SENSITIVITY OF INPUT DATA IN BUILDING HEATING ENERGY DEMAND SIMULATION

A. Geiger[1], A. Nichersu[1] and V. Hagenmayer[1]
[1]Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, Karlsruhe, Germany

ABSTRACT

In the present paper, the sensitivity of input parameters in heating energy demand simulation is analyzed, be it related to spatial model geometry, building physics, or occupant behavior. To this end, based on the standardized data model CityGML Energy ADE 2.0, input data is prepared and simulated with the open-source energy simulation tool EnergyPlus. Results illustrate a possible need to review energy data collection efforts. The parameters displaying the most significant impact during testing: the presence of a cellar, the infiltration rate, and occupancy behavior (setpoint temperature and heating scheduling) are generally omitted during mass data-gathering efforts.

INTRODUCTION

To assist world governments in achieving SDS (Sustainable Development Scenarios), the International Energy Agency documents the evolution of the building sector. According to their latest available report, released by Dulac et al. (2019), buildings are the source of 28% of global energy-related CO_2 emissions in 2018, if indirect emissions from upstream power generation are considered. It highlights two key areas, building envelope improvements and heating sources, as being behind on their improvement goals with fossil fuels still supplying more than 60% of the heating sources.

To tackle the great challenge of reducing building heating demand, simulation tools are used in the planning steps of buildings, district and city energy design and construction. These tools can be classified depending on the scale and number of buildings they simulate. Detailed individual Building Energy Models (BEM) is an established field that performs analyses of building stock at the level of a single building. Urban Building Energy Modeling (UBEM) deals with modeling dozens to thousands of buildings using bottom-up approaches. UBEM tools, standards, and paradigms have been identified in Reinhart and Cerezo Davila (2016) and are often simplified BEM tools that use streamlined workflows. Both BEM and UBEM expect the same parameters for an energy building simulation. These parameters, as classified by Benner et al. (2016), fall in the following categories:

- Geometrical parameters: building geometry and its geographic location in the real world;
- Building physics parameters: most importantly heat capacity and thermal transmittance of exterior building elements (walls, slabs, roofs) and optical properties of windows;
- Meteorological parameters: outside temperature, solar radiation, wind speed, humidity, cloud coverage;
- Usage profiles: the behavior of building occupants and profiles for heating, lighting equipment and ventilation.

In this context, Geiger et al. (2019) describe the usage of an open standardized data model CityGML with an extension to support energy-relevant information, CityGML Energy ADE. This standard is a common information model for the representation of cities and regions in 3D. Data are classified using classes and relations and provide users with the urban object's geometrical, topological, semantical, and appearance properties. Public authorities like the Landesamt für Geoinformation und Landentwicklung in Germany provide CityGML data on a large scale. However, this data is generally not directly applicable to an energy simulation. In addition, energy-relevant parameters such as U-value are missing and, in most cases, geometric outer shells of buildings are not suitable for energy simulation without a-priori data treatment.

MOTIVATION

In both BEM and UBEM, the most important step prior to starting any energy simulation is the collection and treatment of data to create a digital twin. For Germany, 3D building models are provided almost nationwide by public agencies. Available in CityGML format, this data is georeferenced and describes a simplified outer shell. It typically only stores geometric information. Outer surfaces are classified into wall, roof, and ground slab. The geometry must be checked for compatibility with the energy modeling software.

 DOI: 10.3217/978-3-85125-786-1-53

Further information required for energy modeling such as construction year of a building, number of floors or type of building is generally not provided with the spatial model, and, when given, displays limited reliability. Other required parameters, related to building physics or usage profiles, are usually not provided. Due to this missing information in existing 3D city models, strategies are necessary to assess the missing information. Most often, statistical data related to construction year, occupancy, building type, and building physics is used. The present paper aims to determine the sensitivity of the individual parameters that constitute the simulation input.

