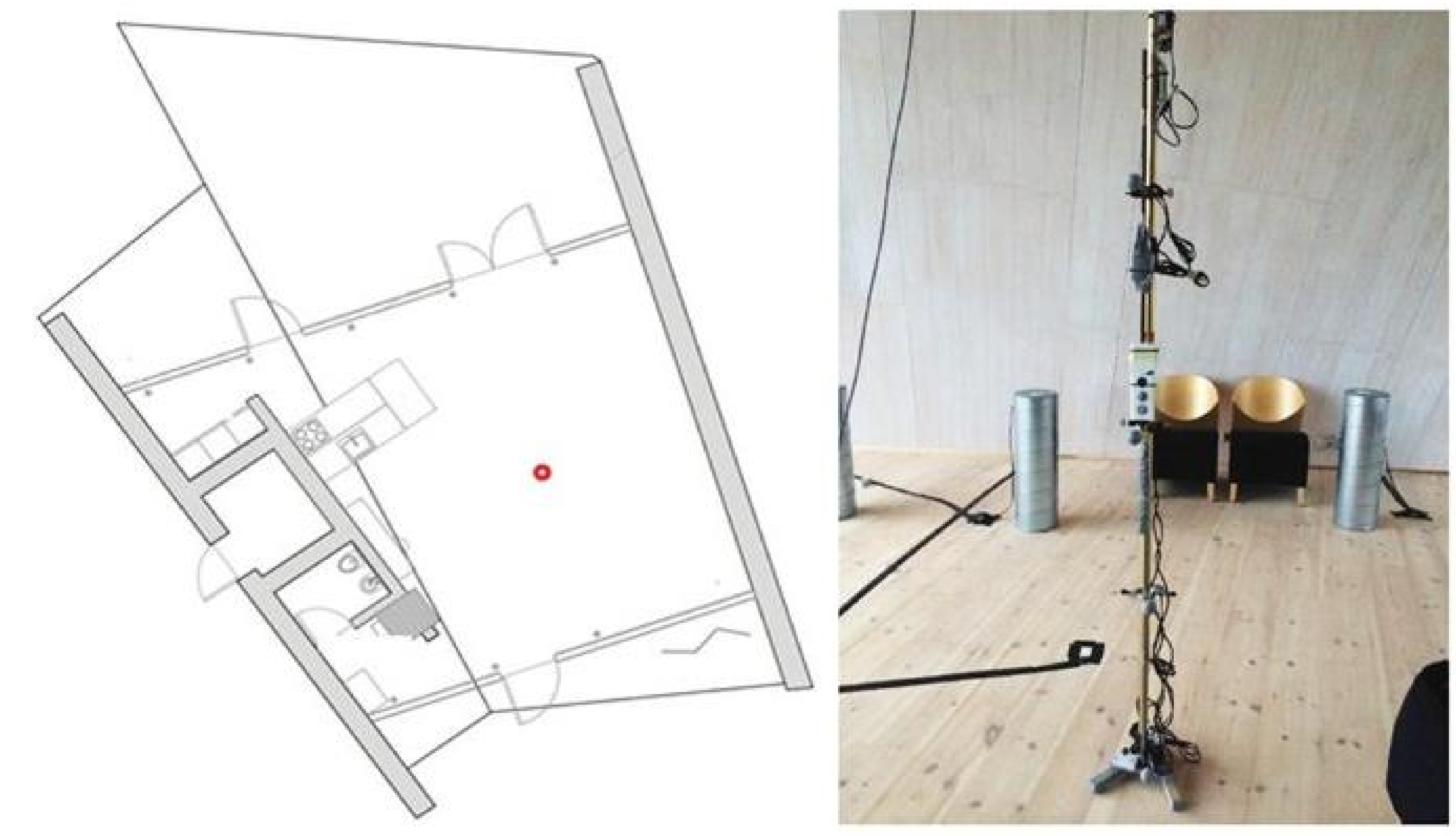
tions which are validated with measurements. One of the main focuses has been on the window area and the respective heating demand, as indicated by previous studies, Skrupskelis and Kazanci (2012), Kazanci et al. (2014).
The effects of different parameters which affect the energy performance and indoor environment of the house were studied by means of commercially available building simulation software IDA ICE. Operative temperatures obtained from the simulation model and from the house were compared in order to validate the simulation model. The energy consumption of different components of the HVAC system was also compared.


