ENERGY SIMULATION OF A RESEARCH CAMPUS WITH TYPICAL BUILDING SETUPS

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ABSTRACT

The availability of input data and appropriate computing times are two major challenges when simulating entire city districts. For dynamic heat demand simulations, we contribute to these tasks by developing an integral tool chain. To reduce the amount of input data, we automatically create typical datasets of building setups for office buildings according to their year of construction and basic geometric data. We use these datasets to automatically parameterize a dynamic building model. The simplified model is based on a common German standard with an adapted handling of heat transfer.

We used the developed tool chain to simulate the buildings' energy demand of a research campus. The results regarding heat demand and delivery rates show good accordance with measured data.

INTRODUCTION

Improving the energy efficiency in the building sector is one key task in the aim of reducing energy demand. However, analysing each building separately for an entire city district is time-consuming and expensive. Especially for public estates, investigating the energy supply system on a city district level seems a promising approach for identifying further efficiency potential, often at a comparably small budget. As mentioned in (Erhorn-Kluttig et al., 2011), there are no standard solutions for energy concepts on a city district level. To support the energy supply design with proper tools is thus of great importance. In the upcoming renaissance of integral energy concepts (Erhorn-Kluttig et al., 2011), the focus is on new districts as well as on existing structures. Planning tools should account for this by using readily available inputs for both cases to simplify the parameterization.

In a current research project, we develop simulation tools combined in a tool chain to investigate a research campus on an integral approach. The analysis is based on design data as well as measurements (Fuchs et al., 2012). The tools involve dynamic simulations of buildings and the connecting heating grid. This allows us to investigate building-grid interactions and phenomena like dynamic heat storage.

Motivation

According to (Hensen et al., 2011) and (Huber et al., 2011), there is a general need for developing integral dynamic energy demand analysis tools, which can support more general planning tools like D-ECA (Erhorn-Kluttig et al., 2011).

Keirstead et al. (Keirstead et al., 2012) analysed 219 papers relating to urban energy system models and identified four main challenges that current modelling practices face:

- Lack of model integration: Tools are developed for distinct purposes and specific aspects.
- System complexity: Applicable solutions in terms of temporal and spatial resolution are needed.
- Data availability and quality: Need of large amounts of input data, e.g. energy demand profiles.
- Policy relevance: The challenges listed above lead to a low policy impact.

In this paper, we present our activities contributing to these challenges, in particular to data related restrictions. We added time and effort constraints for setting up building simulations as another important challenge. We develop simplified thermal building models and typical building setups for design parameters and boundary conditions.

After a short overview of State-of-the-art simulations for city districts, we present the methodology of our developed tool chain. With this tool chain we then calculate the heat demand of a city district with simplified models and typical building setups. Afterwards, we analyse and discuss the results.

STATE-OF-THE-ART

The common analysis of buildings in a city district context derives from the analysis of single buildings. Their heat demand is mostly calculated on a monthly or yearly basis and does not reflect dynamic behaviour. Calculations in Germany are mainly based on standards that are mandatory for new buildings and refurbishments (DIN, 2007 and David et al., 2009).

Dynamic building simulation can yield improved results. Such dynamic models are well-researched

(Clarke, 2001) and used for example in equipment planning (Becker et al., 2012). Robinson and Hensen (Hensen et al., 2011 and Robinson, 2011) classify them into statistical and physical models and the latter type further into (Kämpf et al., 2007):

- Explicit solutions
  - Finite difference method
  - Transfer function models
- Model reduction techniques
- Model simplification techniques
  - Heat balance models
  - Thermal network models
  - Admittance methods

Out of these models, thermal networks seem to be a suitable solution for city district applications (Kämpf et al., 2007).

Using coupled simulations of consumers and energy supply systems can further improve accuracy and dynamic behaviour of the analysis (see Robinson, 2011 and Huber et al., 2012). This allows integral investigations of interactions between subsystems to identify additional savings potential.