For this purpose, an office building in Germany is considered. In the climate zone, Germany is part of, the by far largest component of energy demand for such a construction is heating. Hence, the present paper solely focuses on this component. The office building energy-related parameter values are known. A parameter sensitivity study is performed for multiple parameters in various simulation runs to provide justification for the information the data collection and treatment process need.

To this end, the original CityGML data is enriched with energy-relevant information and stored as CityGML Energy ADE dataset. In their review of the BEM field, Pezeshki et al. (2019) identify the open-source software package EnergyPlus as one of the most frequently used energy modeling software to date. Reinhart and Cerezo Davila (2016) catalog UBEM applications and their respective tools. They recognize EnergyPlus as a tool used in multiple applications. As both fields display widespread use of this tool, the present work performs all heating demand calculations with it. The software is released by the US Department of Energy and is described in detail by Crawley et al. (2001).

BACKGROUND

State of the art in sensitivity analysis of building thermal energy demand modeling

With regard to sensitivity analysis, Tian (2013) performs a literature review and divides existing techniques in global and local methods. Local sensitivity analysis is focused on the response of the tested algorithm around variations of a base case. Global sensitivity analysis targets the influences of uncertain inputs over the entire input space. Local sensitivity methods are applied extensively in building energy analysis as they have the added benefit of low computational time while providing answers that are easy to interpret. Global sensitivity methods bring the ability to explore the interactions between input parameters and allow for self-verification. Tian's review also shows that sensitivity studies generally focus on one single algorithm and tool.

In an evaluation of local (one parameter at a time OAT) and global (Sobol and Morris) sensitivity on a BEM method, Kristensen and Petersen (2016) conclude that local methods are capable of identifying the same cluster of the most important parameter as complex global methods. Limitations for local approaches only show when attempting to create a fine ranking of parameters. The simulation used to reach these statements was performed on an existing residential building stock in a temperate climate. Overall, this study indicates that the OAT method is sufficient for our purpose.

Three other sensitivity analysis studies were identified to be performed in temperate climates with similar BEM methods. In the first one, (Delgarm et al., 2018), the local sensitivity method is referred to as one-factor-at-a-time (OFAT). It uses EnergyPlus and a base model of a room. They conclude that for the thermal demand of a room, the parameter window size has the highest impact. In the second study, de Wilde and Tian (2009) simulate the energy demand for a fictional office building in the UK in a climate change scenario context. The results show that regarding the uncertainty in predicted heating energy, the dominant input factors are infiltration, lighting gain, and equipment gain. Lastly, in what is a comparable research study in an Italian context, Kalogeras et al. (2020) benchmark EnergyPlus and an Italian commercial tool, Edilclimad (based on energy performance ISO 13790 and Italian material norms UNI TS 11300) against each other. The base case is a private clinic located in Sicily, Italy. The tests conclude that for estimation of thermal building energy consumption, the most significant parameters are inner set temperature, availability, and efficiency of heat recovery systems and thermal transmittance.

In conclusion, in the previously identified sensitivity analysis studies, the most significant parameters were found to be window size, infiltration rate, user behavior, floor area, and thermal transmission (no ranking in order of presentation – different studies).

CityGML LOD concept and the Energy ADE

CityGML is an Open Geospatial Consortium (OGC) standard, representing a data model for virtual 3D cities. For spatial structure, the CityGML standard includes a concept of Level Of Detail (LOD) classified from 0 to 4, first presented in the specifications of the standard, Gröger et al. (2012), and further explored by Biljecki (2017). In short, LOD0 comprises a representation of footprints and optionally roof edge polygons marking the transition from 2D to 3D GIS without volumetric representations. Ensuing LODs are more elaborate in terms of geometry and semantic content. LOD1 is a model usually obtained by extruding a LOD0 model. LOD2 adds a simplified roof shape, with multiple semantic classes (e.g. roof,

 DOI: 10.3217/978-3-85125-786-1-53

wall) used to classify the building's outside surfaces. LOD3 entails a detailed architectural building model, which encompasses windows and doors, and is of higher complexity than previous levels. Finally, LOD4 elaborates indoor features while keeping the same outdoor features as LOD3.

