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COMPARISON OF THERMAL SIMULATION MODELS WITH DIFFERENT LEVELS OF DETAIL FOR NON-RESIDENTIAL BUILDINGS

David Jansen[1], Jan Richarz[1], Dominik Vaeßen[1], Dominik Hering[1], Dirk Müller[1]
[1] *Institute for Energy Efficient Buildings and Indoor Climate, RWTH Aachen University, DE,*
david.jansen@eonerc.rwth-aachen.de, jan.richarz@eonerc.rwth-aachende,
dominik.vaeßen@rwth-aachen.de, dominik.hering@eonerc.rwth-aachen.de,
dmueller@eonerc.rwth-aachen.de

Abstract

Building performance simulation of non-residential buildings offer a possibility to determine CO_2 saving potentials. Especially for these often heterogeneously buildings. In order to keep the workload for modeling and simulation as low as possible, reduced-order modeling (ROM) approaches are increasingly used. To evaluate the impact of ROMs on the accuracy, a detailed *Modelica* high-order model (HOM) of an institutional building is generated and compared with two ROM approaches of different levels of detail. One modelled in *Modelica* based on VDI 6007 and one in *Python* based on ISO 13790. Finally, a recommendation is given on the intended use of the models.

Introduction

Buildings account for 27% of global carbon emissions, 11% of which are from non-residential buildings. (Global Alliance for Buildings and Construction, 2021) Non-residential buildings are more heterogeneous and dynamic than residential buildings, and therefore more difficult to simulate, and erroneous data lead to larger deviations. (D'Agostino et al., 2017) An economic analysis by Nief et al. showed that with simulations in the design of building and systems technology, final energy consumption could be reduced by at least 8% (Nief, 2017). The most accurate models possible are needed to represent reality. This conflicts with the requirement for a flexible process that can react quickly to changes in the design of a building and requires as little effort as possible for modeling and simulation. (Østergård et al., 2018; Østergård et al., 2020)

In general, a distinction is made between static and dynamic methods for calculating demand. In static calculations, the state no longer changes without external excitation. With dynamic simulations, transient effects are taken into account, which enables a temporal resolution of the system. The reality can be described much better by a dynamic consideration (Gräber, 2020). The static methods include the annual balance method according to DIN EN 12831 (DIN EN 12831, 2017), as well as the monthly balance method according to DIN V 18599 (DIN V 18599, 2018). Both approaches use averaged values and correction factors to evaluate the energy efficiency of buildings and to design the system technology. The advantage of these methods is that the results are standardized and comparable.

The dynamic simulation methods can be divided into high order models (HOM) and reduced order models (ROM). With regard to ROMs, there are also standardized specifications for the models in ISO 13790 (13790, 2008) with a simplified hourly method or VDI 6007 (VDI 6007, 2015) with a fully dynamic method. Through ROMs, demand models can be used in complex optimization problems or similar use cases, which could not be solved using or even impossible using highly detailed models due to the immense time and computational effort involved (Shalabi and Turkan, 2020). Furthermore, there are different approaches for highly detailed mapping. These are implemented by programs like *EnergyPlus*, *TRNSYS*, *IDA ICE* or *Modelica*. This paper focuses on the dynamic simulation methods and compares three models with different levels of detail in terms of their accuracy and gives an assessment of the respective purposes of the models.

Methodology

Use Case: To compare the dynamic simulation approaches with respect to the use of simulation of larger non-residential buildings, the first step is to define a use case. The building under investigation is the main building of the Institute for Energy Efficient Buildings and Indoor Climate of the RWTH Aachen. The building was chosen because of the high availability of data in the form of construction plans, component catalogs and a Building Information Modeling (BIM) model. Furthermore, the building is intensively monitored, which will also allow a comparison with measured data in the future. The building and the corresponding IFC model are shown in Figure 1.

