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Theory and Reality: a Comparative Analysis of Standardized and Real Building Energy Usage and Impact of Input Simplifications

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Abstract

Designers can select between different energy performance calculation models starting from simplified typology-based seasonal methods to detailed dynamic building simulation tools. Results are significantly influenced by the model simplifications. However, even the most complex and precise model can lead to false results if the necessary set of inputs are not properly determined. In real life conditions, it is often the case that input data are roughly estimated as exact specification is not possible due to time or budgetary limitations. One of the most disputable set of input parameters are related to occupants' behaviour and building operation. Current paper compares different calculation models and occupant profiles based on standardised and measured values. Results are compared to real time consumption data from smart meters. Typical false operation modes are investigated to quantify the wasted energy as a consequence.

The gap between standardised and real occupant behaviour coming out of two case study examples can help decision makers and improve knowledge to better consider the human factor in building energy modelling.

Introduction

With the ever-growing demand for lowering the energy consumption of buildings, researchers urge to determine the most influencing factors that may affect the final energy use of the building stock. Research showed that the six most influencing factors of building performance are climate, building envelope, building equipment, operation and maintenance, occupant behaviour, and indoor environment conditions (Yoshino et al., 2017). It became essential in the course of building design to use advanced calculation techniques, such as dynamic building energy simulations to determine more precisely the energy performance of either a new or a refurbished building. It is assumed that these methods take into consideration all six most influencing factors thus the design will be more robust, decisions made during the design process are better grounded (Fathalian and Kargarsharifabad, 2018).

As simulations use a specific set of input parameters to determine the energy consumption of buildings, it is essential to choose them wisely and it is clear that the results greatly depend on the input parameters selected and the model simplifications applied. Researchers in recent years started to work on quantifying the influence of input parameters on simulated energy use and also established sensitivity analysis frameworks to investigate this matter (Hopfe and Hensen, 2011). A study specifically investigated the effect of zoning simplifications and shading modelling on model development time and changes in simulated heat demand (Klimczak et al., 2018).

In terms of the use of the buildings and occupant behaviour, in many cases modellers use default, simple occupancy profiles and related operation schedules offered by the software package thus introducing significant uncertainty and potentially bias into the models (Hong et al., 2016).

Various studies have analysed the different ways of modelling human behaviour in buildings i.e. occupancy patterns (Feng et al., 2015), active or passive behavioural actions (Delzendeh et al., 2017; Gaetani et al., 2016) and also the different technical ways to code and simulate with building performance modelling software the stochastic and deterministic occupant behaviour models (Gunay et al., 2015; Hong et al., 2017, 2015). However, there are only few researchers who managed to show the impact of occupant-related simplifications and false building operation modes by comparing simulation results to real-world measurement data. This is the gap where this paper is intended to fit and provide new information for the simulation community.

Research introduced in this paper is conducted under the umbrella of a research project titled "*Large Scale Smart Meter Data Assessment for Energy Benchmarking and Occupant Behaviour Profile Development of Building Clusters*" conducted based on data from Hungary and involved in project IEA EBC ANNEX79 - Occupant-Centric Building Design and Operation.

The project seeks to utilize a new and unique opportunity for accessing and processing an enormous dataset collected by smart meters. Recently in Hungary, nearly 10 000 buildings have been equipped with smart meters within the "*Central Smart Grid Pilot Project*". This vast database, supplemented with building surveys, audits, walk-throughs, simulation studies and questionnaires can serve as a great background framework to conduct studies such as this project introduced in this paper.

This paper sets two main goals which are strongly related to each other: first, determining the impact of occupant behaviour and associated deviations from standard operation on calculated energy use and second the impact of model simplifications on energy consumption results. Two case studies have been selected for the analysis of the subject.