Data in CityGML format provided by public agencies in Germany is usually derived from photogrammetric flights (aerial imagery and LIDAR). That means in general that the building is provided with the external hull, without information on the existence of a cellar, which lies beyond the reach of those two sensors types. This external hull is usually provided in LOD2, with higher levels of details being seldomly made available for public buildings.

One of the basic concepts of CityGML is the extension mechanism called Application Domain Extension (ADE). Using this mechanism, it is possible to extend the standard schema with new features and properties. Since the schema of CityGML does not support energy-relevant parameters, the CityGML extension Energy ADE was developed. It represents a "neutral" data model, which can be used as an interface between Building Information Modeling (BIM) tools and Geographic Information Systems (GIS) on the one hand, and building energy simulation tools on the other hand.

TESTING AND EVALUATION

Base case

For the simulations, an office building with research activities is used. It also incorporates a small share of usable space dedicated to laboratories. The building is located within Campus North of the Karlsruhe Institute of Technology, in a suburban spatial context.

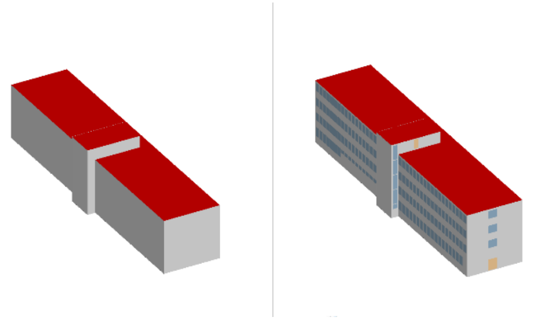

Figure 1: Building 445, base case for the sensitivity analysis

Figure 1 presents Building 445, in LOD2 (left) and LOD3 (right). In the following, the digital twin of Building 445 in LOD2 will be referred to as the base case. It will be used as a comparison to all other values. Building 445 has three fully-fledged floors. It also incorporates a semi-basement (an architectural term that defines a floor half below ground) and an extended stairwell into the roof.

With the Energy ADE, both detailed energy simulation of single buildings (BEM) and global estimation of energy behavior of multiple buildings (UBEM) are supported. For this purpose, the building is extended by extra attributes for building type and construction weight. Building objects are extended with energy-relevant parameters. In addition, elements for thermal zones and usage zones are defined. Thermal zones are bounded by thermal boundaries with the corresponding construction type (e.g. wall, roof). Thermal boundaries can have thermal openings and a reference to the used construction including physical properties. Usage zones are referenced by thermal zones and support schedules for heating, cooling, ventilation and internal gains due to occupants and technical equipment (Agugiaro et al., 2018), (Benner et al., 2016). The modeling of energy conversion, distribution, storage, and emission devices, and the energy flow between them is also supported. Energy ADE thus supports a wide range of applications in the energy analysis of buildings.

The process of adding energy-relevant information to CityGML files extended with the Energy ADE is called an enrichment process. The development, work, and concepts behind the tool and process are described in (Geiger et al., 2018), while the schema for the Energy ADE 2.0 is freely available online (Benner, 2017).

The CityGML LOD2 model of Building 445 is provided by the Landesamt für Geoinformation und Landentwicklung Baden-Württemberg and is corrected during the data treatment phase, both geometrically and semantically. It stands as the LOD2 model for the base case. Further work on the outside hull creates a detailed architectural model of the building by adding windows, doors, a portico, and an entryway, representing the LOD3 building model.

Energy modeling input

The investigation is based on parameter values presented in Table and Table 6. Parameters pertaining to building usage and building physics are estimated as precisely as possible with the purpose of having a consistent digital twin. This makes the energy demand values produced by means of simulation generally ideal. In Table 1, the opening ratio refers to the window to the external wall ratio.

