# Verification of a Low Order Building Model for the Modelica Library AixLib using ASHRAE Standard 140

Moritz Lauster, Ana Constantin,
Peter Remmen, Marcus Fuchs, Dirk Müller
RWTH Aachen University, E.ON Energy Research Center,
Institute for Energy Efficient Buildings and Indoor Climate, Aachen, Germany

## Abstract

Low order building models (LOM) implemented in state-of-the art modeling languages like Modelica allow for simulations with reduced computational effort but have a reduced dynamic behavior. The Modelica library AixLib includes a LOM for urban scale simulations. This paper verifies the LOM using the ASHRAE Standard 140 to evaluate the impact of the low order approach. The model is within the range of the standard except few outliers for free floating temperature test cases. The outliers are related to the reduced dynamics within the LOM and are in an acceptable range in the context of urban scale simulations focusing on heat load predictions.

## Introduction

Modelica is an advanced modeling language that allows for modeling of complex dynamic energy systems. It supports object-oriented modeling and simulation (OOMS) (Wetter et al., 2015; Bonvini, 2012), native equation-based definitions of physical systems and acausal connectors to allow bidirectional flow systems, e.g. heat transfer in walls. Several open-source and commercial simulation environments support Modelica (Modelica Association, 2016) and provide numerical solvers, including variable time steps, event handling and error handling.

Modelica is already used in multiple domains and has a growing community in building performance simulation (BPS). This is bundled in the IEA EBC Annex 60 project "New generation computational tools for building and community energy systems based on the Modelica and Functional Mockup Interface standards" (Wetter et al., 2015). One part of this project aims at harmonizing the use of Modelica for BPS by means of the Annex 60 library, available at https://github.com/iea-annex60/modelica-annex60. While this library serves as common core library with basic functionalities, several model libraries provide the user with additional models, further examples and documentation.

One of these libraries is AixLib (Müller et al., 2016), available at https://github.com/RWTH-EBC/AixLib. AixLib contains an urban building energy model (UBEM) for heat load predictions on an hourly scale. It extends the Annex 60 reduced order model and adds upstream models for windows, solar radiation, infiltration and internal gains.

This UBEM, a low order model (LOM), is based on a thermal network. A comprehensive discussion of such models can be found in Hensen and Lamberts (2011). The order of a model is determined by the number of capacities as they represent the number of state variables. Lumped parameter thermal network models merge several walls to representative accumulated wall elements. In this way, they require low parameterization and computational effort, which depends on the number of state variables. The price of these advantages is a lower precision regarding the dynamic model behavior. Still, these properties make LOM's a preferred choice for urban scale simulations (Nytsch-Geusen and Bartsch, 2001; Kämpf and Robinson, 2007; Robinson, 2011; Coninck et al., 2014; Kim et al., 2014; Lauster et al., 2014, 2015). A vast number of LOM's of various topologies has already been developed and lead to international and national standards (DIN EN ISO 13790, 2008; VDI 6007-1, 2012). Consequently, we made use of these works and implemented such a model in Modelica to use the power of modern numerics (event handling, variable time step, error handling). The presented AixLib LOM is based on the German Guideline VDI 6007-1 (2012), which describes a second order thermal network model. To the authors' knowledge no other up-to-date open-source implementation of this model is available. The AixLib LOM extends the original VDI 6007-1 model by allowing a variable number of accumulated wall elements. This enables scaling the order to the needs of a use case.

To ensure reliable results and evaluate the impact of the low order approach, thorough verification of a model is a necessary step in model development. For this purpose, this paper presents the verification of the AixLib LOM using the ASHRAE Standard 140 (2011), a standard for comparison of BPS models. The following chapters outline the topology and parameter calculations of the AixLib LOM, present the verification results and end in a conclusion discussing the applicability for UBEM.

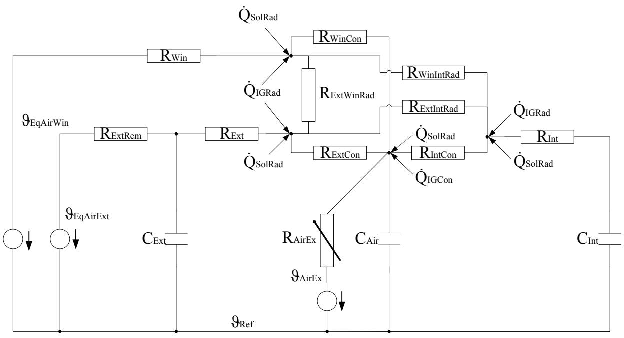


*Figure 1: Thermal network of AixLib LOM*

## AixLib Low Order Building Model

Thermal network models use the analogy to electrical circuits to describe heat transfer and storage through walls and within a room via circuits of resistances (R) and capacitances (C) (Figure 1). Using calculation methods for parallel and series connections of RC-links, it is possible to merge several walls to representative accumulated wall elements. In doing so, the thermal properties of the single wall elements are merged to representative values and the resulting accumulated element can only be excited as a whole. In this way, lumped parameter models have a reduced capability to resolve dynamic reactions if the excitation of the single wall elements vary between each other. Consequently, the appropriate number of accumulated wall elements depends on the use case and should be chosen carefully (Bacher and Madsen, 2011; Reynders et al., 2014). Still, for UBEM, inaccuracies in the system's dynamics seem to be acceptable given the high uncertainties of input data and the focus on the buildings' role in urban scale energy systems, so that a low number of wall elements is feasible. As the lower threshold, a minimum number of elements, resp. order of two is recommended in literature (Bacher and Madsen, 2011; Ramallo-González et al., 2013). In consideration of the aim to use standardized models, the second order model defined in the German Guideline VDI 6007-1 (2012) serves as the basis of the implemented AixLib LOM. The VDI 6007-1 merges wall elements into two different groups:

**Exterior walls** that take part on heat transfer to the outside or to rooms with differing temperatures.

**Interior walls** that can be considered as heat storages without any heat losses.

Both groups are modeled via RC-links with one capacitance for each group. This leads to a model order of two.

