Architectural-Geometrical Simplification for Multi-Zone Building Models for Urban Refurbishment Projects

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Abstract

This article draws a comparison between the described approach and a single-zone modelling approach with fitted parameters. The fundamental differences – accuracy, simulation times, preparation effort – of the modelling strategies are discussed.

A multi-zone approach to model existing buildings within the scope of district simulation for the implementation of refurbishment projects is presented. It incorporates the geometrical simplification of the building body and rules to distribute thermal zones. Afterwards the simulation model is generated automatically from a database that holds the building information.

A case study contrasts both methods by applying them to buildings of a university campus.

Introduction

The German Federal Ministry for Economic Affairs and Energy describes the importance of urban energy refurbishment as follows: "In addition to the energetic optimization of individual buildings, the aim of raising energy efficiency depends crucially on a comprehensive approach to urban areas as well as to local and district heating networks. This potential can be improved significantly via intelligent use and networking of innovative technologies with research and pilot projects" (BINE Informationsdienst 2016)

This focus on urban areas is reflected in the building performance simulation community, which increasingly deals with district modelling and simulation of new and existing buildings. For example, in Germany 64 % of the buildings have been built in or before 1978. This group of buildings, as well, exhibits energy consumption per square meter much higher than that of recently built buildings (BMWi 2014). It is therefore important to not only build new buildings to high energy standards, but also develop refurbishment strategies for older, existing building ensembles since the potential for energy savings is highest with these.

In order to successfully model and simulate existing building stock, methods have to be established that deal with the problem of data acquisition and handling of the building stock. Due to the age of buildings and the owner structure, building information is often hard to acquire. Additionally, poorly documented renovation measures, which have been applied, weaken the accuracy of the acquired data.

When dealing with ensembles of buildings, i.e. districts, campuses, etc. model preparation and simulation times become a concern. Complicated building geometries and distribution of thermal zones lengthen the time spend on modelling, while an increasing number of components negatively influences simulation times. For that reason, simplification in all steps of the modelling process is desirable.

This article presents an approach for architectural-geometrical simplification of buildings for use in multi-zone building models. The method consists of geometrical simplifications of the building's envelope and its interior where also rules for the distribution of thermal zones are suggested. Ultimately, the gathered data is stored in a database and simulation models are generated automatically.

The suggested method is compared to an approach that has been demonstrated in a recent article (Inderfurth, Nytsch-Geusen and Ribas Tugores 2015) where the possibility of fitting thermal parameters of a building model depending on the heat energy consumption was explored, essentially generating grey-box models. The approach leads pragmatically to simulation models that can mirror the thermal characteristics of a building in a limited time frame.

For illustration of the described methods, it is referred to their application to several buildings of the university campus Berlin-Charlottenburg (HCBC). Renovation and energy related refurbishment of campus buildings are crucial inasmuch as facilities of universities should support continuous conduction of research, teaching and other activities within the campus and act as role model for other urban areas. Currently, a multi-disciplinary team of researchers investigates renovation and retro-fit strategies, which target to implement the energy-related climate protection goals of the German Federal Government by the year of 2022.

Architectural-geometrical simplification

Building geometry is essential to any simulation of building performance (Bazjanac 2001). Simulations at urban level lead to complicated input preparation. This complexity emerges from the number of buildings, diversity of building types, lack of data and accordingly assumptions and so forth.

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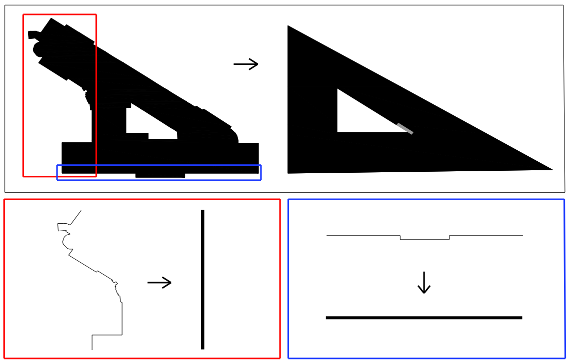

Figure 1: Example of geometrical simplification.

Simplified building models reduce modelling costs (Zucker and Hettfleisch 2010). In this study, manual simplification of the geometry has been applied by architects in order to reduce the number of planar constructions. First, walls with similar orientation have been merged. Second, projections from the main axis by the simplified form have been planed. Third, complicated forms have been translated into simple geometric forms like squares and triangles.

