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VALIDATION OF A THERMODYNAMIC BUILDING MODEL BASED ON WEATHER AND THERMAL MEASUREMENT DATA

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Abstract

The inertia of massive buildings harbours enormous potential for energy savings. In order to address these potentials, the objective of this paper is to present a suitable, validated thermal model. The validation compares the air temperature of a test facility with a thermodynamic model in four type-weeks. The main finding is that the validation according to ASHRAE guideline can be performed using a parametric simulation tool. The key parameters to adapt the model are the infiltration rate and the window and construction properties, particularly the thermal mass. This supports the initial concept of addressing the thermal mass of a building.

Introduction

At the Paris Climate Agreement in December 2015, almost 190 parties consent to the agreement to limit global warming to 1.5°C. (United Nations, 2015) The main cause of this are greenhouse gas emissions. If these remain too high, this will lead to irreversible environmental tipping points, resulting in the severe limitation of (human) life on earth. The European Union has thus committed itself to reduce its greenhouse gas emissions by at least 40% compared to 1990 levels by the year 2030. (European Commission, 2021)

The building sector accounts for around 13.6% of total direct greenhouse gas emissions in Germany, though this can rise to 26% if grey emissions are considered too. The 2019 Climate Report of the German Federal Ministry for the Environment states that the contribution of the building sector is essential to achieve the set energy and climate goals. (BMU 2020)

With its climate protection plan, the German government aims to become climate neutral by 2045. One component of this plan is climate-friendly building and housing. This includes, among other things, long-term strategies for the renovation of existing buildings, high standards for new constructions, and a gradual shift towards renewable energies in the area of building technology. (BMU, 2020)

The German Building Energy Law (GEG) sets out requirements for the building envelope and its systems technology in order to promote an increase in energy efficiency in the building sector and a switch to renewable energies. These challenges are addressed in the scientific field of building technology, where thermal models are commonly used to analyse the effects on the energy efficiency of buildings e.g. evaluating intelligent control strategies.

Therefore, one fundamental step to generate reliable approximations that describe the real circumstances of a building is the validation of a thermal model, comparing the simulated model with measured data. This paper deals with the process of such a validation to create a base case model for future research.

Objective

The objective of this paper therefore, is to provide a validated thermodynamic simulation model according to the ASHRAE Guideline 14:2002. By changing the individual parameters of the parametric simulation model, it gradually approaches the measured values of the test facility. This leads to the following two research questions of this paper:

- Is it possible to validate a thermal model through the local weather and thermal data of the test facility according to the ASHRAE Guideline 14:2002 taking the parametric simulation tool TRNLizard into account?
- Which key parameters can be identified to fulfil the validation criteria according to the ASHRAE Guideline 14:2002?

Methodology

The methodology used is summarised in the following with regard to the previously described research background as well as the outlined research questions. Numerical thermodynamic simulations try to represent the actual physical behaviour of a system. As TRNSYS is validated according to ANSI/ASHRAE Standard 140, the correctness of the simulation engine is proven for various test cases. (Solar Energy Laboratory, University of Wisconsin-Madison, 2017) In order to link the simulation results to the built environment, the thermodynamic simulation model is initially validated against measured data according to the ASHRAE Guideline 14:2002. To this end, a test facility was set up at roof level with measurement equipment to track thermal and weather data. This data further is compared with the simulation data to iteratively adapt the thermal model to fulfil the defined thresholds for the validation.

This forms the foundation for the thermal simulation model in TRNSYS 18, which is fed by the parametric simulation tool TRNLizard performed in the graphic programming interface Grasshopper, a plug-in for the CAD-software Rhinoceros 7. The thermal simulation model can now be adapted parametrically and evaluated dynamically within the simulation environment to analyse the individual effects of a WPC (e.g. thermal inertia, different climates, and key parameters).

