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# SMART BUILDING MANAGEMENT VS. INTUITIVE HUMAN CONTROL
## - Lessons learnt from an office building in Hungary –

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## ABSTRACT

Smart building management and control are adopted nowadays to achieve zero-net energy use in buildings. However, without considering the human dimension, technologies alone do not necessarily guarantee high performance in buildings. An office building was designed and built according to state-of-the-art design and energy management principles in 2008. Despite the expectations of high performance, the owner was facing high utility bills and low user comfort in the building located in Budapest, Hungary. The objective of the project was to evaluate the energy performance and comfort indices of the building, to identify the causes of malfunction and to elaborate a comprehensive energy concept. Firstly, current building conditions and operation parameters were evaluated. Our investigation found that the state-of-the-art building management system was in good conditions but it was operated by building operators and occupants who are not aware of the building management practice. The energy consumption patterns of the building were simulated with energy modelling software. The baseline model was calibrated to annual measured energy consumption, using actual occupant behaviour and presence, based on results of self-reported surveys, occupancy sensors and fan-coil usage data. Realistic occupant behaviour models can capture diversity of occupant behaviour and better represent the real energy use of the building. This way our findings and the effect of our proposed improvements could be more reliable. As part of our final comprehensive energy concept, we proposed intervention measures that would increase indoor thermal comfort and decrease energy consumption of the building. A parametric study was carried out to evaluate and quantify energy, comfort and return on investment of each measure. It was found that in the best case the building could save 23% of annual energy use. Future work includes the follow-up of: occupant reactions to intervention measures, the realized energy savings, the measurement of occupant satisfaction and behavioural changes.

**Keywords:**

Occupant Behaviour, Case Study, Building Operation, Optimization, Building Performance Simulation

## 1. INTRODUCTION

It is a common problem nowadays in the construction industry that there is a large gap between designed and actual, measured energy consumption in buildings (Diamond 2011) (Boermans and Petersdorff 2007) (Newsham, Mancini, and Birt 2009). Besides the limitations of building energy modelling tools, this is partly because designers could not take into account some parameters that are hard to estimate such as workmanship quality, actual weather data. The other, larger part that are causing discrepancies are technology installation quality and operation patterns (Polinder et al. 2013) (Yan and Hong 2014). Daily interactions between building systems and occupants drive total energy use (Sun and Hong 2016). To clearly understand and accurately model occupant behaviour in buildings is crucial in reducing the gap between design and measured building energy performance (Andrews et al. 2011).

The performance gap caused by technologies not implemented or operated correctly can be filled in by an audit or a commissioning process. However, other human behaviour-related aspects are hard to be addressed and quantified such as occupants or operators not understanding the design or operation intent, or lack of motivation to act in a way to save energy. Meier, et al. states that reasonable changes in operators' behaviours can save 5%-30% of building energy consumption theoretically (Meier et al. n.d.). At the same time, if the operation of the building is poor and not fine-tuned for energy-efficient use, less savings can be demonstrated in case of retrofitting projects (Martiskaïnen 2007).

Another issue is that overwhelming majority of designers who take part in the design phases are not involved in the post-occupancy phases. Therefore, the energy-related direct feedback from design strategies is missing. Unfortunately, this missing information loop is hardly addressed by the linear phase structure of different national or international used contractual frameworks such as RIBA (RIBA Plan of Work n.d.) or HOAI (HOAI Design Phases n.d.). It would be beneficial to engage designers into operation-phase building audit and retrofit to provide direct feedback to the designers about the actual performance of their buildings so they can improve design practices.

Building energy modelling (BEM) is an efficient tool to predict energy use in a building and help quantify the energy-saving effect of different intervention measures proposed for a building. In the retrofitting phase of a building's life-cycle, BEM is used to quantify energy saving potential of retrofitting measures (Evins 2013) (Wang and Holmberg 2015).

For four decades now, researchers in the field of energy-related occupant behaviour (OB) work on the quantification of the human-related uncertainties in case of building energy models (Yan et al. 2015) (Yan and Hong 2014) (Hong, Taylor-Lange, et al. 2015) (Gunay, O'Brien, and Beausoleil-Morrison 2013). However, despite of the tremendous effort of OB modelling community to represent humans in BEM in a more realistic way ((Hong, D'Oca, Turner, et al. 2015) (Hong, D'Oca, Taylor-Lange, et al. 2015) (Andrews et al. 2011)), there is only limited use of these tools in the industry yet. This is mostly due to the time and resource-intensive nature of the tools which are most of the time not affordable for market-based building energy efficiency professionals (Gaetani, Hoes, and Hensen 2016) (Polinder et al. 2013).

Besides the appropriate representation and education of occupants in buildings, it is important to ensure energy efficient operation of HVAC systems. One way is to optimize operational parameters of the systems with an optimization algorithm. Optimisation algorithms can be categorised into: genetic algorithms (GA) (Yu et al. 2015), derivative-free search methods and hybrid algorithms (Machairas, Tsangrassoulis, and Axarli 2014). The most commonly used optimisation algorithms in decision support problems are NSGA II and Back-propagation

Network (Yu et al. 2015). These algorithms can be run by coupling building energy modelling tools (e.g., EnergyPlus, TRNSYS, IDA ICE, Dymola, DOE-2) with optimisation toolboxes (e.g., MATLAB, GenOpt, GENE-Arch, modeFRONTIER) (Machairas, Tsangrassoulis, and Axarli 2014) (Nguyen, Reiter, and Rigo 2014) (Amaran et al. 2014). The free tool, used for optimisation in this project, MOBO (M. 2013) shows promising capabilities and may become the major optimization engine in coming years (Nguyen, Reiter, and Rigo 2014).

Most currently available studies investigated the optimisation possibilities of only one indoor environmental or operational parameter of a given building. For example either a proposed HVAC system parameter (Parameshwaran et al. 2010) or AHU inlet air temperature schedule (Candanedo et al. 2015) or heating and cooling setpoints (Hussain et al. 2014) (West, Ward, and Wall 2014) or air exchange rate of a given room (Pantelic, Raphael, and Tham 2012).

In this paper, a Hungarian case study is introduced where OB modelling played a key role in the investigation process. This case study is a sample project of Subtask E of the IEA EBC ANNEX 66 (Yan and Hong 2014), which is dealing with the industry adaptation and application of OB modelling tools.

The owner of a large office building built in 2008 was facing high utility bills and low user comfort in his building which is located in Budapest, Hungary. The building has seven stories with a total floor area of 7000 m$^2$. The design occupancy of the building is 450 occupants. The office building (Figure 1) was designed and built according to the state-of-the-art design and energy management principles. Therefore, the causes of the poor operation were not quite clear. The objective of the project was to evaluate the energy performance and comfort indices of the building, to identify the causes of malfunction, and to elaborate a comprehensive energy concept (Belafi, Zsofia; Reith 2014) (Belafi, Zsofia; Deme, Kornel Dome; Reith 2015) (Deme et al. 2015) to improve operations and reduce energy use.

**Figure 1 - Exterior view of the building**

The aim of this case study is to demonstrate how OB modelling could be implemented into a Hungarian office building project and how it could support the building audit and retrofit analysis process. Limitations and lessons learnt are explained. Authors hope that methods developed in the framework of this project are robust and can be adopted by other building energy professionals.

## 2. METHODOLOGY

In this section, main steps of the building audit project are described. Our workflow was based on literature and was fine-tuned according to the needs and problems of the specific building. Methodological aspects are introduced at each step of the workflow (Figure 2).

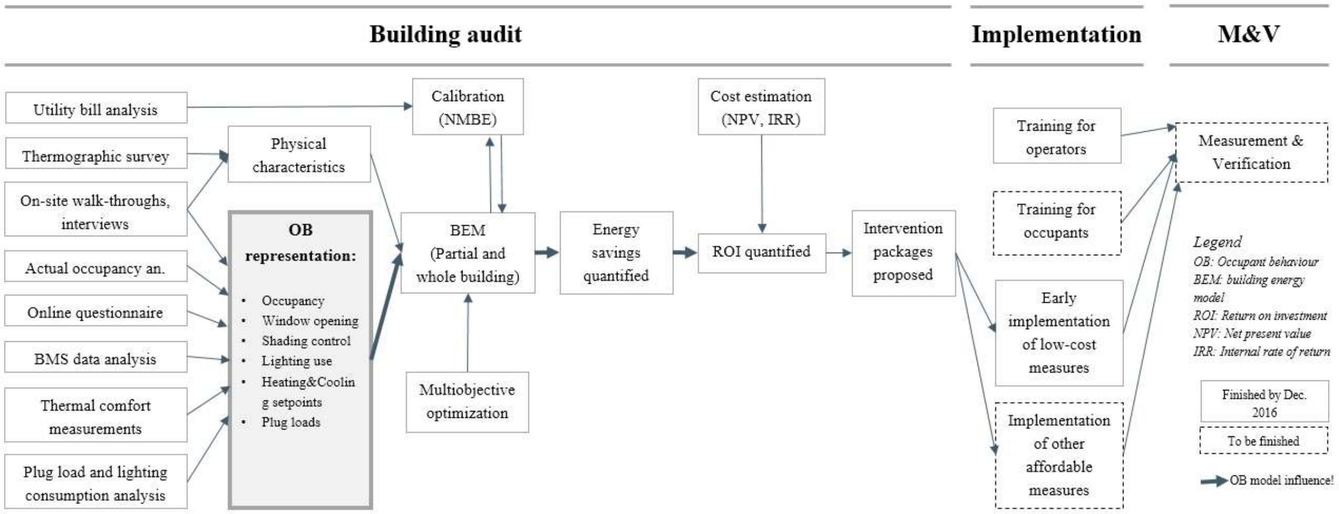


**Figure 2. Workflow chart**

## 2.1 *Building Audit, Data Collection Phase*

In the first phase of the project, building conditions and operation parameters were evaluated focusing on the building management systems (BMS), occupant control behaviour and user comfort. The evaluation tools used include:

- **An online questionnaire** on indoor comfort problems and occupant behaviour. The questionnaire was compiled based on CBE thermal comfort survey (CBE Occupant IEQ Survey n.d.) and was adjusted to building-specific conditions. In addition to thermal comfort questions, occupants were asked about occupancy and energy-related control behaviour. The web-based questionnaire link (Questionnaire n.d.) was sent out in a bilingual format to all workers on 11 March 2014 followed by a reminder two weeks later. Survey was filled in by 212 workers out of 450 which means a high response rate of 47%.
- Analysis of available **BMS data** related to building operation and energy use. Data points included: electricity, natural gas and water submeters, and AHU temperatures (inlet, outlet and before heat recovery unit temperature).
- Analysis of the **room-level HVAC equipment operation and indoor climate conditions** recorded by the BMS. Data points included: Fan Coil usage, valve-state, and thermostat setpoint.

