# QUALITY ASSESSMENT OF AUTOMATICALLY GENERATED SIMPLIFIED THERMAL BUILDING MODELS

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## ABSTRACT

Building modeling and simulation are resource intensive tasks. The modeling effort for thermal building models can be reduced significantly by automatic model generation. In this work, an extension of an existing prototypical building model generation tool chain is discussed. This extension integrates a collaborative mapping solution into building modeling for thermal simulation. The improved tool chain was validated using three models of the same building generated manually, semi-automatically and automatically. Simulations were performed using each model to assess their quality by comparison with measured data. The results show the suitability of the automated process as a cost-effective method to generate models for building performance simulation.

## INTRODUCTION

Using software tools to predict energy consumption in buildings is an established practice. The tools use different simulation methods to calculate energy needs of building systems, such as heating, ventilation and air conditioning (HVAC), lighting or other electric equipment. These methods require different information sources. For example, for thermal building simulations weather data, building geometry, material properties, internal gains, HVAC system components, and building usage information is needed. Some of this information can be provided by standards and norms, while the rest has to be manually generated or imported from other tools used during the building life cycle. Building geometry is often one of the inputs that require the most effort to be provided. It has to be either drawn manually using modeling software or imported from computer aided design (CAD) software. Having a tool that automatically generates these models is important when, for example: the time and costs need to be reduced, fast energy assessment of the building is needed, the availability of building information is reduced, or large number of buildings needs to be simulated.

This paper presents an extension of an existing tool for semi-automated building modeling that has been developed in previous work (Leal, et al., 2014). These models can be used to forecast energy demand of buildings. The extended tool chain automatically creates building models suitable for thermal building simulation on different scales. For that purpose, a collaborative mapping solution was integrated.

By comparing the results of the improved solution with those of the existing solution and a manually created model, and setting all of these in relation to actual consumption recorded on-site, the quality of the models was assessed.

The paper is organized as follows. First, a background of the related work in thermal building simulation modeling and the existing tool chain is presented. Then, the extension for improvement of the existing tool chain is described. Next, the simulations performed with manually created, semi-automatically generated and automatically generated model are explained. The results from the simulations are then analysed. Finally, the paper is concluded and ideas for future work are presented.

## BACKGROUND

Building performance simulation is used primarily in building design where it supports design decision making (Hensen and Lamberts, 2011). Building models on which the tools rely, also called building information models (BIM), are a set of information generated and maintained throughout the life cycle of buildings (Mahdavi, et al., 2007). In these models geometry, spatial relationships, geographic information, quantities and properties of building components are represented, accompanied by their relations. The data requirements for building performance simulation are challenging. Thermal performance simulation, for example, requires three dimensional room models, which include geometry and material properties along with occupancy and equipment schedules.

Dynamic energy performance models have been proposed which may be used to simulate any building by varying the related shape and orientation, construction materials, climatic zone, position, number and geometry of windows and shadows (Buonomano and Palombo, 2014). The results achieved in such case studies may be used for developing suitable design guidelines and interesting physical response, as well as retrofit analyses of the examined buildings. Thus, the building energy efficiency can be modelled and simulated in a modular and scalable manner.

Building energy simulators require a certain level of technical expertise to be used (Chuah, et al., 2013). Consequently, trained professionals are necessary to perform building energy analysis, which result in additional costs. Although trained auditors, in general, produce more customized and accurate building energy analysis, the additional costs involved may deter many building owners from adopting building energy simulation for the assessment of the building performance. Also, most building energy simulators are not retrofit-oriented and they do not offer alternative scenario analysis. Thus, building energy simulator users have to manually create building models to simulate across different retrofit choices. Modeling costs may be reduced by decreasing the accuracy and the complexity of the building model (Zucker and Hettfleisch, 2010).