Methodology

Building operation analysis

Nine public buildings were equipped with smart meters within the TOGETHER (TOwards a Goal of Efficiency THrough Energy Reduction) project co-funded by the European Union. Operation of heating systems were analysed mainly by checking room temperatures to find deviations from standard usage. In case of nearly all buildings significant operation mistakes were found. As a result of time series analysis the operation modes can be classified as follows:

- NORMAL – Normal (standard) operation: full heating during office hours, heating setback at night and during weekends. This operation mode should have been applied in all the buildings.
- WEEKEND – During weekdays the operation is the same as NORMAL, but during weekends the same profile detected as during the week. (Figure 1)
- FULL HEATING – No setback periods out of office hours, the same temperature maintained all the time.
- REVERSE – In one kindergarten the operation periods were set according to standard office hours, but the analysis pointed out that the day and setback temperatures were reversed. (Figure *2*)

The consequences of the found improper operation modes on energy consumption were analysed through two case studies applying dynamic simulation.

In addition to the detected errors in the time programmes overheating was a general problem. This fact is not discussed in the paper as it is widely investigated in the literature.

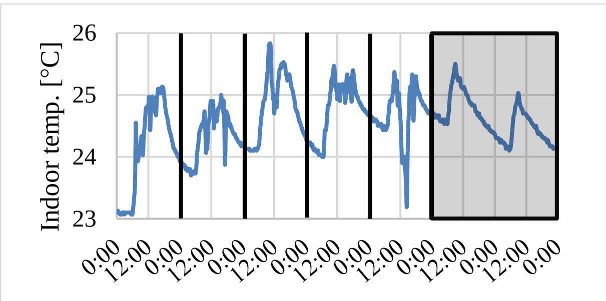

Figure 1: Setback time is during weekday nights, no difference between weekdays and weekend days (winter)

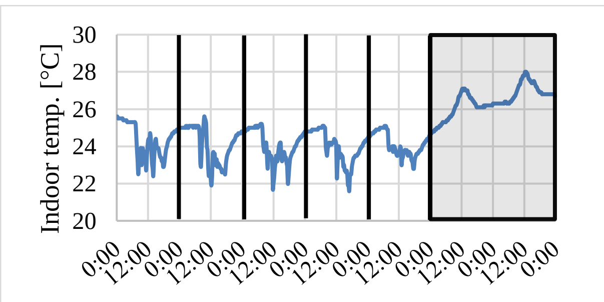

Figure 2: Setback periods during opening hours, full heating at night and weekends (winter)

Case study buildings

Case study 1: Hegyvidék Headquarter Office Building

A municipality building located in the 12th district of Budapest (Hegyvidék) was investigated using dynamic building energy simulation (DesignBuilder software). It was built in 1940 and it has 6 floors, total area of 3407 m^2. Figure 3 shows the main facade of the building and Figure 2 presents the floorplan of the ground floor.

Most of the windows were replaced by double-glazed windows with plastic frame in 2010 and within the TOGETHER project smart meters were installed in the building. Thus, there are data available of water, gas and electricity consumption of the building from October 2017.

Figure 3: Street view of the Municipality building

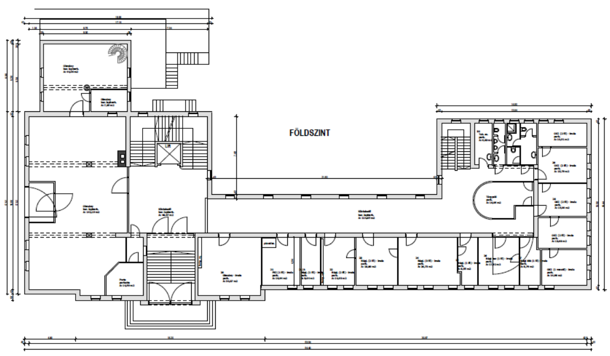

Figure 4: Floorplan of the ground floor

In terms of the building's HVAC system: two low temperature gas-fired boilers supply heat for the heating and DHW systems. The heat emitters of the boiler system are old cast iron radiators with thermostatic valves. All the offices and corridors are air-conditioned, a Daikin VRV system provides their cooling (outdoor units are placed on the roof and indoor units in the offices and corridors, under the ceiling), moreover it also has a heating function during the warmer heating period (spring, autumn). The basement conference room is equipped with 4 heat recovery ventilation units, which provide the necessary fresh air. The boilers and VRV system are operated alternatively, only one of the systems is working at a time (which is in case of colder weather only the boilers). A 43.2 kWp PV system installed on the roof covers a part of the electricity consumption.

