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Indoor environment and energy consumption optimization using field measurements and building energy simulation.

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Abstract

Modern buildings are usually equipped with advanced climate conditioning systems to ensure comfort of their occupants. However, analysis of their actual operation usually identifies large potential for improvements with respect to their efficiency. Present study investigated potential for improvements in an existing office building – a Town Hall of Viborg, Denmark. Thorough field measurements of indoor environment and occupant satisfaction survey were conducted to identify and describe indoor environmental quality problems. Collected data were also used to calibrate computer simulation model, which was used for optimization of building's performance. Proposed optimization scenarios bring 21-37% reduction on heating consumption and thermal comfort improvement by 7-12%. The approach (procedure) can help to optimize building operation and shorten the adjustment period.

Keywords: Indoor environment; optimization strategies; field measurements; energy performance simulation

1. Introduction

The European Union (EU) is willing to lead a post-industrial revolution, attempting to lower CO_2 production and to reduce the dependency on fossil fuels. EU realizes that integration of renewable energy sources is necessary to achieve ambitious targets set by European Energy Policy [1] for 2020 and 2050. The Danish government being not just loyal to the European regulations, but setting an example in sustainable development introduced an ambitious plan. It contains several energy policy milestones in order to reach 100% energy coverage from renewable sources

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by year 2050 [2]. Aforementioned ambitious targets as well as the fact that the building sector is a main shareholder in energy use and in global annual greenhouse gas emissions indicate that there is a need to ensure energy efficient design and operation of buildings. Use of simulation software can strongly support this effort. Extensive use of Building Information Modeling (BIM) and Building Performance Analysis (BPA) is reshaping the way the buildings and their systems are designed [3] today. The building simulation is increasingly used in during design of buildings and their HVAC systems, but it is still rather seldom used subsequently to optimize building's operation [4]. Such simulation aiding operational diagnostics represents a great potential as it can serve as a "playground" for engineers dealing with the task of optimization. Moreover, a recent study [5] concluded that building's energy consumption can be reduced significantly when using the building optimization coupled with computer simulation. Creative and innovative ideas regarding the optimization of HVAC systems can be tried out without direct involvement of the actual building.

1.1. The challenge

Optimization of building's operation can save up to 14% of energy use simply by changing/adjusting the control settings to optimize the operation of the HVAC systems [4]. The goal now is to investigate different optimization approaches. The one followed in this paper was: 1. Preform field measurements and occupant satisfaction survey; 2. Conduct data analysis & identify problems; 3. Create building performance simulation model calibrated according to field measurements; 4. Use the calibrated model to suggest improvements that address identified problems.

1.2. Case Study: Viborg Town Hall

New Town Hall, designed by Henning Larsen Architects [6] and constructed by COWI [7] in 2011, is accommodating municipality of Viborg, see Fig. 1. It is a five-story building with a gross floor area of 19,400 m^2. The Town Hall's energy consumption was designed to meet the requirements for low energy class 1: (50 + 1100/Heated Area) kWh/m^2, according to Danish building regulations [8]. This was achieved by compact building geometry, energy-efficient glazing and solar protection, natural ventilation and mechanical ventilation with heat recovery (efficiency 85%), and district heating as well as groundwater cooling. All installed systems are managed by an intelligent Building Management System (BMS) that measures indoor air quality and temperature. It also controls natural ventilation openings in the building envelope. Mechanical ventilation is used only in meeting rooms and canteen.

Fig.1: (a) Interior view of the atrium with broad staircase; (b) Town Hall architecture and landscape. Photo: [6]

2. Methods

2.1. Field measurements and questionnaire survey

Data measurements (operative temperature, air temperature, CO_2) with 10-15 min. time intervals were carried out in Viborg Town Hall from October 2012 to February 2014 with 10 individual measuring stations. Most of them were located in open plan offices in different floors and with respect to the orientation.