This method could be applied with a small amount of intervention to the original building geometry in the majority of buildings. Most advantageous is it when applied to older buildings built during Gründerzeit[1]. Such buildings often have richly decorated facades in the form of Historicism and lots of facade movements that increase the difficulty of modelling. Fig. 1 shows that over 30 wall parts (marked in red area) have been merged into one planar construction. This planar construction has been modelled so that it has the same volumetric value of all 30 wall parts together. Besides, cantilevered parts, as marked in the blue area, have been aggregated. Small side walls of the cantilevered parts are considered as a part of the flattened wall. Ultimately, it was possible to reduce the number of planar constructions from 56 to 6.

Thermal zoning

Thermal zoning has three meanings depending on the usage. Firstly, zones are space boundaries for building energy simulations. One of the primary challenges in preparing the building geometry for simulations is the determination of space boundaries. These space boundaries are collections of surfaces that fully enclose spaces. They in turn serve as the building blocks of thermals zones that have ideal-mixed volumes of air with uniform temperature (Nathaniel, et al. 2013). Building models are typically comprised of one or more thermal zones that are completely bounded by surfaces (Athienietis and O'Brien 2015).

Secondly, thermal zoning is a requirement of DIN V 18599 for new buildings to represent functions of the rooms as an approach for optimization of HVAC specifications (Lichtmeß 2010).

Third, it is a part of the architectural planning and can be defined as an approach to maximize the effective use of energy by locating rooms according to their cooling or heating requirements (Karasu 2010).

Zoning Criteria

The proposed approach uses a mixture of all these definitions for selection of thermal zones. Buildings have been divided into multiple zones according to the following criteria:

1) Facades: Significant difference of construction types and window-to-wall ratio.
2) HVAC: Heated, not heated, and cooled spaces have been separated into thermal zones. Zones that would cover less than 5 % of the net floor area are neglected.
3) Volume: Zones with significantly more volume compared to the other spaces in the same building have been defined as separate thermal zones. These are mainly spaces like auditoriums, studios, etc. that have either a larger floor area or/and greater clear height than other spaces.
4) Ground level: Floors below ground level and without sun exposure have been defined as separate thermal zones in each building. Crawl spaces without usage have been neglected.
5) Orientation: Standard floors with South-North orientation have been divided so that northern parts together with central corridors are one thermal zone; the southern parts define another thermal zone.

Fig. 2 shows an example of how these criteria have been applied to buildings. The building housing the *Hermann-Rietschel-Institut*, Department of Building Energy Systems, has various thermal zones according to conditioning, volume and orientation. 92 rooms with a net floor area of 4040 m^2 are modelled with six thermal zones. Compared to a single-zone model, this model has six times more details regarding building cubature. Nevertheless, compared to 1-1 modelling, a reduction by 93.5% of the actual number of rooms has been achieved through this method.

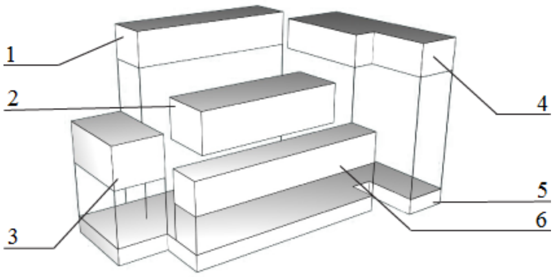

Figure 2: An example for thermal zoning:(1) northern oriented offices (2) test lab with a high volume and high internal load (3) auditorium, cooled and high volume (4) labs (5) basement (6) southern offices

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[1] Gründerzeit literally means “founders’ period” and refers to the entrepreneurial boom of the late 19th-century Germany. Buildings until Bauhaus are listed as Gründerzeit buildings.

Regarding the whole research area, over 14,600 spaces/rooms of 40 buildings can be downscaled to approximately 200 thermal zones. Compared to single zoning, it has five-fold more detail regarding building geometry and 98.6% less detail compared to 1-1 simulation models. Fig. 4 illustrates the thermal zoning by example of the mentioned university campus.

