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Passive House Renovation of an Old Multi-Storey Office Building – Analysis and Monitoring

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Abstract

Denmark is participating in IEA Annex 61 "Development and demonstration of concepts for deep energy retrofit in government/public buildings". The purpose of the Annex is to improve the decision-making process to achieve deep energy retrofits of government/public buildings, starting with the determination of bundles of technologies and corresponding business models using combined public and private funding.

Denmark has contributed to the project with several buildings that serve as case-studies. One of these is a multi-story office building from 1938. The office building has undergone a comprehensive energy retrofit and the overall purpose was to reduce the energy consumption to a level corresponding to the requirements for the German Passiv Haus standard. The initial calculations performed with PHPP (Passive House Institute, 2013) showed that the selected renovation package would achieve this goal.

Measurements of the energy consumption were performed both before and after the retrofit of the building, and these measurements showed that the renovated building did not perform as expected and therefore did not meet the initial goal of reaching the Passiv Haus level, i.e. 15 kWh/m^2 for heating and cooling. The discrepancies between measured and calculated consumption lead to an extensive investigation in search of explanations and possibly methods of reducing the energy consumption of the building to perform similarly to the calculation model. This paper describes the retrofitting carried out for the building and the process of explaining the discrepancies between measured and calculated results.

Keywords - Passive House, Renovation, Office Building, Analysis and Monitoring

1. Background

The office building is situated on Vester Voldgade 123 in Copenhagen, Denmark. Denmark has a temperate climate, characterized by mild winters, with mean temperatures in January of 1.5 °C, and cool summers with a mean temperature in August of 17.2 °C. The mean temperature in the heating season is 5.5 °C.

The building was constructed in 1938 and was initially used as a post terminal. The building was one of the first and largest in-situ cast concrete buildings in Denmark. The building was erected on ancient seabed and therefore supported by concrete piles to approximately -7.5 m below ground. The floor of the basement is reinforced concrete deck, and the concrete piles form significant thermal bridges to the underlying and colder soil layers.

The building was constructed with a load-bearing slabs-/beams-system which resulted in a large degree of freedom in the design of the interior areas. After the post terminal moved to another building the interior was changed to function as an office building. Since the building was originally designed as an industrial building it has relatively thick concrete floor slabs and thus a relatively large thermal mass.

Fig. 1 The office building before retrofit

Facades were originally made up of 150 mm reinforced in-situ cast concrete with 40 mm wood-cement finished inside with 10 mm plaster.

The building is currently owned by the Danish Property Agency and before the retrofit it was used by the Ministry of Education. Today the building is used in part by two different ministries. In addition to its function as an office building, parts of the ground floor houses a kindergarten.

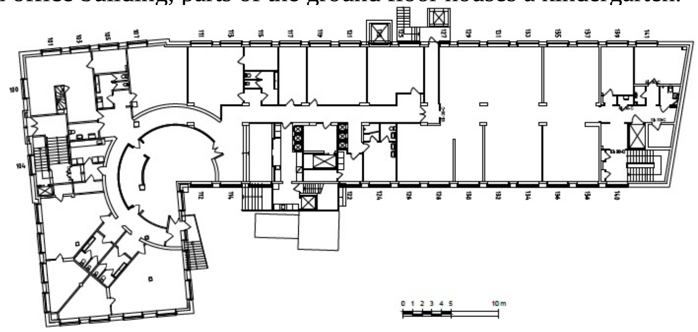

Fig. 2 Typical floor plan of the office building

2. Methods

The initial project proposal only included replacement of windows and replacement of corroded water installations in the building. However, calculations showed that the additional investment of performing a more thorough energy renovation was profitable. The final comprehensive energy retrofit ended up consisting of the following additional elements:

