IMPROVING A LOW ORDER BUILDING MODEL FOR URBAN SCALE APPLICATIONS

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ABSTRACT

Low Order Models (LOM) for thermal building simulations on urban scale exist in parallel to extensively used Higher Order Models (HOM) for thermal simulations of single buildings. However, a comparison of a HOM in IDA-ICE and a LOM in Dymola revealed optimization potential regarding heat conduction through windows and indoor radiation exchange for the LOM. Two test cases proved a phase shift in heat load prediction for a LOM based on the guideline VDI 6007. Therefore, we implemented further resistances which lead to slightly increased calculation time. Nevertheless, this improved model is well balanced regarding computational effort and simulation accuracy.

Vereinfachte Modelle niederer Ordnung für thermische Simulationen von ganzen Stadtteilen existieren parallel zu Modellen höherer Ordnung, die vor allem auf Gebäudeebene zum Einsatz kommen. Ein Vergleich von Wärmebedarfssimulationen eines komplexen Modells in IDA-ICE und eines vereinfachten Ansatzes in Dymola offenbart Verbesserungspotential bezüglich der Wärmeleitung durch Fenster und dem Strahlungsaustausch im Innenraum. In zwei Testfällen zeigt sich unter anderem eine Phasenverschiebung für ein Modell niederer Ordnung basierend auf der VDI 6007. Diese Verschiebung kann durch die Einführung zusätzlicher thermischer Widerstände behoben werden, was allerdings zu leicht erhöhten Rechenzeiten führt. Nichtsdestotrotz stellt das entwickelte Modell eine gute Balance zwischen Rechenaufwand und Genauigkeit dar.

INTRODUCTION

Thermal simulations on urban scale allow detailed investigations of interactions within an energy system and can support holistic optimizations of district energy systems. They aim at analyzing and efficiently directing energy flows between different subsystems like generation units, storages and buildings. To investigate such interactions, dynamic simulations at variable time step seem more promising than static and quasi-static calculations. Thus, a growing community is developing model libraries on building and urban scale (Wetter and van Treeck, Müller and Hosseini Badakhshani 2010, Nytsch-Geusen et al. 2012, Wetter et al. 2011) This evolution led to software tools that exist in parallel to established simulations of single buildings. The approaches on building and urban scale mainly differ in balancing simulation efforts and accuracy. In particular, modelling of heat transfer and storage effects in the buildings' thermal masses is a crucial factor. Thermal network models are a common way to describe such phenomena, because they can be balanced regarding simulation efforts and accuracy depending on the particular problem. They are based on analogies to electrical problems and describe heat transfer and storage via circuits of heat resistances and capacitances. The number of elements defines the spatial resolution, complexity, accuracy and order of the network model. Simulations on building scale are able to use numerical challenging higher order models, a comprehensive discussion of this topic can be found in (Hensen and Lamberts 2011, Clarke 2001, van Treeck 2010). Models on urban scale commonly use a low order approach and accept a loss of spatial resolution while requiring comparably low parameterization and computational efforts (Robinson 2011, Kämpf and Robinson 2007) In consequence, we examined a gap between modelling techniques for applications on urban and building scale. A detailed comparison of higher and low order models provides more insights into modelling approaches in conjunction with calculation times. It reveals modelling differences and helps identifying an optimal balance between simulation efforts and accuracy for low order models on urban scale.

In this paper we investigate two common building models and identify optimization potential for low order model usage in urban scale simulations. The first part of the paper discusses the theory behind the models, reveals sub-models with different approaches and identifies the potential for improving a low order model. In the second part, we set up test cases to reveal the impact of differing modelling assumptions. The third part of the paper presents the results of the test cases and investigates optimization potential. Finally, we analyze the overall impact and calculation times of the implemented modifications and propose an improved low order model.

METHODOLOGY

Comparison

The examined models have been implemented in Dymola (low order models) and IDA-ICE (reference model). The theoretical discussion in this chapter allows the disclosure of deficiencies pertaining to the Low Order Model. With this knowledge at hand, improvements can be derived and new Low Order Models can be proposed. One criterion in our model comparison are heating and cooling energy consumptions per year. As simulating total energy consumption per year is only one part of our goal, the dynamic behavior of heating and cooling power is analyzed as well. The resulting time series are compared using the root-mean-square error RMSE and the coefficient of determination R^2. These values in addition with calculation time are used to identify an optimal balance between accuracy and simulation efforts.