Case study 2: A kindergarten in Hegyvidék

The selected kindergarten was built in 1976. It is located in the 12th district of Budapest and it is used by 149 children and 26 employees. The stand-alone building has two main floors, but it also has two basement levels. The net floor area is 890.5 m^2. Figure 5 shows the north-western façade of the building and Figure 6 presents the floorplan of the 1st floor of the building.

The building was refurbished in 2006 and the windows, doors and the heating system were replaced and thermal insulation was added to the external walls. Smart meters were installed in the building in November 2017 to measure the building's electricity and gas consumption, temperature and relative humidity. An 84 kW gas-fired boiler provides the hot water for the heating and DHW system, and it is regulated according to the outside temperature. The heat emitters are panel radiators with thermostatic valves.

Figure 5: North western facade of the building

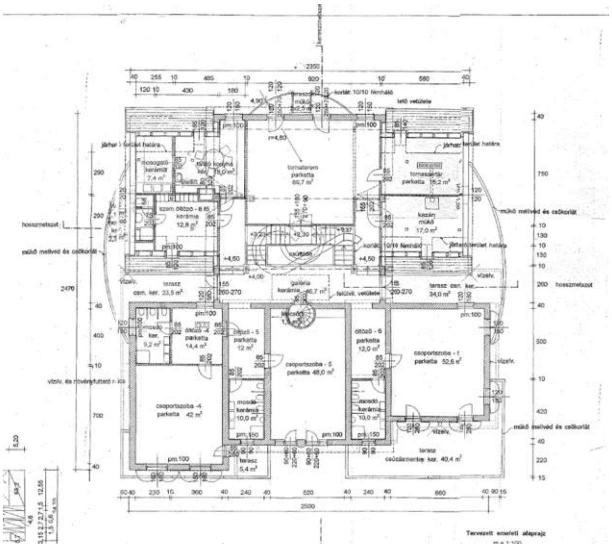

Figure 6: Floorplan of the 1st floor

Model validation

In case of the Hegyvidék Office building, for model validation metered data was used: the average of the metered gas consumption data of 3 years (2014, 2015, 2016) and electricity consumption data of one year (from October 2017). As the gas consumption includes the consumption of boiler heating system and DHW production as well, an estimation was made in order to disaggregate these two uses (assuming that during summer the total gas consumption is used for DHW production).

Apart from smart meters indoor temperature and relative humidity sensors were also installed in the building. Based on the metered data of one year (October 2017 – September 2018), the average indoor temperature is 24 °C and significant setback cannot be observed, during the nights and weekends the temperatures are above 20 °C. The measured temperature profile differs from the schedule provided by the building operator, since no setback can be observed.

Different weather conditions of the measured period and of the simulation can lead to inaccurate results during the validation process. In order to eliminate this difference, a correction was made on the measured gas consumption using the heating degree days of the two different (measured and simulated) period.

The model validation in the kindergarten was also done according to measured data. The electricity consumption is metered in the kitchen and in the boiler room separately and the rest of the electricity consumers are metered together. The gas boiler supplies the heating and DHW systems. The comparison of the measured and simulated heating gas consumption data were done by using the degree day correction method to eliminate the difference caused by the different weather conditions. In this process the measured outside temperature data from the middle of October 2018 to the middle of October 2019 were used. The simulation model results are compared with measured data from the same period in case of electricity.

Building energy modelling

The modelling had to objectives: first, to check the impact of model simplifications and second, to compare the energy wastes resulting from different operation mistakes.

Modelling of Hegyvidék Office Building and simplifications

A principal model was created for both buildings with the most detailed input parameters and then different scenarios with different input parameter's accuracy were tested, which resulted in four different models. Between each model scenarios, one input parameter was simplified. The impact of neglecting the internal thermal mass of partition walls, simplification of occupancy profile and applying simple HVAC instead of the detailed one were investigated in the case study.