### Model Topology

Figure 1 shows the thermal network of the AixLib LOM. While exterior walls are modeled with an RCR-link ($R_{\mathrm{Ext}}$,$C_{\mathrm{Ext}}$ and $R_{\mathrm{ExtRem}}$) from indoor to the ambient, interior walls require only an RC-link ($R_{\mathrm{Int}}$ and $C_{\mathrm{Int}}$). Windows (usually regarded without thermal mass) are handled separately via $R_{\mathrm{Win}}$ as merging them with the highly capacitive exterior walls leads to a noticeable phase shift in heat transfer through windows (Lauster et al., 2014). Ambient excitation due to short- and long-wave radiation is combined with outdoor air temperature to one equivalent air temperature for walls $\vartheta_{\mathrm{EqAirExt}}$ (taking short-wave radiation into account) and one for windows $\vartheta_{\mathrm{EqAirWin}}$ (without short-wave radiation). Solar radiation through windows is handled similarly to internal gains as indoor heat source ($\dot{Q}_{\mathrm{SolRad}}$,$\dot{Q}_{\mathrm{IGRad}}$ and $\dot{Q}_{\mathrm{IGCon}}$). Indoor heat exchange is considered as being linear with constant coefficients and is divided into one radiant polygon network ($R_{\mathrm{ExtIntRad}}$, $R_{\mathrm{ExtWinRad}}$ and $R_{\mathrm{WinIntRad}}$) and one convective star network ($R_{\mathrm{ExtCon}}$, $R_{\mathrm{IntCon}}$ and $R_{\mathrm{WinCon}}$) connected to the indoor air $C_{\mathrm{Air}}$. Infiltration is handled via a controllable resistance $R_{\mathrm{AirEx}}$ and a temperature source $\vartheta_{\mathrm{AirEx}}$. All capacities and temperature sources in Figure 1 can be referenced to a virtual temperature $\vartheta_{\mathrm{Ref}}$ to have a closed circuit system.

The original VDI 6007-1 model is limited to this circuit topology and does not allow changing the model's order by distinguishing between more than these two accumulated wall elements. To overcome this limitation, the calculation core used in AixLib encompasses three different base models. Starting with the original VDI 6007-1 second order model, the third order model adds a further element, e.g. for ground floors and is in turn extended by the fourth order model adding another element, e.g. for roof tops. This flexible and scalable model structure is supported by Modelica's object-oriented approach that allows extending and reusing models.

### Model Parameterization

In addition to the topology of a thermal network model, the calculation of the lumped parameter is a fundamental design decision for LOMs. The number of RC-links per wall is similar to the number of cells for finite element methods (FEM) or computational fluid dynamics (CFD) and defines the spatial resolution. Similarly to FEM or CFD approaches, it is possible to define adapted meshes that use an inhomogeneous distribution of cells and focus on parts with higher dynamics. In particular for models with a reduced number of cells, this allows to capture the dominant dynamics of a system even with reduced computational efforts. For lumped parameter thermal network models, this translates into the question which part of the wall is relevant to represent the wall's dynamic behavior. The corresponding RC-link should only represent this active part of the wall that is similar to the effective thermal mass defined in Antonopoulos and Koronaki (1998). The second resistance for exterior walls $R_{\mathrm{ExtRem}}$ ensures that static heat transfer is modeled correctly by means of the U-value (Figure 2).

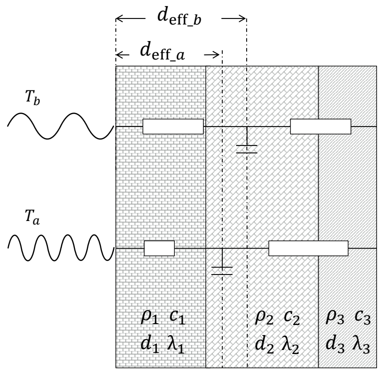


*Figure 2: Illustration of different effective thermal masses and distribution of thermal resistances and capacities*

The effective thermal mass, represented by the thickness of the effective part of a wall $d_{\text{eff}}$, is a function of the thermal properties (density $\rho$, heat capacity $c$ and conductivity $\lambda$ of each layer $n$ of a wall) and the wall's excitation by means of a design frequency or time constant $T$ (Figure 2):

$$d_{\text{eff}} = f\left(\rho_n, c_n, \lambda_n, d_n, T\right) \tag{1}$$

The design frequency describes the typical excitation of the wall. In consequence, when using the effective mass approach, the model's parameter are fitted to this typical excitation. Different approaches from rough estimation of the effective thermal mass (Annex A of DIN EN ISO 13786, 2008 assumes that 10 *cm* of the wall can be activated) or identifying the dominant layer (Ramallo-González et al., 2013) to data-driven optimization methods (Bacher and Madsen, 2011) exist. The VDI 6007-1 (2012) defines a calculation of the RC-link for the presented model. It is based on a comparison of the model's transfer matrix to a solution of Fourier's law of one-dimensional heat transfer for periodic boundary conditions (Rouvel, 1972). The VDI 6007-1 recommends a time constant of 5 *days* as design excitation frequency.

