A COST-EFFECTIVE MODEL- AND MEASUREMENT-BASED METHODOLOGY FOR ONGOING COMMISSIONING*)

Dirk Jacob[1], Sebastian Burhenne[1], Christian Neumann[1] and Sebastian Herkel[1]
[1]Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany

ABSTRACT

The building sector is responsible for a major part of the energy consumption. A considerable reduction can be achieved by improving the operation of the buildings. A methodology to organize and standardize the ongoing commissioning of buildings was developed. The method consists of 4 steps. An important criterion developing this method was cost-effectiveness. Therefore a top-down approach was chosen. A minimal dataset was defined which was measured at all demonstration buildings. In this paper different modeling approaches within the methodology are discussed. Applying this methodology to 17 non-residential demonstration buildings energy cost savings from 4 to 29 % were found.

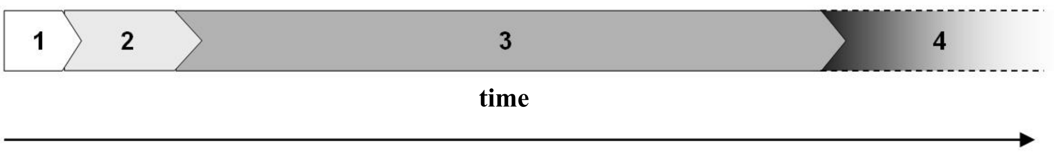
PROBLEM ANALYSIS

A major share of total energy consumption is caused by the building sector. In 2008, it was responsible for around 44 % of the end energy consumption in Germany (AGEB, 2010). The potential for saving energy is particularly high for non-residential buildings. Up to 30 % of the energy can be saved simply by altering the operation management (cf. Katipamula & Brambley, 2005).

In practice, buildings are often operated sub-optimally with regard to energy, without this situation being noticed. This is due to the complexity of the HVAC systems and often the lack of measurement data acquisition and analysis. The energy performance of building operation can be improved by a standardized process which includes the detailed analysis of measurement data. A method was developed to monitor and optimize operation within various projects. Particular attention is paid to ensuring that the methods can be used in practice. Seventeen non-residential buildings throughout Europe were investigated. The buildings are equipped with measurement data acquisition systems. Some of them belong to existing automation systems for building technology, whereas other measurement technology systems were specifically installed for the projects. The knowledge gained in these demonstration buildings should be transferable to other buildings.

METHODS

A four-step procedure was developed to analyse buildings, to optimize operation and then monitor it constantly (see Figure 1).



Step	Description
1	Initial comparison of consumption data with reference data from other buildings.
2	Building energy certification according to the national implementation of the EPBD (Energy Performance of Buildings Directive) and provision of measurement technology for the building or usage of existing measurement technology for data acquisition.
3	Analysis of the measured data and optimization of building operation.
4	Monitoring and continuous control of building operation.

Figure 1: Systematic procedure for building analysis, optimization and continuous operation monitoring.

*) This paper has already been presented in German at the: 2. Energietechnisches Symposium Innovationen im Energiemanagement von Nichtwohngebäuden, Steinbeis-Transfer-Institut Bau- und Immobilienwirtschaft 8th Dec. 2010, Stuttgart, Germany, ISBN 978-3-938062-93-7 (Burhenne et al., 2010).

Benchmarking (step 1)

The first step is to compare the consumption data with reference values. However, there is a wide distribution among available reference values, so that the benchmarking result depends strongly on the reference values used. There is a scarcity of reference values for non-residential buildings which take sufficient account of the building age, usage and building services technology or provide energy coefficients for sub-systems.

Building certification (step 2)

In the second step, the building is certified according to the relevant national implementation of the EPBD (Energy Performance of Buildings Directive) so that the building can be compared with reference data from other buildings. In Germany, non-residential buildings are certified according to DIN V 18599. In some cases, it was found that the energy demand calculated for the certification was much higher than the real consumption. Consequently, the resulting comparison has only limited value as a basis for analysis.