TOOL CHAIN

With regard to the challenges mentioned above, we have to consider the following requirements:

- Ease of use: In particular, easily accessible input data and boundary conditions.
- Modularity: Should be combinable with other models and allow more details if requested.

In addition, our calculations should be robust, fast and give significant results. Figure 1 shows the structure our tool chain is based on. A simplified dynamic building model reduces the system's complexity while keeping an appropriate temporal and spatial resolution. To allow input data on a simple level and keep the possibility of using specific input data if available, we combine the building model with a pre-processing to handle different kinds of data and derive typical building setups.

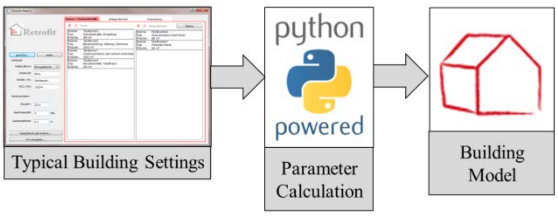

Figure 1: Overview of the tools used for building model parameterization

Typical Building Setups

In practice, the data needed for energy demand calculations is commonly extracted from floor plans and detailed drawings. This is time-consuming and precise information is typically unavailable, especially for entire city districts. One approach to avoid this problem is to use minimal sets of data and adapt them by using statistical data. In this way, the buildings can be set up according to typical building setups. If more detailed information is available, the setups can be refined afterwards. Thus, different kinds of data can be used as input and the level of detail is not predefined.

Heat demand related parameters are usually defined for separate zones, especially for non-residential buildings (DIN, 2007). Necessary parameters for the simulation are in particular related to inner loads, enveloping surfaces and heat capacities.

Lichtmeß (Lichtmeß, 2010) examined a method of zone-area-weighted allocation of the enveloping surfaces (Figure 2). He uses the hypotheses that there is a correlation between the enveloping surfaces and the zone area and the surface can be distributed automatically.

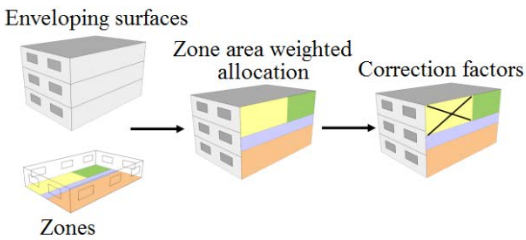

Figure 2 Zoning and weighting of the zones (Hillebrand et al., 2012)

Based on this works, Hillebrand (Hillebrand et al., 2012) designed the Retrofit Matrix Calculation tool, which generates typical building setups for residential and office buildings. Therefore, it estimates the enveloping surfaces with functions taken from (BMVBS, 2010). As input parameters for office buildings, it needs:

- Year of construction
- Height between floors
- Number of floors
- Net floor area

Using criteria like floor structure and window area ratio (PROsab, 2008), it generates a setup of typical zones, e.g. for office buildings:

- Office
- Floor
- Storage
- Meeting room
- Server room
- Bathroom

With the help of this information, the tool creates the setups in three steps:

1. Estimation of enveloping surfaces: The areas and structures are defined for all exterior elements, respectively to the net building area, year of construction and typical ratios.

2. Estimation of typical zone areas: Based on the net floor area and types of zones in a typical office building, the zones are equipped with inner walls, floors and ceilings. Additionally, the inner loads (persons, machines and lighting) are specified according to the zones' usage.
3. Distribution of enveloping surfaces over zones: The areas of the facade elements are distributed over the zones with the help of statistical information. Correction factors are used to consider the zone-geometry and the corresponding ratio of exterior elements.

All properties of these ready-to-use typical building setups can be changed if sufficient data is available, e.g. structure of walls. This makes the tool modular and it is possible to use data of different quality. The setups can be summarized into one set of parameters that can be used as input for our simplified building model.

Dynamic building model

We use the developed building model mainly for city district simulations. Therefore, the model must be modular, easy-to-use, fast, robust and nevertheless display the real system's dynamic behaviour. As shown in section State-of-the-art, dynamic building models are well-researched and still undergoing further improvement. Different approaches have been investigated, while thermal network models seem to be a good solution for city district applications. The discretization regarding the number of heat capacities and resistances per network element as well as the number of elements varies from model to model.