The location of building was set to the nearest location to the site (Budapest/Pestszenlőrinc) from DesignBuilder templates. The winter design temperature in Budapest is –13 °C. For weather information TMY weather data from the PVGIS database ("PVGIS 5.1," 2019) (referring to a 10-year period) was used during the simulation.

The division of each floor into zones was done by function, e.g. the adjacent offices were considered as one zone (Figure 7). Based on previous studies (e.g. (Georgescu and Mezić, 2015) (Klimczak et al., 2018), (Shin and Haberl, 2019) ("DesignBuilder Help - Merging

Zones," n.d.)), merging zones through same activity can reduce simulation time but does not have a notable impact on the results. In the most *detailed* model version, the internal thermal mass of the partition walls was modelled by applying hanging partition walls. Hanging partitions are modelled non-geometrically in EnergyPlus as internal thermal mass and they do not create new zones. It was *simplified* in the next model by deleting the hanging partitions.

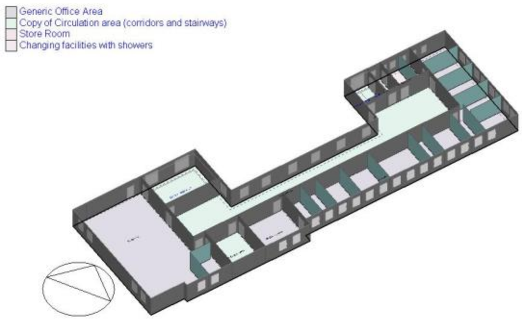

Figure 7: Zones of the ground floor with hanging partitions

The material layers and thermal characteristics of the building components were selected to the findings of a previous energy audit study of the building. External shadings on the street front were also modelled.

The heating, cooling temperature and setback temperatures, the DHW consumption rate and heat production of computers were set based on the metered data (temperature, gas and electricity consumption). Occupancy density was specified according to the number of people working there. Two occupancy schedules were tested: the more *detailed* one was from the metered data based on a previous study on this building (Tóth, 2018) using compact schedule in DesignBuilder and different profiles were created for the days of the week. As a *simplification*, the default occupancy schedule for offices was chosen from the DesignBuilder library. Figure 8 shows the default DesignBuilder profile and the profiles of the detailed occupancy schedule.

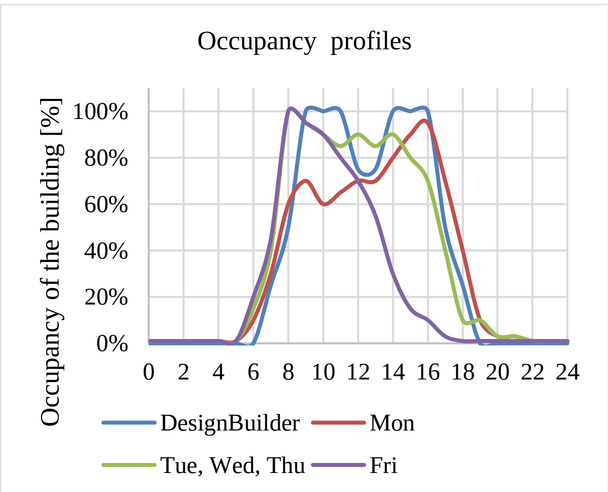

Figure 8: Occupancy profiles

In the *detailed* scenario, the detailed option was set for the HVAC setting which enabled to create circuit diagram of the system (Figure 9).