Existing data models for modeling buildings, such as the Industry Foundation Classes (IFC), provide building model application for different domains, such as lighting, safety and security, or HVAC (BuildingSmart International, 2013). An object in IFC is a generalization of any semantically treated thing or process. This can represent building elements, such as walls and windows, but also spaces or even conceptual items, such as virtual boundaries. Object types are important to model a large number of objects in buildings with similar properties, which reduces repetitive work for modeling.

Another open data exchange standard is the Green Building XML (gbXML) (Roth, 2013). The gbXML[1] schema enables the exchange of data between architecture design tools and energy simulation programs. gbXML is used during the planning phase of the building or during a major retrofit. The information is formatted using XML which provides simplified interoperability.

Since building geometry is required information that is very difficult to provide, there are efforts to retrieve this information from different sources. For example, a CityGML[2] model can be used to perform energy simulations (Agugiaro, et al., 2015). CityGML is a data model for modeling, storing and exchanging virtual 3D semantic city models (Gröger, et al., 2012). Beside geometry of objects, such as buildings and city infrastructure, the model contains semantic information, such as building type, usage and year of construction, as well as topology. Five different levels of detail are defined. Although the quality of such model is usually good, this kind of model is not always available for every city.

Collaborative mapping solutions, such as WikiMapia[3] or OpenStreetMap[4] can offer better availability for some parts of the world. OpenStreetMap is a collaborative mapping solution with a goal to build a free geographic database of the world (Bennett, 2010). While OpenStreetMap started with mapping streets, it has gone beyond that to include footpaths, buildings, and even individual trees. The database is built by contributors, usually called mappers within OpenStreetMap. They gather information by driving, cycling, or walking along streets and paths, and around areas recording their motion using Global Positioning System (GPS). This information is then used to create a set of points and lines that can be turned into maps or used for navigation. Most mappers are volunteers working on the project collaboratively, although both commercial organizations and government bodies have started to contribute to the project. Other data is gathered from public domain databases and maps without copyright protection or in some cases donations of proprietary databases by the companies owning them. In most cases, this needs further work to update and process the data, but it allows mappers to cover areas they cannot physically get to. The database uses a wiki-like system where any mapper can add or edit any feature in any area. A full editing history is kept for every object. This means any mistakes or deliberate vandalism can be rolled back, keeping the data accurate. OpenStreetMap does not use an existing Geographic Information System (GIS) to store its data, but instead uses its own data model to make the process as easy as possible. Furthermore, this provides flexibility for the type and format of the data being included. OpenStreetMap is released under a license that allows anyone to copy, change, and redistribute, as well as use the data for any purpose.

## EXISTING TOOL CHAIN

Previous work on model simplification has been reducing the modeling effort and easing the development of dependent technologies (Leal, et al., 2013). A study of thermal and electrical performance simulation using simplified building models has been performed which assessed the feasibility and adaptability of simplified models for realistic performance simulation purposes (Leal, et al., 2014). Results demonstrated a high level of agreement between the simplified model and an existing office building. For that purpose, a prototypical tool chain was developed which semi-automatically generates simplified thermal building models. The models were limited to typical building geometry templates and their combination. The tools can automatically generate internal building zones. Additionaly, each floor can be assigned with a different usage. This existing tool chain is extended in this work. It consists of tools to collect the information needed for modeling and simulation, a model generator and a simulation environment (Figure 1).

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[1] http://www.gbxml.org/

[2] http://www.citygml.org/

[3] http://www.wikimapia.org/

[4] http://www.openstreetmap.org/

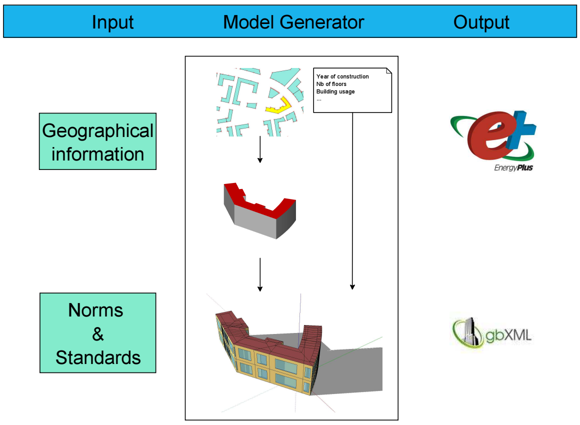

*Figure 1: Overview of the tool chain.*

The model generator needs a minimum set of mandatory input parameters: simplified building geometry, the geographic location of the building, physical parameters for the building envelope and HVAC system configuration. On the one hand, the description of the building geometry may also be taken from the gbXML description of the building. On the other hand, all other additional information of the building can be entered into the tool manually.