Grouping heat transfer surfaces

Besides architectural simplification, surfaces bounding the thermal zones have been categorized in 5 groups with different thermal boundary conditions and structural characteristics, see also Fig. 3:

1) External walls: Walls above and below ground level that have contact with the outside air.
2) Basement walls and grounds: Planar constructions that have full contact to soil (mainly earth and in some cases sand) which is represented with a constant 10 °C boundary condition.
3) Partitions: Planar constructions that divide two thermal zones, with the adjacent zone as boundary condition.
4) Roofs: Like external walls, with outside air as boundary condition.
5) Party walls: Walls with contact to neighboring buildings are considered with a constant 20 °C boundary condition.

Except basement walls and grounds, all groups have opaque and transparent sub-surfaces. Opaque ones present both horizontal and vertical planar constructions that bound the thermal zones. Transparent ones represent the windows and doors made of glass. Considering the amount of the surfaces, doors have been neglected. Big gates have been considered as walls. Subsequently, thermal properties of the planar constructions have been determined manually.

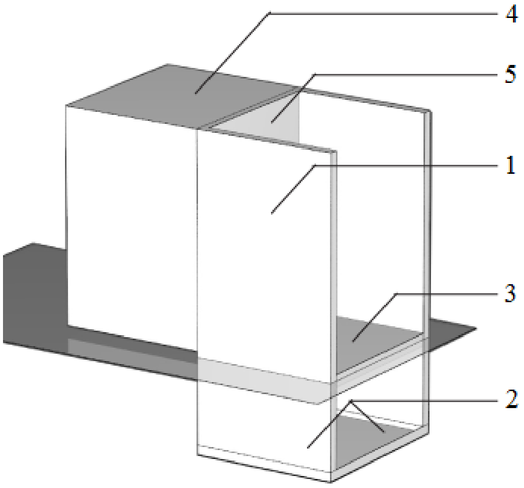

Figure 3: Heat-transfer surface categories

All this input data has been gained through inspections at all buildings, archive research and in case of lacking information through regulations and standards. Using HeidiSQL, the data is added to the project database which runs on a MySQL database server. On average data acquisition takes about 24 working hours per building or 1 hour per 350-400 m² floor area.

Internal thermal gains

In addition to the geometry of a building, internal gains like heat energy emitted from lighting loads, plug loads (e.g. computers) and other major electricity consumers (e.g. scientific experiments, machinery, datacentre) as

Figure 4: All thermal zones of 40 buildings on campus. The number of thermal zones varies between 2 and 9 for each building. The red arrow shows the example shown in figure 2.

well as occupants can have a huge impact on the thermal characteristic of a building.

To account for these a team of engineers inspects the individual buildings regarding installations, equipment and usage. Schedules and thermal power of each contribution to the building energy balance is determined and saved in the project database. An average of 12 working hours per building is required for this task.

Multi-zone modelling approach

A relational database running on a MySQL database management system has been implemented as a central data-handling tool bridging the gap between the architectural-geometrical description of buildings and the object-oriented simulation models based on Modelica. Database systems feature several advantages over e.g. file based handling of building data, these include:

- Only one common and always up-to-date dataset,
- Simultaneous viewing and editing of data by multiple users,
- Enhanced data security due to easy backup of acquired building data and manageable access privileges,
- Comprehensive data analysis with database queries,
- Easy implementation of customized tools to access and edit deeply structured data.

The data is structured hierarchical in tables with single buildings being the fundamental object. Each building is made up from the defined thermal zones, whose number is variable, and basic data like monthly heat and electricity consumption from several years past. A thermal zone table holds information like temperature set points, number of occupants, contributions to internal loads and corresponding time tables where applicable. Furthermore, zones are linked to several planar constructions, i.e. roofs, facades, intermediate walls, as described above, which make up the zone’s thermal envelope. A planar construction table comprises geometrical information as well as construction data. Further database tables manage material properties, detailed time tables and general building information.

The building models for simulation are based on the BuildingSystems Modelica library (Nytsch-Geusen, et al. 2016). In order to ensure a fast and especially error-free translation of building information from the database into ready-to-simulate building models, an automatic Modelica code generation has been implemented in the Python programming language with help of the Mako template module[2].

Python classes for buildings, zones, walls, windows and various component connections have been developed. Instantiated with a corresponding database-ID, objects query the database directly to get their attribute values. The total number of objects can vary greatly, dependent on the number of zones and planar constructions that are required to represent each building according to the rules for thermal zoning and geometrical simplification. Based on Mako, a template of a generic Modelica building model using component models from the BuildingSystems library has been prepared. Via placeholders and loops the template can accommodate any necessary number of elements and connections. Finally, together with a Python object that holds all relevant building information, the template is rendered into a functional Modelica model.