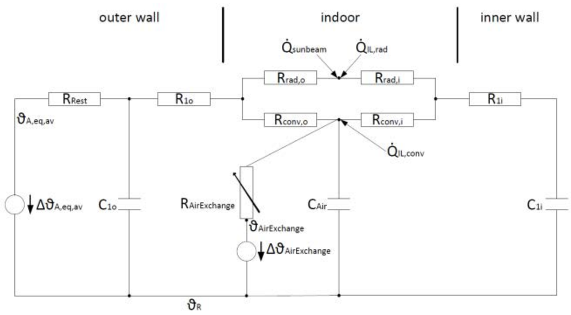

Figure 3 Substitution circuit for simplified building model

From the wide range of such models, we selected an approach defined in the German guideline VDI 6007 (VDI, 2012). It divides the building mass into two capacities representing interior and exterior building elements (Figure 3). While one resistance reflects the heat conduction in the adiabatic interior masses, two resistances describe heat transmission through the exterior elements. In contrast to the standard, we calculate the interior radiant and convective heat transfer separately and not with a combined heat transfer coefficient (Lauster et al., 2012). The model on this level represents one thermal zone and various zones together represent an entire building, their number depending on the building's type and size.

Figure 4 shows the implementation of the thermal network in the object-oriented, equation-based modelling language Modelica in the software tool Dymola. To consider various influences on the heat demand of a building, we added models for shading, inner loads, weather and ventilation.

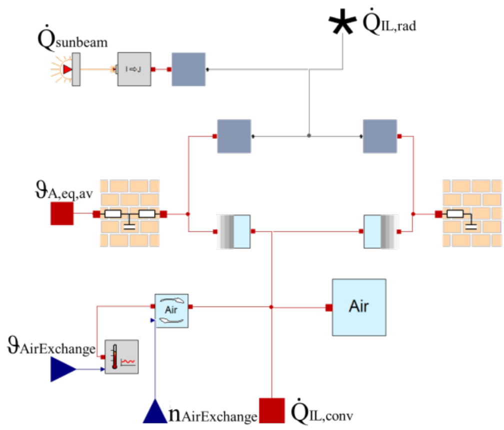

Figure 4 Implemented simplified building model

The Retrofit Matrix Calculation supplies all required parameters for the model bundled in a record. Thus, we are able to set up and simulate typical buildings on different levels of detail in a very easy-to-use and fast way. Nevertheless, we can modify each building and its boundary conditions without affecting other buildings. With this modular approach, the model can easily be coupled with other models, e.g. for heating grids.

USE CASE AND RESULTS

Investigated city district

Figure 5 Research Campus Forschungszentrum Jülich GmbH (FZ Jülich, 2012)

Searching for integral methods for city districts, we investigate the optimization potential of the research centre Forschungszentrum Jülich GmbH (Figure 5). This former nuclear research centre is now in use by different research institutes and covers various scientific applications. More than 200 buildings were built between 1918 and 2012 to suit the different needs. About 24% of the floor areas serve as laboratories, while 60% are in use for office applications (Table 1). The net building areas vary between 6 and 11000 m . This leads to a heterogeneous pool of buildings regarding floor areas, geometries, usage and years of construction. All buildings are connected to a heating grid. While not all buildings are equipped with heat meters, the overall heat demand of the campus is measured on a daily basis.

Table 1 Usage of net floor area

TYPE	RATIO	SIMULATED
Office	30%	Yes
Office/Laboratory	30%	Yes
Laboratory	24%	No
Service and Storage	16%	No

Data availability and quality varies from building to building. Time and effort constraints further limit the usage of detailed floor plans and detailed user behaviour predictions. Thus, we collected years of construction, usages and building volumes for all buildings and complemented it by estimations of number of floors, floor height and delivery rate. With this data, we used the Retrofit Matrix Calculation and set up the building models.