Depending on the availability of the real building data, the level of details of the necessary input parameters can vary significantly. As described in Leal et al. 2013 following parameters are mandatory:

- Building geometry, building height including number of floors and fenestration ratio in %
- Building location and construction year
- Building type and usage

All other parameters can be easily estimated based on this set of parameters using norms and standards (see for example (European committee for Standardisation , 2007), (Österreichisches Institut für Bautechnik, 2007), (Austrian Standards Institute, 2010)).

The model generator creates the building model automatically based on the provided input information. One of its main tasks is to divide the ground floor of the building into thermal zones. According to the main purpose of the building model, having a simplified building model for fast energy assessment, a detailed representation of the internal arrangement of rooms are not taken into account due to simplifications of the building model. Nevertheless, the model generator depending on the building properties specifies outer zones (which are affected by the environment conditions) and core zones. This automated thermal zoning starts out using the straight skeletons (Aichholzer and Aurenhammer 1996) of the outer polygon to shrink it into a core zone or core zones. At the same time it modifies the created zones under the constraint that all zones have to be convex (a boundary condition for some simulation tools which eases ray tracing for solar gains). Furthermore, the model generator specifies all other parameters within the building model, for example building physics properties or internal gains (thermal and electrical). This model is then sent to the designated simulation tool (for example EnergyPlus[5] or TRNSYS[6]) to be simulated. In the existing tool chain EnergyPlus was chosen due to its flexibility and simplification for specifying the simulation input file, as well as its status as an open source tool, which keeps open several possibilities for later development, e.g. parallelization.

## EXTENSION DEVELOPMENT

The previously mentioned prototype of the tool chain requires a minimum user interaction during the modeling process. This was done by using a graphical user interface (GUI) in order to specify all building parameters, but mainly to specify the building geometry of the model to be simulated. To be able to fully automate the model generating process a new information source from a collaborative mapping solution was chosen to specify the building geometry.

One possibility is to use information available in OpenStreetMap and import it into the tool chain. This was done by an import-interface which extracts the mandatory building information, as mentioned before. This information is collected using the extensible markup language (XML) application programming interface (API) of OpenStreetMap[7]. As an input key either the name of the building or the address is used. With this key it is possible to get building geometry (represented as a polygon describing the outline of the building), building height, building type, number of floors, and year of construction. These tags are shown in Table 1 for the building used to validate the tool. If neither the name of the building or the address is available, it is possible to visually find the key of the required building directly in the OpenStreetMap website.

*Table 1: OpenStreetMap tags of the test case building*

| | |
|---|---|
| **addr:city** | Sopron |
| **addr:postcode** | 9400 |
| **building** | yes |
| **building:levels** | 2 |
| **height** | 11m |
| **name** | IKVA Áruház |
| **shop** | mall |
| **start_date** | 1979 |

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[5] http://apps1.eere.energy.gov/buildings/energyplus/
[6] http://www.trnsys.com/
[7] http://wiki.openstreetmap.org/wiki/API_v0.6

To verify the automated modeling process and the quality assessment of the simulation results an existing shopping center (mall) in the city of Sopron in Hungary was chosen. The test case building was built in 1979, has 2 floors and its 11m high. These parameters influence on the one hand the building geometry and on the other hand the physical building properties e.g. u-values of the walls, windows, etc. These properties are specified according to its national norms and standards based on the information of the construction year in addition to the building usage and its location. In case of major refurbishment to newest standards, an update of this parameter would be enough to generate a new, up to date model.

