**DIPLOMARBEIT**

Simulation-assisted monitoring-based thermal performance evaluation of Konrad Frey´s "Kindergarten Pachern"

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines

Diplom-Ingenieurs

unter der Leitung von

Univ.Prof. Dipl.-Ing. Dr.techn. Ardeshir Mahdavi

E 259/3 Abteilung für Bauphysik und Bauökologie

Institut für Architekturwissenschaften

eingereicht an der

Technischen Universität Wien

Fakultät für Architektur und Raumplanung

von

Dipl.-Ing. Christoph Lindner

Matrikelnummer 9925495

Hörnesgasse 22/19; A-1030 Wien

Wien, im Juni 2017.

Die vorliegende Arbeit ist meinem Vater, selbst Techniker,

der mich während meiner gesamten Studienzeit

und darüber hinaus großzügig unterstützt hat, gewidmet.

# KURZFASSUNG

Die vorliegende Diplomarbeit beschäftigt sich mit der thermischen Gebäudesimulation eines Kindergartens des österreichischen Architekten Konrad Frey. Konrad Frey gilt als Pionier der Solar-Architektur der 1970er Jahre in Österreich, war Mitbegründer der „Grazer Schule” und vertritt die Meinung, dass Architektur flexible, kostengünstige und zeiteffiziente Lösungen, in deren Mittelpunkt der Mensch steht, anbieten soll. Das erreicht er über den Einsatz von vorgefertigten Massenprodukten, die je nach Anwendungsfall zweckentfremdet und alltagstauglich eingesetzt werden können. *“Die höchste Qualität schrammt nahe am Banalen”* [Interview für die Sendereihe “A palaver” mit Konrad Frey] lautet einer seiner Grundsätze. In diesem Sinne ist auch der “Kindergarten Pachern” (1995-1998) in Hart bei Graz, welcher Forschungsgegenstand der vorliegenden Arbeit ist, zu verstehen. Als gelungenes Beispiel effizienter “Solararchitektur” ist der nördliche Bereich des Gebäudes in die Landschaft eingebettet, die Fassade, welche zu einem Großteil aus transluzenten handelsüblichen Garagen-Rolltoren besteht, öffnet sich großzügig Richtung Süden. Das Dach ist extensiv begrünt und bietet Platz für einen Kinderspielplatz. Auf einer Brutto Geschoßfläche von 600m² finden drei Gruppenräume, ein Turnsaal, Sanitärräume und zwei Büroräume Platz. Im Rahmen eines Forschungsprojekts der TU Graz in Kooperation mit der TU Wien werden richtungsweisende Gebäude Konrad Freys auf deren Funktionalität untersucht und deren Qualitäten evaluiert. Zu diesem Zweck wurden relevante Bereiche des Kindergartens im Sommer 2016 von einem Forschungsteam der TU Wien mit Sensoren ausgestattet und eine Wetterstation angebracht. Die Messdaten der Sensoren und der Wetterstation, Planmaterial sowie Interviews mit den NutzerInnen des Kindergartens bilden die Basis für ein computergeneriertes Simulationsmodell für die thermische Gebäudesimulation. Zur Bewertung der Übereinstimmung der simulierten mit den gemessenen Werten wird im Zuge eines systematischen Kalibrierungsprozesses die simulierte Innenraumtemperatur jeweils mit der gemessenen verglichen. Nach erfolgreicher Kalibrierung dient dieses virtuelle Modell des Kindergartens als Ausgangspunkt, um thermische Verbesserungen des vorhandenen Baubestands zu simulieren. Weiters können ursprüngliche Absichten Konrad Freys mithilfe dieses Modells nachempfunden werden und so Aufschluss über vorherige Bauzustände liefern. Den NutzerInnen können durch Simulationsszenarien (z.B. „Nachtlüftung”) wertvolle Hinweise zur Verbesserung des Innenraumklimas (z.B. Vermeidung sommerlicher Überhitzung) durch einfache Verhaltensmaßnahmen im Alltag gegeben werden.