Measurement data acquisition was also implemented as part of step 2. As far as possible, use was made of existing measurement technology (building automation system), with measurement technology being added as necessary. The measurement data from all demonstration buildings are transferred to Fraunhofer ISE via Internet. The minimum set of recorded measurement data is shown in Table 1. The data should be recorded with a time resolution of 5 – 10 minutes. In addition to the tabulated data, the following data are desirable (depending on system complexity and configuration):

- Operating information from pumps, fans, control valves and dampers
- Energy delivered to and by the individual sources of heating and cooling energy
- Consumption of the individual heating and cooling circuits
- Electricity consumption according to usage type and sector (e.g. technical building services, lighting, appliances)
- System temperatures (e.g. temperatures before/ after heat recovery and temperature of central hot water tank)

Fault detection, diagnosis and operation optimization (step 3)

After the measurement data acquisition has been established, fault detection and optimization can begin. Figure 2 shows the sequences for fault detection, fault diagnosis and optimization.

Table 1: Minimum data set for demonstration buildings

Sector	Quantity	Unit	Comments
Consumption	total consumption per fuel type	kWh	e.g. gas, oil, biomass
	total consumption of district heating	kWh	
	total consumption of district cooling	kWh	
	total electricity consumption	kWh	
	total water consumption	m³	
Meteorology	outdoor air temperature	°C	on-site meteorological measurements or data from commercial provider
	relative humidity of outdoor air	%	
	global irradiance	W/m²	
Indoor climate	room temperature	°C	for one or more reference zones
	relative humidity of indoor air	%	
System data	supply / return temperatures of the main water circuits	°C	main distribution of heating and cooling energy
	supply air temperature for the largest ventilation units	°C	only if the supply air is processed thermodynamically
	relative humidity of the supply air for the largest ventilation units	%	

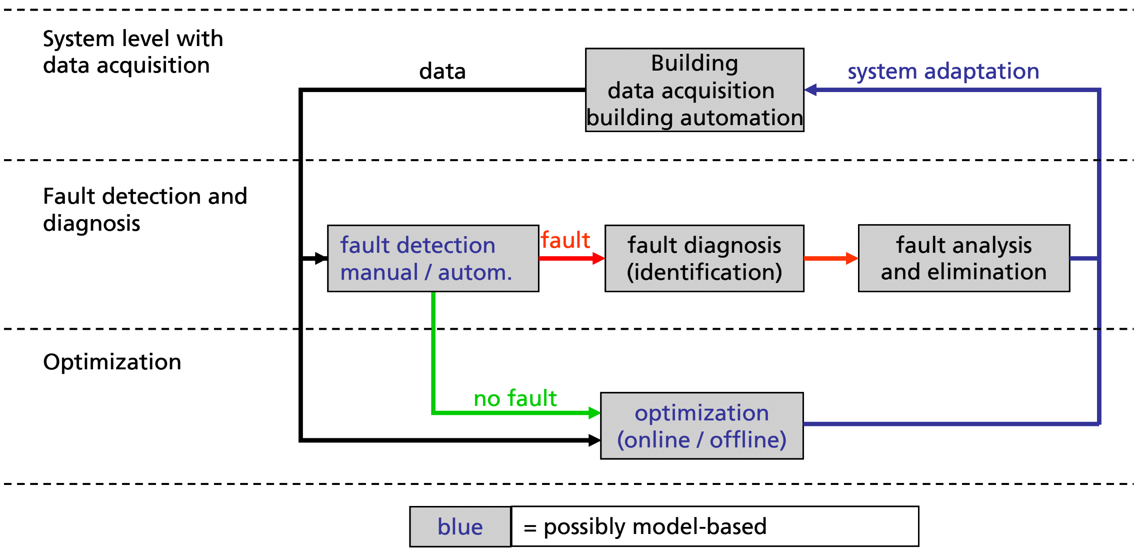


Figure 2: Individual components of step 3 (fault detection, diagnosis and optimization).