Figure 1: Use Case Building and the corresponding IFC model

Model approaches: A total of three different dynamic simulation approaches and their individual implementations are compared:

- ROM based von ISO 13790 in *Python*
- ROM based on VDI 6007 in *Modelica*
- HOM modeled in *Modelica*

The three models will be briefly described below. Both ROM models are reistance (R) and capacity (C) based models that an analogie with electric circuits to describe the transfer and storage of heat. The model based on ISO 13790 is created in *Python*. The resulting model is a 5 capactiy, 1 resistance (5R1C) model which is shown in Figure 2. It is based on a one zone model for residential buildings by (Schütz et al., 2017)). In this work, the model was extended to be applied on non-residential buildings. Therefore, the calculation of cooling demands, the integration of a database for non-residential envelope components as well as a multi-zone approach were newly added. Furthermore, procedures to assign the envelop surfaces to cardinal directions and to the zones were added based on proposed approaches by (Lichtmeß, 2010). The model and its implementation in *Python* allows a subsequent linearization, which enables its use in linear optimization problems. This is one of the main uses of this model. In this paper two models will be created. One uncalibrated model and one which capacities and resistances are calibrated and the capacity of the interior components, which was not considered before, is partially added to the exterior components.

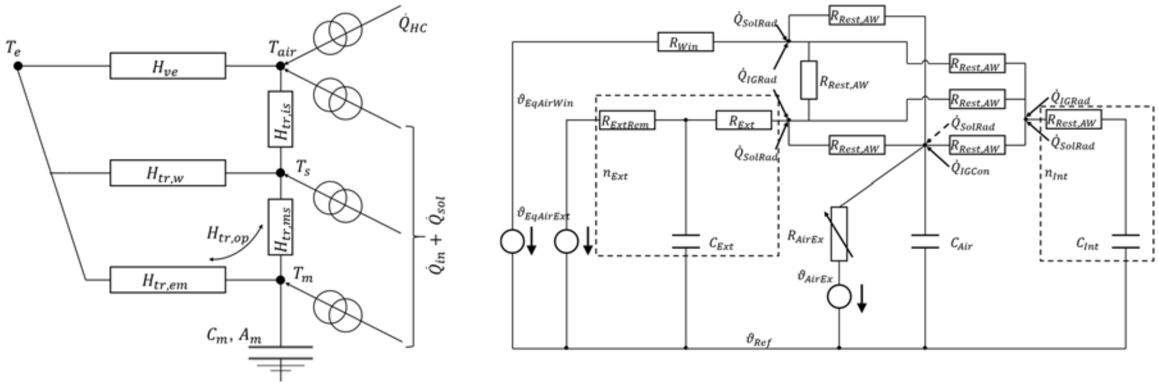

Figure 2: Thermal network of the 5R1C (left) and 11R2C (right) models

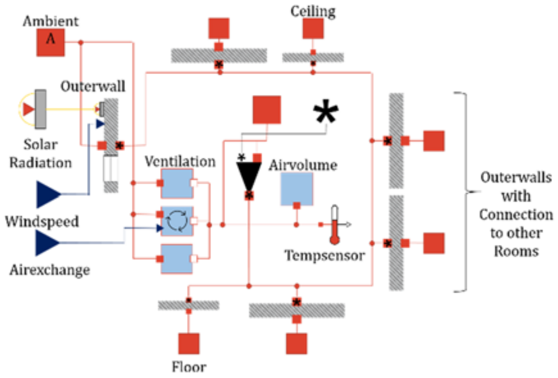

Figure 3: Model of a room instance in the modelica HOM

The VDI 6007 based ROM is created with the *Python* tool TEASER (Remmen et al., 2018). The tool can create different types of simulation models regarding its number of capacities. In this paper the default export of a 11 resistances and 2 capacities (11R2C) model is used. The thermal network of the simulation model is shown in*Figure 2*. No calibration is done for the 11R2C model but an additional zoning setup is created, which will be explained later. The HOM created in *Modelica* (Xanthopoulou et al., 2021) is part of the open *Modelica* library AixLib (Müller et al., 2016). Since modeling large non-residential buildings using the *Modelica* approach is not trivial, the creation of the HOM simulation model is complex and represents the most extensive task, which is, however, necessary in terms of the need for a valid reference. The model is built up room by room, each room is represented by a corresponding instance according to Figure 3. Since HOM modeling also considers the heat exchange between rooms, all components adjacent to other rooms must already