To be able to generate the building geometry based on the polygon information of OpenStreetMap, a transformation from longitude and latitude coordinates into Universal Transverse Mercator (UTM) Cartesian coordinates is necessary to get the correct building dimensions. This coordinates transformation is done automatically by the import-interface of the tool chain.

Figure 2 shows the visualization of the 3D building model represented with the tool chain. It illustrates conceptually the mapping between the OpenStreetMap tags and the building model attributes: the polygon description of the building geometry, the overall building height and the number of floors.

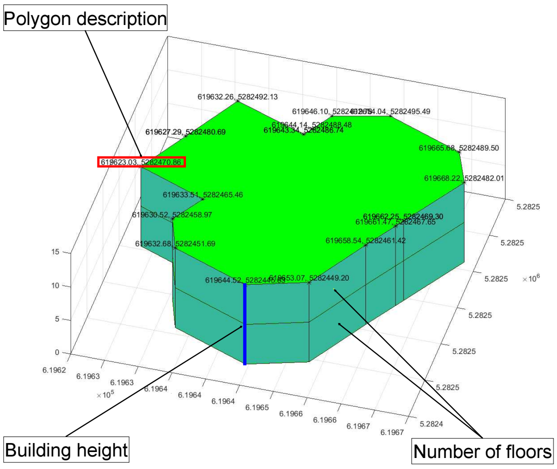

*Figure 2: Visualization of the OpenStreetMap polygon of the test case building*

## SIMULATION

For validation of the improved tool chain with respect to the model generating process and the quality assessment of these models, three models of the test case building were generated using different methods:

First, a model of the test case building was manually created (Figure 3) taking all available information into account e.g. detailed thermal zoning, an exact representation of the building geometry etc. Architectural blueprints were used to draw a model using SketchUp[8]. This model was exported in IDF[9] format that could be used in EnergyPlus. This serves as a baseline for state of the art building modeling and simulation.

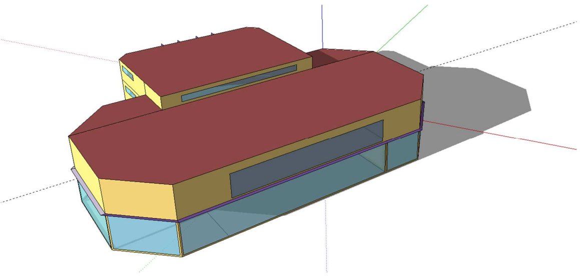

*Figure 3: Manually created model of the test case building*

Second, a simplified building model (Figure 4) was generated with the previously developed semi-automated approach by using a simplified GUI. Due to its limitations the geometry of the building is more simplified compared to the manual approach.

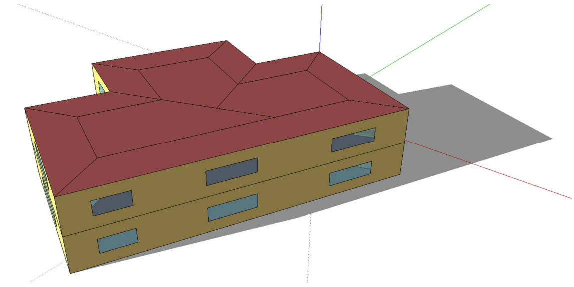

*Figure 4: Model of the test case building generated using the semi-automated approach*

Third, a less simplified building model, concerning the building geometry, was generated automatically using the geometrical information (polygon) and semantic information (meta-data in tags) from OpenStreetMap (Figure 5).

By comparing the semi-automated and the automated approach, an increased flexibility of defining the building geometry can be seen and reduction of the time for modeling.