A tool has been developed to automatically visualize the measurement data. Based on a minimum set of data (meteorological, consumption, indoor temperatures, system temperatures and component operating information), graphs are prepared to display characteristic profiles and relationships concerning the consumption of heating, cooling and ventilation systems. Figure 3 and Figure 4 illustrate one of the implemented visualization methods, so-called "signatures" (or "scatter plots").

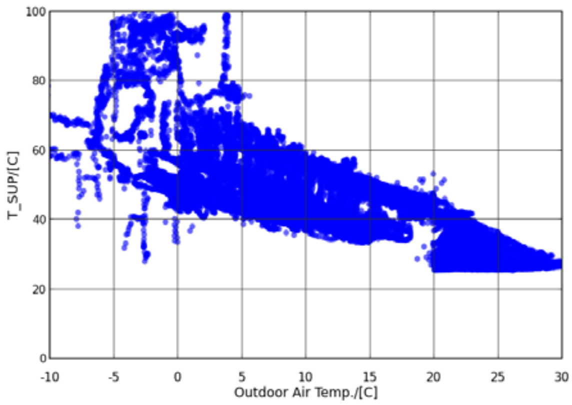


Figure 3: Scatter plot of the raw data with a resolution of 5 minutes. The data were measured in the "Wirschaftsministerium" building (see Table 2 for more information on the building).

Figure 3 shows the raw data, which have a time resolution of 5 minutes. The data are for a heating circuit with a mixer valve, and the supply temperature is plotted versus the outdoor temperature. It is evident that the supply temperature for this system is controlled according to the outdoor temperature. Further interpretation is difficult with such a scattered cloud of points, as all of the raw data are included. The situation has changed in Figure 4, where the data have been filtered and condensed (daily averages). Data are displayed only for times when the pump was operating (pump signal greater than zero). In addition, the points are color-coded according to the value of the pump signal. Not only the supply temperature but also the difference between supply and return temperatures is displayed. It is now easier to interpret the data.

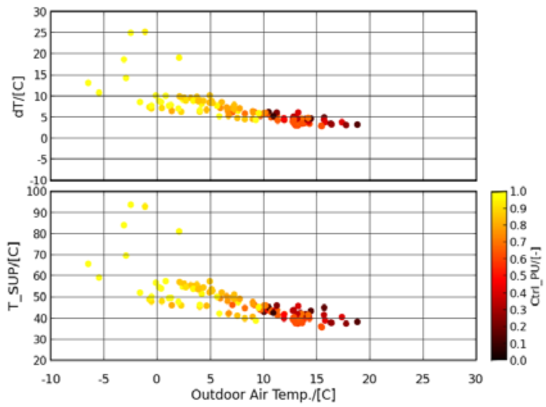


Figure 4: Scatter plot with daily averages. The data were filtered and colour-coded according to the value of the pump signal.

Another type of graph to present measurement data is the so-called "carpet plot". It presents the change with time of a measured quantity as a "pattern", which makes it easier to recognize regular periods of operation or user presence. The y axis of the diagram represents the time of day (0 – 24 hours) and the date can be read from the x axis. The color code differentiates the measured values. If several such graphs are positioned adjacent to each other, the data points can be compared. Figure 4 is an example of such a "carpet plot". It can be seen that the pump was operating constantly in the period from October to December 2008 (1), which was noticed as a result of the visualization. After reporting this to the building operator, a new schedule for pump operation was implemented in December 2008 (2). After this modification, it was observed that the temperature difference between supply and return was very large at night (3). Also, the supply temperature at night appeared to be too high (3). After further analysis, a three-way valve was identified which did not switch off correctly at night. As a result, heating-system water was forced by the main pump into the heating circuit (although the secondary pump was switched off), which caused the high temperatures and large temperature difference. From April 2009 onward, correct operation was implemented (4). To implement this sort of analysis in practice, it is useful to define a standard set of labels for the data points as a "data key". Thus, nomenclature conventions were defined for the data included in the minimum data set. This allows standard plots for the energy and water consumption, the heating and cooling circuits, the ventilation systems and the indoor climate to be generated effectively and automatically. A goal for the future is to develop rule-based systems for automatic analysis of the "operating patterns".