The location of the measurements (left) and the measurement equipment (right).

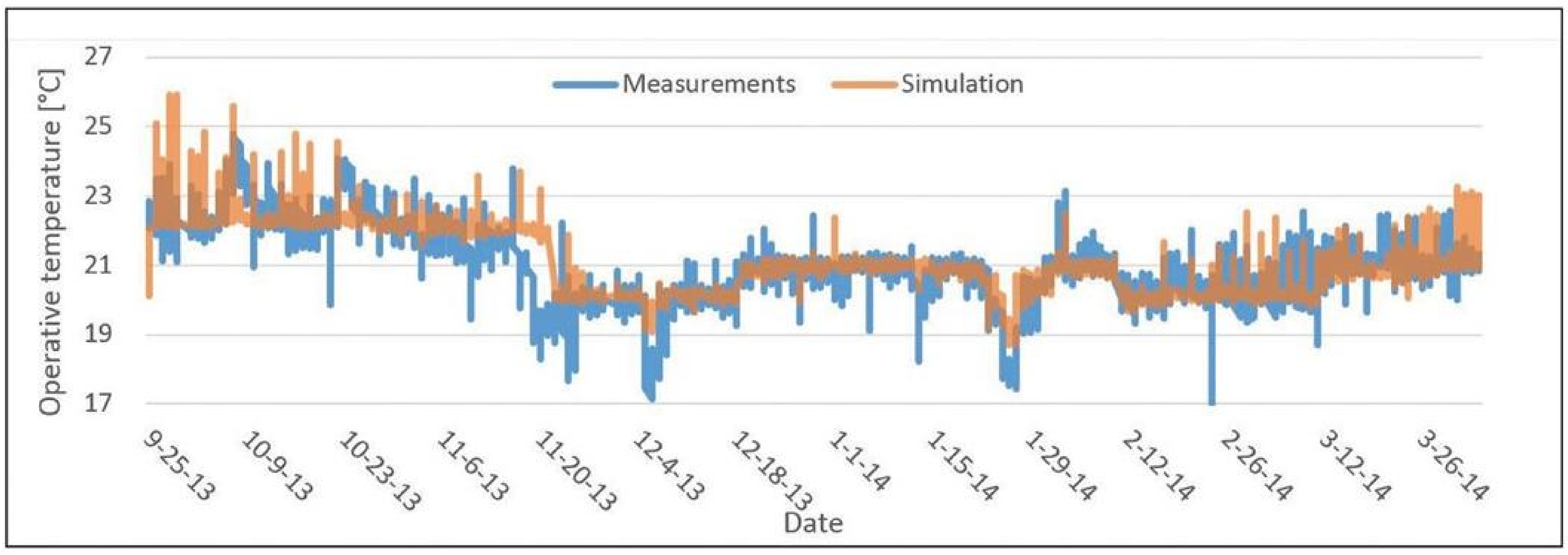


Figure 3: Comparison of operative temperature at 1.1 m.