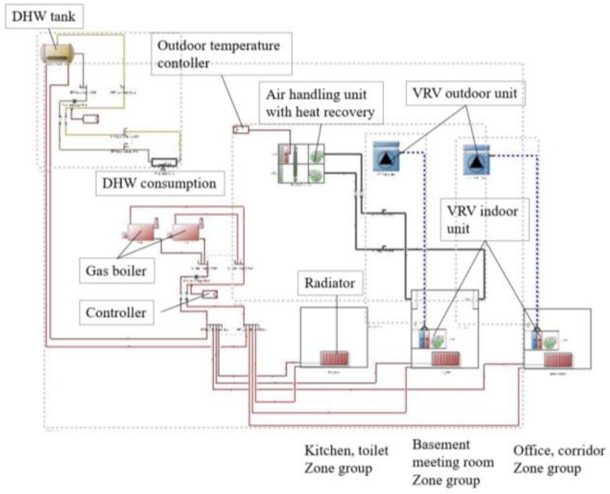

Figure 9: Circuit diagram for detailed HVAC system of the Hegyvidék office building

The bivalent alternative operation of the boiler and VRV system was modelled by usage schedules: the boiler system is working throughout the whole year because of the DHW production but the heating period of the system is limited through the radiators to the colder winter and during the transition periods of the year (early and late heating season), only the VRV system operates in heating and cooling functions. In the *simple* scenario, simple HVAC setting was selected. Applying simple HVAC, it is not possible to specify the circuit diagram, only the main HVAC system and some of its characteristics can be set. Air to water heat pump hybrid with gas boiler was selected as the system from the DesignBuilder templates but only one fuel can be set for the heating system (natural gas was chosen). For the cooling system electricity was selected. Thus, this model scenario does not model correctly the bivalent alternative operation of the two heat supplier systems The results were recalculated manually for this simulation using a partition coefficient between the two systems.

Modelling of the kindergarten and simplifications

In the case of the kindergarten, two models were created: one with simple and one with detailed HVAC system. The input parameters were set according to the design plan, energy certification, audit and on-site walk-throughs and the indoor temperature, the power density of lighting and occupancy schedule were corrected according to the measured data. The location of the building was set again to Budapest/Pestszenlőrinc from DesignBuilder templates. The properties of the constructions and openings were set according to a prior energy audit of the building. For shading, indoor drapes and outside shutters are used. Every room was determined separately as an individual zone.

The occupancy and office equipment schedules were set based on surveying, which includes the reduced number of people during the summer season. In the examined period the kindergarten was on duty in summer. The lighting power density was also set according to the surveying and corrected by measured data and the power density of the kitchen and office equipment and the HVAC system were set according to the measured data.

In the examined building there is radiator heating, hot water boiler and natural ventilation. The gas fired boiler serves the heating and DHW systems, thus it works throughout the year. The heating set point temperature is 24.5 °C and the setback temperature is 23 °C according to the measured data. The heating schedule was set based on the occupancy schedule considering the heating up periods during unoccupied periods. The quantity of DHW is not measured separately so an approximation was used based on the gas consumption during summer weeks. The schedule of the natural ventilation was based on occupancy schedule, modified by the real occupancy behaviour.

The HVAC system of the kindergarten is more simple than that of the office building's. Using simple HVAC setting radiator heating, boiler hot water and natural ventilation DesignBuilder template was set with natural gas fuel and the operation templates were given. Using detailed HVAC the circuit diagram of the HVAC system was built (Figure 10) which provided the possibility to specify the details of the equipment accurately.

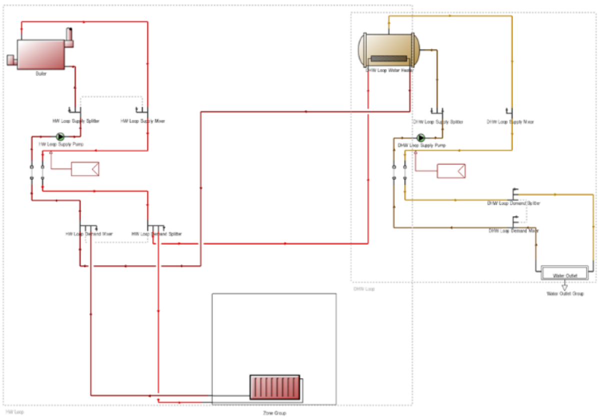

Figure 10: Circuit diagram for detailed HVAC system of the kindergarten

Simulation Input Simplifications Scenarios

In the following table, the different model scenarios of the Hegyvidék Office building are presented. In each step, only one parameter was simplified (one by one) as previously described.