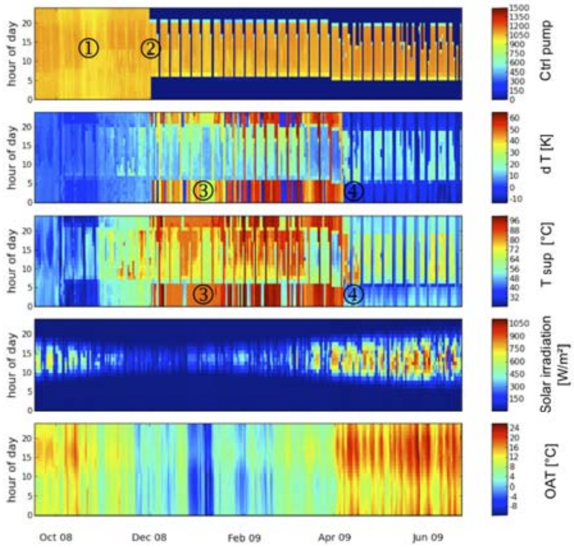


Figure 5: Example of a "carpet plot". The data were measured in the "Kreuzgebäude" (see Table 2 for detailed information on the building).

Once the building is operating without faults, the optimization process can begin. Many different approaches are applied in practice. Most of them are based on the experience of the building operator. Often energy bills and consumption data are analysed, there is an on-site inspection and rough calculations are made to check that the order of magnitude is correct. On this basis, settings for the building automation are made which are intended to minimise the energy consumption. This method is often limited to changing only a few parameters. Only after a certain period of time and renewed analysis of the consumption data is it possible to judge whether the changes actually led to a saving. Interactions within building operation are complex, limiting the chances of success for such an approach. For example, if a shading device is moved, this affects the cooling and the heating loads, the energy consumption for artificial lighting, and glare (cf. Clarke, 2001). Often, building performance simulation is needed to test and quantify the effect of changes in operation management.

The goal of the work was to develop a model-based method to identify control strategies and parameters for energy-optimized operation. Simulation models which allow energy optimization were selected and extended or newly developed. Particular attention was paid to the suitability of the models for applying optimization algorithms. After the models had been calibrated and validated, optimization algorithms were applied to these models. Operating parameters for energy-optimized building operation can be determined with these algorithms. A suitable target function must be selected, which is then minimized (or maximized in some cases) by the optimization algorithm. Possible target functions include the primary or end energy demand, operating costs, life-cycle costs or emission of greenhouse gases. In some cases, certain boundary conditions such as room temperature settings or minimum air exchange rates must be maintained. The target functions are evaluated with a simulation program. This means that a simulation is run automatically after each parameter change by the optimization algorithm to determine the value of the function.

The operating times for the circulation pump of a demonstration building were optimized as the first example. The goal was to identify the periods at night when the pump (and the boiler) can be switched off, while ensuring that the room temperature was kept at the setpoint as long as users were present. The circulation pump operated for 24 hours a day in reality.

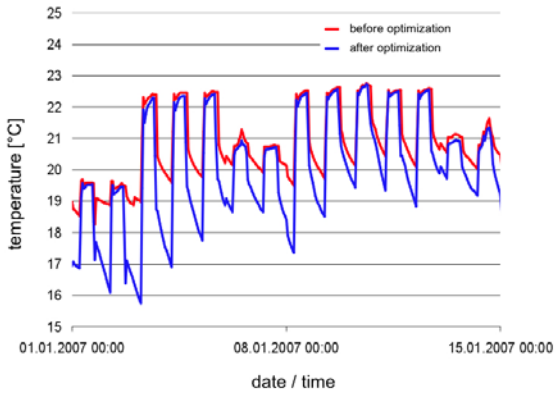


Figure 6: Room air temperature profile before and after model-based optimization.