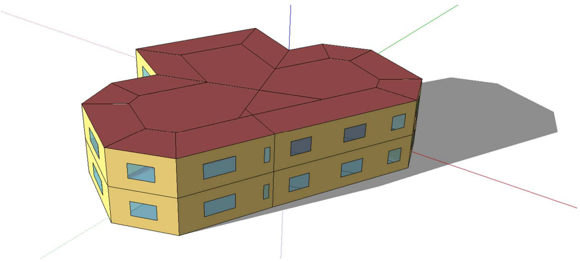

*Figure 5: Model of the test case building generated using the automated approach*

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[8] http://www.sketchup.com/

[9] http://apps1.eere.energy.gov/buildings/energyplus/pdfs/inputoutputreference.pdf

*Table 2: Simulation results*

| MODELING METHOD | CONDITIONED SPACE SURFACE | ANNUAL ENERGY DEMAND | NUMBER OF ZONES | MODELING TIME (MANUAL) | MODELING TIME (AUTOMATIC) |
|---|---|---|---|---|---|
| Manual | 2730 m$^2$ | 117.09 kWh/m$^2$ | 8 | approx. 1 day | / |
| Semi-automatic | 2880 m$^2$ | 106.79 kWh/m$^2$ | 22 | approx. 4 min. | 02:04 min. |
| Automatic | 2813 m$^2$ | 105.27 kWh/m$^2$ | 34 | / | 03:02 min. |

For each building model a thermal simulation was performed to calculate the annual heating energy demand of the building. All models take the same simulation parameter into account, for example a default weather file[10], internal load profiles, HVAC set points or schedules.

## ANALYSIS

Table 2 shows the results of the different approaches. It compares the annual heating energy demand and the time to generate the building model. Based on these results a quality assessment of the building models and the validity analysis of the respective simulation results were made.

According to monitoring data between 2011 and 2013 from the existing building, the average annual energy consumption for heating was 99.13 kWh/m$^2$. Figure 6 shows a comparison between the monitoring data and calculated demand of the different building models. The cumulative error per season for different modeling methods is shown in Figure 7. The automatic modeling seems to be more accurate during the winter months and less accurate during the transitional periods. Figure 8 illustrates the simulated daily energy demand for a specific week in January compared with the measured energy consumption and the outdoor temperature. It shows that the overall dynamic behavior of all modeling approaches is similar. Note that the measured energy consumption is averaged per month since the metering provided only monthly values.

Although manual modeling provides a more detailed building geometry, it seems to be a less accurate