be decomposed here according to their adjacent rooms. Each room has several heat ports according to its number of components. Each of these heat ports must be connected to the other rooms and the environment in the next step. Each floor of the building is then assembled from these spatial models, and finally, the overall building is created by combining the different floors into a building. The graphical representation of the *Modelica* model of one floor is shown in Figure 4. In order to exchange heat between the zones and with the environment, all heat ports have to be connected, which is correspondingly time-consuming due to the total number of 173 rooms.

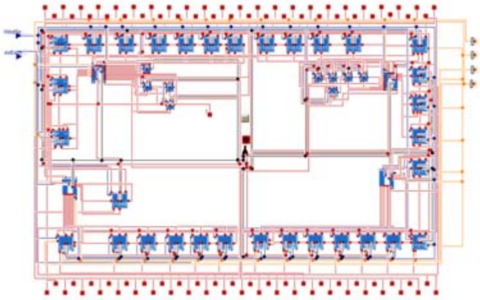

Figure 4: Graphical representation in Modelica of one floor of the Mainbuilding

Zoning: In the field of building simulation, the division of the building into thermal zones has a strong impact on the results of the demand assessment (Brès et al., 2017; Georgescu et al., 2012; Jansen et al., 2021). If we divide the building according to the respective uses based on the described use conditions in the SIA 2024 (SIA 2024, 2015) we get a zoning setup according to Table 1. The Computer-Investitions-Programm (CIP) rooms are used by many students in a relatively small space, resulting in high internal loads.

Table 1: Distribution of areas according to the type of room

ROOMTYPE	NET FLOOR AREA [M²]	PERCENTAGE OF TOTAL AREA [%]
LIBRARY	59.1	0.8
BUERO	1690.1	22.7
CIP	304.6	4.1
TECHNICS	355.2	4.77
MEETINGS	426,4	5.72
TRAFFIC AREA	3428	46.0
KITCHEN	28.1	0.4
LABORATORY	614.9	8.3
STORAGE	267.9	3.6
SANITARY	278.4	3.7

In case of the created HOM, no further zoning is performed besides the assignment of the corresponding use type. This leads to a model with 173 thermal zones. Regarding the 11R2C model previous studies have already shown that due to the lack of heat exchange between the individual thermal zones, this modeling variant is sensitive to zoning. The thesis. The presumption is that over-discretization of zones leads to overestimation of needs (Jansen et al., 2021). To verify this assumption two 11R2C variants are created. A 173 zone model where each room is represented by a zone and a 10 zone model where all rooms of the same use are grouped together. The 5R1C model is. This finally leads to five models ,representing the three model approaches, to be simulated and investigated.

Boundary Conditions: To obtain comparable results, all five model variants are simulated with the same usage profiles and internal loads based on SIA 2024 (SIA 2024, 2015). Based on the given profiles for user occupancy and device usages of this standard, internal loads, are calculated for every zone of the building. The standard test reference year of the DWD for Aachen is used to represent the weather conditions.