The useful energy demand for the building served as the target function. Keeping the room temperature at the setpoint during the presence of occupants was implemented via a penalty function. The times for starting and stopping operation of the heating circuit were used as the variable parameters. With a so-called particle swarm algorithm, an optimal pump operating time between 06:53 and 16:53 was determined. (The building was used between 08:00 and 18:00 hours.) The Software GenOpt was used to perform the optimization (cf. Wetter, 2008). Figure 6 shows the temperature profile before and after optimization. It is evident that the temperature set-point during the day was reached in time, although lower temperatures than previously occurred at night.

By applying this measure, the annual useful energy consumption can be reduced from 22.4 MWh/a to 20.1 MWh/a, which corresponds to savings of 10 %. In addition, the simulations indicate that due to the heat stored by the building mass, the temperature in the building does not fall to critical values (freezing). The lowest temperature found by the simulation for the whole year is 13.8 °C. More details on this optimization task can be found in Burhenne and Jacob (2008).

Continuous operation monitoring (step 4)

Once the building operates without faults and energy-saving measures have been successfully implemented in the building, the building operation is controlled continuously by monitoring (step 4). This should be done automatically. For this purpose, an algorithm has been developed (Jacob et al., 20010) which makes use of the fact that a “basic pattern” for energy and water consumption, which depends on the day of the week, can be recognized in most buildings (Figure 7). This “basic pattern” can be identified with statistical methods. In doing so, interrelationships / correlations among the variables in the minimum data set are taken into account (see Table 1) and different “typical days” (days with different usage, e.g. weekday, weekend) are identified with a cluster algorithm. A regression model based on the presented principles can be used to automatically check the current consumption. The application phase must be preceded by a training phase to determine the model parameters. Figure 8 shows a comparison between the measured values and the values calculated by the model.

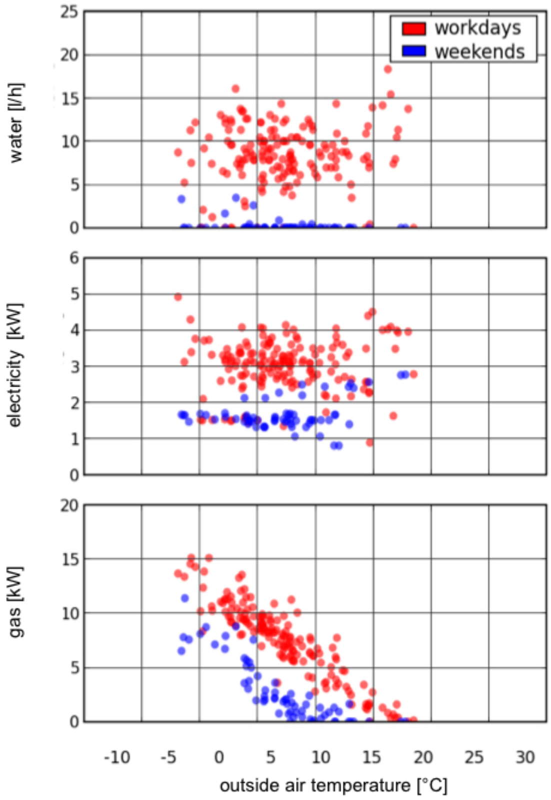


Figure 7: “Scatter plots” with typical consumption patterns. Clear differences between weekdays (red) and weekends (blue) can be recognized. In addition, it is evident that the gas consumption correlates with the outdoor temperature and the heating temperature limit can be read from the graph.