# ABSTRACT

In the wake of an ongoing research project the late works of the Austrian architect Konrad Frey are going to be honoured. Konrad Frey can be seen as a pioneer of energy-efficient architecture who adapted the principles of modern solar houses already in the early 1970s. A number of Konrad Frey´s key buildings are evaluated and discussed by means of computational performance simulation methods within the nationally funded interdisciplinary research project that is being carried out by TU Graz in cooperation with TU Wien. This master thesis focuses on thermal performance evaluation of Konrad Frey´s “Kindergarten Pachern” (built in the late 1990s, located in Hart, near Graz, Styria) by means of deploying building simulation. The envelope design of “Kindergarten Pachern” follows design approaches that are characteristic of solar houses. On the one hand, the building is embedded in the local landscape´s morphology to minimize heat transmission losses and on the other hand, the facade opens up generously towards the south to optimize solar gains. Furthermore the roof is extensively green to offer a passive cooling strategy in the summer and can be used as a huge open air playground. “Kindergarten Pachern” is a single storey building with a total floor area of 600m² that contains standard facilities for the educational usage type “Kindergarten” such as three group rooms, one gym, two office rooms, sanitary facilities and a kitchen.

As a large number of randomly interacting variables combine to dictate the thermal performance of a building, the attempt of this project is to capture these complex natural processes virtually as accurately as possible by means of computational simulation scenarios. Therefore a set of environmental sensors and a weather station are deployed at “Kindergarten Pachern” to examine and support the accuracy of a virtual building model. A research team of TU Wien equipped the “Kindergarten Pachern” with a detailed monitoring system in the summer of 2016. The long term monitoring was carried out for one year to support the energy performance simulation process and the documentation of the building´s actual performance. A simulation model of “Kindergarten Pachern” was designed that was calibrated and evaluated by implementation and comparison with monitored data. The aim was to deploy data streams about outdoor and indoor building conditions to both populate the initial simulation model and to maintain its fidelity through a systematic calibration process. Furthermore plan material that was provided by the Municipality Hart and several on sight visits were incorporated in the process of the simulation model generation. To improve the accuracy of the simulation model interviews with the staff at the kindergarten were carried out on a regular basis to get an insight into user behaviour and the daily routine. Based on a calibrated model of the current state of the building, it was tested whether the original intentions of Konrad Frey in terms of thermal performance and comfort were met. As there have been some changes in the building compared to the original design of the building in the 1990s, previous states of the building were virtually reconstructed and evaluated with the calibrated simulation model. In a follow-up project, a "user manual" is going to be designed that addresses the user behavioural aspects and provides suggestions for the staff at “Kindergarten Pachern” on how to improve the thermal building performance by slightly changing their daily routine.

On the one hand, this work points out that monitored-based building performance simulation can be considered as a  powerful method to predict the “behaviour” of the buildings. As demonstrated in this thesis, the virtual model of “Kindergarten Pachern” reaches a precision level of around 5% (*CV(RMSE)* - values) difference of simulated and measured indoor air temperatures, which is a satisfying result. On the other hand, weaknesses and inaccuracies of building performance simulation which could be detected in the course of the work are discussed.

**Keywords**

Kindergarten, thermal building performance simulation, building monitoring, model calibration, local weather data, Energy-Plus, sensor deployment, refurbishment, cross ventilation, free cooling, solar architecture, Konrad Frey

# ACKNOWLEDGEMENTS

This contribution was written in the framework of the project “The sun houses of Konrad Frey: Environmental Research and Solar Design Knowledge”. This project is funded by the Austrian Science Fund (Grant No. P28677-G26).

The author would like to acknowledge Prof. Mahdavi for his prolific efforts in teaching and his enormous output of scientific work that served as a strong background for this work.

Furthermore, I would like to thank Matthias Schuss and Mahnameh Taheri for their valuable advice and comments, professional guidance and input throughout the process of writing this thesis. It was a pleasure to discuss thoughts and scientific questions with you.

Thanks to Robert and Michi, my former technical physics colleagues, Dominik and Alejandro for joining me at the library and to Werner and Martin.

Thank you, Elisabeth, for reading this paper!

Dear Catherine, thank you for your patience and radiant happiness!

As the following work marks a final point to my studies of physics which I began almost 20 years ago, I want to thank my parents at this point once more for their strong encouragement, support, and trust throughout all these years. Thank you.

Wien, June 2017.

# TABLE OF CONTENTS

# 1 INTRODUCTION

*"Designing sustainable buildings that also fulfil all operational requirements of the users is an unprecedented challenge for our times. Researchers, practitioners and other stakeholders are faced with enormous challenges due to the need to recognize and take account of various dynamic processes around us, such as: global climate change; depletion of fossil fuel stocks; increasing flexibility of organizations; growing occupant needs and comfort expectations; increasing awareness of the relation between indoor environment and the health and wellbeing of the occupants, and consequently their productivity"*

(Hensen and Lamberts 2011, p.1).