## Verification

To evaluate the inaccuracies regarding the model's dynamic behavior and to check the correct implementation of the VDI 6007-1 in Modelica, we chose to verify the AixLib LOM using the ASHRAE Standard 140 (2011). This verification can in addition give some indications about the applicability of the model for UBEM with regard to a comparison to established BPS software for single buildings. The ASHRAE Standard 140 is a standard test suite for the evaluation of building simulation programs (Nouidui et al., 2012; Henninger and Witte, 2014; Constantin et al., 2014). In this paper, we focus on "Building Thermal Envelope and Fabric Load Tests". This part of the standard provides 39 test cases, 13 Base Cases, four Free Float Cases and 22 so-called In-Depth Cases.

*Table 1: Test case overview*

| **Test case** | **Description** |
|---|---|
| 6XX | Low thermal mass |
| 9XX | High thermal mass |
| 600, 900 | Base Cases |
| 620, 920 | Window on east and west side |
| 640, 940 | Thermostat setback strategy |
| 650, 950 | Night ventilation |
| 600FF, 900FF | Free Float of 600,900 |
| 650FF, 950FF | Free Float of 650,950 |

The Base and Free Float Cases are used to test the ability of programs to model all relevant heat transfer phenomena, see Table 1. As the presented model cannot represent details like windows to be shaded from an overhang, we considered eight of the Base Cases within this paper. The In-Depth Cases present a diagnosis procedure by emphasizing on specific heat transfer mechanism, e.g. impact of transparent building elements, if certain Base Cases fail. For the verification, this paper focuses on the Base Cases and Free Float Cases that highlight all relevant phenomena.

The standard by intention focuses on a simple box-shaped room (Figure 3) and allows the user to gain insights in the differences of modeling approaches of specific phenomena such as heat storage and transfer. This qualifies the standard for a thorough verification that allows to judge where deviations originate from. The test room has five exterior walls (including the roof) exposed to the ambient and one interior wall (the floor is regarded as adiabatic on the outer surface). The building is 2.7 $m$ high, has a floor area of 48 $m^2$, the south and north wall have an area of 21.7 $m^2$ each and the west, resp. east wall of 16.2 $m^2$ each. Two windows, each six square meter large, are embedded in the wall facing south.

The ASHRAE Standard 140 provides eight reference results, obtained with standard BPS tools like DOE2 (Hirsch, 2014), TRNSYS (Klein, 2010) and ESP-r (ESP-r Development Team, 2011). All simulations are performed for one year with an output time step of one hour. According to the standard, the example simulation results in themselves do not represent a truth standard and the determination of whether or not results agree is left to the user (ASHRAE

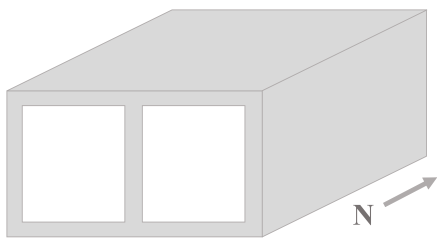


*Figure 3: Base definition of test room given in ASHRAE Standard 140 (2011)*

*Table 2: Overall and effective thermal mass of accumulated exterior wall element for low and high mass test cases in $J/K$*

| | Case 9XX | Case 6XX |
|---|---|---|
| Overall thermal mass | 10103951 | 1796537 |
| Effective thermal mass | 9149340 | 1002580 |
| Share effective/overall | 0.91 | 0.56 |

Standard 140, 2011). The verification in this paper is limited to the original second order model of the VDI 6007-1, leaving out the third and fourth order model, to focus on one model setup. The test room of ASHRAE Standard 140 comes with a set of thermally similar exterior walls (all excited by solar radiation and outdoor air temperature) and thermally similar interior walls. For model order comparison, this setup is quite limited and might not reveal the full impact of the model's order. We chose the second order model as the one with the lowest order for the verification. This model should have the worst dynamic behavior and thus is the one most likely to fail the ASHRAE verification.

### Thermal Parameters

To evaluate the impact of the effective mass approach, Table 2 gives an overview of the overall and effective mass of the accumulated exterior wall element for the high mass and low mass test cases.

The LOM calculates an effective thermal mass of 56% for the low mass case and 91% for the high mass case compared to the overall thermal mass. As the major heat storing layers are directed towards indoor, these values are reasonable and the capacities in the LOM represent the mass that can be activated under the given design conditions. If one would like to avoid the effective thermal mass approach, one could add a second RC-element between $C_{Ext}$ and $R_{ExtRem}$ (Figure 1) and consider the entire thermal mass. For the high mass case, this second capacity mass could in maximum represent 9 % of the overall thermal mass. For the low mass case, this value would rise to maximum 44 %. Still, these thermal masses are "hidden" behind the effective part of the wall and are not participating noticeably at heat storage related to indoor.

### ASHRAE 140 Test Cases

For each test case, the ASHRAE Standard 140 provides annual reference values of eight BPS tools. The results in this paper are presented as normalized to the median of the reference values. For each test case, the reference values are given as error bars with the minimum, maximum and median reference values out of the eight BPS tools. In this way, it is easy to evaluate if the range of reference values is violated and if the simulation results tend towards one of the boundaries. In addition to annual values, the standard encompasses time series for solar radiation, free float temperature and heating/cooling loads. The results

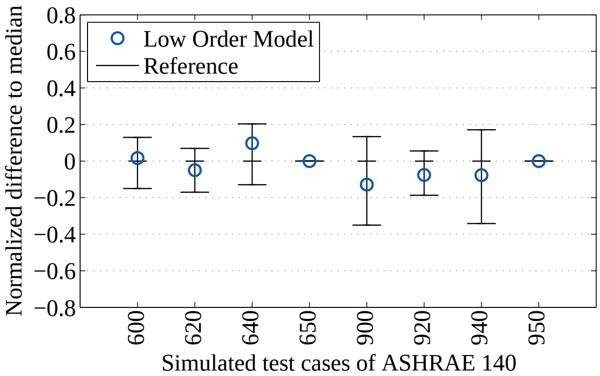


*Figure 4: Results of LOM and reference values for annual heating load*

are compared to the minimum/maximum of the reference results at each time step to evaluate if the two tested models are within the defined corridor.