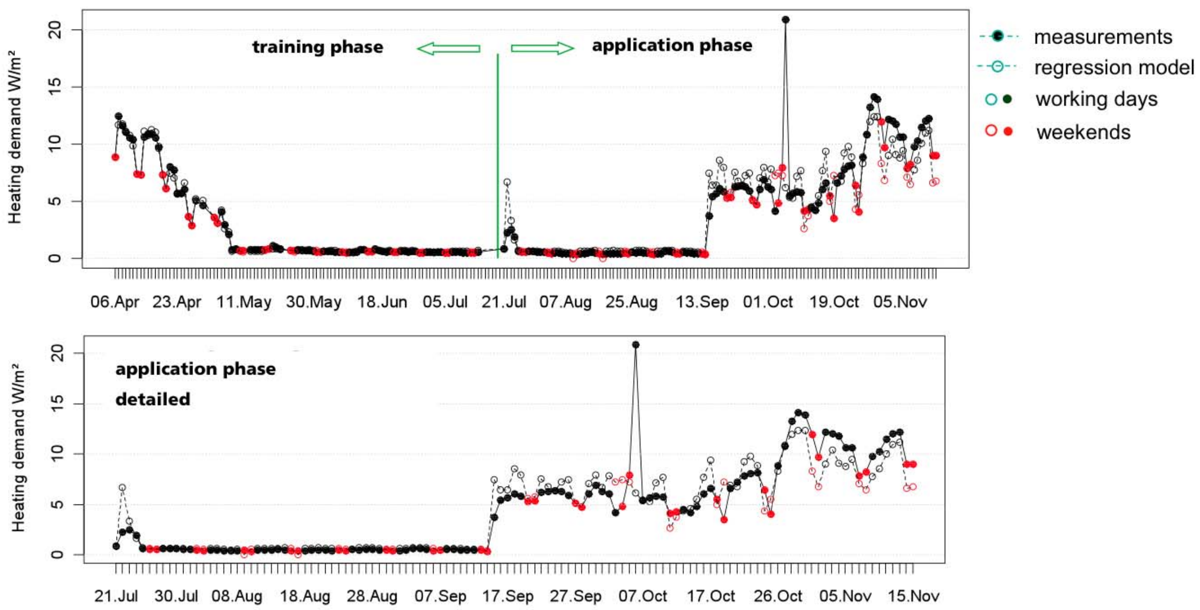


Figure 8: Comparison of the measured data with the results of the regression model. If the measured values deviate strongly from the values determined with the model, this indicates a fault, which could be detected by this approach. The measured values were recorded in the “Kreuzgebäude” (Table 2, Komhard, 2008).

On 6th October, the measured heating energy consumption deviated strongly from the calculated value (the measured data were deliberately altered in order to test the algorithm). A fault appears to be present which could be detected with the help of this model. Holidays are also successfully recognized by the model and allocated to the "weekend" cluster (e.g. 3rd October (public holiday in Germany), which is visible as the additional red point before the weekend). This is necessary, as otherwise the model would indicate an operating fault if the days were incorrectly classified.

RESULTS

A total of 17 buildings was analyzed within the presented projects, 12 of them within the "Building EQ" project, which has already been completed. The cost for data acquisition of the minimum data set was between 2,500 and 46,000 Euros, and depended mainly on the existing building automation system. The annual energy costs varied between 59,000 and 400,000 Euros per year. The savings potential that was identified for the buildings analyzed within the projects amounted to 4 – 29 % of the annual energy costs. Detailed information on the buildings can be found in Table 2 and Table 3. From this information, it can be inferred that the analysis and optimization of large non-residential buildings is economic in most cases. A critical point from the economic perspective is the cost of personnel to achieve the potential savings. Experience in practice indicates that such measures are successful only if methods and tools are available to optimize the building operation efficiently. A step toward providing such instruments was taken in these projects.