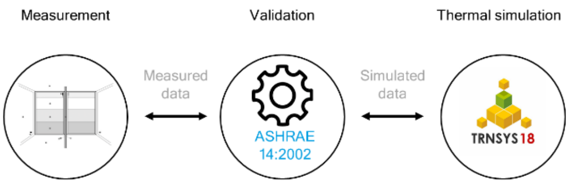


Figure 1: Graphic illustration of the methodology (own representation)

Fundamentals

The validation process according to the ASHRAE Guideline 14:2002, the structure of the simulation, the measurement room and its measurement equipment are outlined in the following sections.

ASHRAE Guideline 14:2002

The scope of the ASHRAE Guideline 14:2002 is to provide a standard for "*pre-retrofit and post-retrofit data to quantify the billing determinants (e.g., kWh, kW, MCF, etc.) used for calculation of energy and demand savings in payments to energy service companies, utilities, or others*" (ASHRAE Standards Strategic Plan Ad Hoc Committee, 2019). A major step is to validate the model with measured data so as to form a valid foundation for the analysis and respective statements. By adjusting single assumptions of the simulation model and comparing them with the measured parameters, a simulation can be adapted better to reality. This process is called calibration and leads to the question: when is a calibration of the model precise enough to represent reality? The ASHRAE Guideline 14:2002 introduces two mandatory terms (and one optional term) to prove the validation that is outlined below.

The Normalized Mean Bias Error (NMBE) describes the mean percentage of deviation of the simulation values from the measured ones. To keep the values comparable, the mean deviation is normalized with the average measured values. This outlines the regression line of the sample. The NNBE must be within ± 10% to fulfil the requirement. When considering the NMBE, positive and negative differences could outweigh each other and the threshold would be met overall despite large individual deviations.

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_i^n (m_i - s_i)}{n - p} \cdot 100\ (\%) \qquad (1)$$

The Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) describes the error deviation between the simulated and measured data and provides feedback on the significance of the model. By squaring and further assigning the square root of the values, the negative effect of the NMBE is compensated and a more adequate evaluation can be carried out. In general, the CV(RMSE) shows the variability of the error between the measured and simulated values, which must be smaller than 30%.

$$CV(RMSE) = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_i^n (m_i - s_i)^2}{n - 1}} \cdot 100\ (\%) \qquad (2)$$

In addition, the Coefficient of Determination (R^2) can be added to the process of validation, but is not mandatory according to the ASHRAE Guideline 14:2002. It is recommended that this be greater than or equal to 0.75. It describes the proximity of the simulation to the regression line of the sample. The absolute ideal would be 1.

$$R^2 = \left(\frac{n \cdot \sum_i^n (m_i - s_i) - \sum_i^n m_i \cdot \sum_i^n s_i}{\sqrt{n \cdot \sum_i^n {m_i}^2 - \left(\sum_i^n m_i\right)^2 \cdot \left(n \cdot \sum_i^n {s_i}^2 - \left(\sum_i^n s_i\right)^2\right)}} \right)^2 \qquad (3)$$

Symbol	Description	Unit
m_i	Measured value	**[-]**
s_i	Simulated value	**[-]**
n	n° of measured data points	**[-]**
$\bar{m}$	Mean of the measured values	**[-]**

Software - structure of the simulation

A thermal simulation is performed for the validation and further thermal simulations. A dynamic thermal simulation is an appropriated tool to analyse and evaluate multi-dynamic behavior, as is the case in the building physics of a room. The general functions of the thermal simulation tool TRNSYS will be explained below. Further, TRNLizard and its serial connection to the CAD-software Rhino, including the parametric, visual programming interface Grasshopper, are outlined.

The software used for thermal simulations in this paper is called TRaNsient SYstems Simulation (TRNSYS). TRNSYS is a simulation software to calculate energy concepts for multizone buildings. TRNSYS is able to perform energy simulations on a small and large scale, from domestic water systems up to complex, multi-zone building simulations. It can simulate solar systems, HVAC systems, renewable energy systems, cogeneration plants or geothermal heat-pump systems. (Solar Energy Laboratory, University of Wisconsin-Madison, 2017)

TRNLizard is a plugin for the visual programming environment Grasshopper of the 3D modeling software Rhinoceros 3D (Rhino). Grasshopper is primarily used to build generative algorithms and allows the user to create their own scripts by dragging components onto a canvas or via code. TRNLizard is one of many free plugins that combines the powerful parametric modeling tool Rhino/Grasshopper with the previously described features of the thermal simulation software TRNSYS to enable advanced, parametric thermal simulations. The thermal model with its building properties is set up according to the follwing test facility.