Reference Model

The building performance simulation software IDA ICE 4 gives the opportunity to study the indoor climate and energy consumptions of entire buildings. IDA-ICE provides two zone models that differ in depth of modeling for different simulation tasks. The model "CeDetZon" is used for indoor climate simulation tasks while the "CeSimZon"-model is developed for energy consumption calculations (Bring et al. 2000). In contrast to "CeDetZon", "CeSimZon" works with a lower spatial resolution and thus needs lower computational effort. It has been successfully validated using the standard ASHRAE 140 (Equa Simulation AB 2010).

For the comparison in this paper, we use the "CeSimZon"-model as the focus is on building energy performance calculations. This reference model "CeSimZon" is based on two internal capacitances, one for the air load and one for internal masses like internal walls or furniture. Internal walls are handled as adiabatic, and thus do not contribute to heat losses (Figure 1). Their thermal masses can be activated as thermal storage to up to fifty percent of their overall mass. Walls that are connected to the outside are handled separately in modular sub-models. The standard wall model in IDA ICE 4 is the "BDFWall"-model. In contrast to a finite difference model, it has been numerically optimized by introducing an adapted integration method. A FORTRAN subroutine has been implemented that allows using the Backward Euler-Method or the Midpoint-Method. These integration methods are implicit integration methods and support high numerical stability.

The "CeSimZon"-model uses two energy balances to calculate the indoor air temperature and the mean radiant temperature. These two equations are connected via heat balances for the zones' surfaces.

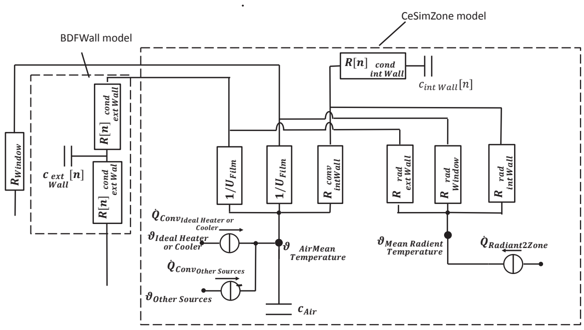

Figure 1: Reference Model

Dominant terms in the calculation of the indoor air temperature are convective heat fluxes from internal sources like wall surfaces, heating and cooling devices and enthalpy fluxes caused by air exchange. Coefficients of heat transfer can be calculated with various models of different level of detail. Starting with constant values, IDA-ICE comes with an external FORTRAN subroutine "U_Film" calculating for instance detailed natural convection. These algorithms consider the temperature difference between surface and air, the slope of the surface and the hourly air exchange rate for calculating the heat transfer coefficient (Bring et al. 2000).

In the calculation of the mean radiant temperature, heat fluxes originate from heating and cooling devices, wall surfaces and lighting. Direct, diffuse and reflected diffuse shortwave radiation are absorbed or reflected at the wall surfaces.

Low Order Model I

In this study, we implemented a second order model based on the German Guideline VDI 6007 (German Association of Engineers 2012) as seen in Figure 2 in Modelica using the simulation environment Dymola. The model divides the building mass into two capacitances representing all internal and external building elements respectively. The heat transfer through the outer wall, including windows, is described by two resistances while another resistance is used to damp the adiabatic inner wall capacitance.

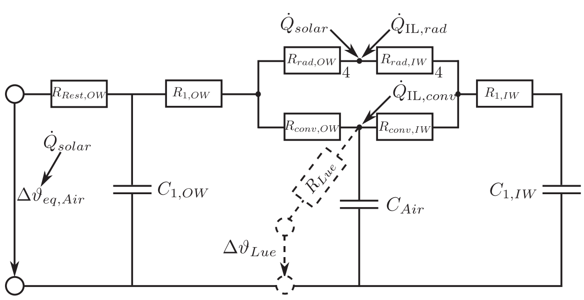

Figure 2: Low Order Model I

The indoor heat exchange between the walls and the air node can be calculated in different ways. While the VDI 6007 defines a combined coefficient of heat transfer, we distinguish between radiative and convective heat transfer. Outdoor radiation sources like solar radiation on walls are considered via an adapted equivalent outdoor air temperature $\vartheta_{eq,Air}$ (Lauster et al. 2014a). Solar radiation through transparent elements is handled as heat flux on the indoor radiation node, similar to radiative internal gains.