According to Green (2009), future buildings should on the one hand meet higher sustainable requirements and on the other hand, provide a positive indoor environment depending on parameters such as temperature, air quality, lighting and acoustic levels that are stimulating, healing or relaxing, according to the function.

According to Hensen and Lambert (2011) the focus of today's building performance is strongly put on cutting down the energy demand. As the relatively low volume of the new building projects in Central Europe has to be considered, it is necessary to widen the field of building performance analysis to existing buildings and refurbishment measures to reach the sustainability and comfort targets.

To achieve the goals mentioned above, computational building performance modelling and simulation is a powerful method to predict design impacts on the energy consumption of a building as well as on indoor climate and comfort levels.

Computational building performance simulation is multidisciplinary, problem-orientated and wide in scope. The power and complexity of building performance modelling and simulation arise from its interdisciplinarity. Mainly theoretical aspects of physics, mathematics, material science, human behavioural, environmental and computational sciences provide the background for building performance simulations. (Hensen and Lamberts 2011) Besides all the strengths and opportunities building performance simulation provides to predict "reality", we have to keep in mind that building performance simulation is only as good as the input parameters are defined and the simulation process is designed. As Polly (2011) remarks, it depends on the accuracy of the analysis and predictions whether a building performance simulation is a successful procedure. Bellinger (2004), from the field of operational research, remarked: *"After having been involved in numerous* *modelling and simulation efforts, which produced far less than the desired results, the nagging question becomes: Why? The answer lies in two areas. First, we must admit that we simply don´t understand. And, second, we must pursue understanding. Not answers but understanding"* (Bellinger 2004, p.1).

The following master thesis project will focus on building performance simulation, namely on the evaluation and calibration of thermal performance aspects of "Kindergarten Pachern", an existing educational building of the Austrian architect Konrad Frey located in Hart, Styria. The project is part of an ongoing research cooperation between TU Graz and TU Wien to evaluate and honour the late works of Konrad Frey. In the course of this research project "Kindergarten Pachern" was equipped with extensive monitoring infrastructure from the summer of 2016 till the summer of 2017. Simulation results are validated by being compared with the measured data (e.g. simulated and monitored indoor air temperature). To improve the reliability of this method different run periods (winter period, summer period) have been defined and simulated.

Considering the large number of parameters (e.g. material properties, occupants´ behaviour, internal gains) and uncertainties involved in the simulation process, a regular and systematic calibration-validation process is required to gain a promising potential toward increasing the accuracy of the predicted building performance.

## 1.1 Motivation

According to the World Business Council for Sustainable Development (WBCSD), the energy use in buildings can be cut down by up to 60 percent until 2050 if we act immediately (Hopfe 2011). Björn Stigson, president of the WBCSD, formulates: *"Energy efficiency is fast becoming one of the defining issues of our times, and buildings are that issue's 'elephant in the room'. Buildings use more energy than any other sector and as such are a major contributor to climate change"*

(Hopfe 2011, p.1).

Being an architect means having responsibility towards the built environment and towards the people we build it for.

Margarete Schütte-Lihotzky (2004) once mentioned that the beauty of architecture is based on the diversity and complexity of different disciplines that have to be merged. Therefore scientific aspects, sociological aspects as well as creative aspects have to be taken into account within the architectural discourse.

Planners and designers have to make all efforts possible to create sustainable and flexible, open minded and generous architecture that is ecologically friendly and economically affordable and fits people´s needs to a high extent. The only possibility to achieve these goals is to work interdisciplinary and combine all relevant sciences to achieve state of the art solutions that put the human being into the centre of interest.

As the work of Konrad Frey in general is very interesting, so is “Kindergarten Pachern”, which is a pretty good example of a low-budget as well as low-tech building that can be seen as a role model for further building development dealing with adaption and the re-usage of building components being used in a creative way. As the building performance demands for an educational building such as a “Kindergarten” are very high in general, the thermal performance of “Kindergarten Pachern” is an interesting example to be evaluated and eventually improved depending on the outcome. After calibrating the simulation model, methods to improve the thermal comfort qualities are going to be discussed and examined. Based on these results the building can be adapted to ensure the thermal comfort of the users.

This research project provides an opportunity to test the architectural design of Konrad Frey and to find out whether the original intentions in terms of thermal comfort are met at “Kindergarten Pachern” or whether optimization is needed to improve the overall building performance. Therefore the thermal simulation process of this master thesis will contribute to the field of research done so far in refurbishment and optimization projects.