Boundary conditions

Data like occupancy, set temperatures, infiltration and ventilation rates are well documented for typical buildings in different standards. For our simulations, we used the sources in Table 2:

Table 2 Standards for input data

STANDARD	USAGE
DIN V 18599 – 10 (DIN, German Institute for Standardization, 2007)	Occupancy (max values) Lighting Ventilation Heating and Cooling
SIA 2024 (SIA, Swiss society of engineers and architects, 2006)	Occupancy (daily schedules)
DIN 1946 – 6 (DIN, German Institute for Standardization, 2009)	Infiltration

Simulation

A generation of typical building setups for laboratories is not yet implemented in the Retrofit Matrix Calculation tool. Thus, we focus on buildings mainly used as offices, what reflects about 60% of the overall net floor area (see Table 1). Each building is considered either with its year of construction or with its year of retrofitting. Thus, retrofitted buildings are handled equally to new buildings of the subsequent year.

The computer system we used is defined in Table 3, the simulation of one year with an hourly output step took 1.6 hours.

Table 3 Computer system for simulation

CHARACTERISTIC	VALUE
Operating system	Windows 7
Number of processors	8
Clock speed	2.9 GHz
Working memory	32 GB

Limitations

The nature of investigating entire city district leads to various challenges and limitations, which also effect the presented work. The major limitations in our investigation currently are:

- Heat flows between zones and buildings are not considered
- Only 60% of the overall net floor area is simulated, as we have no typical building setups for laboratories or storage buildings. In addition, we analysed only non-residential buildings, as there are no residential buildings on the campus.
- All buildings are represented by typical setups, buildings with special conditions are not handled separately.
- User behaviour is considered with daily schedules on a statistical basis.
- Building technology is represented by ideal heater systems without heat losses, time delays or control strategies.

Thus, the temporal and spatial resolution as well as the level of detail of this work is limited to a certain extent and can be improved.

In our further work, we will address some of these limitations, e.g. by considering stochastic user behaviour and typical building setups for laboratories.

Daily heat load

For the investigated research campus, we have measurement data of the overall heat demand. As we simulate 60% of the net floor area, comparing measurement and simulation lead to a deviation related to the missing 40% of the buildings (see section Simulation and Table 1). Nevertheless, such a comparison can show, with which accuracy the simulation can represent the characteristics of the real heat demand. We use a linear correction function to consider the missing 40% of the buildings. In this way, we get a corrected simulation that is used to analyse the characteristics.

Figure 6 shows the mean daily heat load for one year, scaled to the measurement's maximum. The simulation calculates 42% of the measured yearly heat demand, especially as labs with higher demand are not considered. This leads to a mean difference of

58% scaled to the mean measured heat load (Table 4).

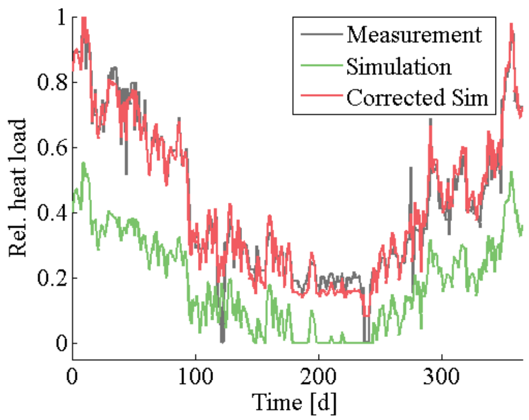

Figure 6 Mean daily heat loads

To calculate the correction function, we compare the difference between simulation and measurement to the measured heat load. Figure 7 shows the comparison, the values again scaled to the measured maximum heat load. The scatter plot follows a best-fit line (red line) with the equation:

$$\Delta y_{meas\text{-}sim} = 0.39 * y_{meas} + 0.08 \quad (1)$$

Thus, we get a corrected simulation in Figure 6 by recalculating the simulation data, taking Equation 1 into account. The corrected simulation calculates 100.6% of the measured yearly demand (Table 4).