Capacities in low order models (LOM) can be calculated with the Beuken model defined in VDI 6007 and ISO 13786 (Deutsches Institut für Normung e.V. 2008). They highly depend on the thermal mass that can be activated. Thus, this mass depends on the thickness of the wall that can be used to store heat (periodic depth of penetration). The depth is described by a time period T that corresponds to the periodical loading behavior. This time period thus highly influences the model's dynamic behavior and should be chosen carefully. The ISO 13786 defines a range of values depending on the application. The VDI 6007 specifies a time period of five days, we kept this value to comply with the guideline's specifications (Lauster et al. 2013a). Capacities in higher order models commonly reflect a fixed thermal mass, thus they do not use the time period as an input.

While we kept most parts of the theory and model description given in VDI 6007, we did not follow the given analytical equations. We rather took advantage of Modelica's abilities to formulate acausal equations in an object-oriented structure. We defined a sub-model for each element in Figure 2, describing either heat transfer phenomena (resistance) or storage effects (capacitance). A detailed description and validation can be found in (Lauster et al. 2014b). This model has already been extensively used in city district applications. It is mainly applied in heat load predictions for dynamic investigations of district heating systems (Lauster et al. 2013b, Fuchs et al. 2013), optimal design of energy supply units (Harb et al. 2014a) and analyses of energy management systems (Harb et al. 2014b). Such problems are commonly tackled on city district scale and illustrate the advantages of fast and easy-to-use low order building models. Although Low Order Model I showed sufficient performance in these use cases, we identified optimization potential that motivated the study presented in this paper.

Low Order Model II

Low Order Model II bases on LOM I but addresses problems regarding heat conduction through windows. The thermal resistance of windows in Low Order Model I is included in the thermal resistance of the combined outer wall. Thus, heat conducted through windows has to pass through the thermal capacitance of the combined outer wall. Commonly, the thermal capacity of windows is expected to be negligible. In order to reproduce this effect, outer walls and windows have to be modelled separately as seen in Figure 3.

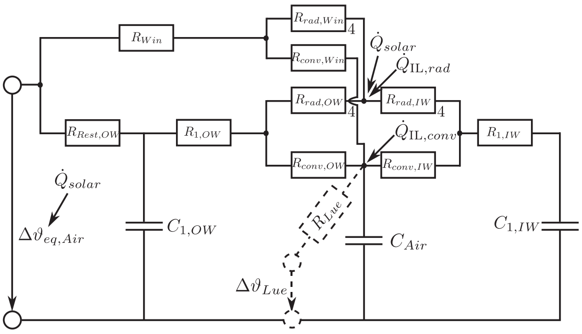

Figure 3: Low Order Model II

One resistance for the windows themselves and two resistances for modelling convective and radiative heat transfer at the inner surface of the combined windows are added (Leppmann 2014). The resistances of the combined outer wall are then calculated without the windows.

Low Order Model III

When considering solar radiation, two aspects of Low Order Model II are troublesome. The first aspect concerns the long wave radiation node inside the building. As the short wave radiation transmitted through the windows is directly connected to the long wave radiation node, a long-wave radiation exchange between outer walls, inner walls and windows is not possible. Furthermore, a disproportionate amount of solar radiation may leave the building through heat conduction of the window. This is solved by explicitly separating long and short-wave radiation.

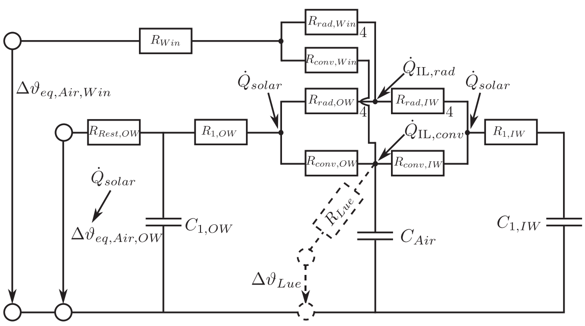

Figure 4: Low Order Model III

The second aspect concerns the equivalent outdoor air temperature. By modelling windows with a separate resistance, it is no longer justifiable using a combined equivalent outdoor air temperature for both conduction paths, outer walls and windows. In LOM III, the equivalent outdoor air temperature for the combined outer wall is treated as before, barring the influence of the windows. The equivalent outdoor air temperature for the window conduction path does not include solar radiation, but only the influence of ambient air temperature and long-wave radiation exchange with the environment. The implementation of the aforementioned aspects leads to the model structure of Low Order Model III, shown in Figure 4.