Test facility

The base case model of the thermal simulation model forms an in-situ measurement test facility located on a rooftop in an urban environment. The structure and design of the test facility as well as its technical equipment and underlying measurement concept is examined in the following so as to perform the validation of the thermal simulation model.

At the exposed location on the rooftop at a height of approximately 28 meters above the ground floor (3.8 meters above the 5th floor), the test facility is mainly influenced by the urban weather conditions (48°08‘20“, 11°34‘30“). The central main cube is a full-scale test room facing south-west. This analysis described in this paper was carried out in the main cube with a length of 4.30, a width of 4.30, and a height of 3.30 meters. The main orientation, including a large glass façade (window-to-wall ratio 90%), faces 23° southwest. The sun's position changes during the year so that its azimuth angle varies with lower angles in the wintertime and steeper angles but longer periods in summer..

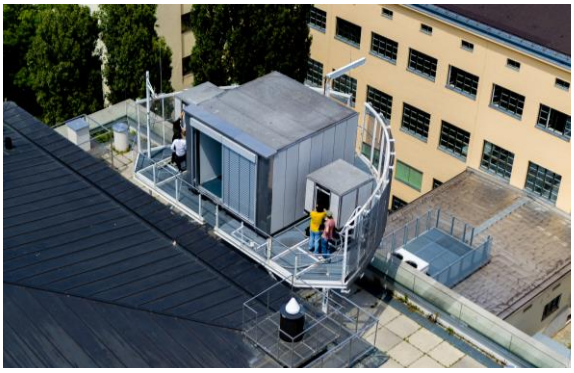


Figure 2: Perspective view of the test facility (Picture: own representation 2021)

As Figure 2 shows, the main cube comprises three rooms. The anteroom houses the technical and measurement equipment which supplies the two test chambers. It also grants physical access to the test chambers. With a width of 1.55 and a depth of 2.87 meters, the two test rooms are structurally identical and offer almost identical physical conditions. Since this paper does not focus on a specific façade and uses the measurement rooms mainly to validate the simulation model, only the test room facing southeast is considered for the validation.

At the time of the analysis, the main façade is equipped with a special window. The double-glazed window consists of five electrochromic layers as well as a heat-mirror foil which together result in a very well insulated and low-transmitting window. Typically, the electrochromic layer can adapt its transmittance (a chemical process to darken the color of the window) to regulate the overall transmittance of the glass, thus affecting the interior visual and thermal conditions. This effect was not active during the validation period for the simulation model, since this paper does not focus on the high-performance window. Figure 3 shows the internal visual conditions of the tinted window compared with an external shading system, even though the sun shading systems are not acivated during the validation mesaurement periods.

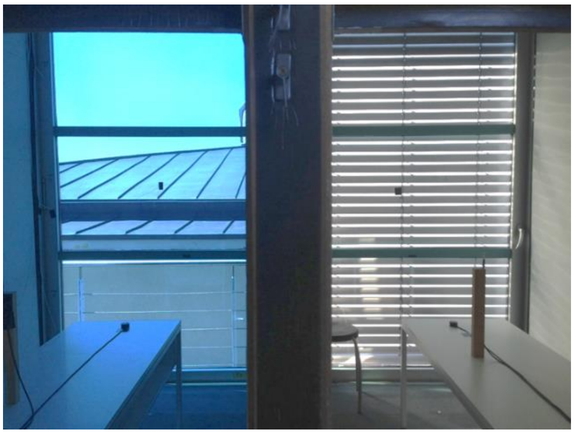


Figure 3: Facade/section view of the test facility (Picture: own representation 2021)

So as not to affect the individual measurements, both the thermal envelope as well as the interior wall between the two test chambers are very well insulated to generate high-quality measurement results. Further, no building technology is activated during the measurments and the room is unoccupied and without internal loads. Table 1 shows the construction details from the outside to the inside as well as the individual u-values of the thermal envelope.