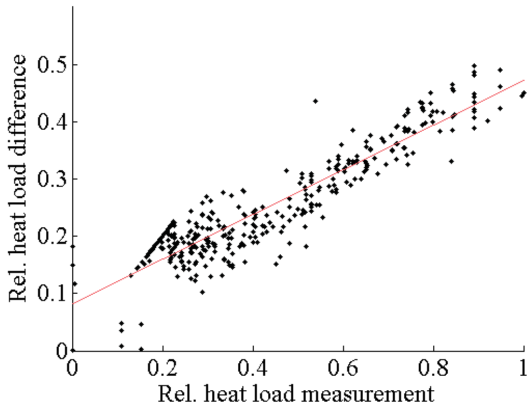

Figure 7 Deviation compared to measured heat loads

To analyse the characteristics, the corrected simulation values are plotted against the measured heat loads in Figure 8, with the values scaled to the measurement's maximum. For a perfect match between simulation and measurement, all values would lie exactly on the bisecting line (red line) and the coefficient of determination (R) would be one. For our case, the scatter plot has a coefficient of determination of 0.97 regarding the bisecting line (see Table 4).

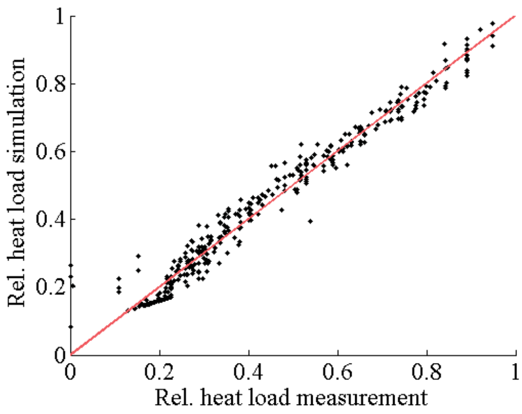

Figure 8 Comparison of corrected simulation and measuremed heat loads

The linear correlation of the difference to the measured heat load in Figure 7 might originate from one or more factors that in turn determine the heat load (e.g. outdoor air temperature). Thus, we cannot draw conclusions what are the underlying crucial influences on the simulated heat load out of this analysis. However, the high coefficient of determination for the corrected simulation in Figure 8 indicates that we can simulate the system's characteristics. Nevertheless, we cannot distinguish between the influences of missing buildings and insufficient modelling approaches on the simulation-measurement difference. To minimize the difference, we thus have to improve our models and find typical building setting for laboratories.

Table 4 Simulation statistic

CASE	CALCULATED	Ø DIFF	R	RMSE
Original	42%	58%	-	-
Corrected	100.6%	7.5%	0.97	0.23

Delivery rates

Another possibility to compare simulation and measurement is the calculation of delivery rates. As they are building specific, the missing 40% of net floor area do not affect the results (see Table 1). The delivery rate is the maximum heat load that can be delivered to the building. It is a design parameter of the building's heat transfer station. As half of the simulated buildings are used for experimental as well as office applications, these groups of buildings will have higher delivery rates than necessary for heating purposes only, e.g. for experimental setups. As the simulation calculates only heat loads related to the heating of the building, the calculation of delivery rates for the group of pure office buildings will be more accurate than for the mixed-use buildings.

Figure 9 shows the comparison between simulated and real delivery rates for all simulated buildings. For all outliers, the simulation underestimates the real delivery rate. We assume that this corresponds to the different usage of the buildings. To extract the different groups of buildings, we calculated the root mean square error (RMSE) of all values regarding the bisecting line (thick red line). For a perfect match of simulated and real delivery rates, all values would exactly fit to the bisecting line. We marked all data points that are outside the root mean square error as third fit buildings (blue points), assuming that they correspond to buildings with large areas for experimental issues. This assumption is backed up by the fact that they follow their best-fit line with a R^2 of 0.85. It indicates a linear correlation within this group. For the remaining group of data points, we then repeated the calculation of the root mean square error regarding the bisecting line and marked all points outside the RMSE as second fit (green points). This group of data points follows its best-fit line with an R^2 of 0.96 (Table 5) and might relate to buildings with small experimental areas.