As has been noted by Troncoso it is common practice to adjust model parameters iteratively by trail-and-error to match the simulated consumption with the measured data (Troncoso 1997) However, this so called “fudging” takes away from the credibility of the model. Therefore, this study forgoes calibration of the auto-generated models until a systematic and justifiable method has been implemented as part of the introduced modelling process.

Code generation, including all database queries, takes on average 1.2 s per building. The simulation times are highly dependent on the actual size of the equation system, i.e. the total number of components inside of the model. Tests with an average of 4 to 5 zones and 39 planar constructions per building have been performed. For a one-year simulation, they exhibit an average simulation time of around 300 s per building.

Single-zone modelling approach

In contrast to the multi-zone approach described above and motivated by sparse data availability often found with existing building setups, a parameter identification strategy has been presented in (Inderfurth, Nytsch-Geusen and Ribas Tugores 2015), which finds simulation parameters based on heat consumption and basic geometric data alone. Here an immutable single-zone Modelica building model is used to replicate the thermal characteristics of buildings. It has a simplified geometry where all facade and roof elements are aggregated into one exterior wall, one interior wall element, one base plate and 4 window models with distinct orientations. By adjustment of nine thermal parameters the model is fitted to the heat energy consumption of a particular building by means of an optimization algorithm. Fitted parameters include the set temperature for heating, the air change rate, several thermal capacities as well as thermal transmittances. The identification process takes around 8h per building and incorporates between 400 and 500 iterations of the optimization algorithm. Accordingly, the simulation time for a single building model after parameter identification is around 60 s for a one-year simulation.

This method, essentially, creates a grey-box model for each individual building. As noted in (Coakley, Raftery and Keane 2014), while grey-box models can accurately predict the building performance, given reliable input data, the models need to be re-calibrated when changes are made to the building envelope or its installations.

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[2] www.makotemplates.org

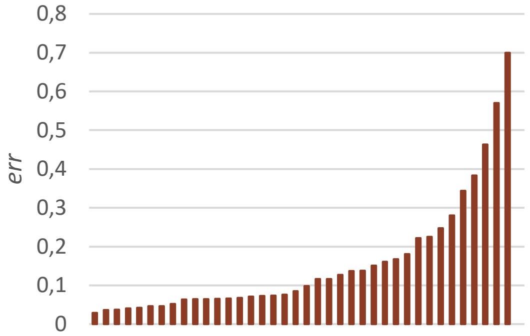

Figure 5: Error in simulation of heat consumption of 38 test buildings after parameter identification.

An extended test of the identification strategy on 38 buildings exhibits an average error of 12.8 %, see fig. 5. While half of the investigated buildings exhibit an error of less than 10 % others show an error of up to 70 %. Reasons for the higher error rates can be attributed mostly to thermal effects that have no representation in the fixed underlying building model. These include e.g. internal gains through machinery or thermal processes like absorption chillers.

Nevertheless, the identification strategy results in an error rate lower than 20 % in 75 % of the investigated cases. This is accomplished with an almost entirely automated workflow. This circumstance prompts a comparison of the described multi-zone approach with researched parameters and this single-zone approach with fitted parameters.

Simulation results

The comparison of both methods is performed based on exemplary buildings located at university campus Berlin-Charlottenburg, home of Technische Universität Berlin and Berlin University of the Arts. Multi- and single-zone approach are applied to 6 buildings (B1 to B6) and the results are compared. In case of one building (B5) actually measured heat consumption data with hourly samples of 65 days in early 2015 is available for a detailed evaluation.

The yearly deviation *dev* is defined as:

$$dev = \frac{Q_{sim} - Q_{con}}{Q_{con}} \quad (1)$$

The term *"dev"* gives the overall relative yearly deviation between simulated heat consumption Q_{sim} and measured heat consumption Q_{con}. It is positive when the simulated yearly energy is higher than the measured energy and negative when vice versa.

The error *err* is defined as follows:

$$err = \frac{\text{sgn}(dev)}{Q_{con}} \cdot \sum \left| Q_{sim,i} - Q_{con,i} \right| \quad (2)$$

While *err* is also positive or negative, depending on the direction of deviation, it takes the monthly deviations $Q_{sim,i} - Q_{con,i}$ into account. This ensures that positive and negative deviations do not compensate for each other. Accordingly, $|err| \geq |dev|$. Ideal values for both parameters would be 0.