- Extensive exterior insulation of the facade incl. basement walls below ground
- Insulation of thermal bridges in wall/roof joint, at outside concrete stairs and other joints
- General air proofing of the building envelope and subsequent testing by blower-door (aim was an air change < 0.6 h^{-1} at 50 Pa pressure) according to the Passiv Haus definition
- Rainwater harvesting from approx. 1,200 m^2 roof for use in toilet flushing
- New water pipes incl. technical insulation to most stringent Danish insulation requirements
- Automatic exterior shading of windows on southeast and southwest facades
- New LED lighting in corridors and offices. In offices the lighting is controlled based on daylighting and movement sensors (PIR)
- New CAV ventilation for offices with an air-change-rate of 1.5 h^{-1} during office hours
- New VAV ventilation for meeting rooms with a variable air-change-rate of 0-5 h^{-1} controlled by temperature- and CO_2-sensors

- Preheating and cooling of CAV ventilation air using horizontal ground collectors and two 21 m deep wells (top of limestone layer). Groundwater is about 3.5 meters below ground
- 35 m^2 solar collectors connected to a storage tank for storage below the building. The purpose of the storage is to reduce heat losses to the ground. This reduces the heat loss via the poorly insulated basement floor incl. thermal bridges through the foundation and supporting concrete piles

Renovation began in 2011 and was completed in January 2013. Table 1 sum up the renovation project.

Table 1. Summary of information regarding the renovation project

Owner:	Year of construction:		Address:
Danish Property Agency	1938		Vester Voldgade 123, Copenhagen, Denmark
Consultant:	Area:		Energy label:
Lars Ørtoft Consulting Engineers A/S, Jesper Strunge Jensen Consulting Engineers A/S	Basement: 1. – 4. floor: Room height:	1,274 m^2 5,460 m^2 2.85 m	Before: F After: A1
Architect:	Estimated costs:		Use:
tnt Architects A/S	Initial project: Energy retrofit: Total:	1.60 mill. € 1.33 mill. € 2.93 mill. €	Offices and kindergarten
Contractor:			
G.V.L Contracting A/S			

Fig. 3 The office building after retrofit

3. Results

The total heating consumption for the building was measured prior to the energy retrofit. Table 2 shows the measured consumption corresponding to 3 years before the retrofit. The table shows both the actual measured consumption and also the degree-day adjusted consumption.

Table 2. Measured and degree-day corrected heating consumption before retrofit

	2009-2010		2010-2011		2011-2012	
	Meas.	Corr.	Meas.	Corr.	Meas.	Corr.
Consumption, MWh	548.0	573.8	660.0	604.3	540.0	630.1
Consumption, kWh/m^2	106.2	111.2	127.9	117.1	104.7	122.1

The mean corrected value is 602.7 MWh which includes the domestic hot water consumption.

There is no separate meter on consumption or distribution of hot water and therefore this is taken as the total district heating consumption during summer, when there is no need for heating the building. The consumption for domestic hot water including heat losses in pipes etc. has hereby been determined as approx. 25 MWh/year, corresponding to approx. to 75 l/m^2 per year heated from 10 °C to 55 °C.

Before the energy retrofit the electricity consumption was measured as 96,540 kWh/year (on average for the years 2008-2009).

In order to evaluate the proposed energy retrofit of the building, the expected energy consumption for the renovated building was calculated. The calculation was performed using standardized values for building use etc. Table 3 shows a summary of the calculated results.

Table 3. Calculated energy consumption after the energy retrofit [MWh]

	District heating			Electricity		
	Heating	DHW	Total	Build. ops.	Other	Total
Consumption	129.9	29.7	159.6	79.8	84.8	164.6

Comparing the measured results before retrofit and the calculated energy consumption after retrofit yields expected energy savings of 468.1 MWh heating energy and an increase in electricity consumption of 68.1 MWh. The increase in the electricity consumption was expected since the internal alterations of the building corresponds to a change from one person cell offices to more intensively used open plan offices (typically with 4 people) on the same area as two people used before. A doubling of the number of people would inevitably increase the electricity consumption (and also the internal heat gains).