Operation models

For operation models have been applied and compared following the classification of the above smart meter analysis: NORMAL, WEEKEND, FULL HEATING and REVERSE. Set temperatures were adopted to the real usage of the two pilot buildings. Figure 11 presents the four options for one winter week for the Hegyvidék office buildings. Energy wastes compared to the NORMAL model was determined by the simulation.

Table 1: Different model scenarios of Hegyvidék Office

		V1	V2	V3	V4
Internal mass	Simple		X	X	X
	Detailed	X			
Occupancy profile	Simple			X	X
	Detailed	X	X		
HVAC	Simple				X
	Detailed	X	X	X	

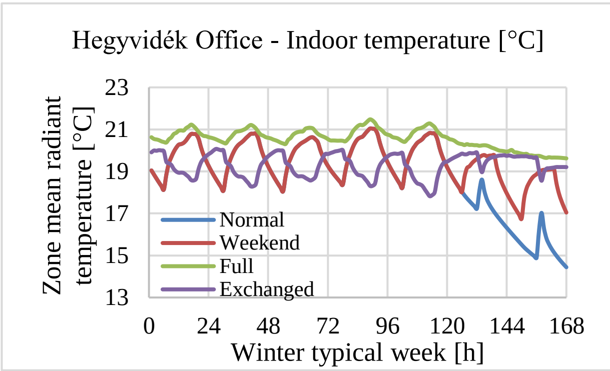

Figure 11: The standard and the three improper building operation schedules for a winter week in the Hegyvidék office building simulation model

Occupant profile development for electricity use

For the office building the occupant profile was developed taking into account the measured electricity consumption data. In case of the building the total electricity consumption was measured along with the PV production and at four other submetering points, which include the consumption of the heat pumps, two servers and an outdoor outlet for markets. From the total consumption the measured submetering data was subtracted and the remaining data was further analysed, which showed a good representation of the office usage pattern derived from the walk-through audit. The daily profiles were created according to the method presented by (Serrano-Guerrero et al., 2018).

Results

Impact of model simplifications

Hegyvidék Office

The results of the different model scenarios are presented in the following diagrams (Figure 12 – Figure 14). The percent values are referring to the relative difference in comparison with the actual measured consumption. In the first chart the consumptions appear separately and in order to be able to sum up the two different energy types (gas and electricity), they are in primary energy units.

The simplification of hanging partitions (V1→V2) and occupancy profile (V2→V3) had minimal effect on the results and HVAC system's setting (simple or detailed HVAC, V3→V4) had the most significant impact, especially on the gas consumption. The gas consumption with simple HVAC was almost 25% less than with detailed one.