Comparative criteria: In order to compare the different simulation approaches, a total of six Key Performance Indicators (KPIs) are used:

- Deviation in peak heat load
- Normalized Mean Bias Error (MBE)
- Root Mean Square Error (RMSE)
- Coefficient of Variation of Root Mean Square Error CV(RMSE)
- Time required for modeling and simulation

The calculations are based on the equations 1 to 3.

$$\mathrm{MBE_{month}} = 100 \cdot \frac{\sum (Q_{\mathrm{H,model}} - Q_{\mathrm{H,ref}})_{\mathrm{month}}}{\sum Q_{\mathrm{H,ref,month}}} \qquad (1)$$

$$\mathrm{RMSE_{month}} = \sqrt{\frac{\sum (Q_{\mathrm{H,model}} - Q_{\mathrm{H,ref}})^2}{n_{\mathrm{intervals}}}} \qquad (2)$$

$$\mathrm{CV(RMSE_{month})} = 100 \cdot \frac{\mathrm{RMSE_{month}}}{\frac{\sum Q_{\mathrm{H,ref,month}}}{n_{\mathrm{months}}}} \qquad (3)$$

Based on the recommendations in ASHRAE 14 and on the measurement and verification guideline of U.S. Deparment of Energy, a model with hourly resolution can be accepted as calibrated if the $MBE < \pm 10\,\%$ and the $CV(RMSE_{month}) < 30\,\%$ (ASHRAE 14, 2014; U.S. Department of Energy, 2015). These are general recommendations and will be used as orientation for the analysis of the models.

Simulation Results

All five models are simulated based on the same boundary conditions for the time period of one year. The first step is to examine the cumulative monthly requirements. The corresponding comparison is shown in *Figure 5*. The HOM builds the reference model for all considerations. The 11R2C in the 173 zone variant has consistently low deviations in the cold months December to February.

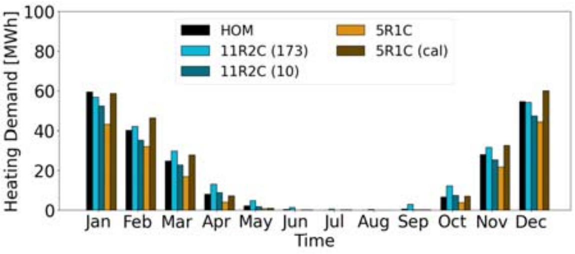

Figure 5: Monthly heating demand results

In the transition period, however, it shows higher differences. The deviations of the 11R2C (10) model are at a constant and comparatively low level, except for December where an increased deviation occurs. The uncalibrated 5R1C model underestimates demand in all months, whereas the calibrated model performs better at the monthly observation level and tends to overestimate demand only slightly. However, the primary focus of the research is to quantitatively evaluate the ability of the models to correctly represent the dynamic processes. In order to get a first impression of the dynamic behavior, the course in the form of daily mean values is shown in *Figure 6*. The legend additionally shows the total annual heat demand. The trajectories show that the uncalibrated 5R1C model underestimates demand at many times, especially during the cold months. Furthermore, it becomes clear that the overestimation of the demands of the 11R2C (173) model occurs primarily in the transition periods and that heat demands are also predicted in the summer months, which do not occur in the reference model. Additionally the daily peak loads, which are important for the design of the heating, ventilation and air conditioning (HVAC) of the building, are well represented by the 11R2C (10) model. The 11R2C (173) model often overestimates the peaks. The calibrated 5R1C model also tends to overestimate the peak loads. To compare the results with the recommendations for the KPIs mentioned at the beginning, the RMSE (as box plot), MBE and CV(RMSE) for the four models are shown in *Figure 7*.