Measurements were performed after the retrofit and these results did not match the calculated values. In fact there was a huge discrepancy between the measured and calculated consumption after retrofit. The measured values after the retrofit are shown in table 4.

Table 4. Measured energy consumption after energy retrofit [MWh]

	District heating			Electricity		
	Heating	DHW	Total	Build. ops.	Other	Total
Consumption	258.9	25.0	283.9	-	-	142.4

The actual measured energy savings for the building was therefore 343.8 MWh heating energy and an increase in electricity use of 45.9 MWh, meaning that the heating energy savings were significantly overestimated by the calculations.

This lead to a comprehensive investigation of the building's energy consumption since something was clearly not as expected. The investigation revealed quite a few possible explanations for the differences in calculated and measured results.

Most importantly the investigation showed that the building's heating plant supplies two separate buildings on the premises, i.e. a kindergarten and a gardener's lodge with heating and hot water. These buildings would supposedly have the same consumption before and after the retrofit since they were not altered in the process and their consumptions were evaluated as 19.1 MWh and 34.0 MWh respectively. In addition to this the two extra buildings supplied by the heating central in the office building would also result in additional heat pipe losses of 5.3 MWh.

Another important aspect that was revealed in the inspection of the building was that the quite complex energy systems were not performing as intended, e.g. the solar energy storage below ground was not utilized properly. This meant that the energy consumption after the retrofit was approx. 50 MWh higher than originally expected. Table 5 shows the correction of the measured values before/after retrofit.

Table 5. Measured district heating consumption before/after retrofit with corrections [MWh]

	”before”	”after”
Gross district heating consumption	602.7	283.9
- heating kindergarten	34.0	34.0
- heating gardener's lodge	19.1	19.1
- heat losses from pipes	5.3	5.3
- domestic hot water use	25.0	25.0
- commissioning issues	0.0	49.3
Net district heating consumption	519.3	151.2

These corrections to the measured consumption would help close the gap between measured and calculated consumption, however there were still quite significant differences between the actual and theoretical consumption.

A model was therefore created to also calculate the energy consumption before the energy retrofit. Table 6 shows the calculated results along with measured results for comparisons. Calculated results are obtained using the Danish compliancy checker Be10 [2] which is very similar to PHPP (as will be shown later).

Table 6. Calculated and measured energy consumption before/after energy retrofit [MWh]

	District heating			Electricity		
	Heating	DHW	Total	Build. ops.	Other	Total
Calc. before	476.3	28.9	505.2	84.1	78.9	163.0
Calc. after	129.9	29.7	159.6	79.8	84.8	164.6
Calc. savings	346.4	-0.8	345.6	4.3	-5.9	-1.6
Meas. before	519.3	25.0	544.3	-	-	96.5
Meas. after	151.2	25.0	176.2	-	-	142.4
Meas. savings	368.1	0.0	368.1	-	-	-45.9

If the calculated and measured results in table 6 are compared it is clear that there are still some significant discrepancies in results. The calculation model underestimates the heating energy consumption both before and after retrofit and on the other hand it significantly overestimates the electricity use, especially in the before situation. Therefore the models were changed and all inputs for the models were qualified as far as possible using the actual data from the building, i.e. not using standardized input for internal heat gains, indoor temperature etc.

The results corresponding to the revised calculation model are given in table 7.

Table 7. Calculated energy consumption before/after energy retrofit, revised model [MWh]

	District heating			Electricity		
	Heating	DHW	Total	Build. ops.	Other	Total
Calc. before	557.3	22.2	579.5	83.6	13.9	97.5
Calc. after	142.6	22.6	165.2	57.8	83.7	141.5
Calc. savings	414.7	-0.4	414.3	25.8	-69.8	-44.0

If the calculated results from table 7 are compared with the measured results from table 6, it is clear that the calculation model now overestimates the savings in the district heating whereas there is a good correspondence between the calculated and measured electricity consumption. The model overestimates the heating energy use before the retrofit by 6.5 % and underestimates the heating energy use after retrofit by 6.2 %, meaning that savings are overestimated by more than 12 %.