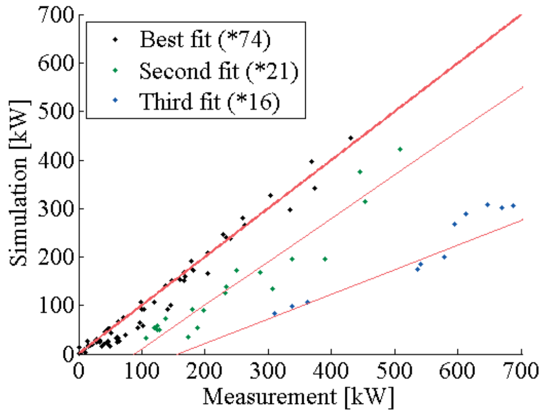

Figure 9 Delivery rates

The remaining group of data points is marked as best fit (black points). It still represents 66% of the simulated buildings, which corresponds to the fact that 50% of the simulated buildings are pure office buildings (see Table 1). The best-fit group correlates to the bisecting line with a coefficient of determination of 0.97.

Table 5 Statistic delivery rates

FIT	REFERENCE	R	RMSE	VALUES
Best	Bisecting line	0.97	20 kW	74
Second	Best-fit line	0.96	34 kW	21
Third	Best-fit line	0.85	108 kW	16

Annual heat demand per square meter

A second building specific value is the annual heat demand per square meter. It is also unaffected by the missing 40% of net floor area (see Table 1). To reflect the influence of the year of construction, Figure 10 shows the simulated annual heat demand per square meter per class of years of construction. As we have no building specific measurement data for annual heat demand and statistical data is mainly for residential buildings, we can only analyse the profile of the distribution. However, the heat demand declines in direction of newer buildings and displays a typical distribution (DVGW, 2011). Even though, the heat demand for buildings built after 1983 is above the average compared to the other classes. We are using a fixed infiltration rate of 1/h for all buildings. As this overrates the infiltration for newer buildings, we can improve the results by defining year-of-construction related infiltration rates. The influence of the other parameters (as number of floors) is visible in the standard deviation.

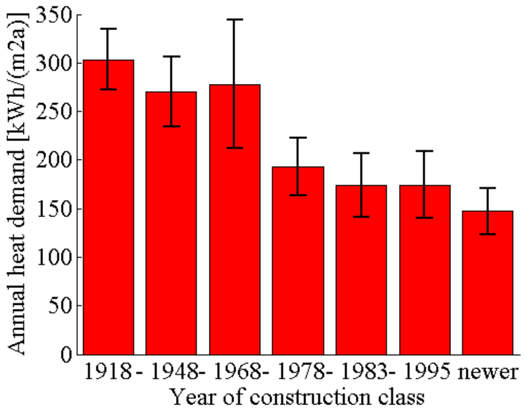

Figure 10 Simulated annual heat demand per construction class

CONCLUSION

To improve dynamic heat demand simulations for city districts, the simulation models have to be simplified and should be based on easy accessible input data.

Thus, we developed a tool which calculates typical buildings setups by means of area-weighted interior and exterior building elements according to the year of construction. Refinements are possible if data that is more detailed is available. The tool is applicable for office buildings and provides an interface to a simplified dynamic building model. The building model is based on the German standard VDI 6007 (VDI, 2012), although we adapted the calculation of the interior heat transfer. Due to the used simplifications, the model is particularly applicable for city district simulations.

With the developed tool chain, we simulated all office buildings of a research campus. The results were compared to measurements, design and statistical data. The comparisons show that we can represent the characteristic of the heat demand, delivery rates and typical annual heat demands. Nevertheless, further models are required to arrive at results in accordance with measurements on a daily or hourly basis without a correction function, e.g. for ventilation and laboratories.

NOMENCLATURE

y_{meas} = measurement value

$\Delta y_{meas\text{-}sim}$ = difference simulation and measurement

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