Concerning weather data, the data used is produced at an hourly resolution by using Meteonorm, a commercial software, described in detail in Remund et al. (2020). It represents typical values for the region of Karlsruhe, Germany.

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Table 1: Building physics and descriptive parameters

Volume (m^3)	9608.92		
Surface on the ground (m^2)	783.59		
Number of floors	3		
Opening ratio	40%		
Infiltration rate (l/h)	0		
Building specific heat capacity (J/K)	1		
Windows glazing ratio	0.7		
Windows U-values ($W/(m^2*K)$)	1.8		
	Roof	Façade	Ground
U-values ($W/(m^2*K)$)	0.484	0.558	0.393
Thickness (m)	0.3	0.3	0.2

Table 6 Usage profiles office building

Heating profile	0 – 24 h 21 °C	Weekday
	0 – 24 h 21 °C	Weekend
Cooling profile	Cooling deactivated	
Ventilation profile	0 h – 8 h 0 1/h 7 h – 21 h 1 1/h	Weekday
	0 h – 24 h 0 1/h	Weekend
Shading profile	No shading devices	
Lighting Profile (luminance 200Lux efficiency 50W/m heat emission $4W/m^2$)	0 h – 8 h 0% 7 h – 18 h 100% 18 h – 24 h 0%	Weekday
	0 h – 24 h 0 %	Weekend
Occupant Profile (82 W per Person, 32.85 m^2 / Person)	0 h – 7 h 0% 7 h – 8 h 20% 8 h – 9 h 40% 9 h – 10 h 60% 10 h – 12 h 80% 12 h – 13 h 40% 13 h – 14 h 60% 14 h – 16 h 80% 16 h – 17 h 40% 17 h – 18 h 20% 18 h – 24 h 0%	Weekday
	0 h – 24 h 0 %	Weekend
Equipment Profile ($7 W/m^2$)	0 h – 7 h 10% 7 h – 8 h 20% 8 h – 9 h 40% 9 h – 11 h 80% 11 h – 12 h 40% 12 h – 13 h 20% 13 h – 14 h 40% 14 h – 16 h 80% 16 h – 17 h 20% 17 h – 24 h 10%	Weekday
	0 h – 24 h 0 %	Weekend

Use case definition

The use case is centered on the estimation of heating demand for a single office building within a reference year at an hourly resolution. The influence of the surrounding buildings through shading is ignored. For the estimation, a LOD2 or LOD3 spatial model stored in the CityGML 2.0 format is made available. The spatial data goes through the enrichment process with energy-relevant parameters (building descriptive parameters, building physics parameters, and occupancy behavior) stored in the Energy ADE, thus providing a digital twin suitable for energy simulation. The enrichment process is described by Geiger et al. (2018). This output file is then loaded in the simulation environment of EnergyPlus.

Sensitivity tests

The method applied in the present paper is called local sensitivity analysis, or O(F)AT, for details see the Background chapter. This approach requires that only one input parameter is changed while the others are fixed. It has the strength of providing feedback on each tested parameter individually.

The parameters tested are classified as follows:

- Spatially and geometrically dependent:
  - LOD
  - Number of stories above ground
  - Existence of a cellar
  - Wall opening ratio
- Building physics dependent:
  - U-values
  - Infiltration rate
  - Specific heat coefficient
- Occupancy dependent:
  - Constant inner temperature
  - Business hours scheduling

The next subchapters present reasoning and scientific questions that justify the design and selection of tests.

Spatially and geometrically dependent parameters

The lack of detailed spatial information is listed as a potential drawback in UBEM applications (Reinhart and Cerezo Davila, 2016). The tests quantify the influence of a higher LOD and the presence of a cellar on demand modeling. Table 2 presents the building volume and height of samples.