Table 1: Overview of the individual construction layers and the building envelope (Source: Molter 2016 & u-wert.net GmbH, 2022)

External wall U-value 0.175 W/(m^2K)	**Roof** U-value 0.222 W/(m^2K)
Ethernit board 8 mm	Sealing membrane + wooden framework
Air layer 30 mm	Mineral wool 160 mm
Wooden batten + foil 30/60 mm	Rafter layer with foil 80/160 mm
EPS board 30 mm	Wooden framework 19 mm
Mineral wool 120 mm	Air layer 30 mm
Wooden stand + foil 60/120 mm	Wooden batten 30/50 mm
Wooden composite board 16 mm	Wooden composite board 16 mm
Air layer 60 mm	
Wooden composite board 16 mm	
Floor U-value 0.266 W/(m^2K)	**Internal wall** U-value 0.437 W/(m^2K)
Wooden framework 19 mm	Wooden stand wall 50/35 mm
Wooden rafters + foil Core: mineral wool 80/160 mm	Core: vacuum insulation with pyrogenic silica
Timber formwork 19 mm	
Carpet 5 mm	

In general, three categories of measurements are performed at the test facility: the recording of weather and thermal data as well as visual measurements in the cubes. As this paper focuses on thermal and energetic performances, the visual data is excluded from the analysis, as shown in the following concept figure. The weather data is recorded by the nearby weather station. It is roughly 400 m away and at 28 m it has a comparable height to the test facility.

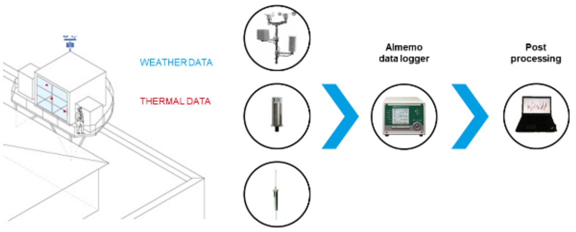


Figure 4: Measurement concept at the test facility (drawing: own representation; pictures: AHLBORN Mess- und Regelungstechnik GmbH, 2020)

The weather station comprises different sensors to dynamically record dry-bulb and wet-bulb air temperature, each at a height of 2 and 28 meter, the wind direction, the wind velocity, as well as the horizontal global and diffuse radiation.

The thermal data inside the test cubes focuses on the temperature. The operative temperature consists of the mean surface temperatures and the air temperature in a room. An Almemo FHAD 46-C2-sensor in the middle of the room measures the air temperature of the room. The six individual inner surfaces (ceiling, floor, walls and window) are equipped with PT-100 sensors to track the individual mean surface temperatures. Using the individual inner surface areas as well as the temperature values, the operative temperature is calculated in every time step. (AHLBORN Mess- und Regelungstechnik GmbH, 2020)

The thermal data is collected by a data logger in the anteroom of the test facility and is then stored and processed for the first time for every time step. The ALMEMO® data logger in turn is connected to a local computer in the anteroom that saves the data once more and can be controlled remotely. In a third phase, an ethernet connection transfers the data to an internal server to finally store the data one last time. These processes repeat every minute to ensure a safe data structure and to prevent data losses.

Validation

This chapter first exaimes the calibration process for the weather data with a nearby meteorological weather station. The second section describes the calibration and validation of the thermal simulation model with the dynamic measurements. The following figure outlines the iterative process of the validation. The simulation and measurement data are initally processed and converted into graphs for visual control. If the curves of the graphs do not match, an initial calibration process begins in which the model settings are adapted by an iterative process. Following the visual control, the aforementioned normalized mean bias error, the coefficient of variation of the root mean square error, and the coefficient of determination are calculated. Once again, the model's results are evaluated in an iterative process and it is adapted to finally generate a validated simulation model.