In order to evaluate occupants' satisfaction with indoor environmental quality, questionnaires were distributed via Internet among employees working at Viborg Town Hall on 10.5.2013. In the survey, occupants were asked to express their satisfaction with indoor temperature, air quality, acoustic and lighting conditions. A six point scale ranging from 'Clearly Satisfied' to 'Clearly Dissatisfied' as shown in Fig. 3 was used. In order to compel occupants to be more definite, the scale did not offer an opportunity for a "neutral" vote.

2.2. Data analysis

By processing the data subsequently, thermal comfort and indoor air quality was classified according to European Standard EN15251 [9] and Danish Standard DS474 [10]. Analysis was conducted using three different time frames: monthly, annually and seasonally (winter & summer). Hourly data of CO_2 concentration and operative temperature were obtained from the field measurements. Indoor air quality was evaluated based on measured CO_2 levels during occupancy period with respect to the outdoor concentration, which was determined to be 360 ppm. Thermal comfort was evaluated according to temperature range for heating and cooling period according EN15251 [9]. Predicted Mean Vote (PMV) had to be calculated, for that reason an application of ASHRAE 55-2004 [11] was employed. Assumptions were made during PMV calculation regarding the air velocity (0.1 m/s) and clothing insulation (winter 1.0 clo, summer 0.6 clo) while the operative temperature and relative humidity were attributed as the variable values.

All variables were examined to find out to which extent they satisfy the requirements of European standard EN 15251 [9]. The standard allows categorization of buildings according to provided indoor environmental quality into four categories. Indoor environment in the Viborg Town Hall should fulfill the category II (normal level of expectation for new buildings and renovations) during at least 95% of occupied time.

The questionnaire analysis focused mainly on satisfaction with thermal environment and indoor air quality. Thorough investigation was conducted regarding satisfaction with thermal environment and sources of discomfort. Other available data like acoustic, lighting, and cleanliness conditions were not analyzed in the present study.

2.3. Developing representative simulation model

A building performance model was utilized for a 'calibrated-simulation'. It was built in simulation software IDA ICE [12]. The goal at this stage was to closely match the model with the measured values of the actual building by tuning the simulation inputs. Objective functions and constraints were set as those which cannot be changed (geometry, U-values, etc.) and as independent variables were set as those which were not clearly defined (occupancy, set points, etc.). The model was matched with reality by repetitive running of the simulation and changing the independent variables and comparing the results. Two tools were used in order to evaluate the accuracy of the model: Validation according to Coefficient of Variation of Root Mean Square Error (CV-RMSE) [4] and visual comparison of temperature developments plotted on the graph. Results from each simulation round were imported to spreadsheet, which automatically calculated CV-RMSE of hourly averages and monthly averages for chosen (worst performing) locations. Similarly, operative temperature development graphs were plotted for visual comparison. Mostly those plots helped to identify many differences between model and reality (measurements) as for instance occupancy patterns, set points timing and temperatures or night ventilation strategy and in that way further helped to lower CV-RMSE. The validation was made according to the operative temperature development in the building; however simulated energy consumption and CO_2 development were also compared with measured to ensure that they were beneath 10%. Weather data for matching period and location were obtained from Danish

Meteorological Institute (DMI) [13]. The applied data refer to the normal operation of the building without any intervention to extend the operating variables (passive testing technique).

2.4. Optimization

The optimization relied on parametric simulation and scenario modelling. During the parametric simulation, issues which focused for instance on CO_2 concentration were isolated from the overall performance and addressed separately. In order to find the optimal solution (modification), the study relied on a coupling loop applied to simulation-based optimization [5]. The loop was built upon a building simulation and an optimization program. Simulation outputs were retrieved and verified if they meet optimization's criteria (e.g. reduce the number of hours outside comfort zone), in case of failure the loop returns to simulation program introducing new input settings (e.g. alternative set points). When the criteria were met then the same procedure was followed for another issue. The accuracy and the applicability of parametric simulations were focused on future performance of the building, which was why at this point the weather file was replaced by standardized climatic input, Design Reference Year (DRY) [14]. Scenario modeling was afterwards used to combine separate modifications into new building control schedules.