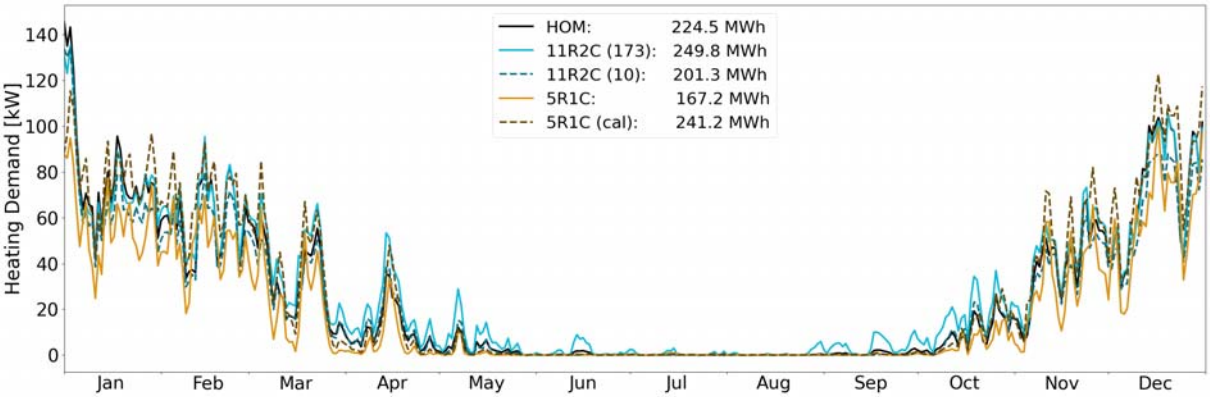

Figure 6: Trajectory of the heat demand of all five models based on daily averages and total heat demands

First, the thesis that an overdiscretized model tends to overestimate the demand is to be verified. For this purpose, the two 11R2C models are first examined in more detail. The MBE, which provides information about the sign of the deviations, already shows that the overestimation decreases over all months for the 10 zone model compared to the 173 zone model. Furthermore, the CV(RMSE) and the variance also decrease according to the boxplots for the 10 zone model.

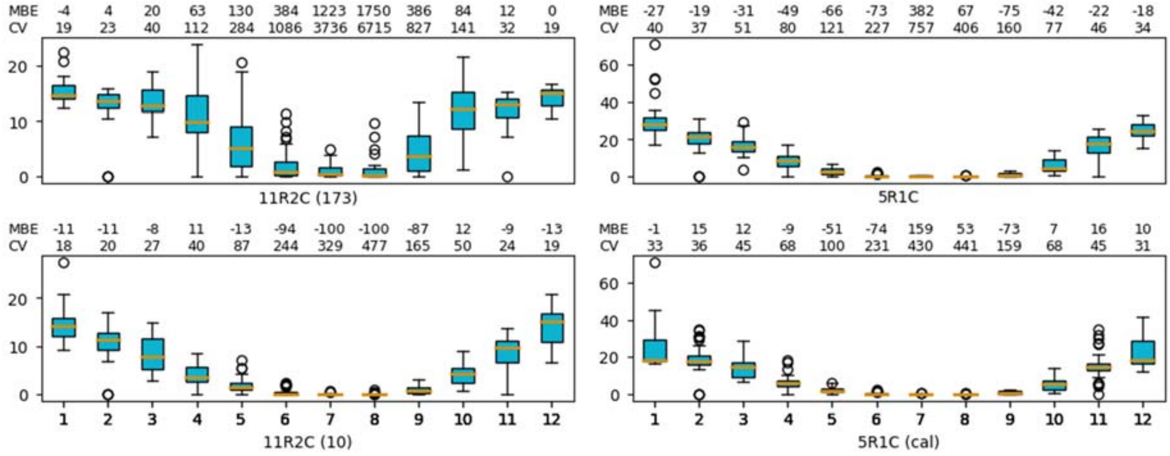

Figure 7: Box plot of the RMSE for the four reduced models including the MBE and CV(RMSE) for each month

This shows that the uncertainties and the dispersion are lower for the 10 zone model. The comparison of the results with the required maximum deviations shows that the 11R2C (10) model is within the specifications in most months. Only in the transition periods there is a slight violation of the MBE specification (max. 10 %) and in May a more pronounced violation of the CV(RMSE) specification (max. 30 %).Analysis of the two 5R1C models using the MBE shows that the uncalibrated model tends to underestimate needs, while the calibrated model tends to overestimate needs. The decreasing CV(RMSE) shows that the mean relative deviations are decreasing. However, the spread of the results remains relatively high. In comparison with the specifications, it can be seen that the calibrated 5R1C model can partially meet the MBE specification in half of the months of the heating period. However, the CV(RMSE) specification is exceeded in all months.