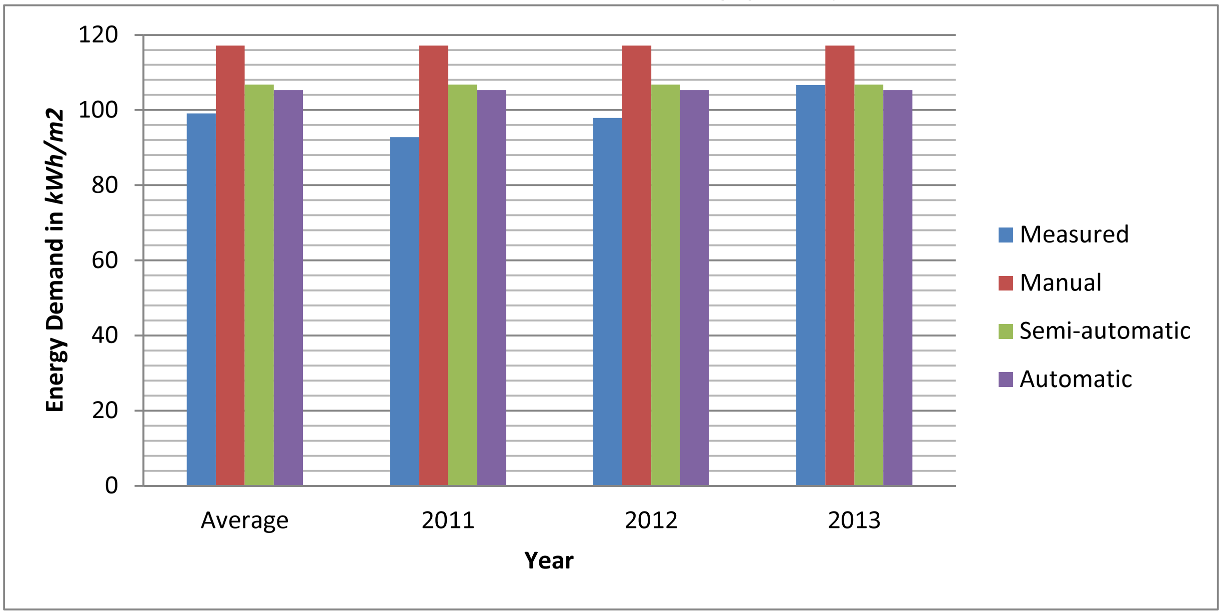

*Figure 6: Annual energy demand for heating based on the simulations with the 3 modeling methods compared to the energy consumption for heating measured during a period of 3 years*

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[10] http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data2.cfm/region=6_europe_wmo_region_6

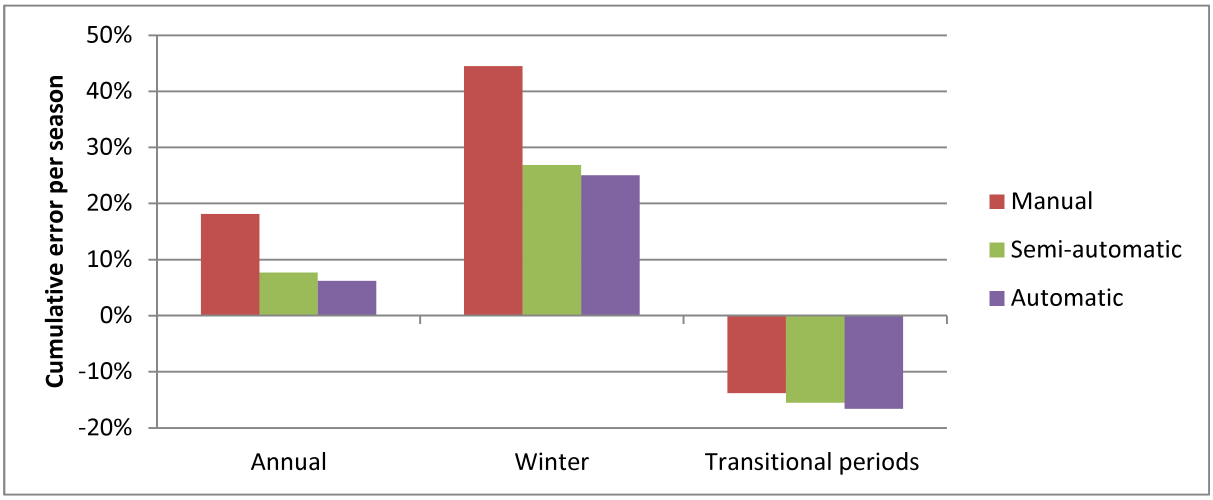

*Figure 7: Cumulative error per season for different modeling methods on yearly basis, winter only (December – February) and transitional periods (March –April and October - November)*

method for annual energy demand calculation. This might be due to excessive amount of inaccurate details resulting in additional errors. On the other hand, the semi-automatic approach generates too simplified geometry because of the user interface limitation. Automatic model generation provides the best results for annual energy demand. However, if more detailed results are needed, for example, to identify overheating of rooms in summer, manual modeling is preferable.

As shown in Table 2, the time to model the building significantly improves as completely automatic building model generation is introduced. Compared to manual modeling which takes approximately 1 day for the building used for this case study, and the semi-automatic modeling which needs 4 minutes to manually set the parameters and 2 minutes to automatically calculate the zones, using information from OpenStreetMap requires only 3 minutes to automatically calculate the zones without additional manual effort.