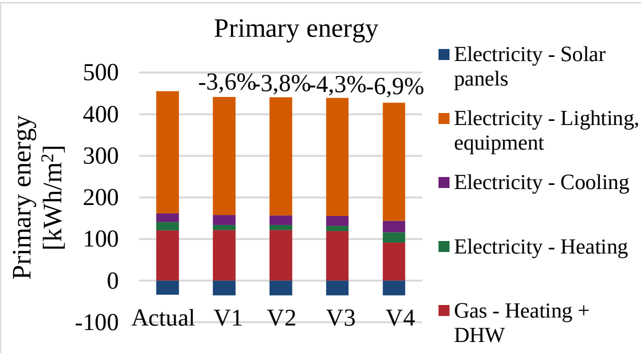

Figure 12: Primary energy consumption of Hegyvidék Office

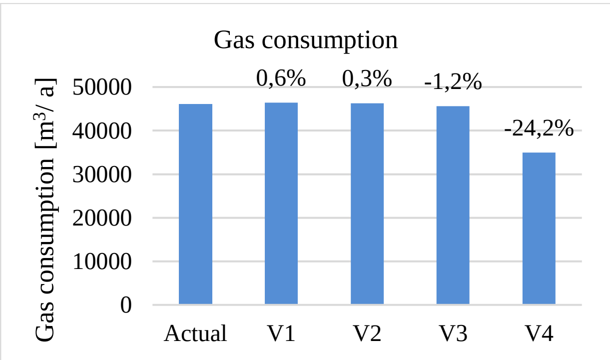

Figure 13: Gas consumption of Hegyvidék Office

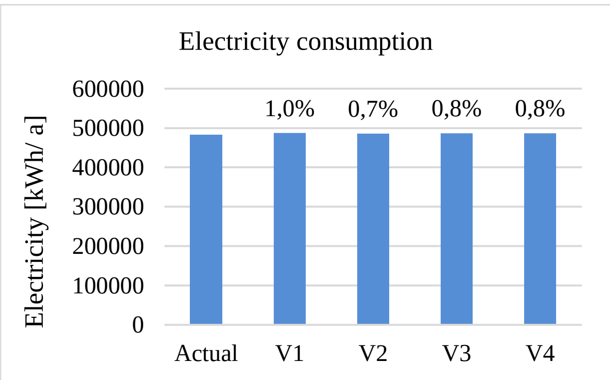

Figure 14: Electricity consumption of Hegyvidék Office

Kindergarten

The comparison of gas and electricity consumption in case of the kindergarten can be seen on the following diagrams (Figure 15 and Figure 16). There is larger difference between measured aand simulated gas consumption data using simple than detailed HVAC system in the process of simulation. There is no significant difference between the measured and simulated electricity consumption data. The electricity consumption of the boiler room is measured separately, thus it could be simulated accurately using the simple HVAC system too: the electricity consumption of the HVAC systems could be given manually and there was no need for the program to calculate it. The derogation from the measured data was calculated compared to the one year long measured data in both cases.

Neither the Hegyvidék Office nor the kindergarten case show significant difference between the electricity results of simulation models. The diverse differences between the gas consumption results are because of the different HVAC systems, the different occupancy and the different building usage. The degree of detail influences the electricity consumption in a building less but influences the gas consumption more significantly.

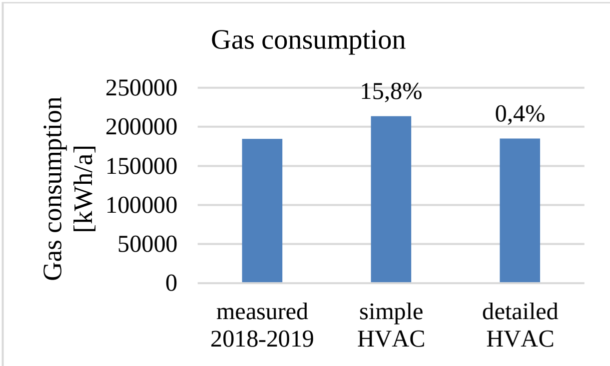

Figure 15: Gas consumption of kindergarten

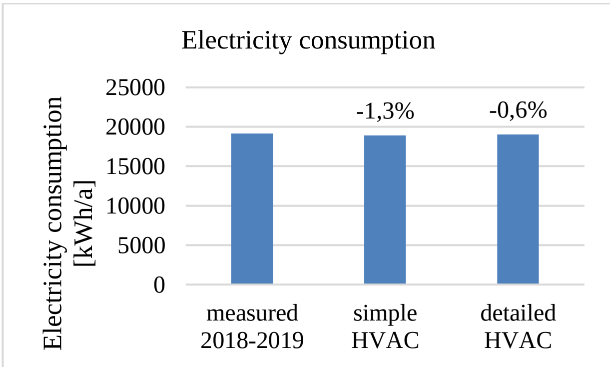

Figure 16: Electricity consumption of the kindergarten

Impact of improper operation schedules on energy use

Figure 17 compares results on energy use for the two pilot buildings. The reference value (100%) is the energy consumption of the NORMAL operation mode. As expected, the highest energy waste corresponds to FULL operation when there is no heating setback at all out of office hours. It is followed by the REVERSE and the WEEKEND operation mode. Wastes are in the range of 9-25%, which are significant particularly considering that they are caused only by deviation from standard behaviour and building usage and are independent from the buildings' quality.