Table 2: Required times for modelling, parameterization and simulation

	HOM	**11R2C (173)**	**11R2C (10)**	**5R1C**
COLLECT DATA	+ +	+	-	--
MODELING	50 H	1 H	10 MIN	0
PARAMETERS	26 H	5 H	20 MIN	5 MIN
TOTAL	**76 H**	**6 H**	**30 MIN**	**5 MIN**
SIMULATION	**143 MIN**	**42 MIN**	**3.8 MIN**	**25 S**

After analyzing the accuracy of the results, the time required for modeling, parameterization, and simulation is compared in

Table 2. In addition, the simulation times are shown. It must be noted that the calibration effort for the 5R1C model is not included. The simulations were performed on a computer with 6x3.07 GHZ and 24 GB RAM. Cvode (Hindmarsh et al., 2005) was used as a solver for the Modelica simulations with step size of 3600 s. Accordingly, it is clear that the HOM requires an immense amount of work compared to the reduced modeling approaches, but in return provides a wealth of information for thermal demand analysis. However, this amount of information is not required for every application. The modeling and parameterization effort for the 173 zone variant of the 11R2C model is 92 % lower compared to the HOM but still requires 6 h as each room and its associated components must be modeled and parameterized. The 10 zone variant of the 11R2C model and the 5R1C mode both have very low creation times. Nevertheless, the 5R1C model is faster here, since no explicit modeling has to be performed, only parameterization. Regarding the simulation times the execution of the HOM simulation takes significantly longer, however, it is still acceptable for non-time-critical use cases. The 5R1C model outperforms the other models simulation time. Although the 11R2C (10) model with a simulation time of 3.8 min is also suitable for simulation studies and scenario analysis.

Discussion

After analyzing the results, we discuss the results and make a recommendation for the respective use cases of all models. As expected, all ROMs are significantly faster in modeling, parameterization and simulation than the HOM. The 5R1C model is by far the fastest model. Furthermore, it is confirmed that highly discretized zoning in ROM models is counterproductive and produces unnecessary effort. The 11R2C model (10) provides the best results in terms of variance and error KPIs, yet is very fast in terms of modeling and simulation. Considering the results, the approaches can be assigned to different use cases and planning phases in the construction process. The 5R1C model as most simplified approach partly provides acceptable results if calibrated and even the uncalibrated 5R1C model can qualitatively represent the dynamic behaviour of the heat load. However, calibration is necessary for an quantative observation. In particular, the ability to easily incorporate the model into other methods through direct implementation in *Python* is one of the biggest advantages of the model. This, along with the ease of linearization, makes the 5R1C model suitable for incorporation with optimization models. Furthermore, the speed of the model allows a large number of variants to be analyzed quickly and makes the model particularly interesting for use in the early planning phase, where the design of the building is still very open. Since the 11R2C variant with 10 zones performs better in every respect and is additionally faster to parameterize and simulate, there is no reason to create an 11R2C model that is highly discretized with respect to zoning. The 10 zone model performs very well and can meet ASHRAE 14 specifications in the heating period with a few minor exceptions. Because of its good combination of speed and accuracy, it is suitable for both the early planning stages and the slightly more advanced planning stages where system design comes to the fore. However, for very detailed analyses, especially at the room level, a HOM should be used. Due to its time-consuming parameterization, the HOM is primarily suitable for the late planning phase in the case of non-residential buildings, when the design of the building has already been largely determined. It can then be used to carry out precise analyses of, for example, thermal comfort and continue to provide important findings through operational information even after the building has been commissioned. In this case, the high effort is justified.

Summary and Outlook

In this paper, three modeling approaches and five different models were compared and recommendations were made for the use of each model. Core findings are that high-resolution zoning is counterproductive in reduced simulation approaches and that even highly simplified models, such as the 5R1C model, can be used to qualitatively consider different scenarios of a building. Furthermore, more accurate, but still reduced, models, such as the 11R2C represent a very good compromise between accuracy and effort. When comparing the time required for the different model variants, it was further shown that for most use cases it is not the simulation time but the model creation that is decisive.