- Analysis and benchmarking of **Plug load and lighting electricity consumption** per office block (1-10 office rooms).
- **Occupancy analysis** based on two years of motion-sensor data for offices and meeting rooms.
- Annual **utility bills** (electricity, natural gas, water) were analysed to provide an additional double-check to validate energy and water meter logs.
- **Interviews and on-site walk-through** investigating building usage in offices and meeting rooms. Walk-through and these interviews were conducted on 3 April 2014. 63 offices and 10 meeting rooms were audited. In these offices, 181 work stations were logged. Weather and BMS data were logged and analysed for this day to determine correlations between indoor and outdoor physical parameters and occupant behaviour patterns (window opening, thermostat setpoint adjustment and shading use).
- **Thermal comfort measurement** in the offices receiving the most negative feedback based on the results of the questionnaire and survey. These measurements were carried out to show work-safety compliance based on local, Hungarian building code (3/2002. (II. 8.) SzCsM-EüM -joint decree on minimum level of work-safety requirements 2002) on 7 April 2014 in the morning hours.
- **Thermographic survey** of the building envelope on 21 February 2014 in the morning hours. Air temperature difference between the indoor and outdoor spaces was 18.2ºC. Type and make of the thermographic sensor was FLIR PM675.

### 2.2 *Intervention measures, saving estimations*

After the main problems were discovered and intervention areas were identified, a list of proposed interventions was compiled. Each of these measures would save energy or water in the building. Based on savings achieved, financial viability of implementation of these measures was investigated (more details: section 2.4).

Yearly energy saving was estimated by building energy modelling (more details in section 2.3) in case of shading and secondary heating and cooling system control and ventilation-related measures. Savings and panel distribution in measures related to solar renewable energy use were calculated using software PVGIS (PVGIS n.d.) and Ecotect (Autodesk, Autodesk Ecotect Analysis 2011). For these calculations, PV and collector panel efficiency decrease with time was considered as well. Annual water and energy savings were calculated based on steady-state, annual efficiency improvements for water saving measures.

### 2.3 *Building Energy Modelling*

For a large office building with complex energy systems, it would be unrealistic to expect that the actual energy saving potential of measures proposed could be estimated using "manual" calculation. However, with the capabilities of today's computers, systematic approaches are becoming more feasible and practical to use in such projects in order to estimate energy use and energy cost of buildings (Najihah et al. 2015).

Our team chose the dynamic, zonal simulation tool IDA ICE (IDA Indoor Climate and Energy 4.6 (accessed: 01.03.16) n.d.) for annual energy saving estimation. For a dynamic energy model, it is essential to use appropriate parameters to represent the building. Two types of models were used in our investigations for different purposes: a partial (one-floor) model and a whole-building energy model. This section describes types of data input to the two types of energy models.

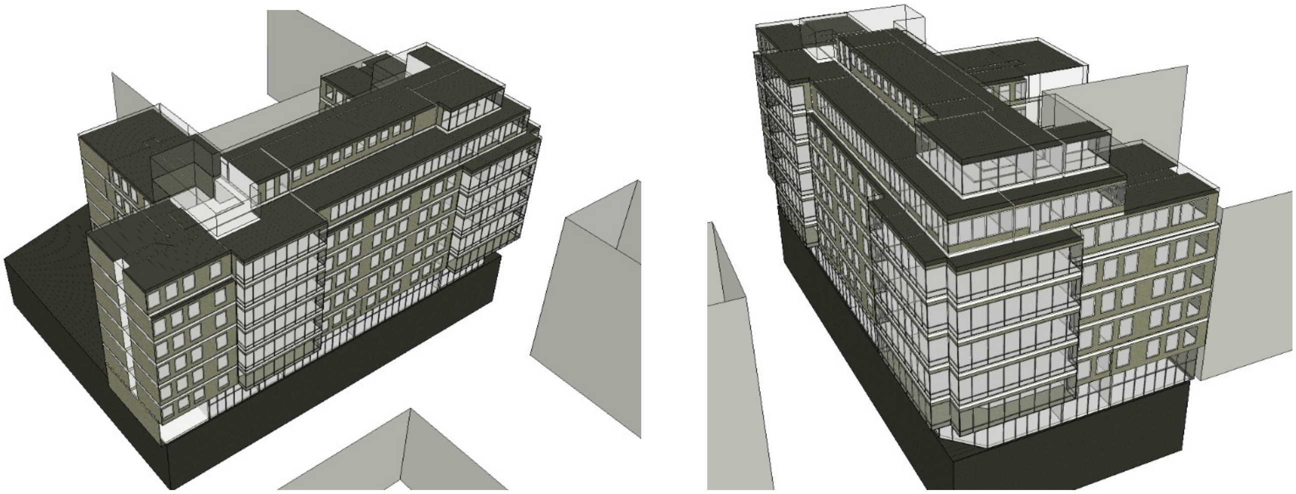


**Figure 3 - 3D view of the building energy model in IDA ICE**

#### 2.2.1. The Partial Building Energy Models

Occupant behaviour-related **sensitivity analyses** were carried out using a partial one-floor model representing an average floor (2nd floor) of the building. Based on results from the onsite walk-through, interviews, and fan coil (FC) valve state investigations, we could build up a real **thermostat-use** case. This case was compared in energy consumption to a base-case where thermostat setpoint modifications were not allowed for users, i.e., the system was controlled by fixed setpoints: with a minimum 22.5ºC and a maximum 24ºC.

The same partial building energy model was used for a window-opening sensitivity analysis where window opening frequencies and durations were evaluated in terms of heating energy consumption during the winter season. This analysis supported the calibration process of the whole-building energy model.

### 2.2.2. The Whole-Building Energy Model

Physical parameters related to the construction materials and installation quality were determined based on the comprehensive building audit. As-built plan drawings were used to establish the building’s geometry and construction materials. Thermographic images were used to identify thermal bridges and leaking windows and doors that were installed in low quality.

HVAC parameters were determined based on the audit of the primary HVAC equipment including the boiler, chillers and air handling units (AHU), as well as the secondary systems such as FC units.

The building audit results (more details in section 2.1) enabled us to do an indirect analysis of occupant behaviour (occupancy, FC usage (valve states), window opening, manual shading control overwrite frequency, plug loads, lighting, personal heaters). The final modelling of these aspects is described in Section .

For model calibration, the owner provided five years (2009-2013) of utility bills and monthly submeter logs. The calibration process included monthly analysis and fine-tuning of operational patterns due to the effect of occupants’ behaviour and control actions (see section  as well).

As an indicator of the model calibration quality, normalized mean bias error (NMBE) was used, which is defined in ASHRAE Guideline 14-2002 (ASHRAE 2002). This guideline is widely used for building energy model calibration. The NMBE acceptance threshold is 5% if monthly calibration is used.

NMBE is calculated as:

$$(1) \quad \text{NMBE} = \frac{\sum_{i=1}^{n} \left( y_i - \hat{y}_i \right)}{n * \acute{y}} * 100$$

where $y_i$ is the measured data with n data points, which is averaged in $\acute{y}$ . This is compared to the modelled values ( $\hat{y}$ ).

## 2.4 *Payback period calculations*

Yearly energy savings were determined by building energy modelling as described above. Dynamic payback period calculations were carried out based on net present values of initial investment costs of intervention measures proposed and annual utility bill savings (Deme 2015). Net present values were calculated as:

$$(2) \qquad NPV = -C_0 + \sum_{t-1}^{n} \frac{1}{(1+r)^t} \times C_t$$

Where:

NPV: Net Present Value of investment
$C_0$: Initial investment
$C_t$: Cash flow in a given year
t: Time period (year)
n: Estimated lifetime of the investment
r: Discount rate

Exchange rate used for calculations was 310 HUF = 1 EUR. The estimated lifetime of the investment and the discount rate was considered as 25 years and 10% respectively. At the base year, the utility cost of natural gas, electricity and water was 0.03, 0.07 EUR/kWh and 0.64 EUR/$m^3$ respectively. During the lifetime of the investments an increase of 1.5% per year of these rates was taken into account based on a study by Ecofys (Boermans and Petersdorff 2007).

Internal rate of return (IRR) was also calculated for each investment for further evaluation.

$$(3) \qquad 0 = -C_0 + \sum_{t=1}^{n} \frac{1}{(1+IRR)^t} \times C_t$$

## 2.5 *HVAC control optimization* (Deme et al. 2015)

In the first phase of the project, it was found that the operational parameters of the HVAC system were not in accordance with the operators' and owner's intentions. This was partly due to the freedom of operators and occupants of the building to interact with systems. Often this behaviour resulted in controversial operation and extreme levels of energy consumption while thermal comfort was unexpectedly low (See detailed results of building audit in section 3). At this point the owner added an additional task to the project scope: optimization of key HVAC control parameters to either increase indoor comfort of occupants or lower energy consumption. These parameters were:

- Setpoints of the central ventilation system Air Handling Unit (AHU): the supply air temperature based on outdoor air temperature (Figure 4).