3. Results

3.1. Indoor climate

While annually plots were describing the overall performance of each representative zone (in regards of orientation, level and usage), monthly plots provided potential to expand the research and display possible malfunctions during the day/week. Fig. 2(a) illustrates a percentage overview of compliance with category II for all measuring stations regarding operative temperature. When reading horizontally it can be found how different areas operated in specific month/period of the year. Further, when reading vertically, it can be comprehended how some areas of the building performed during whole measuring period. The blank cells depict data-holes in measurements. Not all the measurements were started at the same time and there were also occasional malfunctions of measuring stations. The most unsatisfactory environment (orange-red color) appeared to be in open plan offices (L1 & L3-L8). Fig. 2(b) is an example of seasonal operative temperature classification.

Summing up the findings of monthly, annually and seasonally analysis for every parameter, it was concluded that the building was overheated during summer as well as winter period and limits of 100 hours above 26 °C and 25 hours above 27 °C (defined in [10]) were exceeded. The indoor air quality did not fulfill the expectations of EN15251 [9] however the problems were only minor as the CO_2 concentration varied within category III only 20% of the year.
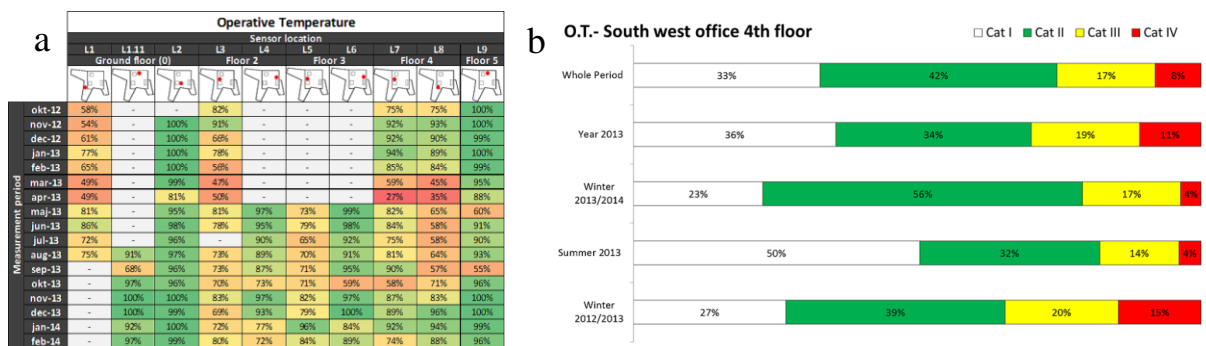

Fig. 2. (a) Percentage overview of operative temperature in category II by location and period; (b) Categorization of south west office, floor 4, shown as recommended by EN 15251 [9].
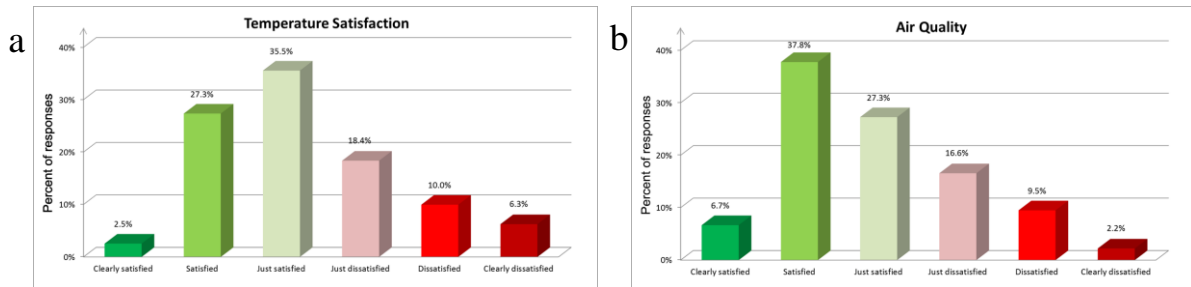
Fig. 3. Survey responses: (a) Temperature satisfaction; (b) Air quality satisfaction.

According to results from the questionnaire survey depicted in Fig. 3(a), 65% of the people were by some means satisfied with the temperature. This complies with the outcome of measurement analysis showing that during April 2013 the operative temperature ranged in category I and II.