The next step is to compare the results of the different simulation models with measurement results. This is possible in high-resolution form due to the extensive measurement technology of selected use case. The results of this comparison can provide further insights into the use of the respective simulation models.

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References

ASHRAE. ASHRAE 14: ASHRAE, 2014.

Association of German Engineers VDI 6007, 2015.

Brès A, Judex F, Wilde P, Suter G. Impact of zoning strategies for building performance simulation. In: 17th EG-ICE International Workshop: Nottingham; 2017.

D'Agostino D, Cuniberti B, Bertoldi P. Energy consumption and efficiency technology measures in European non-residential buildings. Energy and Buildings 2017.

Deutsches Institut für Normung e. V. DIN EN 12831, 2017.

Deutsches Institut für Normung e.V DIN V 18599, 2018.

Georgescu M, Eisenhower B, Mezic I. Creating zoning approximations to building energy models using the Koopman operator. IBPSA USA Sim Build, 2012.

German Institute for Standardization 13790: Beuth, 2008.

Global Alliance for Buildings and Construction. 2021 Global Status Report for Buildings and Construction, 2021.

Gräber M. Stationäre und dynamische Simulation, 2020. https://tlk-energy.de/blog/stationaere-und-dynamische-simulation (accessed March 20, 2022).

Hindmarsh AC, Brown PN, Grant KE, Lee SL, Serban R, Shumaker DE, et al. SUNDIALS: Suite of nonlinear and differential/algebraic equation solvers. ACM Transactions on Mathematical Software (TOMS) 2005;31(3).

Jansen DP, Richter VE, Cordoba Lopez D, Mehrfeld P, Frisch J, Müller D, et al. Examination of Reduced Order Building Models with Different Zoning Strategies to Simulate Larger Non-Residential Buildings Based on BIM as Single Source of Truth. In: Proceedings of 14th modelica conference 2021. Sweden, Linköping; 2021.

Müller D, Remmen P, Constantin A, Lauster MR, Fuchs M. AixLib - An Open-Source Modelica Library within the IEA-EBC Annex60 Framework. Fraunhofer IRB Verlag; 2016.

Nief A. Wirtschaftlichkeitsanalyse von Klimatisierungskonzepten und energieeffizienter Maßnahmen für Rechenzentren mittels Gebäude- und Anlagensimulation. Wien; 2017.

Østergård T, Jensen RL, Maagaard SE. A comparison of six metamodeling techniques applied to building performance simulations. Applied Energy 2018.

Østergård T, Jensen RL, Mikkelsen FS. The best way to perform building simulations? One-at-a-time optimization vs. Monte Carlo sampling. Energy and Buildings 2020.

Remmen P, Lauster M, Mans M, Fuchs M, Osterhage T, Müller D. TEASER: an open tool for urban energy modelling of building stocks. Journal of Building Performance Simulation 2018.

Schütz T, Schiffer L, Harb H, Fuchs M, Müller D. Optimal design of energy conversion units and envelopes for residential building retrofits using a comprehensive MILP model. Applied Energy 2017;185:1–15.

SchweizerischerIngenieur-und Architektenverein, SIA: Zürich, Switzerland. SIA 2024, 2015.

Shalabi F, Turkan Y. BIM–energy simulation approach for detecting building spaces with faults and problematic behavior. Journal of Information Technology in Construction 2020.

U.S. Department of Energy. M&V Guidelines: Measurement and Verification for Performance-Based Contracts Version 4.0; 2015. EERE Publication and Product Library, Washington, D.C. (United States).

Xanthopoulou K, Mehrfeld P, Kangowski P, Lanzerath F, Müller D. Validation of a building model as part of the AixLib Modelica library for dynamic plant and building performance simulations. Energy and Buildings 2021;250.