Table 2: Sample buildings spatial parameters

SAMPLE / GEOMETRY	WITH CELLAR	WITHOUT CELLAR
Volume (m^3)	11241.14	9608.92
Building height (m) (without elevator house / plant room)	14.1	12.02
Building height (m) (with elevator house / plant room)	16.7	14.62

In CityGML, the number of stories above ground of a building is often provided with the spatial model as a separate attribute. However, because of the many irregular shapes of rooftops, the automatic extraction process from photogrammetric products is prone to error. This is also the case for Building 445, which due to the extended stairwell is defined as having one extra floor. When the attribute is completely missing, it is

 DOI: 10.3217/978-3-85125-786-1-53

guesstimated by the energy modeler prior to the simulation run. This significant geometrical parameter is then used to assess the number of people and equipment present in the building using averages. As such, it has a significant impact on the internal gains of thermal energy for the building.

One of the most important sources of thermal energy in any building is the amount of direct solar radiation that can go through the windows. The amount directly correlates to the opening ratio in its general impact in the total demand.

Building physics parameters

From building physics, U-values play a significant role in establishing the thermal behavior of materials concerning heat gains and losses. U-values are calculated based on material thickness and thermal conductivity. Please note that the relative reduction and rise of these values are applied differently to windows compared to the façade, ground, and roof, as explained in the Results chapter. Specific heat capacity influences the amount of thermal energy that a building can store, from both external heat gains, and internal sources (equipment, occupants, and lighting).

Most buildings are not airtight and are purposefully designed as to allow for a natural exchange of the air inside the building (natural ventilation). In addition, unintentional outdoor airflow (infiltration) occurs. Testing different values for infiltration gives an idea of the significance of the impact that energy refurbishment aimed at these issues can play. These measures include, for example, the replacement or sealing of windows and doors that are not airtight, important factors related to energy demand. In the base case, the value of infiltration is set to zero.

Occupancy parameters

Inner temperature is most often fixed as a single value in UBEM and sometimes provided with a schedule in BEM. This is why there are two distinguished tests in this parameter section. The first one tests a variation in the inner set temperature and a second one assesses the usage of a scheduler for the inner set temperature. The scheduled temperature reduction was set for out of business hours, 0h-7h and 19h-24h during weekdays and 0h-24h during weekends.

RESULTS

Spatially and geometrically dependent parameters

LOD and cellar impact

The first test performed concerns the external hull of the building, namely the comparison between different LOD spatial models and the existence of a cellar. Figure 2 depicts the variation in between spatial models of different details present in the outer surfaces.

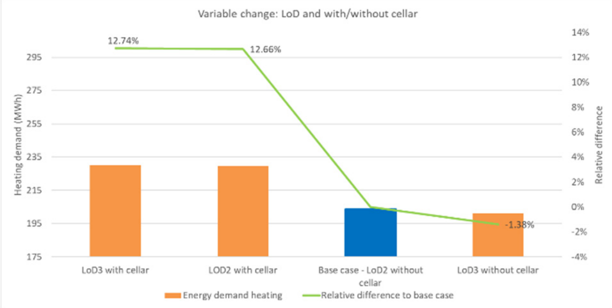

Figure 2: Influence of LOD and cellar presence

The LOD increase does not significantly change the result of the heating demand (1.38%), however, these results are highly dependent on the opening ratio variable. The addition of a cellar has a substantial influence (an increase of 12.66%, respectively 12.74% with LOD3).

Number of stories above ground

Figure 3 depicts the influence of this parameter upon energy demand in both simulation environments.

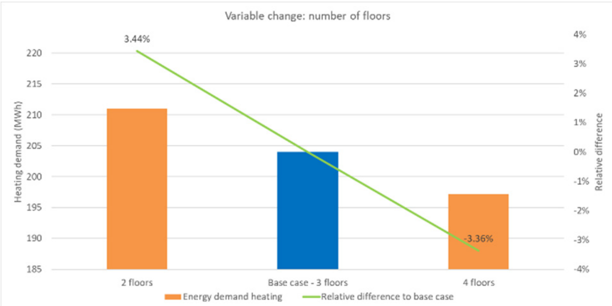

Figure 3: Influence of number of floors

The tests include a variation of +/- one floor with a corresponding change in either direction of approximately 3.5% relative to the base case.