House details

The house considered in this study was a single family, detached, one-story house with a floor area of 66 m^2 and a conditioned volume of 213 m^3. The house had two large glazing façades oriented towards North and South. The largest glazing façade was oriented towards North with a 19° turn towards the West. The house and its two glass façades may be seen in Figure 1.
The U-value of the external walls was 0.09 W/m^{2}K and the glazing facades had an average U-value of 1.04 W/m^{2}K.
The HVAC system of the house consisted of a reversible air-to-brine heat pump, water-based radiant heating and cooling system and an air handling unit that was coupled with the domestic hot water tank via a reversible air-to-water (or water-to-air, depending on the operation mode) heat pump.
There was a flat plate heat exchanger placed in between the hydronic loops of the house and the heat pump in order to avoid frost damage during the winter months.
The main sensible heating and cooling strategy of the house relied on the low temperature heating and high temperature cooling principle via the hydronic radiant system. There were pipes embedded in the floor and in the ceiling structure. The embedded pipes in the ceiling were designed to be used for cooling purposes while the embedded pipes in the floor could be used for heating as well as cooling during the peak loads. Four loops were located in the floor and six loops in the ceiling. A mixing station was installed in the system, in order to control the flow to the individual loops, the flow rate, and the supply temperature to the embedded pipes.
Fresh air to the house was provided by an air handling unit (AHU). Passive and active heat recovery options were available in this AHU. The passive heat recovery was obtained by a cross-flow heat exchanger while the active heat recovery was obtained by a reversible air-to-water heat pump that was coupled to the domestic hot water tank. The air handling unit could supply fresh air at a flow rate of 320 m^3/h at 100 Pa. The design ventilation rate was determined to be 0.5 ach. Humidification of the supply air was not possible due to the limitations of the air handling unit.

Physical measurements and the simulation model

During the measurement period, air and globe temperatures were measured at a representative location and at different heights. The measurements of the globe temperature at a height of 1.1 m (operative temperature for a standing person) were used for the comparison of the measurements with the simulation results.
The geometry of Fold was modeled in Google SketchUp to construct the advanced shapes of the house. The geometry was then imported into IDA ICE where windows, constructions and other parameters were specified. The Early Stage Building Optimization (ESBO) tool in IDA ICE was used as a base for the implementation of the HVAC system. The ESBO HVAC system was then modified in order to represent the real system.
A weather file was constructed with experimental weather data located 25 km away in a straight line from the house to eliminate as many sources of errors as possible. The weather file consisted of six parameters: dry-bulb temperature, relative humidity, wind direction, wind speed, direct normal radiation and diffuse radiation on a horizontal surface. The first four parameters were obtained directly from the datasheets of the weather station. The solar radiation parameters were calculated from the global solar radiation in the datasheet according to the method described in Kragh et al. (2002).

Results

The results from the measurements, simulations, comparisons and the results of the improvement suggestions are presented.

Temperature

Figure 3 shows the operative temperatures from the measurements and from the simulation results.
It may be seen in Figure 3 that the temperature predicted by the simulations has a tendency ▷

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to be higher than the measurements. The relative difference between measurements and simulation results was 2.7% during the measurement period. It was observed that the difference was higher when there was direct solar radiation. When this contribution was higher than 100 W/m², the relative difference between the two temperatures increased to 4.6%.

Energy consumption
A comparison of energy consumption for the heat pump and the ventilation system was conducted for the simulation and measurements. In order to obtain the energy consumption from the simulations, the power in the given time step was multiplied with the length of the time step. Furthermore, the power output from the ventilation system had to be re-calculated using Coefficient of Performance (COP) values given by the manufacturer.
The result showed that the energy consumption in the simulations was 13.7% lower for the heat pump and 23% lower for the ventilation system compared to the actual energy consumption.

Improvements
Based on the measurements in the house and the simulation model, several improvement options were investigated. In order to compare the different scenarios, the thermal indoor environment was evaluated according to EN 15251 (2007) (based on the operative temperature). The energy consumption was also taken into account when comparing the different improvements.
Previous studies have shown that a major concern regarding Fold is the high heating demand, Kazanci et al. (2014), and since the current study uses the data obtained from the heating season, the focus of the improvements were to minimize the heating demand. Nevertheless, improvements regarding the cooling season were also investigated.

The improvements with the highest impact regarding both thermal indoor environment and energy consumption were reducing the window area and infiltration. The results of the investigations on these improvements are presented in table 1 and table 2.
In these tables, the reference case refers to the current state of the house. The values for the reference case are obtained from the IDA ICE model.
When the window areas were reduced, the daylight in the house was also considered in order to assure that the daylight levels abided the regulations of 200 lux based on the Danish Building Regulations, Energistyrelsen (2014). The investigation showed that the reference case abided the regulations 93% of the time. The case with the smallest window area abided the regulations 82% of the time.