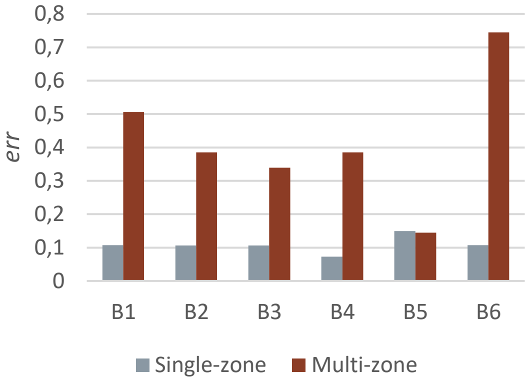

Figure 6: Error values of all 6 buildings for single-zone (grey) and multi-zone (red) approach.

Fig. 6 shows the error for single- and multi-zone simulations of 6 exemplary buildings from the university campus. The single-zone approach yields an average error of 10.8 % which is slightly less than the average of the 38 test buildings shown in fig. 5. The multi-zone approach exhibits much higher errors when applied to these 6 buildings, with an average of 41.8 %. In contrast to the other cases, building B5 has a slightly lower error value of 14.5 % for the multi-zone approach against the 14.9 % of the single-zone simulation.

Fig. 7 shows the measured heat load of building B5 with hourly samples as well as the simulated heat load from single- and multi-zone approach. In the depicted time frame of 50 days (from January and February of 2015) the single-zone simulation yields on average the lowest heat load; the measurement has the highest. Based on the positive *err*-value for building B5, an overestimation of the heat load would be expected. However, with a yearly deviation *dev* = 2.8 % compared to *err* = 14.5 % it is apparent that positive as well as negative deviations are present over the course of the simulation period, which cancel each other out to result in a low *dev*. It should also be noted that the low yearly deviation has been achieved without model calibration.

Taking a look at the overall progression of the heat load, it can be observed that the curve's peaks and valleys mostly match, see detail in Fig. 7. Especially, both simulated curves show the same basic shape.

Conclusion

Based only on the evaluation by means of the *err*-value, the single-zone approach can reproduce the thermal behaviour of the buildings better overall. However, the parameters are fitted exactly to the consumption data of the year of evaluation. The performance of the specific model for future consumption data, must be evaluated after corresponding data has been acquired. As