Fig. 4 Solar thermal installation on the roof (left) and automatic solar shading (right)

4. Discussion

Measurements and calculations of energy consumption before and after a comprehensive energy retrofit of the office building located Vester Voldgade 123 have been carried out. Table 8 shows the final results after an extensive analysis of the building systems. The “Be10 standard” refers to the calculation where the input data is taken as standardized values. The “Be10 qualified” and “PHPP qualified” calculations refer to the situation where the data is qualified as far as possible.

Table 8. Calculated and measured energy consumption before/after retrofit

	Before		After		Savings	
	Heat.	Elec.	Heat.	Elec.	Heat.	Elec.
Measured	544,3	96,5	176,2	142,4	368,1	-45,8
Be10 standard	505,2	163,0	159,6	164,6	345,6	-1,6
Be10 qualified	579,5	97,5	165,2	141,5	414,3	-44,0
PHPP qualified	570,4	99,4	158,4	141,8	412,0	-42,4

The measurements of energy consumption before and after the retrofit and thereby the achieved energy savings still differ from the corresponding calculated results. For the two models where the input is qualified to match the actual parameters for the building there is a reasonably good agreement between measured and calculated energy consumption. Heating energy savings are still overestimated in the models by approximately 12 %. However, it is important to note that the measured consumption before retrofit actually differs more than 10 % from year to year, even after degree day correction. This indicates that a 10 % discrepancy between measured and calculated energy savings is a reasonable deviation and that it is difficult to get closer without having even more specific data on the use of the building, indoor temperatures etc.

The calculation using standardized values actually comes pretty close to estimating the heating energy savings; however this is pure coincidence since it significantly underestimates the heating energy consumption both before and after the retrofit.

The two calculations corresponding to Be10 with qualified parameters and PHPP with qualified parameters provide reasonably similar results for district heating consumption before and after energy renovation, but since consumption before is overestimated by up to 6.5 % and consumption after is underestimated by up to 10 %, the calculated energy savings ends up being approximately 12 % too high. The electricity consumption before renovation is overestimated by up to 3 % and the electricity consumption after is underestimated by approx. 0.5 %. This means that the calculated additional consumption is underestimated by up to 7.5 %.

Comparing the differences between the calculated and the measured energy consumption it is clear that the deviations between the calculated consumption (qualified models) and measured consumption can easily be explained through further alignment of the input data for the programs. This has not been done since there is no data to support the further alignment of the models. It should be noted in this context that it is energy consumption before that has the largest deviations and this is an effect of the before-situation not being very well known since it was not investigated in detail before after the renovation was completed.

5. Conclusion

In summary, it can be concluded that through a detailed and careful qualification of input data for energy calculation programs such as the Danish compliancy checker Be10 and the Passiv Haus calculation tool PHPP, it is possible to perform calculations of energy consumption before and after an energy-renovation, and thus determine the expected energy savings with reasonable accuracy. In order to achieve ‘correct’ calculations it is crucial to qualify the input data as much as possible and therefore it is very important to have detailed knowledge of the building constructions, temperatures, ventilation volumes, domestic hot water consumption, electricity consumption, use of building (operational hours) etc. both before and after the retrofit. The more accurately these parameters are known the higher level of consistency can be achieved between modelled and actual consumption, and standard values will often lead to discrepancies.

Another important conclusion that can be drawn from this project is the importance of commissioning. In 2014 a Danish Standard was introduced [3] and this project has underlined its importance for complex buildings or where systems are utilized in new and innovative ways, i.e. the solar storage below the building was not working and not performing as expected and this was realized because a very thorough investigation was carried out. New buildings and buildings undergoing deep energy retrofit will often contain very complex HVAC systems and there is a need to make sure that these systems are performing as planned before the building is handed over to the users.

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