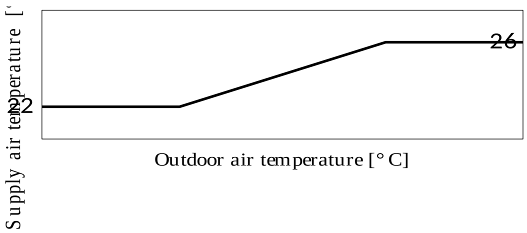


**Figure 4- AHU supply air temperature setpoint**

- The daily setpoints of the minimum and maximum temperature in the offices of the building (See Figure 5, 6).

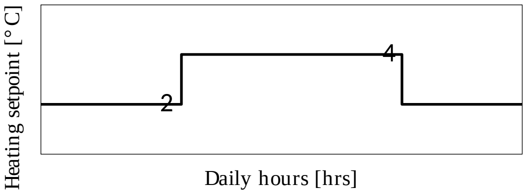


**Figure 5 - Daily 24-hour heating setpoint**

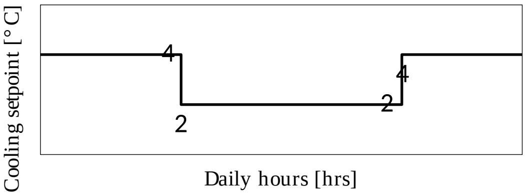


**Figure 6 - Daily 24-hour cooling setpoint**

It should be noted that ventilation is used only to provide fresh air as a common practice in European office buildings. Therefore, the supply air temperature is automatically adjusted to the average indoor air temperature of the building.

In the optimization process, four characteristic sample offices were used representing the main office types (size, façade type and orientation) of the building.

- SW: south-facing office with windows
- N: north-facing office, inner yard with windows
- E: east-facing office, inner yard with windows
- SC: south-facing office with curtain wall façade

The optimization simulations were run for July and January. Genetic algorithm NSGA-II was used to find the optimal solutions (Pareto front). Objective functions to be minimized were: monthly energy usage in kWh (including heating, cooling, lighting, equipment and HVAC losses, using system efficiencies of the actual building) and predicted number of people dissatisfied hours (PDH defined as the integral of the PPD measure multiplied by the total number of present occupants).

The dynamic building energy simulation software IDA ICE (IDA Indoor Climate and Energy 4.6 (accessed: 01.03.16) n.d.) was connected to a multi-objective optimisation plugin called MOBO (Multi Objective Building Optimisation) (M. 2013). MOBO is able to handle single and multi-objective optimization problems with continuous and discrete variables and constraint functions. It has a library of different types of algorithms (evolutionary, deterministic, hybrid, exhaustive and random) (Palonen, Hamdy, and Hasan n.d.).

At the end, two ideal solutions were chosen from the Pareto front and proposed to the building owner in accordance with the owner’s initial goal:

- Energy use is minimised while keeping the same indoor comfort values experienced currently in the building (Case A) .
- Possible maximal indoor comfort values are reached while keeping the current energy use (Case B).

As the last step of the optimization process, it was determined that the indoor comfort parameters fall within category I of the standard EN 15251 (EN 15251. 2008).

### 2.6 *Intervention packages*

Main problems and potential intervention areas were determined based on the results of the building audit. Final intervention packages were compiled based on the payback-period-based comparison of each individual measure. At the end of the current project, interventions were accepted by the owner to be implemented. As part of this process, a training session was hold to the operators where current problems and planned interventions were proposed and also a session for occupants is planned to facilitate further energy savings in the building.

## 3. FINDINGS FROM BUILDING AUDIT

As the first step, the current HVAC system was audited. Heating is provided by a natural gas-fired condensing boiler. The primary cooling system consists of two chillers placed on the roof. The air handling units supply only fresh air to the rooms, inlet temperature is the same as the room temperature. The secondary heating and cooling system is fan coil units.

### 3.1 *Heating system evaluation*

The heat supply system is in good condition, complies with standards (Hungarian transposition of EPBD: TNM Ministry Decree No. 7/2006 (V.24); Government Decree 176/2008 (VI. 30.); Governmental Decree 264/2008. (XI. 6.) n.d.). It was found that due to the operation and location of FC units in office spaces, there are significant thermal comfort complaints. These complaints were mainly coming from those offices where the thermostat was not capable of adjusting the FC fan speed.

It is a waste of energy that the FC units operate in heating and cooling modes right after each other. This caused significant local comfort problems. In many cases, workers were complaining about draught during the winter as well. There were many individual solutions found as occupants attempt to reach thermal comfort (Figure 7).

- Home-made boxes to block and/or redirect fan coil inlet air.
- Personal electric heaters next to the legs.
- Thermostat and fan coil switched off completely.

**Figure 7 - Individual thermal comfort mitigations**

### 3.2 *Cooling system evaluation*

Chillers that supply cooling to office spaces operate with an appropriate efficiency of COP 3.0 during summer. Meeting rooms have decentralized cooling units that can operate during the whole year. Chillers on the roof are close to the outlet of underground parking area ventilation. During hot summer days the outlet air from these spaces is colder than external air temperature thus it provides cool air to the chiller's environment and thus the efficiency of the chiller can be higher.

### 3.3 *Ventilation system evaluation*

Ventilation system of the building is in good condition. The electricity consumption of air handling units is slightly higher than average: this is due to the low efficiency of current run-around coil type heat recovery unit.

### 3.4 *Water and sewage system evaluation*

Utility connection to the water system is through an 80/20 combi-water meter. There is a pressure booster and many submeters installed in the system. Domestic hot water is decentralized: 4*200 l tanks with electric water heater for the kitchen and many 10-50 l tanks with electric water heaters on office floors.

Rainwater is collected in this building in two 8.6 $m^3$ storage tanks as the sewage system is not capable of accepting large amounts (more than the 2-year 15 minutes heavy rain fall) of precipitation at a time. This way water is stored on level -3 of the building and pumped into the sewage system once it is allowed.

### 3.5 *Transversal survey results*

First finding of the surveys was that 94% of occupants indicated that they control their thermal environment either by shading or thermostats. Occupants are basically satisfied with acoustics, cleanliness and lighting of their office spaces. Dissatisfaction is experienced in connection with office temperature and air quality. There was a free-text complaint part of the survey where occupants mainly submitted complaints about the absence of operable windows, FC units and lighting control. Sewage smell was recorded by more than 30 occupants from many points in the building.

During the summer and winter months 29% and 26% of the occupants respectively feel thermal discomfort. In both seasons they feel their offices too hot. Meeting rooms are used by 67% of respondents (142 workers). 50 people of them uses shading adjustments, 34 open windows and 40 sets the thermostat setpoints regularly in meeting rooms.

### 3.6 *Walk-through results*

During the walk-through, we found 14 offices with windows open. Lighting was on in 77% of the office spaces. There are three types of wall-mounted thermostats. STR 350 and STR 150 are multifunctional thermostats where not only the temperature can be set but also the level of FC fan speed, lighting and shading state. Users currently can turn up or down thermostat setpoint by + or - 3°C.

**Figure 8 - Wall-mounted thermostat types: intelligent: STR 350, STR150 and simple: STR102**

The share of multifunctional and simple thermostats is 53-47%. On the day of the walk-through according to our records, 48% of thermostats were in heating mode and 52% in cooling. Based on the BMS records for that day, a large variety of indoor air temperatures could be seen ranging from 19 to 28°C. On Figure 9, FC unit modes used on the very same day can be seen. There is no connection between FC mode and temperature. For example there is no tendency that in the heating offices the temperature is lower.