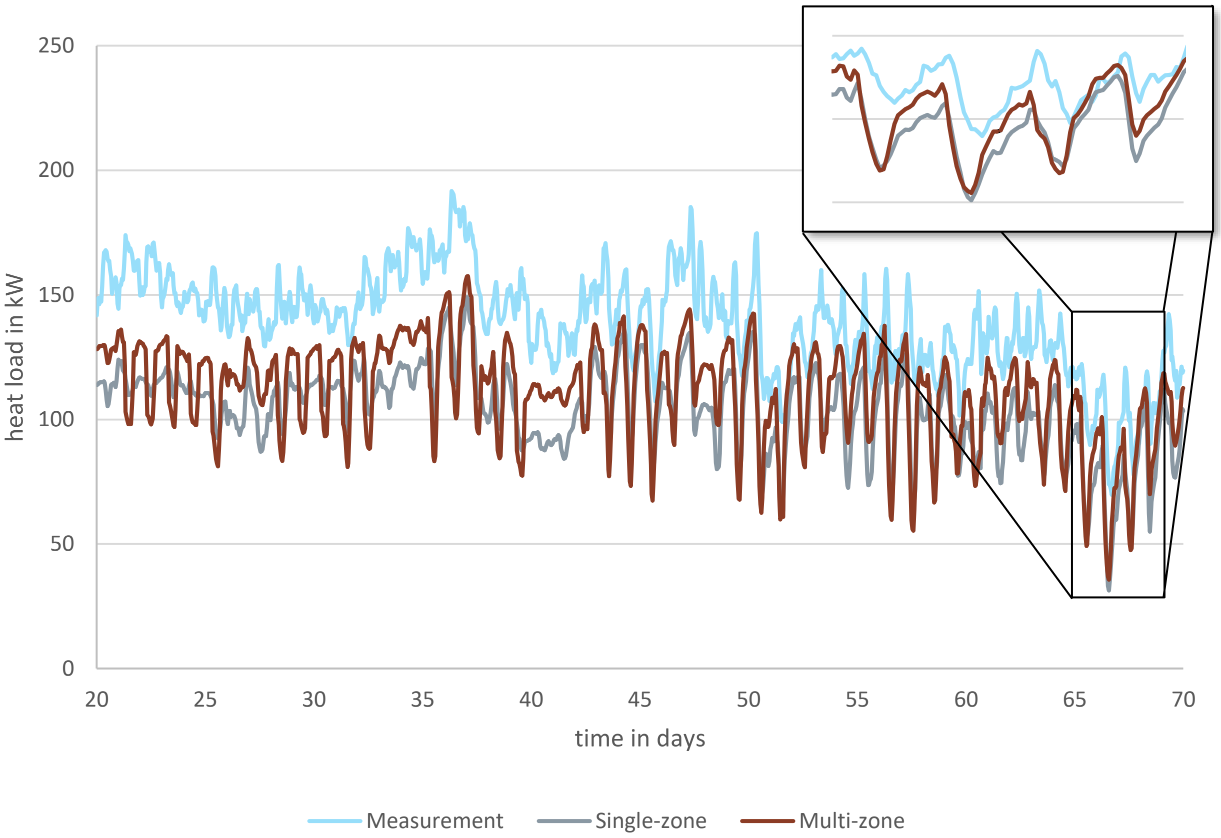

Figure 7: Heat load of building B5 in W, single-zone simulation, multi-zone simulation and measurement.

mentioned above, the fitted single-zone models cannot be used to test renovation measures. For example, it is unclear how to implement the refurbishment of only one facade in the underlying grey-box model, which aggregates all facades into one external wall element.

On the other hand, the multi-zone approach relies completely on investigated detailed data sets. Even with a higher error than the single-zone approach the underlying models offer a greater flexibility. For example, the models include wall structures which can be modified to represent renovation and thermal optimization measures. As has been discussed, the thermal zoning is in part a result of possible renovation scenarios. Overall the multi-zone approach allows for a better representation of load distribution inside of one building. Especially the representation of cooling loads is more accurate, since cooling and heating loads of multiple zones do not compensate each other, like they would in case of a single-zone model. Furthermore, a deviation of simulated and measured energy consumption can also hint at inefficient energy supply, because the measured consumption data includes the thermal losses of inefficient working heating equipment.

The application of both approaches to a set of 6 buildings shows that architectural-geometrical simplification in conjunction with well investigated parameter sets is a productive method. Nevertheless, within the scope of the district simulations it is labor-intensive. Gathering data for this level of detail takes about 36 working hours per building, compared to 8 hours for the almost entirely automatic identification process of the single-zone approach.

Simulation times for a one-year simulation of around 60 s and 300 s for single- and multi-zone approach, respectively, enable the simulation of the entire building stock in a short time frame.

It is suggested to apply the single-zone approach with fitted parameters only when the actual state of a building needs to be modelled and no refurbishment options should be investigated. However, it is highly recommended to use multi-zone building models if it is intended to model and simulated buildings for refurbishment projects at urban level. The model’s level of detail gives more insight into the thermal characteristics of a building and renovation measures can be implemented. In that way, simulation results can be better incorporated into the planning process.

Summary and Outlook

An analyzing method has been developed to approximate the buildings’ thermal characteristics in simulations through (a) simplifications of the form, facades and the partitions at the whole campus area and (b) division of buildings into thermal zones that are defined per significant difference in utilization, facades, thermal mass and set-point temperatures.

Benefitting from the database system, multi-zone building models in Modelica can be generated automatically. The building models are composed of components of the BuildingSystems Modelica library (www.modelica-buildingsystems.de). They feature a number of thermal zones, dependent on the applied architectural-geometrical simplification and are parameterized with parameter sets based on in-depth analysis of the building stock.

The simulation outputs are compared to results which are based on fitted single-zone building models from a preceding project that dealt with the same building stock.

Going forward, an automated process for architectural-geometrical simplification of buildings should be researched and implemented in order to enhance time efficiency, especially for applications in urban areas.

Finally, a calibration method for the described multi-zone models should be implemented. Models whose parameters are fitted to the consumption data within narrow bands of variation could improve the accuracy of the simulation-based reproduction of the heat consumption. An analysis of the multi-zone building models regarding their sensitivity to minor variations in the input parameters would be the first step in this regard.

It is aimed to condense the presented approach into a universal method that can be applied to district simulation in general.

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