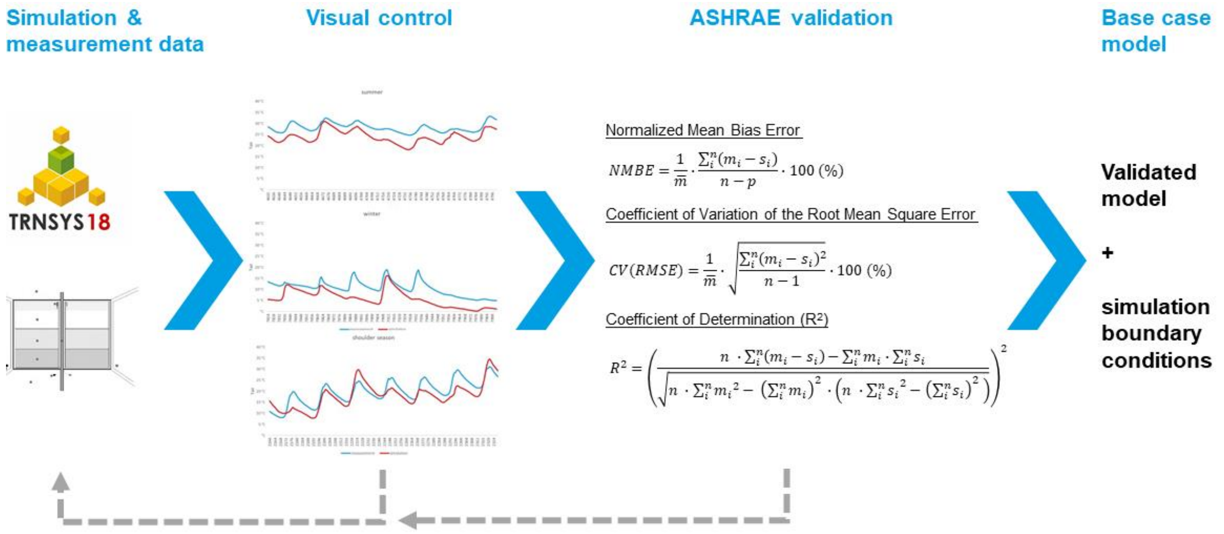


Figure 5: Methodology of the validation process of the simulation model with final base case model (own representation)

Weather data

The weather has a major impact on the performance of a building as it influences the energy balance in various ways, such as solar radiation or pressure differences. The exposed location of the measurement rooms means they experience more extreme weather conditions than a normal urban environment, which leads to the need for accurate and correct weather data..

Even though there is a weather station at the test facility itself, the weather station at the accompanying meteorological facility was found to supply more reliable data. The weather data from this station still has a high locality and is sufficient to evaluate the simulation variants. The recorded data is then prepared for implementation in the thermal simulation software. This process is concluded by a conversion into hourly values by calculating the arithmetic mean for each weather parameter per hour. Further, these parameters are extracted and transformed into a weather data file in the EPW-format to comply with the international common standards for various thermal simulation tools.

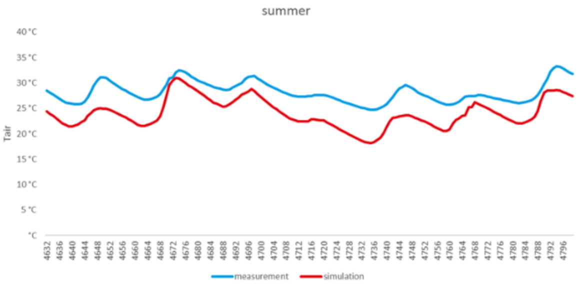
As regards the validation, a consideration of a whole year is seen as unnecessary and may even mean that the validation itself cannot be completed. Smaller time frames representing the different seasons are more suitable and are not dominated by data losses and unpredicttable disturbances while generating the same outcomes. Therefore, four type-weeks are chosen since they represent the typical weather conditions in winter, summer, spring and fall season in the moderate climate of Munich

- Shoulder week 1 16.03.2020 – 22.03.2020
- Shoulder week 2 01.04.2020 – 07.04.2020
- Summer week 13.07.2020 – 19.07.2020
- Winter week 23.11.2020 – 29.11.2020

Results - Validation Simulation Model

The simulation model is validated according to the parameters of the measured and simulated indoor air temperature. As outlined previously, the validation is performed according to the NMBE, CV(RMSE) and R^2 for the time step of one hour in the defined time periods. The individual steps to adapt the simulation model are not explained (in line with the focus of this paper) but the simulated model generally shows more comfortable conditions in all periods (shown examplarily for summer in Figure 6). This formed the basis for the iterative process to address the thermal envelope of the building model and to make it more airtight so as to increase the simulated temperatures in summer and reduce the indoor air temepratures in winter, as it the case in the measurement test facility.