TEST CASES

For our tests cases, we used a two-story single family dwelling with a living area of 150 m² (Figure 5). The walls are heavy and insulated according to the German Energy Savings Ordinance 2009 (German Federal Diet 2009). The geometry represents a typical German single family dwelling. A model of this building as well as the specifications are published in the context of the IEA EBC Annex 60 (Wetter and van Treeck, Constantin et al. 2014).

Figure 5: Test Case of a single family dwelling

The single family dwelling is modelled in both simulation environments. In order to gain insightful simulation results, all boundary conditions are set to equal values in both programs. In particular calculation of long-wave radiation heat exchange with the sky and the environment follows different approaches in IDA-ICE and our LOM-models. In consequence, we excluded outdoor long-wave radiation in our test cases as this was not the focus of the present study. Coefficients of convective heat transfer, emissivity and absorptivity, thermal transmittances and ground temperature are set to fixed and equal values with regard to both programs. Ideal convective heating and cooling elements are used in both simulation environments, holding the indoor air temperature within the limits of ϑ_{upper}=23°C and ϑ_{lower}=22°C.

The test cases cover a whole year using a Test Reference Year weather file provided by Deutsche Wetterdienst for a weather station at Mannheim, Germany (Christoffer et al. 2004). This file provides information about outdoor air temperature and solar radiation.

In **Test Case 1,** only the ambient air temperature is considered while diffuse and direct solar radiation are excluded from the simulation. This test case aims at identifying model properties without solar radiation to analyze solely heat conduction effects.

Test Case 2 additionally takes diffuse solar radiation into account. Direct solar radiation is treated in different ways in IDA ICE and our LOM-models, equal boundary conditions could not be achieved within this study. We thus excluded direct solar radiation from our comparison.

LIMITATIONS

As the focus of this study is on heat conduction effects and the influence of different thermal network architectures, we considered a limited number of boundary conditions. In addition, models are always restricted to their modelling assumptions. In particular the following limitations apply to the present study:

- Coefficients of convective heat transfer are set constant to sustain comparability, although more detailed models are available in IDA-ICE.
- Subject of this analysis is a specific one family dwelling; different test setups might show deviating results.
- All models are based on assumptions; results are compared to each other but not to measurement data.
- No direct solar radiation is considered as weather models were not part of the comparison.
- Outdoor long-wave radiation is excluded in this study as the models base on non-comparable assumptions.
- While the Reference Model in IDA-ICE is set up as a three-zone model, the low order models are based on a single-zone approach.

RESULTS

Test Case 1

Figure 6 shows the heating power of the first two low order models and the Reference Model for Test Case1 (no solar radiation). The cumulative heat consumption per year is almost equal for LOM I and the Reference Model with a difference of 0.11 %. The time series of all models clearly correlate to the outdoor air temperature. Nevertheless, the Reference Model shows immediate reactions to changes in outdoor air temperature whereas the Low Order Model I reacts significantly damped and bearing a phase shift to the outdoor air temperature. This effect can be explained by the architecture of Low Order

Model I and its way to include heat conduction of windows.