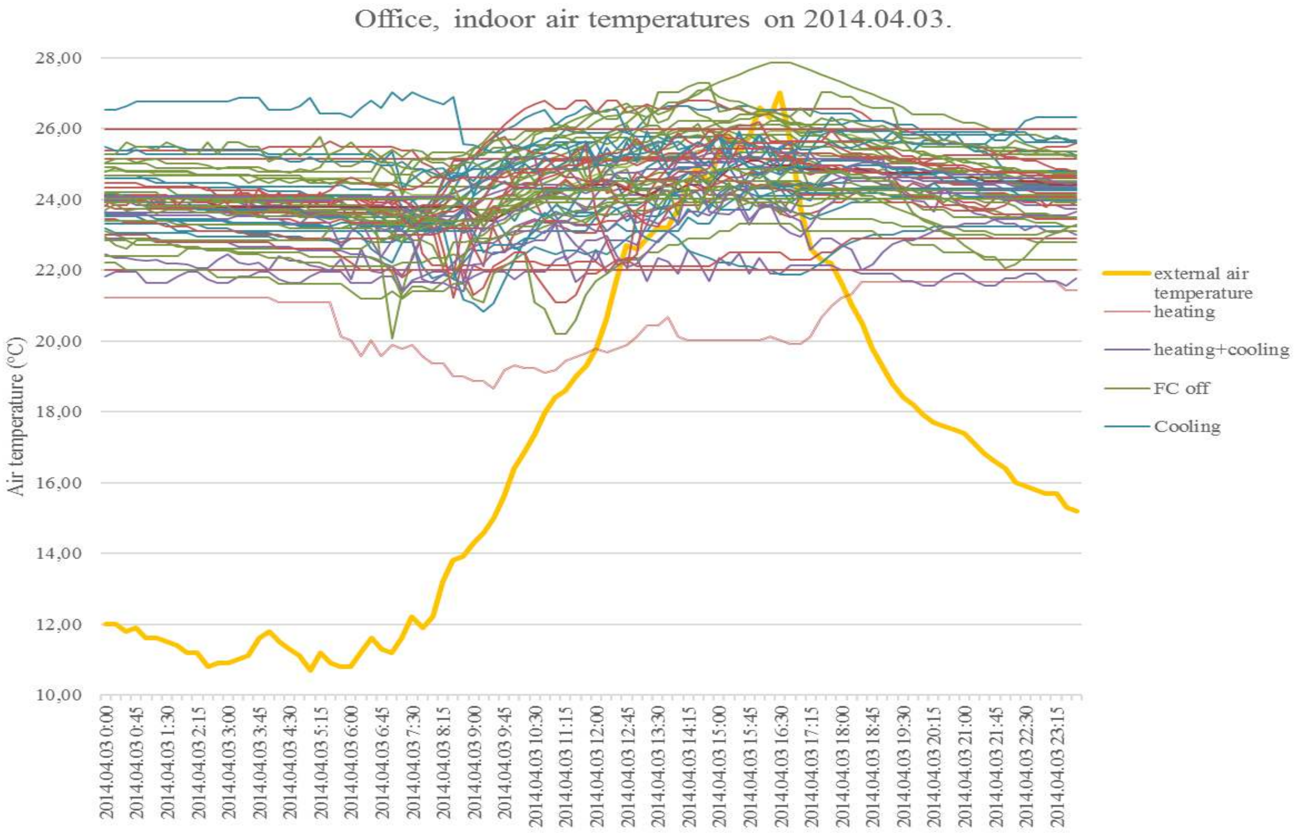


**Figure 9 - Measured indoor air temperatures on the day of walk-through**

It was also investigated whether there is any connection between orientation and FC mode used on that given day. But no correlation was found. It was recorded what IT devices are used in the offices. Results are showed on Figure 10. Majority of workers uses desktop computers with 1.3 screens on average.

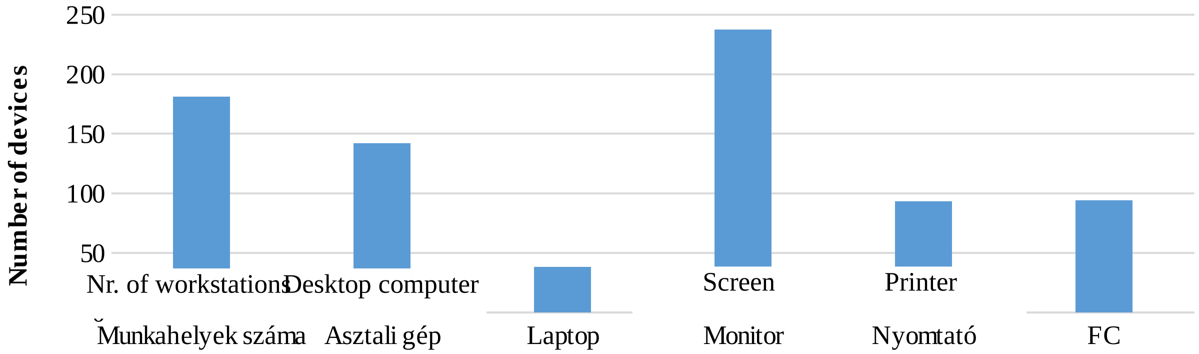


**Figure 10 - Number of IT equipment in offices**

During the walk-through, air quality, smells, lighting states were recorded as well. 14% of the cases, unpleasant air quality was found and 3% of the rooms had sewage smell.

### 3.7 *Thermographic camera findings:*

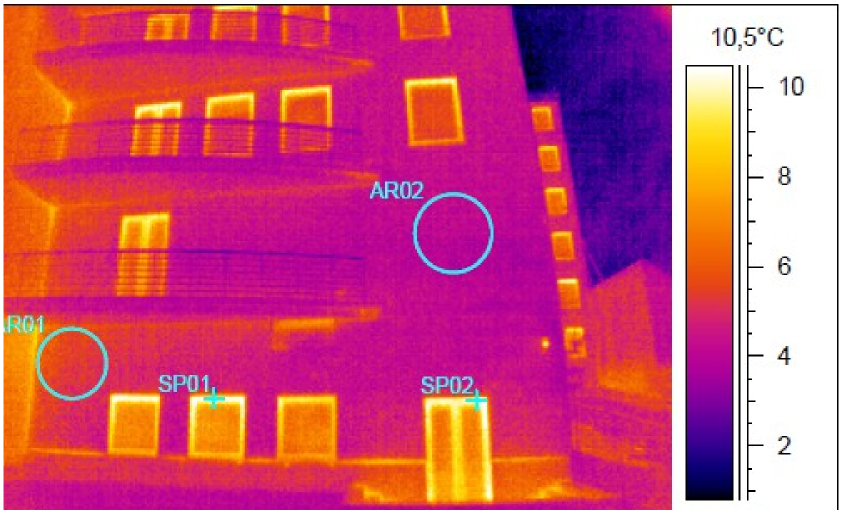


**Figure 11 - Thermographic view of northern facade**

The thermographic camera investigations showed that the insulation of solid surfaces is in good condition, thermal bridges were not shown to have significant effect on the outdoor surface temperatures. However, window-frame deformations and significant air leaks were shown.

### 3.8 *Fan coil operation mode analysis*

**Figure 12 – Fan coil operation modes on the day of walk-through**

FC and other operation conditions (valve state, ventilator state, indoor temperature setpoint, measured air temperature, occupancy state) were investigated on the day of the walk-through. Data were obtained from the BMS system:

- Only data from 44 offices could be used out of 83 as many of the datasets were deficient.
- 20,5% of these offices showed permanent occupancy during the whole day. These sensors must be broken.
- 21 offices were only in heating mode, and 17 were only in cooling during the day. Six offices used both heating and cooling during the same day, where simple thermostats were installed and the heating setpoint in the morning hours was higher than the cooling setpoint in the afternoon.
- In 14% of the offices, the FC units were left on during absence. The control link between the motion sensor and the FC unit is not working.
- Heating setpoints were between 22-25,5°C.
- Cooling setpoints were 18,4-25,5°C.
- Southern glass-wall offices could not be cooled down below 25-26°C.

### 3.9 *Thermal comfort measurements*

Thermal comfort measurements showed that office air temperatures are compliant with locally applicable work-safety codes (3/2002. (II. 8.) SzCsM-EüM -joint decree on minimum level of work-safety requirements 2002). Also air velocity was always below 0.1 m/s which is compliant with local code.

### 3.10 *Plug load and lighting electricity use*

Office blocks were investigated for lighting and plug-load electricity consumption. Submetered electricity data was analysed for two years: 2013 and 2014. Figure 13 shows the huge variability (4-500%) between office blocks. Office blocks 409-414 and 608-610 & 620-621 consumed the most lighting and plug-load energy. Benchmark value shown on Figure 13 is based on the U.S. office consumption average (EIA 2003).

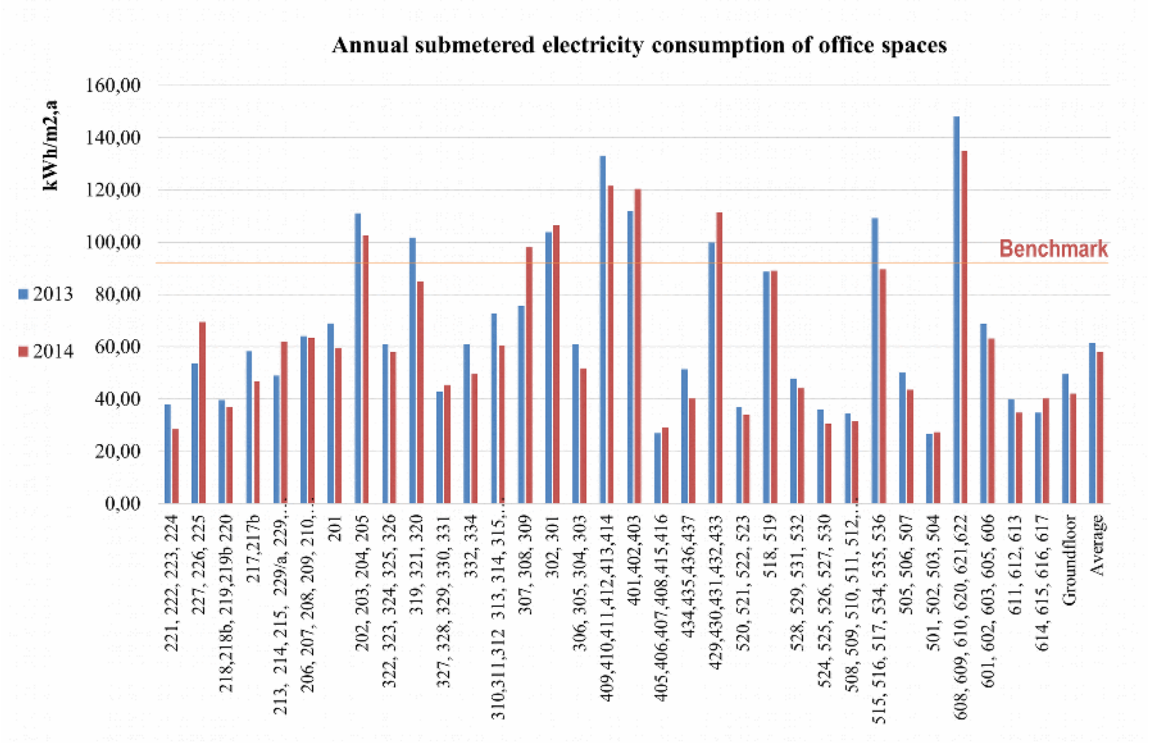


**Figure 13 - Submetered lighting and plug-load energy consumption of office-groups**

### 3.11 *Building energy use pattern analysis*

Energy use patterns of the building were identified based on utility bills, submeter data and local walk-through. In the sankey chart on Figure 14, energy flows can be seen depending on the final area of consumption. Major losses were identified in both the heating and cooling systems. There were many flows that were not submetered despite the belief of full submetering of the owner.