Wall opening ratio

For this parameter, a large variation was selected, from 0 to 99% in incremental steps of 10 percentage points. Results from both simulation environments are presented in Figure 4.

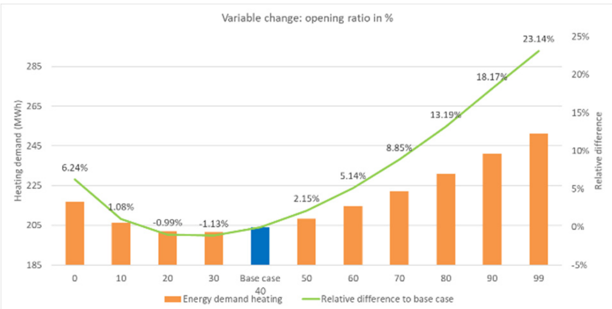

Figure 4: Influence of opening ratio

DOI: 10.3217/978-3-85125-786-1-53

The results show a low to moderate impact of the changes. The reduction of the parameter presents reduced thermal demand of around 2% for every 10% opening surface. Opposite, the increase in surface presents a heightened demand of relative 3% value for every 10% of added surface.

Building physics dependent parameters

U-values / thermal conductivity variations

In the case of the ground, façade, and roof, U-values are dependent on two factors: thickness and thermal conductivity. In order to be able to apply the variation of U-values, the wall thickness is considered constant. At the same time, an exponential increase/decrease of 5%, 10%, 20%, 35%, and 50% is applied in thermal conductivity. For windows, the same coefficient reduction/increase is applied directly on the U-values. The results are presented in Figure 5.

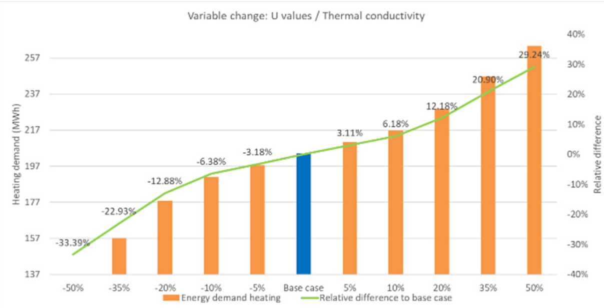

Figure 5: Influence of U-values / thermal conductivity variation

The behavior of thermal demand upon parameter change is synchronized in between negative and positive parameter changes. For every 5% increase / decrease there is a 3 to 3.5% decrease / increase in thermal energy demand.

Infiltration rate

The building's air exchange ratio is set to 0 for the base case. In each test, an additional 0.2. ACH unit is added with the maximum tested value being 1.4 ACH. Figure 6 depicts the results in this test.

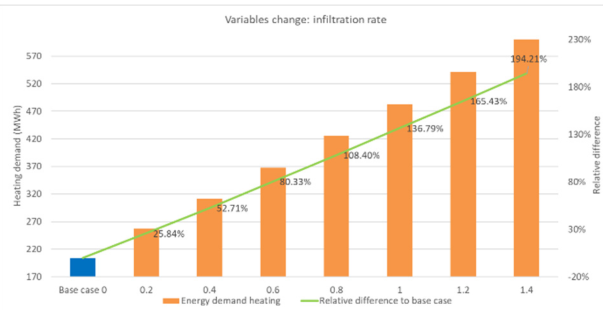

Figure 6: Influence of infiltration rate

The results show an increase of approximately 26% for each 20% added. This value corresponds to the greatest change in thermal energy demand out of the parameters that are tested.

Specific heat capacity coefficient

This parameter was tested with an exponential rise / reduction of +/- 5%, 10%, 15%, 20% and 25%, as is presented in Figure 7.