CONCLUSION

The projects to date have demonstrated that there is major optimization potential in many non-residential buildings. It is possible to realize this potential with the methods and tools presented here. On the medium to long term, an application field for optimization with simple simulation models could be the integration of such procedures into building automation (Model Predictive Control). For instance, optimal building operation could be constantly recalculated and implemented on the basis of weather predictions and the anticipated building usage. Such predictive control is already applied today in the chemical, steel and cement industries (cf. Venkatasubramanian et al., 2003). As many of the significant inputs to the models (e.g. building occupation level, opened windows, user behaviour) often cannot be determined reliably, it is useful to take account of this uncertainty in the simulations for optimization. This allows the uncertainty to be evaluated and improves the applicability of the methods.

Within the underlying projects, the hydraulic circuits in the buildings proved to be particularly prone to faults. Here, methods for model-based fault detection and diagnosis are needed. This problem is addressed in the ModQS project. That project is running from May 2010 to June 2013 and is supported by the German Federal Ministry of Economics and Technology (BMWi) (project number: BMWi 0327893A).

ACKNOWLEDGEMENT

BuildingEQ was a project of the "Intelligent Energy Europe Programme" funded by the European Commission (project number: EIE/06/038/SI2. 448300). Within this project, the goal was to develop methods and tools which could be used to optimize non-residential buildings permanently by making use of all the data that had been gathered in the certification process (e.g. according to the German EnEV regulation or DIN V 18599). Emphasis was placed on feasible and cost-effective measures. The project was managed by Fraunhofer ISE, with partners from Germany, Italy, Sweden and Finland participating.

The ModBen project (project number: BMWi 0327410A) is running within the "EnOB" Research Programme for Energy-Optimized Building, which is funded by the German Federal Ministry of Economics and Technology (BMWi). ModBen addresses the development of model-based operation analysis as part of an integrated energy management system to ensure energy-efficient operation on a long-term basis. Fraunhofer ISE is coordinating this project and working on it together with two German partners.

This paper is a summary of the work to date on this subject at Fraunhofer ISE. In addition to the authors, the following persons contributed significantly: Nis Andresen, Sebastian Dietz, Susanne Komhard, Christian Reetz, Nicolas Réhault and Sebastian Zehnle.

Table 2: Demonstration buildings and potential savings (Part 1)

Name	Kreuzgebäude	Wirtschafts-ministerium	Multifunktions-gebäude	Kreiskrankenhaus	State Treasury	Aurora 2
Location	Essen, Germany	Düsseldorf, Germany	Stuttgart, Germany	Hagenow, Germany	Helsinki, Finland	Joensuu, Finland
						
Year of construction	1985	1953 - 1961	1995	1937 / 1998	1984	2006
Usage	offices	offices, canteen	offices, laboratories	hospital	offices, restaurant	offices, medical centre, lecture theatres, seminar rooms
Floor space	19,500 m²	30,000 m²	8,140 m²	13,275 m²	16,120 m²	8,100 m²
Electricity consumption	51 kWh/(m²a)	44 kWh/(m²a)	62 kWh/(m²a)	121 kWh/(m²a)	84 kWh/(m²a)	117 kWh/(m²a)
Heating energy consumption	77 kWh/(m²a)	80 kWh/(m²a)	100 kWh/(m²a)	232 kWh/(m²a)	178 kWh/(m²a)	106 kWh/(m²a)
Energy costs	135,000 EUR/a	290,000 EUR/a	60,000 EUR/a	400,000 EUR/a	226,000 EUR/a	68,000 EUR/a
Data acquisition costs	23,000 EUR	35,000 EUR	6,000 EUR	20,000 EUR	2,500 EUR	7,000 EUR
Potential savings	20,000 EUR/a	35,000 EUR/a	12,000 EUR/a	50,000 EUR/a	13,500 EUR/a	20,000 EUR/a
Percentage of annual energy costs	15%	12%	20%	13%	6%	29%
Non-dynamic amortisation period	< 1.5 years	< 1 year	< 0.5 years	< 0.4 years	< 0.2 years	< 0.4 years
Possible costs for engineering services for a non-dynamic amortisation period of 3 years	37,000 EUR	70,000 EUR	30,000 EUR	130,000 EUR	38,000 EUR	53,000 EUR