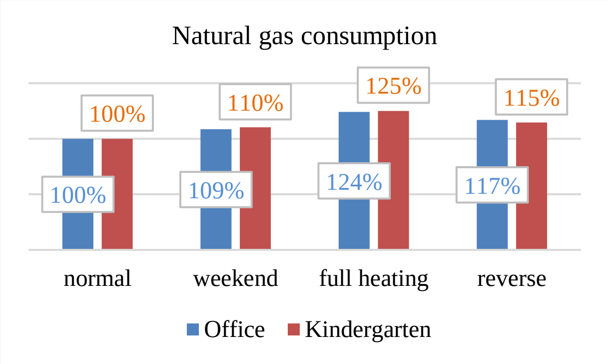

Figure 17: Impact of improper operation schedules on energy use in the two case study buildings

Discussion & Conclusion

The detailed models provided close results to the metered data, the difference was about 1% in case of natural gas and electricity consumptions as well. Although in order to reach such close results to the actual consumption, the input parameters of the model should be accurate enough which is not met in case of simple HVAC modelling. Using simple HVAC in the simulation models, the simulation time was significantly lower compared to the detailed HVAC modelling. However, complex HVAC systems should be modelled with detailed HVAC settings to avoid major errors in simulation results.

Figure 18 presents the relative simulation times of the different model scenarios compared to the most detailed model version.

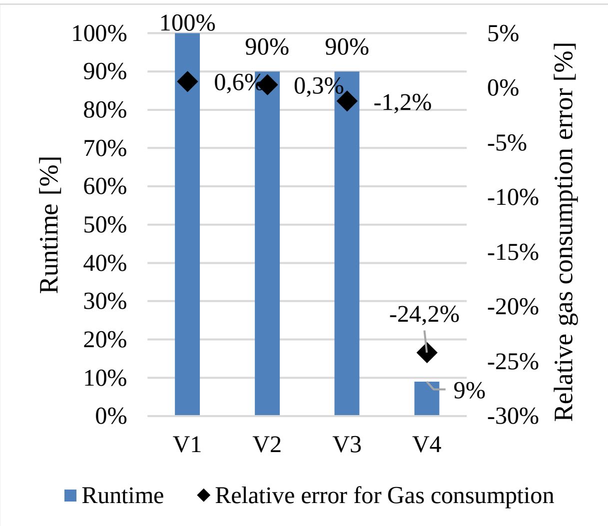

Figure 18: Simulation times of the model scenarios for the office building

With simplifying the hanging partitions, the simulation time slightly decreased, however the simplified occupancy schedule did not cause any change in simulation time. The simple HVAC scenario caused a significant reduction.

To conclude, the reliability of building simulation strongly depends on the quality of input data and the complexity of the system. Simplifications in input can lead to errors comparable to the errors related to simplified calculation tools instead of simulation models. As a consequence, it is advised to carefully select the applied tool to the project objectives and complexity of building, available timeframe, budgetary and expert knowledge capacities. Working time is also an important factor. For instance, selecting the simple HVAC setting takes a few minutes, at the same time to set a detailed HVAC for a complex system requires hours (or days) and on-site walk through, data analysis and higher knowledge capacities could be needed. Based on our simulation results we found that the more complex the HVAC system of the building is the larger difference between the simulated and measured data is if simple HVAC settings are used. For simple monovalent systems the simple HVAC model can be sufficient.

It was also investigated in the paper how improper heating schedules can influence energy consumption. The considered operating modes were determined on the basis of operation errors from real life practice detected by smart meter data analysis. Typical mistakes were highlighted and modelled by simulation and the wastes reached even 25% in the case study buildings. The results pointed out the very significant saving potential in building operation analysis and demand side management.

Acknowledgement

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