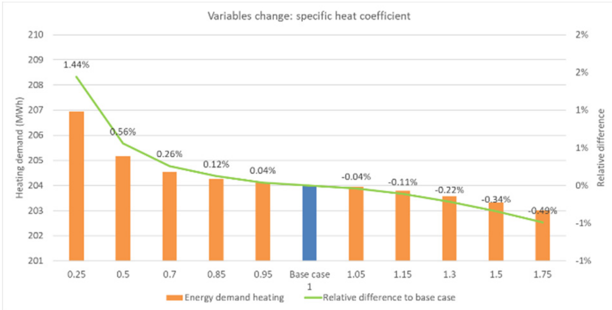

Figure 7: Influence of specific heat capacity

According to the results, there is a small difference with the relative rise/reduction in value of 1 to 100. Initially, for every 1%, there is a 0.04 difference. This increases slightly towards the extreme of the graph.

Occupancy parameters

Constant inner temperature

For the base case, the setpoint value for inner temperature in Building 445 is set at 21°C. Two variations of the base case are tested. In the first one, the general temperature is tested at intervals of 2°C in gradual steps from 15°C to 25°C, as illustrated in Figure 8.

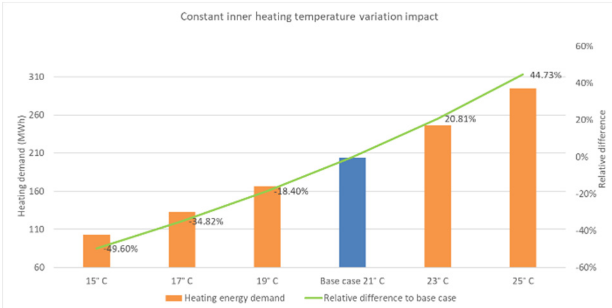

Figure 8: Impact of changing the constant inner temperature

Results show that for every 2°C rise/reduction, there is an approximate corresponding 21% rise / 18% reduction of the annual heating demand.

Business hours scheduling

In the second variation, the 21°C set temperature is kept for all business hours. For nights and weekends, the temperature is tested in steps of 1°C from 21°C to 16°C. This is portrayed in Figure 9.

Providing the simulation with an additional heating schedule results in a 4.4% reduction of total energy demand for every 1°C shrinkage outside of office hours.

 DOI: 10.3217/978-3-85125-786-1-53

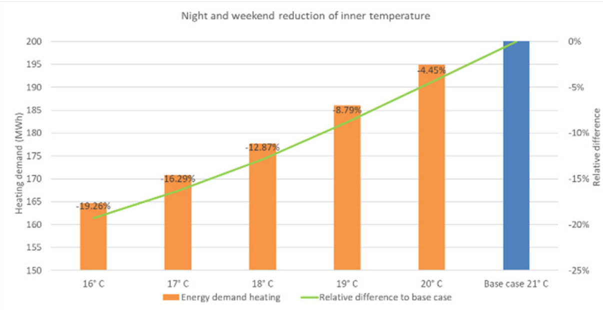

Figure 9: Impact of a heating schedule at varied temperature values

Summary

In order to assess the impact of errors in parameter estimation, all parameters' results are collected in a single chart, Figure 10, not with the purpose of ranking, but of comparing parameter sensitivity. It can be observed that four parameters lead to sensitivity impacts of above 10% in the final heating demand upon a change of less than 10%. These are constant inner temperature, the existence of a business hours scheduler with temperature reductions, infiltration rate, and U-values / thermal conductivity.