## 1.2 Structure of the thesis work

*Chapter 1* “Introduction” prepares the reader for the following discussions and provides an overview of the work of the Austrian architect Konrad Frey. An interview with Konrad Frey that gives a deep insight into his personal thoughts and ideas about architecture is provided.

*Chapter 2* “Background” provides an overview of relevant research in the field of building performance simulation. State of the art solutions, background information and relevant literature reviews that form the basis for this work are going to be presented.

*Chapter 3* “Methodology” describes the scientific method of the present work and steps that were taken. The chapter ends with a hypothesis that has to be verified or dismissed depending on the results.

*Chapter 4* “Results” presents significant results and explanations where necessary.

*Chapter 5* “Discussion” sums up the final results accompanied by discussions and interpretations.

*Chapter 6* “Conclusion” is a summary of the most important results of the work and illustrates the scientific contribution of the work.

*Chapter 7* “Further research” raises questions that have not been solved in the frame of this master thesis and have been subjected to further research.

## 1.3 The work of Konrad Frey

The students *”had learned what being an Architect means these days”* and had been *“challenged to see architecture from the diversity of different points of view”* (Architektur Aktuell 2017, frontpage). These are feedback comments from students of Konrad Frey´s class at TU Graz. Konrad Frey (born in 1934) is considered as a pioneer in solar architecture. After studying chemistry in Graz and the USA he graduated in architecture at TU Graz in 1967 and worked for several years at “Arup Associates London” before he founded his first office in London together with Florian Beigel.

In 1974, he moved back to Austria and continued his work that is characterized by the joy and curiosity of experimenting (Architektur Aktuell 2017). Especially his early works (see Figure 1-1) show the utopian idealism and visionary faith in technological evolution. Influences of *Archigram*, *Yona Friedman* and the *Japanese Metabolists* can be found (Architektur Steiermark 2017). As a key representative of the avangardistic Graz School of Architecture (Grazer Schule) - alongside with Günter Domenig, Helmut Richter, and others - Frey´s works deal with a wide range of different types of buildings spanning from social housing to private residences, schools and office buildings. Frey´s interests in energy-efficient buildings date back to the early 1970s. With “Haus Fischer” (see Figure 1-2) at Grundlsee, Styria, (1975-77) he created Austria´s first solar house the so-called “Sonnenhaus Österreich”. His pioneering work has to be seen in the integration of both active and passive solar components (Schuß et al 2016). “Haus Zankel“ (CH, 1977-85), an experimental solar house near Genf (see Figure 1-3), represents a key building of the avangardistic Graz School of Architecture. To show the wide range of Konrad Frey´s work, a few more buildings have to be mentioned, such as the “Kinderhaus mit Solardusche für Älpler” (AT, 1980); “Kunsthaus Mürzzuschlag” (AT, 1991); “Sozialbauten Dosenfabrik” (AT, 1991); “Bildungshaus Schloß Seggau” (AT, 1994); the “Cogenerationskraftwerk Magna” (AT, 1997); and “Kindergarten Pachern” (1995-98). Characteristic of all his work is a high functionality that is expressed in high grades of detailing during the design process, a focus on economical aspects and the use of prefabricated elements in a non-expected context (TU Graz 2017). To put it in a nutshell, Konrad Frey´s goal is to build “better – simpler – cheaper” by using ordinary market products from e.g. “Baumarkt”. These common mass-products are put in an adequate context to build “Low-Budget-Loft-Houses” designed in a smart way (Nextroom 2017).

*„Buildings have to improve, have to become rich, useful, user-friendly and dense, but with simple means. Architecture has to disturb, has to offer more than the client can imagine”* (Konrad Frey in Nextroom 2017, frontpage).

The obtained experiences are summed up in multiple publications. Konrad Frey was one of the co-authors of one of the first handbooks for energy-efficient building designs published in Austria (Wagner and Böck 2013).

### 1.3.1 Exemplary projects and buildings by Konrad Frey

Konrad Frey´s early works deal with functionalistic modern architecture and controlled environment in a critical way. His design intents show a similar approach as Reyner Banham´s well-tempered environmental ideas. Although the utopian concepts that still appear futuristic - suggesting innovative technologies necessary to lead society into a new and brighter surrounding – were not built, they provided a strong and relevant background for following generations of architects. The collage above (Figure 1-1) shows his manifesto "Aufruf an alle Grazer" (1966) for the refurbishment of the Municipality Building of Graz. Konrad Frey interpreted architecture by that time as a monumental landscape with adaptive temporary spaces that are movable and flexible to be able to interact and to fit users´ needs at any given time (Architektur Steiermark 2017).