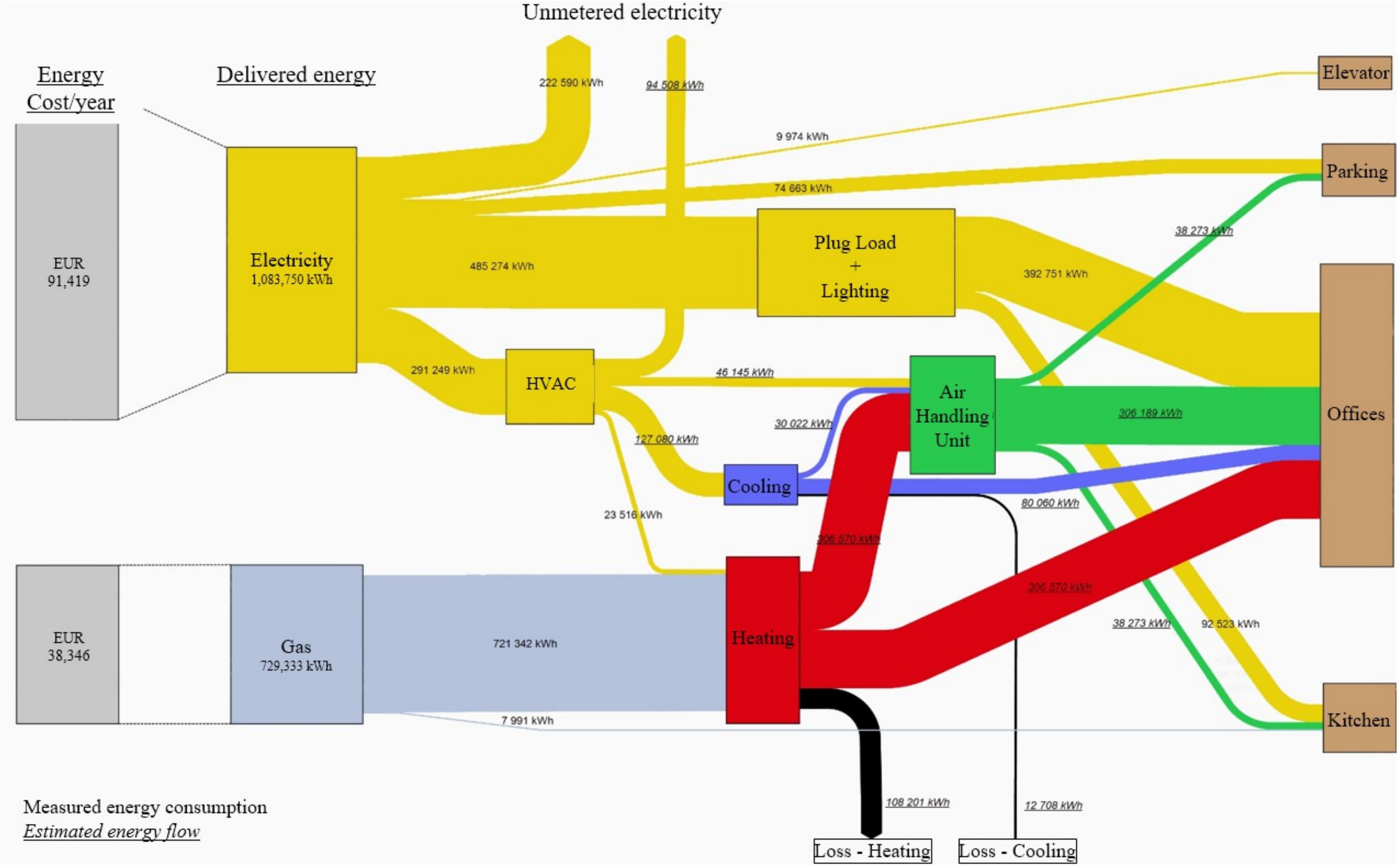


**Figure 14 - Sankey diagram of energy use patterns**

### 3.12 *Problems identified, potential areas of interventions*

During the audit process, serious thermal comfort issues and complaints were recorded. According to survey results, 42% of workers were unsatisfied with thermal comfort or air quality. This ratio is 75% in those offices where windows are fixed, not operable. In these offices, occupants have only one option to control their thermal environment: changing the FC setpoint. This was one of the most important areas of intervention. On the one hand, possible thermostat setpoints needed revision and also an investigation was needed on the reasons of discomfort on the level of secondary system (FC unit).

According to survey results, 21% of workers are dissatisfied with visual comfort in their offices. Regarding natural light, it was identified that the shading system's control algorithm is too forgiving and as occupants had the chance to overwrite it, its operation is not efficient. The artificial lighting system's control is not providing uniform, consistent levels of lighting based on daylighting sensors. Both the sensors and control algorithms should be revised.

In the free-text comment section of the questionnaire, 30 workers were complaining about sewage smell. During the walk-through these areas were identified as rooms with close vicinity to restrooms. Thermographic camera investigations showed that window frames are deformed or installed improperly. Therefore, there are significant air leak causing-heat losses on the façades.

In general, primary HVAC systems were in good condition, system efficiencies could be increased by supplementary measures such as boiler control temperature adjustment, use of free-cooling during the nights, replacement of current heat recovery unit of AHU and cooling naturally the hot-side of chillers.

Utility bills could be further decreased by the use of renewable energy sources such as solar thermal collectors and photovoltaic system. Water savings could be reached by lowering the potable water use for cleaning, irrigation and toilet flushing purposes. Also we found that the contract with the building's natural gas provider should be revised as the owner pays a disproportionately large gas volume availability fee.

## 4. INTERVENTION MEASURES

After the intervention areas were determined (Section 3.12), intervention measures were elaborated and investigated from the perspective of potential energy or water saving and return on investment. There were two areas during the course of the project where based on preliminary data analysis, the owner decided to act as soon as possible, not waiting for our calculation results. These were the cleaning or replacement of plumbing traps to get rid of the sewage smell and adjustment of window frames where the thermographic camera showed the most significant air leaks. These two measures were therefore not subject of the detailed investigations discussed in this section.

The intervention measures investigated included:

1. Shading control overwrite

Currently, external shading devices are controlled based on a direct solar radiation intensity sensor and a wind velocity sensor placed on the roof. Eastern façade shading devices are time-controlled and close only during morning hours (until noon). On the southern façade, they are closed only after noon if the solar radiation is high. The idea behind this is that direct radiation affects these facades only during these hours. However, in this case the significant heat load from diffuse radiation is ignored which enables solar heat gains into the building contributing to the cooling energy demand increase. It was proposed to skip the time-dependency part of the shading control algorithm in case of all facades and to install two additional sensors on the facades which measure solar radiation received by the façade and use this signal as an input to the shading control.

2. Lighting system re-calibration

Artificial lighting in office and meeting room spaces are controlled by daylight and motion sensors. During the audit, it was found that most of the motion sensors are faulty. Also as occupants had the chance to call the operators and reset the light levels according to personal preference (usually set higher), during the walk-through it was found that almost all lights were on on a perfect sunny day. By recalibrating the system for a given desk-level illumination level (500 lux), significant amount of energy can be saved.

3. Boiler primary temperature setting

The condensing boiler was in good condition but operated with a water flow temperature of 67°C. The ideal flow temperature would be between 55-60°C. This way the boiler can operate more efficiently in condensing mode for a longer time during the year. Therefore, the reset of the boiler’s flow temperature was proposed.

4. Natural gas volume availability contract revision

Peak gas consumption was investigated and it was found that it never reached the contracted volume. In case further energy-efficiency measures are going to be implemented, this peak demand will be even lower. Therefore, it was proposed to reset the current gas volume availability from the current 100 to 65 $m^3/h$. This would cut down significantly the utility bills.

5. Optimized thermostat settings and inlet air temperature and schedule.

A seasonal optimization was carried out for operation setpoints of heating, cooling and ventilation system. Thermostat setpoint schedules and inlet air temperature schedules were proposed with significant energy savings estimated. The optimization process and results are described in Sections 2.5 and 7.

6. Automated nocturnal cross-ventilation

To decrease cooling demand during summer, it was proposed to install automatic window-openers for nocturnal-cross ventilation to let cool night-air in from the outside. Also to increase efficiency of night-time ventilation the omission of suspended ceilings was suggested. This way the cooled thermal mass can be increased and the cooling effect of large concrete slab surfaces can last longer.

7. Radiant ceiling heating and cooling panels

Currently the secondary heating and cooling HVAC units are FCs in office and meeting room spaces. This solution is commonly used due to lower initial financial burden compared to other secondary systems. However, FC units generally operate with low comfort parameters (draft and noise) while consuming more energy than other more efficient alternatives. Therefore, it was proposed to change the secondary systems of the building to radiant ceiling heating and cooling panels. In case the owner decided to implement both solutions 6 and 7, radiant panels should be chosen to provide access for the room air to the high thermal mass concrete slabs and not as part of an enclosed suspended ceiling system.

8. New heat recovery unit for the AHU

The current heat recovery unit in the AHU is a run-around coil which operates with a 40-45% efficiency. It is proposed to change it to a rotary heat exchanger which works with a higher efficiency of 85%. Significant amount of heating and cooling energy consumption can be saved and also an additional advantage is that it can recover latent heat from the exhaust air.

9. Adiabatic cooling of the hot-side of existing chillers

Existing chillers were in good condition but their operation efficiency can be increased by passive cooling of the hot-side of the chillers. By means of adiabatic cooling, environmental temperature of the chiller's hot side decreases due to the cooling effect of evaporating water drops blown onto a net next to the condenser unit. This way by a limited amount of additional water use, electricity consumption can be saved and also the life expectancy of the chiller increases.