The calculations of diffuse and direct solar radiation on tilted surfaces have been verified prior to the Base Cases and lie within the bounds of ASHRAE Standard 140. The results are not presented here to focus the discussion on the impact of low order modeling approaches.

#### *Annual Heating and Cooling Loads*

Figure 4 shows the annual heating loads for all considered eight Base Cases. The AixLib LOM is within the range of reference values for all cases while tending to underestimate the heat load compared to the median, in particular for high mass cases. Still, the median can only serve as orientation. The ASHRAE Standard 140 is a software to software comparative verification method so that no "true" reference value is given. For Base Cases 650 and 950, no heater is installed. Consequently, all values fall together on zero. However, to keep the eight-case-representation throughout all tests, we integrated the two test cases even for these tests. For the light-weight Base Case with night-setback (640), the LOM underestimates the impact of the thermal mass on the long term and calculates relatively high annual heat loads compared to all other test cases. This is a first indicator showing the LOM's property to be a lumped parameter model configured to a specific design frequency. Thus, for events with highly differing frequencies (e.g. fast transients) or variable excitations for each wall, the LOM introduces a certain deviation. Still, regarding annual heat loads, this effect seems to be acceptable. The main driving factor of heat loads is typically outdoor air temperature, which is the same for all exterior walls.

Figure 5 gives the annual cooling loads for all eight Base Cases. The LOM is within all bounds and shows the same behavior for all test cases. It tends to be near the median for low mass cases (6XX) and between the median and the minimum reference value for high mass cases (9XX). For the high mass Base

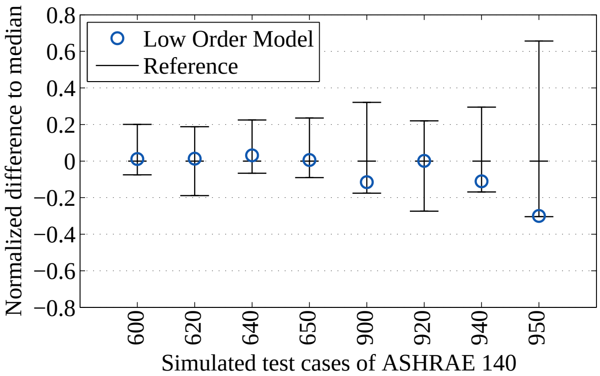


*Figure 5: Results of LOM and reference values for annual cooling load*

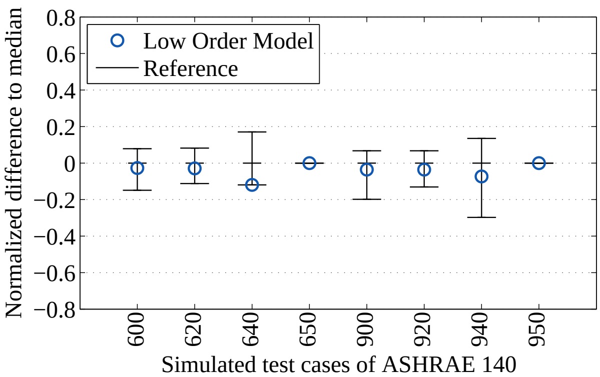


*Figure 6: Results of LOM and reference values for peak heating load*

Case with night ventilation (950), which can also be classified as a situation with fast transients, it falls together with the minimum reference value, but still is within the bounds. This is again related to the design frequency and lumped parameter approach of the LOM. Cooling loads are typically determined by solar radiation and internal gains. These inputs typically have a higher characteristic frequency than outdoor air temperature (Ramallo-González et al., 2013). As the design frequency according to VDI 6007-1 is meant to represent general excitation, it tries to find a balance between both worlds. In addition, solar radiation excites walls with different orientation one after the other following the path of the sun. For a lumped parameter model, these excitations are merged to excite the accumulated wall element as a whole. This results in a reduced resolution of the system's dynamics. To achieve a finer resolution of short-term effects, one could change the design frequency (and accept a different behavior in heating cases) or add further accumulated wall elements, e.g. one for each orientation. Translated to acoustics, this would mean to use two speakers instead of one to play two different songs at the same time. However, as the LOM is within the range for all annual cooling load tests, there is no reason to do so based on these tests.

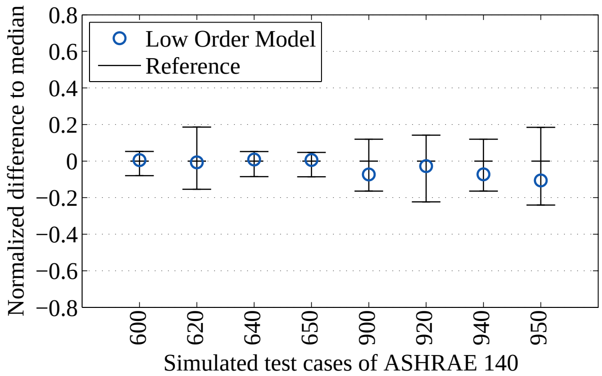


*Figure 7: Results of LOM and reference values for peak cooling load*

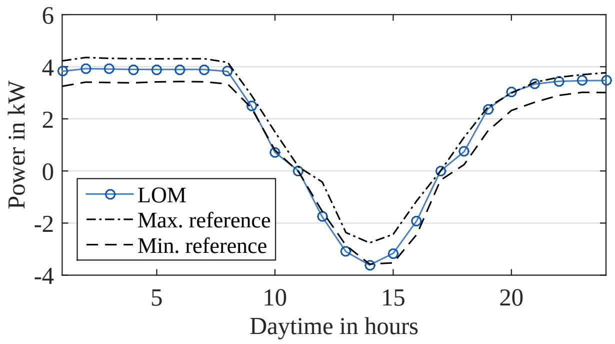


*Figure 8: Time series of heating/cooling power for January 4th, Test Case 600*

*Peak Heating and Cooling Loads*

In addition to the annual values, the ASHRAE Standard 140 provides peak heating loads of that year, given in Figure 6. The peak loads are mean hourly values to unify different time steps within different simulation engines. The LOM is again within the range of reference values for all tests cases and tends to be near the median value. This again indicates that the design frequency and the second order approach meet the characteristics of heating cases quite well. Base Cases 650 and 950 are again set to zero as no heater is installed.