As can be seen in Fig. 3 (b) high air quality satisfaction was found. Unlike for the period of the year, there was no connection observed regarding position in the building and CO_2 concentration.

3.2. Validation

The model was calibrated to actual operation of the Viborg Town Hall. For hourly average temperatures, model demonstrated average inaccuracy (CV-RMSE) of 4.6% meeting the goal of maximum 10%. However, creating the validated model did not serve just one purpose. As [4] suggests, the simplest detection of faulty operation is done by comparison of calibrated model with a design simulation. In this case, the design simulation was not available however one of the 'side effects' (outcome) of calibration was still identification of operational issues not detected during the measurements analysis. This identification was taking place when the unreasonable settings for model were required in order to match the reality. As for instance the set points for heating in the model must have been unusually high resulting in conclusion that there was unnecessary high heat supply in real building. Further on, it was identified that there was only limited use of installed Thermo Active Decks (TAD), as they had to be often shut down completely in the model.

3.3. Optimization

Following modifications were proposed to address the identified issues:
- *Modification A*: Set points for Radiators (RAD) and TAD were lowered during occupancy and unoccupied period for 1-2°C to address overheating during winter.
- *Modification B:* In order to increase the usage of the TAD, the heat supply shifted from RAD to the TAD. RAD served as backup and set points were lowered while TAD operated also during occupancy.
- *Modification C:* Proposed operation of openings responsible for natural ventilation to be controlled by operative temperature (set-point 23 °C in winter and 24 °C in summer) instead of predefined schedule.
- *Modification D:* Proposed use of CO_2 sensors that would operate the openings in order to eliminate the air quality issues. Set point was set for 800-850 ppm.
- *Modification E:* Utilized TAD cooling with full power of 40 W/m^2 during the warmest days of the year with the set point of 25 °C.
- *Modification F:* Radical approach to night ventilation with intention to cool down building's mass. Gradual control of ventilation openings according to outside temperature.

Various optimization scenarios incorporating several of previously mentioned modifications were proposed based on results from parametric simulations. This paper outlines two strategies. First was focused on indoor environment combining modifications A, C, E and F. Second was focused on energy savings combining modifications A, B and F. Table 1 shows the influence of the scenarios on the model. Nominal values are shown also with calculated relative change underneath from the reference simulation (run with DRY without changes to operation).

Table 1. Influence of the two scenarios to the IDA ICE model

	Heating	Cooling	CO_2 outside cat. I, II	OT outside cat. I, II	PMV outside cat. I, II
	[kWh/m²/year]	[kWh/m²/year]	[hours]	[hours]	[hours]
Reference	**31.4**	**5.3**	**1193**	**450**	**243**
Scenario 1:	24.9	2.8	919	396	58
	-21%	-47%	-23%	-12%	-76%
Scenario 2:	19.9	4.8	1307	421	66
	-37%	-9%	9%	-7%	-73%

4. Discussion & Conclusion

According to computer simulations, the modifications have the potential to improve building's energy consumption and indoor environment quality. The scenarios built upon modifications were found applicable to the building without further investments. It was concluded that their application would result in energy savings for heating 21-37% and lowered the number of hours outside comfort range for 7-12%.

However statistician George E.P Box is quoted as saying: "*All models are wrong, but some are useful. The key is to make models as useful as possible*" [15]. For instance, a model is useful if it is able to help explaining past and predict future observations. In this study, model validation assisted to identify problems with overheating and unnecessarily high set points for heating. . Rather high agreement between the model and measured data (CV-RMSE of 4.6 %) gives the model credibility to be used for optimization.

It should be mentioned that the procedure applied in the present paper can become time consuming due to combination of field measurements and simulation. However more extensive use of BIM in the future should assure existence of building simulation model and therefore dismiss the need of creating one from the scratch. Moreover, establishing this procedure in prospective demand for building commissioning should rapidly shorten the required time. Either way, it has a potential to become an efficient tool to propose optimal building operation and accelerate systems' adjustment.

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