10. Solar thermal collectors for kitchen domestic hot water (DHW)

DHW supply is decentralized in the building using small, efficient electric heaters for the limited amount of DH used by office workers in sinks. Solar thermal collectors were proposed to be installed to supply DHW to the kitchen where most of hot water is used in the building (approximately 500 l/day). The size of the systems proposed is 8 m$^2$ of panel area with 2 m$^3$ DHW storage tank.

11. Photovoltaic panels (PV) on the roof

It was proposed to install a PV system of 34 kW on the roof. This is the maximum performance that can be reached by covering all unshaded roof surface area. Tilt angle was 15°; orientation of the roof was 19° off from south to the west.

12. Rainwater use for cleaning and irrigation

Currently, water and sewage utility prices are not high in Hungary and also the country has a significant fresh, potable water source. Therefore, it is not common to invest into water saving measures. However, rainwater is collected in case of this building as the sewage system is not capable of accepting large amounts of precipitation at a time. This way water is stored on level -3 of the building anyway and pumped into the sewage system once it is allowed. This rainwater is proposed to be used for irrigation and cleaning purposes on site.

13. Greywater system for toilet flushing.

Majority of water consumption was coming from toilet flushing (~ 2.200 m3/year). Therefore, it is proposed to reuse grey water in the building for toilet flushing. Greywater already used in sinks should be treated following these steps to be able to use for toilet flushing: filtering, settling and disinfection.

## 5. OCCUPANT BEHAVIOUR MODELLING

Based on the results of the building audit, a dynamic building energy model was built according to the methodology described in section 2.2 to estimate energy savings for most energy-related intervention measure. As occupants have many control options in this building, and during the audit process they showed extremely wide variety of occupant behaviour patterns, the most important part of the building energy model was to represent appropriately occupancy and the behaviour of users which had an enormous effect on the building's energy consumption and therefore on our predictions as well. These behaviours were determined based on the audit findings. This section describes how the information was extracted and then represented in the most resource-efficient yet precise way.

Occupant actions that have the largest effect on energy consumption patterns of this building were thermostat usage and window opening behaviour. These were investigated in a partial energy model as discussed in section 2.2. Here results of these investigations are introduced.

As shown in section 3, FC usage patterns showed a great variety on the day of the walk-through. To investigate the effect of this phenomenon on the energy consumption of the building, a partial model of the building's second floor was developed. Variation in energy consumption was investigated using the sensitivity analysis. The Base-case did not allow occupant controls and thermostats were set to the ideal setpoints determined by the building owner. Then alternative cases were investigated with various levels of control options. The most extreme scenario was what we found in the building on the day of the walk-through: occupants were allowed to use heating and cooling within the very same day in neighbouring offices with setpoint temperatures ranging from 18ºC to 28ºC.

Our results showed that heating and cooling energy consumption was increased by 10% and 5% respectively in the extreme case compared to the base case. These thermostat use patterns were implemented into the final whole-building energy model.

The same partial energy model was used to carry out sensitivity analysis on the effect of window opening on the heating energy consumption. Window opening frequencies and schedules were determined based on data collected from the building:

- BMS system window state signals,
- As-built plans analysis (actual presence of operable windows in the rooms),
- Walk-through (current state of operable windows),
- Interview and survey results.

Simulated heating consumption results were compared to actual natural gas consumption of the building. After many iterations, a deterministic, time-based window-opening schedule was obtained that represented most of the real-world window opening habits of users. This behaviour is heavily time-based: workers opened windows once an hour during weekdays and working hours for five minutes in their own offices.

In the following sub-sections, occupant-related aspects and findings are introduced which were later on implemented into our final whole-building energy model.

### 5.1 *Occupancy*

To determine realistic occupancy schedules for the whole-building energy model, motion sensor data recorded by the BMS system was analysed in three different room types: 4-person offices, private offices and meeting rooms. The annual average occupancy varied between 62 and 77% in offices, while meeting rooms were used only 20-23% of the working hours. The motion sensors used in the building did not count the number of occupants in a room, they only reported occupancy status. Therefore, data from meeting rooms and 4-person offices were fine-tuned based on our walk-through logs, survey feedback and references of typical number of occupants in office buildings. Occupancy schedules were fine-tuned by walk-through results which found 143 workers present out of 180, which means a 79% of overall occupancy rate, slightly higher than findings from the BMS data analysis. Final occupancy patterns were implemented into IDA ICE as static schedules for offices and meeting rooms.

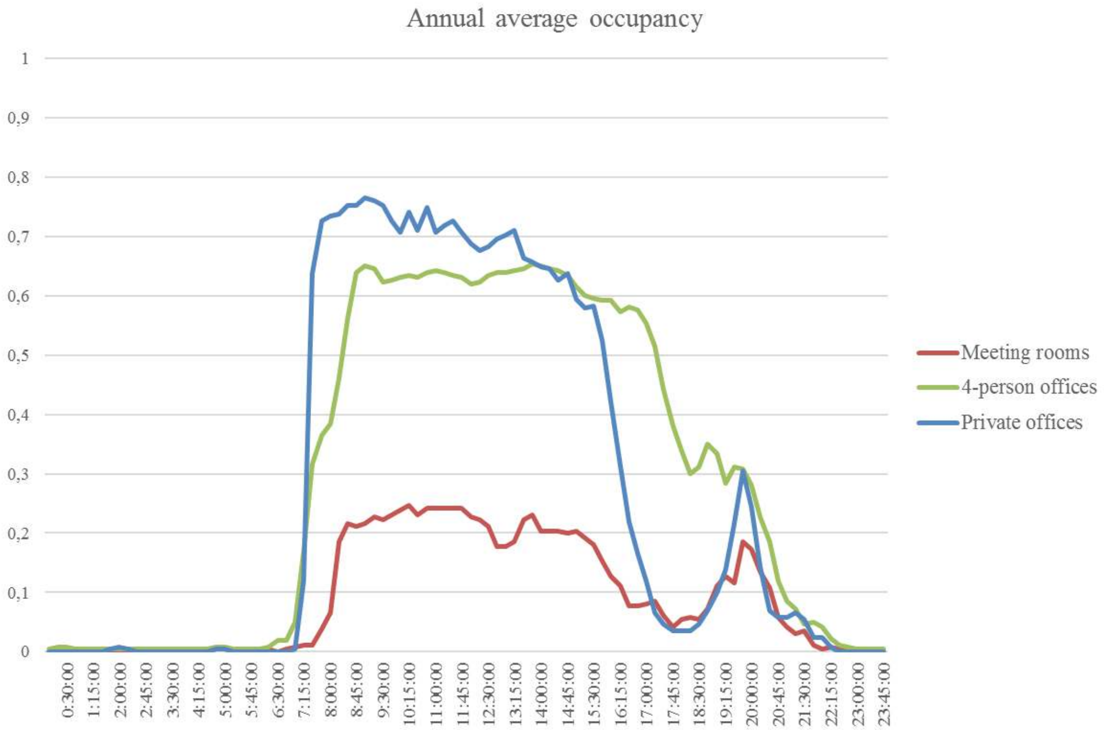


**Figure 15 - Annual average occupancy of three types of rooms on weekdays**

### 5.2 *Window opening*

Heating energy consumption sensitivity analysis was used to determine window opening schedules. Investigations showed that window opening habits were mostly time-driven. Also during the calibration process, we found that the more precise modelling of window opening behaviour brings the estimate heating energy use closer to the actual heating energy consumption of the building. Therefore, real-life window schedules were used in the final whole-building energy model.

### 5.3 *Shading*

Shading usage was analysed using as-built plan analysis (presence of external shading in the rooms), walk-through results about interior shading devices' presence and current state, and interviews and surveys. usage

External shading louvers have a centralized control driven by solar irradiance and wind velocity. As there is a possibility to overwrite this control by occupants calling the building operators, external shading controls were adjusted in the whole-building energy model based on:

- Actual BME system signals about the state of shading louvers,

- Interview and survey results about the overwrite frequencies.

Internal shading was found to be present only in 27% of rooms and often not used. Therefore, internal shading were not modelled in the whole-building energy model.

### 5.4 *Lighting*

Based on walk-through observations and interviews, we found that the lighting system would need a daylighting recalibration as building users could call a dispatcher service and set their own lighting levels. Accordingly, the lighting control in the energy model was modified.

### 5.5 *Heating and cooling setpoint adjustments*

Firstly, BMS data analysis was carried out about the FC unit valve states and temperature setpoints in each room. Secondly, the partial model was used to determine the appropriate representation of occupants' thermostat usage.

### 5.6 *Plug loads*

As part of the plug load-related indoor heat gains, computers, printers, fridges, personal fans, heaters and other electric equipment were modelled based on the survey results and also the equipment log filled in at the onsite walk-through. At the same time, plug-load and lighting energy consumption analysis was done per room groups based on electricity submeter data (See Section 3). Based on these sources, the distribution of large plug-load electricity consumers were finalized.

## 6. BUILDING ENERGY MODEL CALIBRATION

The electricity consumption of the baseline building energy model representing the current state of the building was calibrated to measured energy consumption.