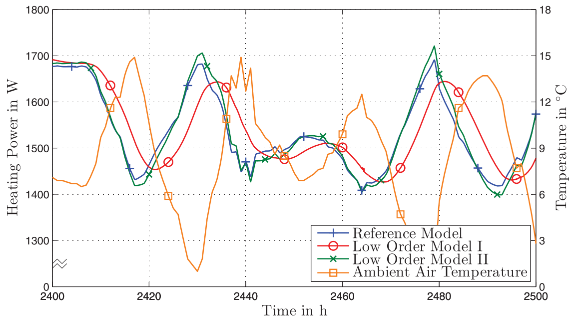

Figure 6: Heating power and outdoor air temperature, Test Case 1

Heat conduction without a capacitance, which is the expected simplified behavior of a window, cannot be represented by this model. Here, all windows are merged with the outer walls to one representing element. That leads in consequence to virtual capacities for the windows and to a damped and shifted reaction on ambient air temperature variations. To adjust this behavior, it is necessary to introduce a separate resistance for the windows in parallel to the outer walls (LOM II). The heating power of Low Order Model II in Figure 6 is thus considerably closer to the Reference Model. No phase shift is present and reactions to peaks in the outdoor air temperature occur at the same time with similar amplitude. Comparing the low order models with the Reference Model, the RMSE can be reduced from 61.74 W to 37.67 W and R^2 can be increased from 0.9919 to 0.9970. Although there is a substantial improvement to the dynamic behavior of the low order models that comes with this modification, this is only valid for Test Case 1 without solar radiation. For improving the low order models under conditions that include solar radiation, further modifications have to be applied.

Test Case 2

Figure 7 shows the cooling power of the Reference Model and the Low Order Models I, II and III over three days in summer. This test case includes solar radiation and serves as a more general test case. The aim is to assess the influences of our modifications under mixed boundary conditions. LOM I shows still the expected behavior and reacts damped and shifted. However, the deviation compared to Test Case 1 decreases as the solar radiation outweighs the influence of the outdoor air temperature for the presented time period. LOM II shows a significantly improved behavior compared to LOM I, the reasons have been discussed for Test Case I. Still, LOM II cannot reflect the behavior of the Reference Model, especially for peaks of cooling power. This is related to the combined equivalent outdoor air temperature for walls and windows as well as an insufficient handling of solar radiation through windows (as discussed in Chapter Methodology). These two aspects have been essentially improved in LOM III. However, the results for LOM II and LOM III do not differ much with LOM III being slightly closer to the Reference Model. Especially in times of low cooling power as well as for peaks, LOM III shows an improved behavior.

The correlation between the low order models and the Reference Model is worse than in Test Case 1. In Test Case 2, the multi-zone approach of the Reference Model with each wall modelled separately including several capacities each leads to a smoothing of solar radiation influence. The low order models are clearly not able to reflect the interactions between the single wall elements, especially regarding radiation exchange. In addition to that, using one capacitance per wall element each limits the calculation of layer related heat displacement within a wall. The combination of these simplifications, two wall elements and one capacitance each in a single-zone-model, leads to the deviations shown in Figure 7.

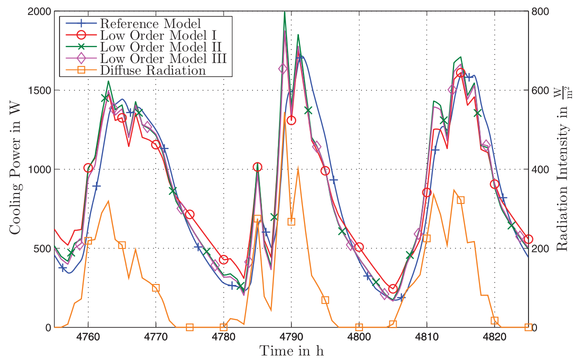

Figure 7: cooling power and diffuse radiation, Test Case 2

Even LOM III shows fast and overshooting reactions to solar radiation changes compared to the Reference Model. Although LOM III is an improvement of LOM I and II, it seems to be at a limit of which dynamic behavior can be reproduced with the simplifications at hand.

Table 1: Comparison of Detailed Model with LOMs, Difference in Heating Energy Consumption, RMSE and R^2 of Heating Power, Test Case II

	Diff $Q_{H,Year}$	RMSE	R^2
LOM I	-2.52 %	79.73 W	0.9898
LOM II	-2.37 %	76.40 W	0.9908
LOM III	-1.95 %	72.38 W	0.9917

The results in Table 1 show a continuous improvement regarding heating power from LOM I to LOM III in comparison with the Reference Model for

Test Case II. An analysis of cooling power shows similar results, except cooling energy consumption per year, where LOM III reveals a weak point, see Table 2. The fact that both heating and cooling energy consumption per year are lower in the LOMs can be explained by the effect of comparing single-zone (LOM) and multi-zone approaches (Reference Model). The lower resolution of single-zone-models leads to a compensation of spatially separated cooling and heating demands. Multi-zone models in contrast are able to distinguish between such heating and cooling loads. Thus, defining the zones is a critical part of the simulation setup.