Table 2: Demonstration buildings and potential savings (Part 2)

Name	HUT Engineering Department	Senate Headquarters	Lecture Halls	Electronic Department	Informatic Systems	Duka House
Location	Espoo, Finland	Helsinki, Finland	Milan, Italy	Milan, Italy	Milan, Italy	Göteborg, Sweden
						
Year of construction	1966	1934	1998	2007	1961	1810
Usage	offices, lecture theatres, seminar rooms, canteen	offices, conference rooms, canteen	seminar rooms	offices	offices	shops, private school
Floor space	8,600 m²	11,690 m²	2,970 m²	3,720 m²	2,270 m²	1,770 m²
Electricity consumption	85 kWh/(m²a)	114 kWh/(m²a)	104 kWh/(m²a)	250 kWh/(m²a)	270 kWh/(m²a) (including cooling)	35 kWh/(m²a)
Heating energy consumption	101 kWh/(m²a)	66 kWh/(m²a)	93 kWh/(m²a)	97 kWh/(m²a)	88 kWh/(m²a)	130 kWh/(m²a)
Energy costs	59,000 EUR/a	Building operates without faults. No operation optimization is possible or necessary.	63,000 EUR/a	156,000 EUR/a	95,000 EUR/a	
Data acquisition costs	5,000 EUR		32,000 EUR	46,000 EUR	32,000 EUR	
Potential savings	14,000 EUR/a		12,000 EUR/a	10,000 EUR/a	4,000 EUR/a	
Percentage of annual energy costs	24%		19%	6%	4%	
Non-dynamic amortisation period	< 0.4 Years		< 3 Years	< 5 Years	< 8 Years	
Possible costs for engineering services for a non-dynamic amortisation period of 3 years	37,000 EUR		4,000 EUR			

REFERENCES

AGEB 2010. AG Energiebilanzen e.V. Bilanzen 1990-2008. Bilanz 2008. Unter: http://www.ag-energiebilanzen.de/viewpage.php?idpage=63. [25.08.2010][Accessed: 28.09.2010].

Burhenne, S., Jacob D. 2008. Simulation Models to Optimize the Energy Consumption of Buildings. Conference proceedings of the ICEBO 2008 8th International Conference for Enhanced Building Operations. Berlin. Germany.

Burhenne, S., Jacob, D., Réhault, N., & Neumann, C. 2010. Projekterfahrungen aus der Betriebs-optimierung von Nichtwohngebäuden. In J. Krimmling & B. Landgraf (Eds.), 2. Energie-technisches Symposium. Innovationen im Ener-giemanagement von Nichtwohngebäuden. Steinbeis-Edition ISBN 978-3-938062-93-7.

Clarke, J.A. 2001. Energy Simulation in Building Design. Glasgow (2nd Edition).

Jacob, D., Dietz, S., Komhard, S., Neumann, C. and Herkel, S. 2010. Black-box models for fault detection and performance monitoring of buildings, Journal of Building Performance Simulation, Taylor & Francis, UK

Katipamula, S., Brambley, M.R. 2005. Methods for Fault Detection, Diagnostics, and Prognostics for Building Systems—A Review, Part I, HVAC&R RESEARCH (11/1), pp. 3-25.

Komhard, S. 2008. Model-Based Approach for Per-formance Monitoring of Commercial Buildings. Master thesis, FHTW Berlin.

Venkatasubramanian, V., Rengaswamy, R., Yin, K., Kavuri, S.N. 2003. A review of process fault detection and diagnosis. Part I: Quantitative model-based methods, Computers and Chemical Engineering (27), pp. 293-311.

Wetter, M. 2008. GenOpt® Generic Optimization Program User Manual. Berkeley: Ernest Orlando Lawrence Berkley National Labratory.