After an iterative process of adaptation, the thermal model is finalised with the window properties with a g-value of 0.3 and a U-value of 0.68 W/(m^{2}K). This is due to the fact that the eletrochromic windows with a heat mirror foil perform better than the initial assumptions for the base case model. Further, the thermal bridges are set to 0.1 W/m²K and the infiltration is lowered to 0.25. The combination of the very well insulated windows and the very airtight thermal envelope again led to this assumption. These adapted parameters and the invidual calidbration steps are outlined in the master thesis of Brunet 2021. The updated simulation model’s graph course as well as the overall NMBE, CV(RMSE) and the R^2 are shown in Figure 6 and Table 2.



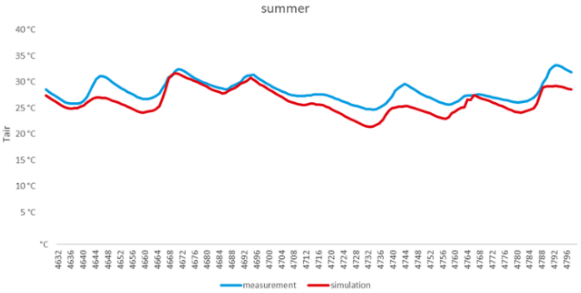


Figure 6: Vourve for the simulated (red) and the measured (blue) air temperature for the summer before (top) and after (low) validation (own representation based on calculations acc. to the master thesis by Brunet, 2021)

Table 2: Valdiation results: Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and the Coefficient of Determination (R^2) (source: calculations acc. to Brunet, 2021)

Index	3 week period	4 week period	Criteria
NMBE	7.9 %	-0.7 %	± 10 %
CV(RMSE)	20.5 %	25.9 %	<30 %
R^2	0.82	0.69	> 0.75

Conclusion

Even though the weather data came from a weather station 400 m away, a validation with this weather data is conclusive. Thus, the first research question as to whether it is possible to validate a thermal model with local weather and thermal data using a parametric simulation tool like TRNLizard can be answered in the affirmative. A validation using the parameter of air temperature is possible following several adaptions of the simulation model. This also satisfies the limitation criteria of the ASHRAE Guideline 14:2002. The values for the 3-week and 4-week time slots lie well within the NMBE range of ± 10% and the CV(RMSE) is within the upper limit of 30%. Only the lower limit of the Coefficient of Determination (R^2) at 0.75 can be complied with in the 3-week period, though this is not a criterion that has to be fulfilled.

To answer the second research question: the two main parameters that enable this validation are the infiltration rate and the thermal bridges. Lowering these parameters leads to an optimized thermal behavior for the summer and winter weeks. The indoor temperatures can thereby be raised to a level at which they almost coincide with the measured temperatures. However, this adaptation affects the results for the shoulder week, particularly the first week, in a slightly negative way, so that the criteria values change unfavorably. In the authers opinion, this may be due to the rather light construction and fast thermal responses of the test facility which needs to be examined in further studies.

Outlook

Since the validation was prove to be successful, a validated thermal simulation model of the test facility is now ready for further thermal simulations. This can be used as a basis for testing various control strategies, such as weather predicitve control strategy (WPC). These strategies may then conversely be performed at the test facility with the goal of reviewing the thermal model. In addition, adaptations to the model itself can be carried out, such as changing the envelope and usage, which can then be revalidated. Furthermore, this model may be adapted, so that a WPC can be examined in other locations (e.g. different climates) and various building typologies or types of usage to identify energy savings from a more global perspective.

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