Using the method described in section 2.3, NMBE for electricity consumption was 3%. At this point, the model was considered to be precise enough to predict energy savings. Calibration results can be seen in Figure 16 - BEM calibration results for electricity consumption

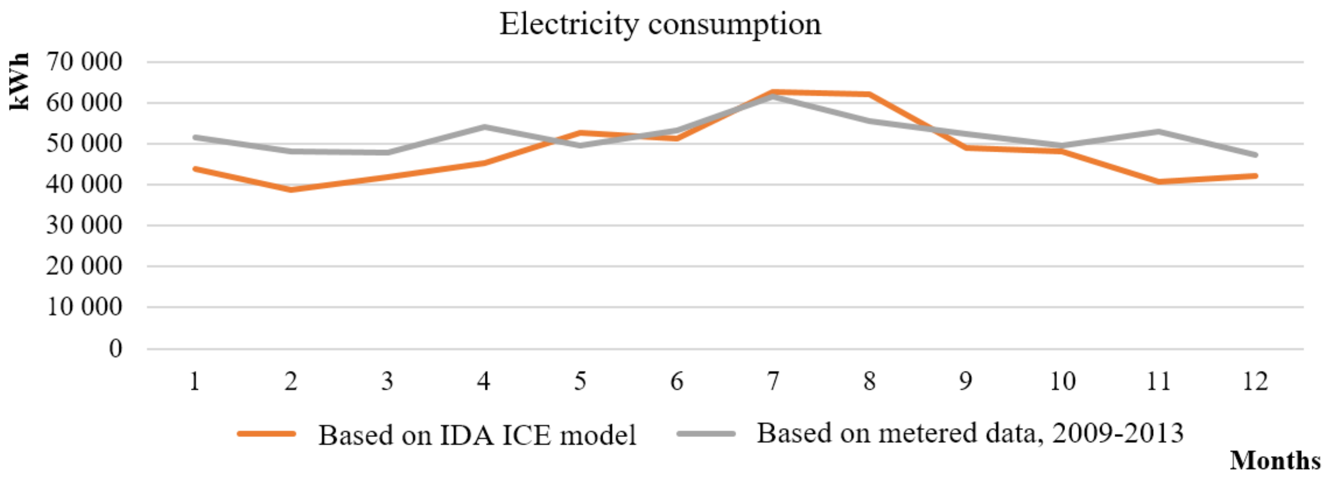


**Figure 16 - BEM calibration results for electricity consumption**

## 7. HVAC CONTROL OPTIMIZATION

With the combination of all the variables and office zones, 2016 variations were run for heating (January) and cooling (July) seasons, using the genetic optimization algorithm, NSGA II. Results of the optimization run of SW office for the heating season is shown in Figure 17 as an example, the extreme optimal cases are marked as follows:

Δ: current operating conditions

◊: case A - minimum energy use, with current PDH (comfort) level

O: case B - minimum PDH values (maximum thermal comfort level), with current energy use level

Between the two cases selected on the Pareto front, either case is better (either from energy use or comfort perspective) than the current case. The vertical lines indicate the boundaries of comfort categories I, II and III of the standard EN 15251. These categories are separated by the average PPD values (6% and 10% respectively), calculated from PDH results for each zone.

Optimization Pareto front example – Office facing South-West:

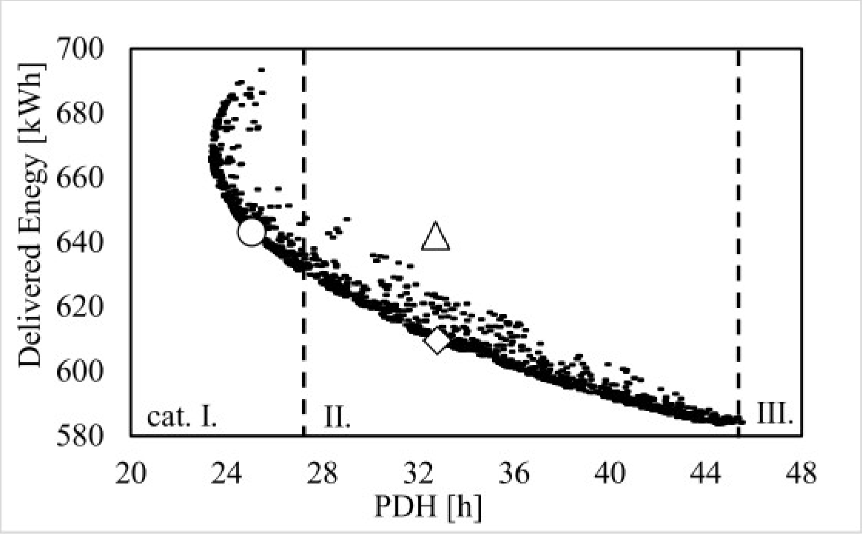


**Figure 17- Results of optimization of delivered energy for Zone SW (January)**

Legend:

Δ: current operating conditions
◊: case A - minimum energy use, with current PDH values
O: case B - with minimum PDH values, with current energy use value

Example of optimal AHU inlet air temperature control for each zone in the heating season (January):

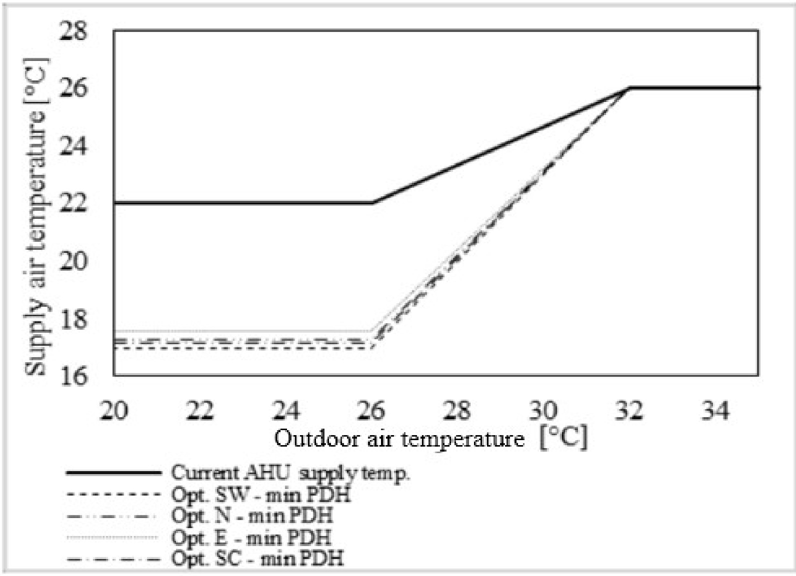


**Figure 18. - AHU supply air temperature optimization results in heating mode (January)**

## 8. ENERGY CONCEPT, INTERVENTION PACKAGES

After quantifying the energy or water-saving of each intervention measure, investment costs were calculated for each measure to determine the financial viability for the owner. To calculate payback period of each intervention measure, net present value and internal rate of return of investments were determined.

Measures 1 to 5 have a payback period less than three years. Measures 6 and 9 have a payback in less than 9 years, measure 8 in approximately 17 years. The investments of measures 7, 10, 11, 12 and 13 would not pay back within 25 years. Therefore, they were not cost effective during their estimated lifetime.

Internal return rate (IRR) is more than 70% for measures 1-5 which were considered to be a successful, profitable investment; whereas, measures 6 and 9 have a moderate IRR. Measures with low IRR (10-12) would not be cost effective for investment. IRR is not applicable for intervention measures 7 and 13.

**Table 1 - Payback period and internal rate of return of intervention measures**

| Intervention measure | Dynamic payback period [year] | Internal Rate of Return [%] |
|---|---|---|
| 1 | 1.64 | 70.4 |
| 2 | 0.29 | 377.5 |
| 3 | 0.64 | 171.5 |
| 4 | 0.30 | 368.4 |
| 5 | 0.06 | 1841.5 |
| 6 | 7.31 | 20.4 |
| 7 | > 25 | - |
| 8 | 16.95 | 10.7 |
| 9 | 4.32 | 27.8 |
| 10 | > 25 | 3.6 |
| 11 | > 25 | 0.7 |
| 12 | > 25 | 0.8 |
| 13 | > 25 | - |

After the payback period calculations, intervention measures were selected and organized into intervention packages depending on the level of payback periods:

- Short-term package – payback time 0-3 years.
- Middle-term package – payback time 3-9 years.
- Long-term package – payback time 9+ years.

The trend of annual utility costs for each intervention package is shown in Figure 19

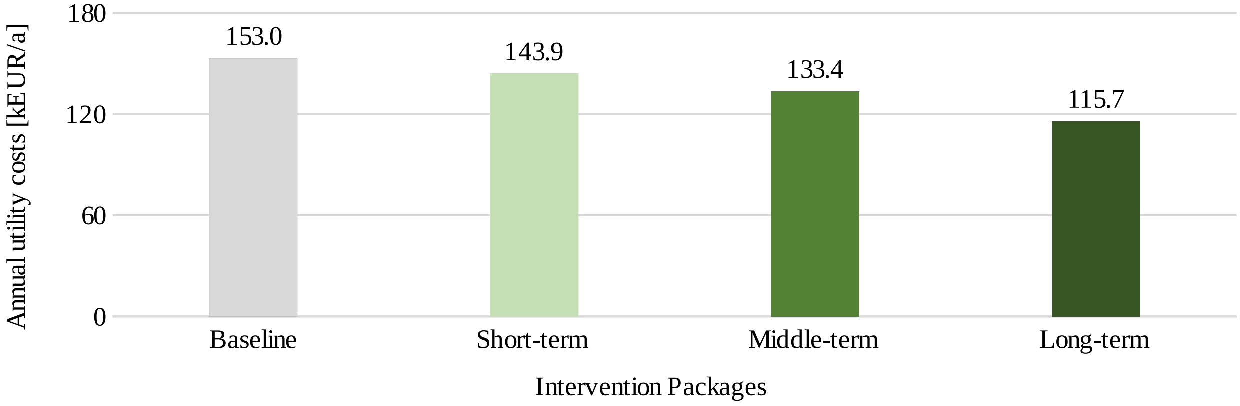


**Figure 19 - Predicted annual utility costs in case of intervention package implementations**

## 9. DISCUSSION

### 9.1 *Building audit findings*

As an outcome of the preliminary analyses, our investigation found that the state-of-the-art building management, heating, cooling and ventilation systems are in good condition but it was operated by building operators who are practically not aware of the building management processes. Creative, home-made thermal comfort-restoring solutions were found throughout the building which implies that comfort problems are permanent in the building.