The peak cooling loads show a similar behavior like the peak heating loads (Figure 7). The LOM is within the range for all test cases, tending to the median for low mass cases (6XX) and between median and lower bound for high mass cases (9XX) as discussed for Figure 5.

To analyze the dynamic behavior of a model in detail, the ASHRAE Standard 140 provides time series for a reference day for low and high mass test cases, see Figures 8 and 9. The LOM is well within the range of reference values except between 12:00 and 14:00 for the low mass case (600) in Figure 8, where it violates the lower bound. An analysis of the upstream window model revealed slight overestimations of incidence angle dependent solar gains compared to other tools. Still, this seems acceptable for urban scale ap-

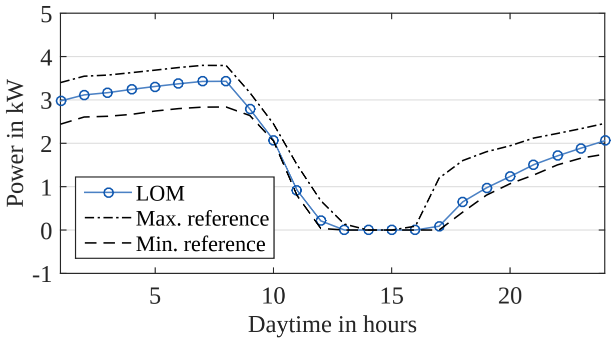


*Figure 9: Time series of heating/cooling power for January 4th, Test Case 900*

*Table 3: Occurrence of peak heating loads*

| Test Case | LOM | Match |
|---|---|---|
| 600 | 04-Jan 02:00 | No(ESP - 3h) |
| 620 | 04-Jan 02:00 | No (ESP - 4h) |
| 640 | 04-Jan 08:00 | No (ESP + 1h) |
| 900 | 04-Jan 08:00 | No (ESP + 1h) |
| 920 | 04-Jan 07:00 | Yes (ESP) |
| 940 | 04-Jan 08:00 | No (ESP + 1h) |

plications with high uncertainties in input data and focus on the general buildings' behavior.

To analyze the occurrence of peak values within the investigated year, the ASHRAE Standard 140 provides time stamps of all peak values. Table 3 gives the time stamps of the LOM for peak heating loads and compares if it matches the occurrence of one of the reference values. Deviations of 1 $h$ are considered not critical, as they can depend on the method each tool uses in calculating the integral over an hour. The deviations for the LOM for Test Cases 600 and 620 are 3 $h$, respectively 4 $h$. However it is important to mention that although the minimal air temperature is reached at 2:00 in both cases, it remains nearly constant until 5:00-6:00, which is the occurrence time for ESP-r.

For the cooling peak loads (Table 4) the results for the LOM match the results from TRNSYS, with the sole exception of Test Case 650, where a deviation of almost one day is recorded. However, both days, October 16th and 17th, have very similar load profiles

*Table 4: Occurrence of peak cooling loads*

| Test Case | LOM | Match |
|---|---|---|
| 600 | 16-Oct 14:00 | Yes (TRNSYS) |
| 620 | 26-Jul 17:00 | Yes (TRNSYS) |
| 640 | 16-Oct 14:00 | Yes (TRNSYS) |
| 650 | 16-Oct 14:00 | No (ESP + 23h) |
| 900 | 17-Oct 15:00 | Yes (TRNSYS) |
| 920 | 26-Jul 17:00 | Yes (TRNSYS) |
| 940 | 17-Oct 15:00 | Yes (TRNSYS) |
| 950 | 02-Sep 15:00 | Yes (TRNSYS) |

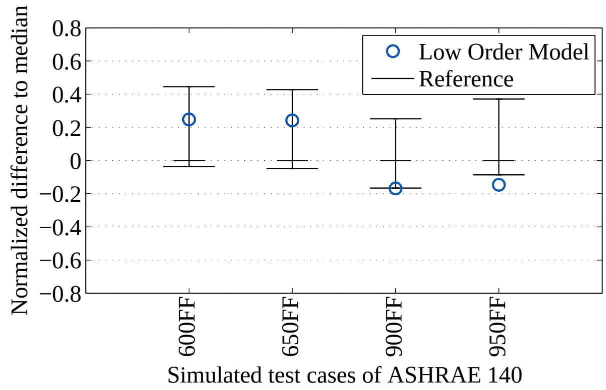


*Figure 10: Maximum free float temperatures*

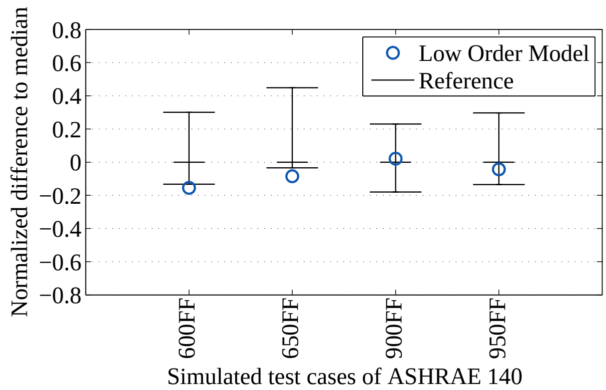


*Figure 11: Minimum free float temperatures*

and close maxima for the cooling loads.