Table 2: Comparison of Reference Model with LOMs, Difference in cooling energy consumption, RMSE and R² of cooling power

	Diff $Q_{C,Year}$	**RMSE**	**R^2**
LOM I	-3.44 %	90.25 W	0.9261
LOM II	-2.88 %	88.98 W	0.9338
LOM III	-5.49 %	83.88 W	0.9383

Measurements of calculation time for the LOMs show that improving the LOM increases the computational effort as well (see Table 3). Using LOM II instead of LOM I yields an increase of 12.45%, LOM III an increase of 6.57%. Noticeable is that, although LOM III uses a second equivalent temperature for windows, computational effort is lower than for LOM II. This is due to a change in treatment of indoor long-wave radiation. In both cases the Stefan-Boltzmann Law is used, but the number of participating elements differs. While LOM III encompasses two elements, one for inner and one for outer walls, LOM II considers solar radiation through windows directly at the long-wave radiation node via a third equation (see Chapter Methodology). This third equation complicates the iterative solution of Stefan-Boltzmann's Law and leads to higher computational costs.

Table 3: Computation time for low order models

	LOM I	**LOM II**	**LOM III**
Time	28.9 s	32.5 s	30.8 s
Equations	642	654	700

CONCLUSION

Low Order models (LOM) for thermal simulations on urban scale exist in parallel to extensively used Higher Order Models (HOM) for thermal simulations of single buildings. As these two model alternatives mainly differ in balancing simulation efforts and accuracy, a detailed comparison of models on urban and building scale helps to understand the differences of the modelling approaches. On this basis, it is possible to identify an optimal balance of simulation efforts and accuracy and to define criteria for model usage.

We compared two different modelling approaches in this study. The low order approach for urban scale applications is based on the German Guideline VDI 6007. It has been implemented in the modelling language Modelica. The higher order model is used in the software IDA-ICE and is specialized on single building simulations. A detailed analysis of the models' principles revealed different optimization potential for the LOM, mainly related to the consideration of windows. We distinguished between heat conduction effects and effects related to solar radiation through windows. This led to two new versions of LOM I, LOM II with an improved handling of heat conduction and LOM III with an additionally optimized consideration of solar radiation through windows.

To analyze the impact of our improvements on the simulation output, we set up test cases using a single family dwelling and different boundary conditions (with and without solar radiation). We designed two different Test Cases, the first one focusing on heat conduction, the second one representing more general conditions including solar radiation. The simulation of the four models (three low order and one reference, high order model) proved the divergent behavior of low and high order approaches.

Test Case 1, focusing on heat conduction through windows, proved our enhancements from LOM I to LOM II (introducing a separate resistance for the windows) as correct. Especially the dynamic reaction to outdoor air temperature changes could be improved.

Test Case 2 additionally takes solar radiation into account and forces the implementation of further changes regarding the consideration of outdoor and indoor radiation, leading to LOM III. However, LOM III showed no major improvements compared to LOM II, being only insignificantly closer to the Reference Model. Nevertheless, some deviations remain between LOM III and the Reference Model that still shows a damped and smoothed behavior. The deviations are clearly related to intrinsic simplifications regarding the spatial resolution of the low order models. By merging all walls to two representing elements, using one capacitance each and a single-zone approach, the low order models force a lower discretization. They cannot reflect interactions between single wall elements or layer related heat displacement and storage within a wall. Thus, our ongoing work focuses on investigating the influence of different discretization strategies for wall elements.

As expected, improving the low order models influences as well the models' calculation time. Due to changes in the indoor radiation exchange modelling, LOM III is even faster than LOM II. In consequence, we propose using LOM III under acceptance of slightly higher calculation time compared to LOM I.

As the differences between LOM III and the Reference Model are comparably small, other sources of deviations come into focus. Due to uncertainties in boundary conditions of real use cases, the intrinsic modelling differences might be overlaid by the influence of such boundary conditions.

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