When the unpleasant sewage smell and window-frame deformations were identified, owners acted immediately based on preliminary data analysis. There were the cleaning or replacement of plumbing traps to get rid of the sewage smell and adjustment of window frames where the thermographic camera showed the most significant air leaks.

Based on the extensive analysis of the building's operation and occupants' behaviour, intervention measures were identified and evaluated to propose intervention packages. The owner specified that most probably only investments with short-term return would be made. Short-term investment return period was determined by financial specialists as 0-3 years. It is important to highlight that the project was carried out in the last phase of an era when financial crisis still affected the construction industry in Hungary. In the future, it should be a subject of further investigation whether more realistically accepted return on investment period would increase in the future, once the industry gets on an upward trajectory.

### 9.2 *Occupant behaviour modelling*

Window opening schedules used in the energy models were static as it was found that the use of commonly known stochastic window opening models would require an extreme amount of effort which could not be included in the project scope. This time-driven window opening behaviour might come from a cultural and local occupant habit: occupants usually open windows for five minutes every hour in Hungarian residential buildings. People open windows similarly in their workplaces. To identify other possible drivers, further investigations would be needed such as a qualitative, extended transversal survey.

Fan coil usage patterns showed a huge variability in the building. These behavioural patterns were represented in our building energy model to obtain energy saving data  for each retrofitting measure assuming the same user behaviour in the building. However, another approach was presented to the owner as well: there is a huge potential in energy savings if occupants are trained to better interact with the building systems. According to the international studies, an annual energy saving of 14-22-30% can be reached if occupants behave in a more energy-conscious way (Buildings 2011) (PSCMAG.com business economics 2011) (The Wall Street Journal 2013).

Occupancy data analysis of the building showed that, shocking to the building owner, all HVAC equipment (fresh air, heating, cooling) were running at 100% occupancy mode. Therefore, it was proposed to take the data from the motion sensors as an input to optimize the HVAC control mechanisms. This way further energy savings could be achieved which was beyond the project scope. In a later phase, a training session was hold to the building operation staff, but after that the whole operating team changed and many obvious operating mistakes were discovered.

Currently, only motion sensor data were available in the building to determine occupancy status.  In future, data of number of occupants could be obtained by people count sensors, or through the analysis of $CO_2$ levels in the rooms, which was used by Lam et al. and other researchers with some level of success (Lam et al. 2009) (Federspiel 1997) (Sowa 2002).

### 9.3 *Occupant robustness in buildings*

During the process of conducting this audit project, many questions arose in connection with the occupants' freedom of control in relation to environmental office parameters. It was found that in this building, occupants had maximum freedom to act to restore their comfort and 94% answered in the survey that they actually used these controls: window opening, shading control overwrite, lighting system recalibration, and heating/cooling setpoint adjustments. At the same time, somewhat surprisingly large percentage (29% and 26% during summer and winter respectively) of office workers complained about thermal discomfort. This phenomenon is a typical vicious spiral where building operation staff does everything to satisfy occupants' needs, consuming vast amount of energy, while at the same time occupants still have thermal discomfort, are unsatisfied and keep complaining.

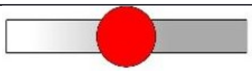
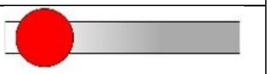
The occupants' freedom of control influences the impact of occupants' behaviour on the energy consumption of buildings, thus influencing the energy robustness of a building (Hoes et al. 2009). Numerous studies have shown that occupants sub-optimally use such controls to improve comfort during times of significant discomfort, but are much more passive when the source of discomfort is alleviated (O'Brien 2013). O'Brien also states that one cause for people to act in energy-intensive ways is if they encounter prolonged and consistent discomfort (O'Brien 2013). Another fact is that occupants prefer to have control over their environment no matter they are connected or not (placebo controls) to actual HVAC equipment (Paciuk 1989).

Therefore, the ultimate design question is how much freedom should be given to the occupants. In other words, what is the optimal level of energy-robustness of buildings? According to literature, robust design refers to the design process as a whole, carried out in such a way that it is difficult for users to make inappropriate decisions (Palme et al. 2006). However, it is still unclear when an occupant's action can be called "inappropriate" and whether there are other options in the hands of building operators (such as building use training for occupants) than sealing windows or locking thermostats in a box.

### 9.4 *Occupant-related uncertainties of measures*

It was also investigated whether occupant behaviour had any impact on the energy or water savings calculated for the intervention measures (Table Error: Reference source not found2). OB impact was described by three levels: negligible, medium and high. Based on the energy use pattern analysis of the building, it was found that the overall DHW energy consumption of the kitchen is only 0.4% of the whole building, therefore the OB impact of installing solar thermal collectors were set to negligible. As office lighting's share is about 11%, occupants' effect on energy consumption is considered medium (5 to 20%). While the heating, cooling and air-conditioning of office spaces takes approximately 32.7% of the building's energy consumption, occupants' impact can be considered high. Questionnaire survey results showed that 94% of workers in the building used environmental controls in their office environment. Automatic shading controls were overwritten by 28.3% of occupants. Therefore, the behaviour of workers/occupants have a high influence on energy consumption.

**Table 2 - Occupant behaviour impact and modelling of Measures 1, 2, 5, 7 and 10**

| **Measure** | **1 -** Shading control overwrite | **2 -** Lighting system re-calibration | **5 and 7 -** Optimized thermostat settings and inlet air temperature schedule, and radiant ceiling heating and cooling panels | **10 -** Solar thermal collectors for kitchen domestic hot water (DHW) |
|---|---|---|---|---|
| Influencing Parameters | Heating, cooling and lighting use | Lighting use | Heating, cooling and ventilation energy use | DHW energy use |
| OB impact level (Negligible, medium, high) |  |  |  |  |
| How is it modelled ideally? | Stochastic shading control algorithms | Daylighting control models, new manual overwrite models | Stochastic setpoint adjustment algorithms | DHW use schedules |

It was found that occupants have a high level of impact on the shading control overwrite (measure 1). With the overwrite of the automated shading control, savings could be calculated based on the assumption that occupants will not switch to manual operation again as the new control strategy provides higher visual comfort. This assumption introduces uncertainties into our model. This uncertainty could be resolved by the use of more advanced, stochastic shading control models built on the actual behaviour of building occupants. However, this is not realistic to be included in a commercial project of this scale at this point due to extensive resource demand of advanced energy modelling.

For the lighting system recalibration (measure 2), occupants have a moderate level of impact on the lighting energy consumption as a recalibrated daylighting control would enhance visual comfort in all office spaces. Energy saving estimation would be more accurate if new lighting control overwriting models were developed and implemented into building energy models.

Energy savings from optimized thermostat setpoints, supply air temperature and schedule (measure 5), the use of radiant ceiling panels for heating and cooling instead of fan coil units are highly dependent on occupants' behaviour. More advanced, stochastic thermostat setpoint adjustment algorithms are available in literature ((Andersen et al. 2009), (Guerra-Santin and Itard 2010), (Langevin, Wen, and Gurian 2014), (Nicol and Humphreys 2002). However, application of these models was not realistic in this project as the required effort was well beyond the project budget.

Reliability of water-saving estimation is dependent on the water use of occupants in the building. For the installation of solar thermal collectors (measure 10), this effect is considered low as domestic hot water use is not a significant energy consumer in this office building without showering facilities and only with a moderate sized kitchen.

A sample-office retrofit was proposed to the owner to test the occupant-education program effectiveness and other intervention measures on a small scale to have exact energy-saving figures in the building. This reference office is still under consideration. In case the owner decides to build it, installation of an extensive monitoring system is planned.

## 10. CONCLUSIONS

An office building audit project was introduced in this paper. The building was designed and built according to state-of-the-art design and energy management principles but operated with very low energy efficiency and poor user comfort.

After an extensive building operation and use audit, causes of malfunction were identified and intervention packages were proposed. The energy consumption and occupant behaviour patterns of the building were simulated with energy modelling software. The baseline model was calibrated to annual measured energy consumption, using actual occupant behaviour and presence, based on results of self-reported surveys, occupancy sensors and fan-coil usage data.

Realistic but still static occupant behaviour models were created and used. This way our findings and the effect of our proposed improvements could be more reliable. The possible applications and usability of advanced, stochastic occupant behaviour measures were investigated and it was found that the use of these algorithms is out of the time-frame and resources of a commercial audit project in Hungary.

Based on the extensive analysis of the building, intervention packages were proposed to the owner. The owner decided that only investments with short-term return (0-3 years) would be made. As this approach might be a side-effect of the recent financial crisis, in the future, it should be a subject of further investigation whether generally accepted return on investment periods would be longer, once the industry gets on an upward trajectory.

Right now, building energy simulation is a great, useful tool to inform designers on design optimisation and decision making. However, it is used most effectively in Hungary in the early design phase of a building. This project has proved that it can be used for fault detection and operation fine-tuning in a building’s operational phase.

Future work should include investigations on energy-robust design and retrofit, and education of occupants and operators on building use in commercial offices.

## 11. NOMENCLATURE

NPV: Net Present Value of investment

C0: Initial investment

Ct: Cash flow in a given year

t: Time period (year)

n: Estimated lifetime of the investment

r: Discount rate

PDH Hours of people dissatisfied, i.e. the integral of the PPD measure multiplied by the total number of present occupants [hrs]

H1 Setback heating setpoint [°C]

H2 Heating setpoint [°C]

C1 Cooling setpoint [°C]

C2 Setback cooling setpoint [°C]

TSi Supply air temperature [°C]

TEi External temperature [°C]

Ti Daily hours [hrs]

## ACKNOWLEDGMENTS

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