*Free Float Cases*

In addition to the Base Cases that focus on thermal loads, four Free Float Cases investigate the differences of free floating temperatures without heating or cooling equipment. The ASHRAE Standard 140 provides minimum, maximum and mean free float temperatures for all four test cases. This paper presents only the maximum (Figure 10) and minimum (Figure 11) free float temperatures as the mean temperatures replicate their behavior and provide no further insights.

While the LOM is within the ranges for thermal load calculations, it fails for Test Case 950FF regarding maximum temperature (with 900FF being just within the boundaries) and for Test Case 600FF and 650FF regarding minimum temperatures. In all three cases, the LOM predicts too low temperatures. This allows the conclusion that in high mass cases temperature excitations are damped too strongly while in low mass cases the temperatures overshoot. The overshoot leads to high maximum temperatures compared to the median and off minimum temperatures. Still, all test cases are close to the boundaries with less than 5 % off. In the context of UBEM, these deviations of extreme values for indoor air temperatures seem acceptable. A detailed analysis of this behavior is given in the discussion of the exemplary free float

*Table 5: Occurrence of maximum free float temperature*

| Test Case | LOM | Match |
|---|---|---|
| 600FF | 17-Oct 16:00 | Yes (TRNSYS) |
| 650FF | 17-Oct 16:00 | Yes (TRNSYS) |
| 900FF | 17-Oct 16:00 | No (TRNSYS + 1h) |
| 950FF | 02-Sept 16:00 | Yes (DOE2) |

*Table 6: Occurrence of minimum free float temperature*

| Test Case | LOM | Match |
|---|---|---|
| 600FF | 04-Jan 08:00 | Yes (DOE2) |
| 650FF | 04-Jan 02:00 | Yes (DOE2) |
| 900FF | 04-Jan 08:00 | Yes (DOE2) |
| 950FF | 04-Jan 07:00 | Yes (DOE2) |

days, Figures 12-15.

As mentioned before and visible in Tables 5 and 6, the lumped parameter low order approach introduces no relevant time shift. For all Free Float Cases, the occurrences of minimum and maximum temperatures match one reference value. The only exception is for maximum temperature of Test Case 900FF with being one hour off in times with nearly steady state behavior.

The time series for two exemplary days of two test cases each in Figures 12-15 reveal the same behavior as discussed for Figures 10 and 11. While the LOM for light-weight test cases fluctuates and overshoots from the lower bound in cold times to the upper bound in hot times, it shows the contrary damped behavior for heavy-weight test cases. For Test Case 950FF, a heavy test case with fast transients (night ventilation is turned on and off), the RC-links represent a design frequency that is too low to predict the reaction to an occurrence of fast excitation. In addition, the lumped parameter approach limits the ability to resolve the varying dynamic behavior of all single walls. The reduced order model predicts a reaction to situations with fast or distributed transients that is too smooth compared to the other BPS tools. As shown in Table 5, this affects only the amplitude of events, a phase shift is not introduced. Similar observations as for Test Case 950FF can be made for Test Case 600FF and 650FF. Here, the reaction of the light-weight room is too excessive and temperatures overshoot. These observations pick up the observations and discussion for Figure 5. Adding further RC-links in series to the wall models is a further approach to achieve a higher resolution of dynamic effects. It allows considering further, higher frequencies in addition to the first chosen design frequency. This leads to a finer resolution of short-term effects, e.g. heat storage in the first layer towards the room. Each RC-link is analogue to a low-pass in electrical science, filtering high frequencies while frequencies lower than

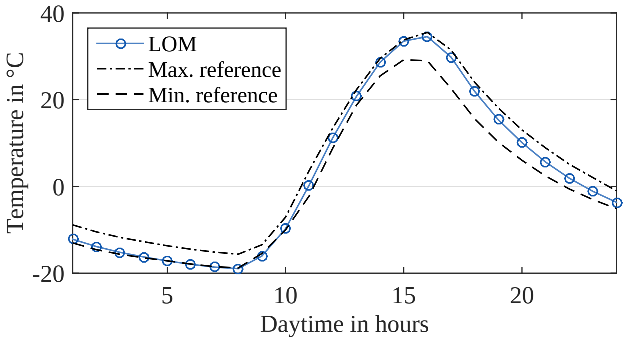


*Figure 12: Time series of free float temperatures for January 4th, Test Case 600FF*

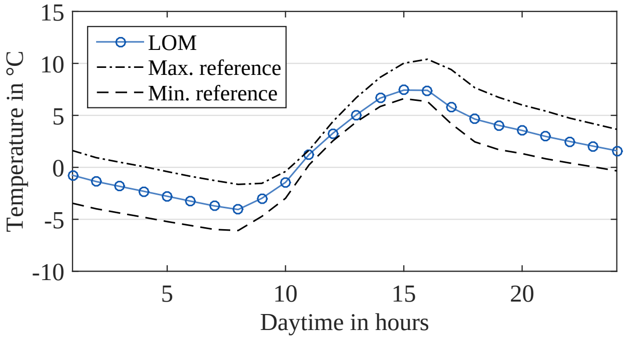


*Figure 13: Time series of free float temperatures for January 4th, Test Case 900FF*

the design frequency can pass. Adding a second RC-link with a higher design frequency between indoor and the first RC-link introduces an element that focuses on frequencies on a higher level. In the figurative sense, this is like dividing a full-range speaker into sub woofer and tweater.