Although significantly improving the time needed to model a building, using collaborative services has drawbacks, such as validity and availability of data. The information that services such as OpenStreetMap contain is provided by users in a collaborative manner. This means that every user can contribute to the service to their best knowledge. Often streets and buildings are only provisionally modeled based on a satellite image underlay, which might introduce errors. Thus, polygons are sometimes distorted, simplified or unnecessarily complicated. On the other hand, additional meta-data, such as those in Table 1, can be unreliable and incomplete. All this influences the results of the simulation.

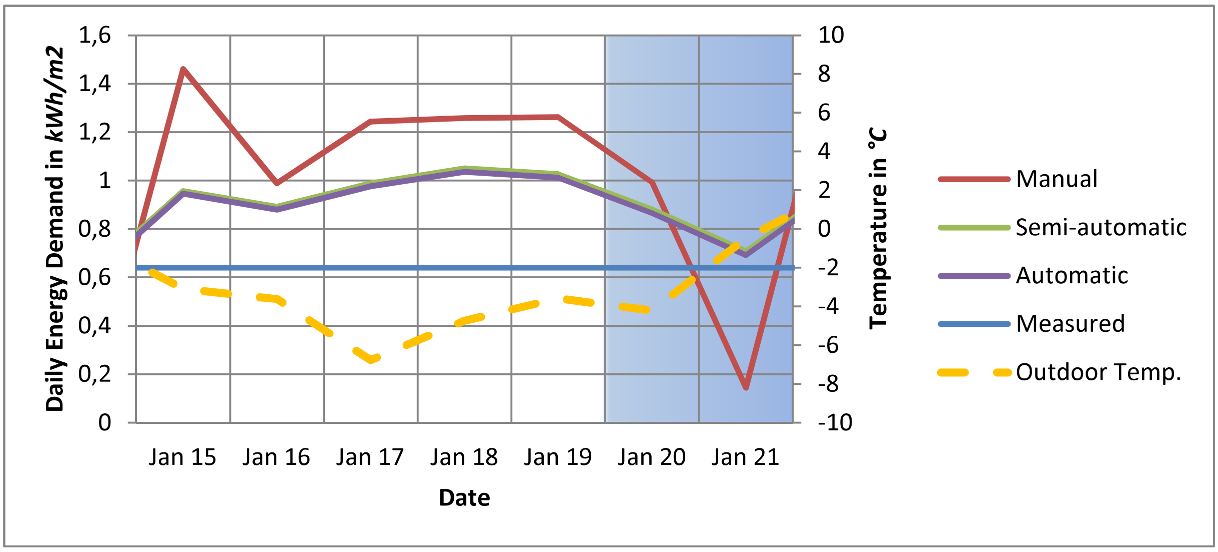

*Figure 8: Daily energy demand for heating for a specific week based on the simulations with the 3 modeling methods in comparison to the measured energy consumption for heating and the outdoor temperature*

## CONCLUSION

This paper has shown that using a collaborative mapping solution might be a cost-effective source for building thermal simulation models. The automated process was validated by comparing it to a previously developed semi-automatic process and manual modeling. The results of the simulation were compared to the actual energy consumption. This can be also used for first assessments whether a building which is monitored and evaluated consumes a reasonable amount of energy.

An automated building energy simulation model generation tool chain was extended. Its advantages are reduction of resources and complexity related to building modeling and simulation. Consequently, the employment of energy performance modeling and simulation on the entire building process is made more feasible.

Based on the analysis of the results, it can be concluded that although using collaborative mapping services as information source for automatic thermal simulation model generation has its drawbacks, the manual effort that is needed for modeling is eliminated and the results of the simulations are satisfactory. Therefore this method can be used to generate models for building performance simulation in a cost-effective manner.

While the results show the feasibility of the method, further tests with additional buildings should be performed to better evaluate it. In future, monitoring data from the test case building with higher resolution will be available which will provide even better analysis of the simulation results. Future work will focus on coupling with official data including additional semantic data to fully automate the process. This will allow us to create building models and run simulations faster on large scale for building complexes, neighborhoods and even whole cities.

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