In Table 2 the values for the infiltration are given at an induced pressure of 50 Pa.
Different alternatives were also investigated in addition to the previously explained parameters:

- Different orientations of the building.
- Thermal bridges.
- Automatically controlled exterior solar shading (there was no solar shading except the overhangs).
- Natural ventilation. Natural ventilation was provided from 10% of the window area in the glazing façades that could open and it was controlled based on the temperature set-points in the house.
- Thermal mass was simulated by adding 0.1 m concrete in the walls.
- An increased embedded pipe system (EPS) area was simulated with EPS installed in the walls

The respective results of these variations are given in Andersen & Schøtt (2014).

Optimized Fold
An optimized version of the house was proposed to make it more energy efficient and improve the indoor environment. In the optimized house, the area of the glazing façades was reduced by 25% and the U-value of the glass was lowered to 0.5 W/m²K. The infiltration was set according to the require- ▷

Window area reduction		Reference	5%	10%	15%	20%	25%	38%	58%
Indoor environment category	I	71%	74%	76%	79%	81%	84%	89%	94%
	II	27%	24%	22%	20%	17%	16%	11%	5%
	III	2%	2%	2%	1%	1%	1%	1%	0%
	IV	0%	0%	0%	0%	0%	0%	0%	0%
Energy consumption	kWh/year	6371	6151	5943	5729	5519	5311	4742	4125

Table 1: Results of reduced window area.

Infiltration (L/s/m²)		Reference (5.3)	1.5	1.0	0.5
Indoor environment category	I	71%	80%	81%	81%
	II	27%	19%	18%	18%
	III	2%	1%	1%	1%
	IV	0%	0%	0%	1%
Energy consumption	kWh/year	6371	5552	5438	5323

Table 2: Results of reduced infiltration.

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ments for Danish houses in 2020, Energistyrelsen (2014), and the thermal bridges were reduced to make it more appropriate for a modern house. In the optimized house, there was also natural ventilation. The results of the thermal indoor environment and total energy consumption for the reference case and the optimized cases are shown in table 3.

The optimized model significantly improved the thermal indoor environment and there was no duration when the operative temperatures were outside the range of category II according to EN 15251. Furthermore, the temperature never exceeded 26°C, indicating that there was no overheating. The energy consumption was reduced by 68% when the proposed improvements were implemented.

		Reference	Optimized
Indoor environment category	I	71%	97%
	II	27%	3%
	III	2%	0%
	IV	0%	0%
Energy consumption	kWh/year	6371	2023

Table 3: Results of the optimized house.

Discussion

Despite being designed and constructed as a competition house, the house could still be improved in different ways. This study investigated some of the parameters that could be improved.

Various factors could have caused the discrepancies between the measurements and the simulation results. The house had been transported and it had been assembled (three times) and disassembled (two times). Hence it is likely that the infiltration and thermal bridges changed from the original values. In addition, the house had been stored in containers for several months, which could have lowered the performance of the building envelope.

By building a new house, the infiltration and the thermal bridges will be reduced. The cost of these improvements is estimated to be minimal. Most of the proposed improvements in this study are changes that would have to be made in the design stage of the house. For example, it would be troublesome to change the overall design of the glazing façades after the construction is completed, hence the practicality of the different improvements should be considered. It would, however, be possible to change some of the windows with insulated wall segments.

Conclusion

The measurements were used to validate the simulation results in this study. It was found that the average relative difference in operative temperature between the simulations and the measurements was 3%. The relative difference in energy consumption for the heat pump was 14% and for the ventilation system was 23%. The simulations were used to investigate the effects of several parameters, such as window area reduction, infiltration, thermal bridges, orientation, exterior solar shading, natural ventilation, thermal mass and increased embedded pipe system area, on energy consumption and thermal indoor environment.

The simulations showed that the most important improvement was to reduce the heating demand of the building by reduction of the window area, infiltration and thermal bridges. The improved house design performed better in both thermal indoor environment and energy consumption than the reference case. The duration in indoor environment category I of EN 15251 increased from 71% to 97% and the annual energy consumption was reduced by 68% compared to the reference building.

Acknowledgements

This study was supported by Elforsk, project number 344-060, titled "Sustainable plus-energy houses".

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