In conclusion, the LOM overestimates the damping effect of thermal mass for high mass cases and underestimates the effect for low mass cases for the given physical properties of the room, the model's order of two and the chosen design frequency. As for all other tests, the impact of these inaccuracies is fairly small with Test Case 600FF being off less than 0.5 $K$ at 9:00 and Test Case 900FF being as well off less than 0.5 $K$ from 10:00 to 18:00.

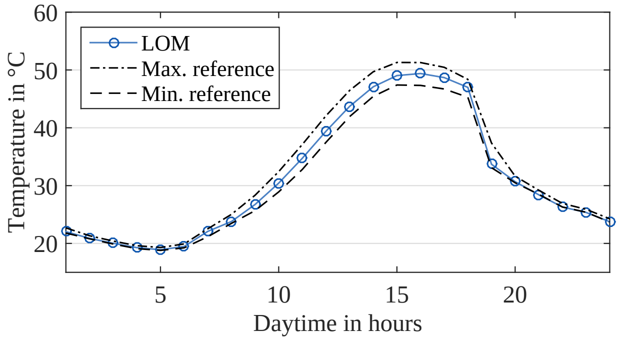


*Figure 14: Time series of free float temperatures for July 27th, Test Case 650FF*

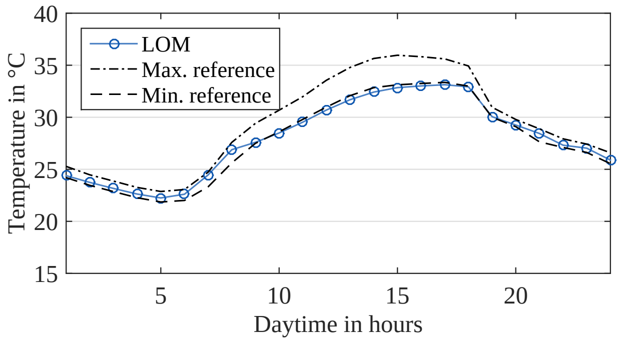


*Figure 15: Time series of free float temperatures for July 27th, Test Case 950FF*

## Limitations

The limited complexity of the ASHRAE Standard 140 test cases with regard to geometry and boundary conditions is a strength and a weakness at the same time. While the focus on simplicity allows in-depth analysis of differences and to identify fundamental properties of models, drawing conclusions for more complex applications is difficult. A higher number of varying wall elements with regard to thermal properties and boundary conditions with a wider range of frequencies might impose a different dynamic behavior. Low order models with their limited ability to distinguish dynamics of different time scales and affected wall elements might underestimate such influences. Thus, this verification can only prove the applicability of Low Order Models for simple dynamic situations.

Based on the verification results and the general model properties, the LOM shows some limitations:

**Merging walls** leads to radiant heat exchange only between the accumulated wall elements but not for different orientations. As a result, the model is not suited for in-depth analyses of complex geometries.

**Reduced dynamic behavior,** in particular in situations with fast transients.

**Room temperatures,** in particular minimum and maximum values, might be under- or overestimated to a degree outside of the verification bounds.

**Specific building constructions** that lead to extremely light- or heavy-weight buildings increase the effects of under- and overestimation.

**Excitation frequencies** for effects with major impact that are deviating from typical frequencies, e.g. daily, require an adaption of the design frequency.

Still, whether these limitations prohibit the use the LOM highly depends on the use case. For UBEM, the information density is low and computations need to be fast for the single buildings. In this case, the strengths of the LOM can outweigh its limitations.

## Conclusion

This paper verifies a second order thermal network model based on an effective mass approach using the ASHRAE Standard 140. Such models are of particular interest in domains like urban building energy modeling with high requirements regarding computational efficiency. The model is implemented in Modelica, part of the open-source Modelica library AixLib (`https://github.com/RWTH-EBC/AixLib`) and named low order model (LOM). It is based on the German Guideline VDI 6007-1 (2012), which condenses the vast amount of previous works and models to a national standard. To the authors' knowledge no other up-to-date open-source implementation of this model is available. To ensure reliable results and evaluate the impact of the low order approach, thorough verification of a model is a necessary step in model development.

The LOM is within the range of reference results for most test cases and close to the bounds for a few outliers. All outliers are within 5 % deviation from the nearest bound. Still, different conclusions can be drawn from the set of test cases. While the LOM successfully passed all tests regarding annual and peak heating and cooling loads, its results tend to the lower bounds, in particular for cases with fast transients like night ventilation. This tendency becomes even more visible for free float test cases, where its results lies outside the bounds for maximum and minimum indoor temperatures. For low mass cases, the LOM tends to predict too high fluctuations in indoor temperature and tends to underestimate the impact of the thermal mass. This effect is inversed for high mass cases, where the temperature shows a damped behavior compared to the reference results and the effect of thermal mass seems to be overestimated. This behavior gets worse if fast transients appear.

All these observations can be explained by the reduced dynamic behavior of the model. By utilizing the effective mass approach, which initially allows the reduction to an order of two, the LOM deviates for a short time after highly dynamic events. The LOM is configured to a specific design frequency and shows deviations if the actual excitation differs greatly from that. Furthermore, by merging all wall elements to two accumulated elements, the model can only consider two different excitations, for exterior and interior walls. This leads to an additional smearing of the detailed dynamic behavior. Besides adding further wall elements, adding RC-links in series to the existing wall elements and changing the design frequency are possible options to modify and improve the model's dynamic behavior. If high precision in highly dynamic situations is necessary, the focus is on precise room temperatures, the room is extremely light- or heavy-weight or the different wall elements are excited differently, one should consider a model with a higher order than two and use optimal design frequencies. Still, low order models are a valuable option in applications where computational effort and simulation times outweigh ultimate dynamic accuracy. In particular for urban building energy modeling, aiming in our case at heat load prediction on an hourly scale, the accuracy of annual heat loads and peak heat loads is the main focus. In addition, urban scale simulations often face high uncertainties in input data that outweigh model uncertainties. Even for cooling loads, the LOM is a suitable option based on the ASHRAE verification.