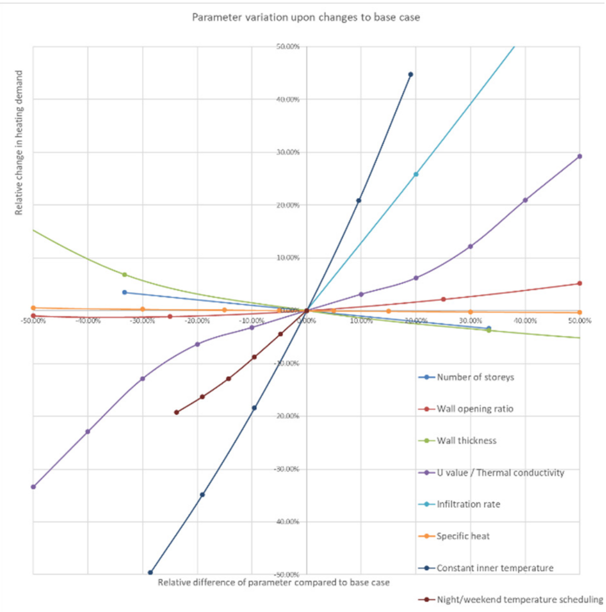

Figure 10: Parameter significance consequent to variation of base case

DISCUSSION

Spatially and geometrically dependent parameters

One of the tested parameters, the presence of a cellar, brought a significant difference to the base case. In energy modeling practice, this represents an often-overlooked spatial detail and can significantly alter thermal energy modeling results performed as described in the use case. However, our base case incorporates a heated semi-basement and the simulation treats the building as a single thermal zone. That means that extrapolating this result to other cases requires further testing.

Comparing the enhanced spatial description of Building 445 in LOD2 and LOD3 does not present significant differences. LOD2 does not include any windows surfaces. The results support the idea that for the scope of thermal energy modeling at a large scale, LOD3 is not required. However, the opening ratio used in the LOD2 simulation is very precise when compared to the real Building 445 and presents an ideal scenario. This plays a considerable role in the small impact the enhanced spatial model plays in the result and in general, is not the case in UBEM where statistical values are used for this parameter. The best way to interpret this test is that modeling the total size of the window area correctly is important and that the spatial distribution of windows is not significant (as long as there are no shadowing effects).

Concerning parameters related to the geometry of the façade: wall opening ratio has a minimal impact.

The number of floors only has a marginal impact on results. The number of floors is directly correlated to internal gains by means of the surface size.

Building physics dependent parameters

Pertaining to building physics dependent parameters, two of the parameters tested, U-values and infiltration rate, have significant impacts on final thermal demand. Of these parameters, U-values traditionally receive more attention due to their inclusion within building energy performance certificates, while the infiltration rate is often neglected. The third tested parameter of the category, specific heat capacity, has a negligible impact.

Occupancy dependent

Both approaches tested for modeling the habits of building residents, constant inner temperature, and heating scheduling, result in significant impacts. These observations provide a testimonial that data-gathering efforts should also use occupancy profiles or provide connections to socio-economic indicators that can refine energy use behavior.

CONCLUSION AND OUTLOOK

The present paper provides an understanding of the sensitivity that input energy-relevant parameters have in the outcome of thermal energy modeling simulations for an office building with research activities located in the region of Karlsruhe, Germany. The results should not be interpreted by focusing on one parameter alone but rather on the entire data collection and treatment effort.

For our base case, the most sensitive parameters in tests are infiltration rate, setpoint temperature, and scheduling of night/weekend setpoint temperature. Small variations of this input have a large impact on

DOI: 10.3217/978-3-85125-786-1-53

final thermal energy demand. The tests concerning U values and the presence of a cellar show a moderate to significant impact. Our results are in line with four similar studies presented in the state of the art sub-chapter that identify the infiltration rate, user behavior, floor area, and thermal transmission as having large impacts on thermal demand of building stock in temperate continental climate.

Results are indicative of what could be a gap in the energy data collection processes. This pertains to the general lack of cellar information, the often neglected infiltration rate, and occupancy behavior (setpoint temperature and heating scheduling). Out of all the parameters with significant results, only U values are collected regularly in energy performance certificates.

Buildings from other sectorial activities and geographical locations need to be systematically analyzed to see if the current results and interpretation can be similarly observed.

ACKNOWLEDGEMENT

We thank our colleagues Karl-Heinz Häfele and Joachim Benner for their assistance with manuscript review and topical discussions.

Funding was provided by the Helmholtz Association and the German Ministry of Education and Research, Research project SEKO.

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