## Acknowledgment

We gratefully acknowledge the financial support by BMWi (German Federal Ministry of Economic Affairs and Energy), promotional reference 03ET1410B.
This work emerged from the Annex 60 project, an international project conducted under the umbrella of the International Energy Agency (IEA) within the Energy in Buildings and Communities (EBC) Programme. Annex 60 will develop and demonstrate new generation computational tools for building and community energy systems based on Modelica, Functional Mockup Interface and BIM standards.

## References

Antonopoulos, K. A. and E. Koronaki (1998). Apparent and effective thermal capacitance of buildings. *Energy 23*(3), 183–192.

ASHRAE Standard 140 (2011). Standard method of test for the evaluation of building energy analysis computer programs.

Bacher, P. and H. Madsen (2011). Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings 43*(7), 1511–1522.

Bonvini, M. (2012). *Efficient Modelling and Simulation Techniques for Energy-related System-level Studies in Buildings: Doctoral Dissertation.* Milano: Politecnico di Milano.

Coninck, R. D., F. Magnusson, J. Akesson, and L. Helsen (2014). Grey-box building models for model order reduction and control. In *Proceedings of the 10th International Modelica Conference*, pp. 657–666.

Constantin, A., R. Streblow, and D. Müller (2014). The Modelica HouseModels library: Presentation and evaluation of a room model with the ASHRAE Standard 140. In *Proceedings of the 10th International Modelica Conference*, pp. 293–299.

DIN EN ISO 13786 (2008). Thermal performance of building components - dynamic thermal characteristics - calculation methods.

DIN EN ISO 13790 (2008). Energy performance of buildings - calculation of energy use for space heating and cooling.

ESP-r Development Team (2011). Esp-r.

Henninger, R. H. and M. J. Witte (2014). Energyplus testing with building thermal envelope and fabric load tests from ansi/ashrae standard 140-2011.

Hensen, J. and R. Lamberts (2011). *Building performance simulation for design and operation.* Abingdon, Oxon and New York, NY: Spon Press.

Hirsch, J. J. (2014). Doe-2: Building energy use and cost analysis tool.

Kämpf, J. H. and D. Robinson (2007). A simplified thermal model to support analysis of urban resource flows. *Energy and Buildings 39*(4), 445–453.

Kim, E.-J., G. Plessis, J.-L. Hubert, and J.-J. Roux (2014). Urban energy simulation: Simplification and reduction of building envelope models. *Energy and Buildings 84*, 193–202.

Klein, S. A. (2010). Trnsys 17: A transient system simulation program.

Lauster, M., M.-A. Brüntjen, H. Leppmann, M. Fuchs, J. Teichmann, R. Streblow, C. van Treeck, and D. Müller (2014). Improving a low order building model for urban scale applications. In *Proceedings of BauSIM 2014*, pp. 511–518.

Lauster, M., M. Fuchs, M. Huber, P. Remmen, R. Streblow, and D. Müller (2015). Adaptive thermal building models and methods for scalable simulations of multiple buildings using Modelica. In *Proceedings of the 14th International IBPSA Building Simulation Conference*, pp. 339–346.

Lauster, M., J. Teichmann, M. Fuchs, R. Streblow, and D. Müller (2014). Low order thermal network models for dynamic simulations of buildings on city district scale. *Building and Environment 73*, 223–231.

Modelica Association (05.05.2016). Modelica tools.

Müller, D., M. Lauster, A. Constantin, M. Fuchs, and P. Remmen (2016). AixLib - an open-source Modelica library within the IEA-EBC Annex 60 framework. In *Proceedings of BauSIM 2016*, pp. 3–9.

Nouidui, T. S., K. Phalak, W. Zuo, and M. Wetter (2012). Validation and application of the room model of the modelica buildings library. In *Proceedings of the 9th International Modelica Conference*, pp. 727–736.

Nytsch-Geusen, C. and G. Bartsch (2001). An object oriented multizone thermal building model based on the simulation environment Smile. In *Proceedings of the 7th International IBPSA Building Simulation Conference*, pp. 411–418.

Ramallo-González, A. P., M. E. Eames, and D. A. Coley (2013). Lumped parameter models for building thermal modelling: An analytic approach to simplifying complex multi-layered constructions. *Energy and Buildings 60*, 174–184.

Reynders, G., J. Diriken, and D. Saelens (2014). Quality of grey-box models and identified parameters as function of the accuracy of input and observation signals. *Energy and Buildings 82*, 263–274.

Robinson, D. (Ed.) (2011). *Computer modelling for sustainable urban design: Physical principles, methods and applications* (1. publ ed.). London u.a: Earthscan.

Rouvel, L. (1972). Berechnung des wärmetechnischen Verhaltens von Räumen bei dynamischen Wärmelasten. *Brennstoff-Wärme-Kraft 24*(6), 245–262.

VDI 6007-1 (2012). Calculation of transient thermal response of rooms and buildings - modelling of rooms.

Wetter, M., M. Fuchs, P. Grozman, L. Helsen, F. Jorissen, M. Lauster, D. Müller, C. Nytsch-Geusen, D. Picard, P. Sahlin, and M. Thorade (2015). IEA EBC Annex 60 Modelica library - an international collaboration to develeop a free open-source model library for buildings and community energy systems. In *Proceedings of the 14th International IBPSA Building Simulation Conference*, pp. 395–402.