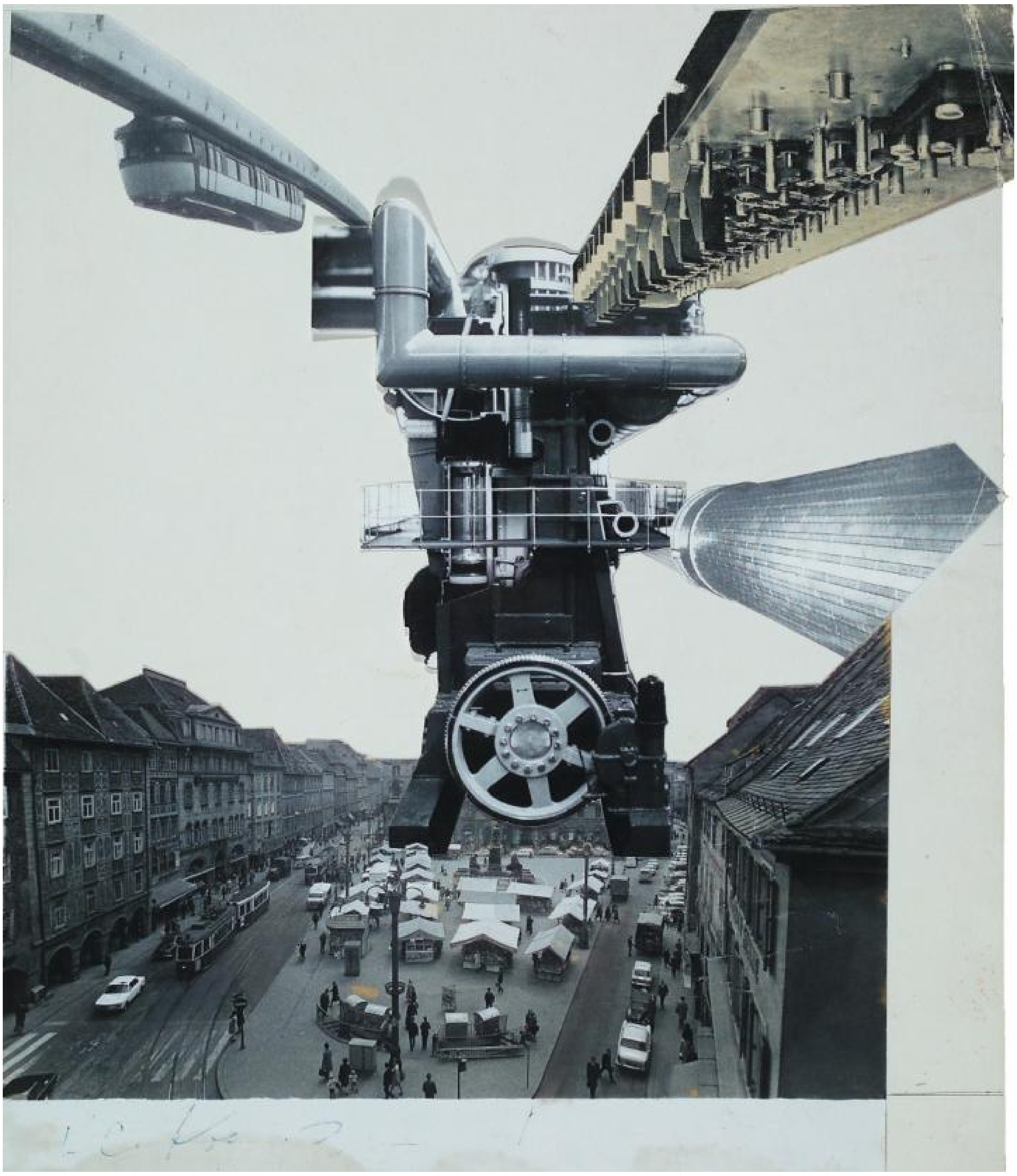

*Figure 1-1 Manifesto "Aufruf an alle Grazer", 1966 (source: Architektur Steiermark 2017)*

As a result of the oil crisis in 1973, local and cheap wooden materials were chosen for the main construction of “Haus Fischer” (Figure 1-2). To maximize energy efficiency, the building is integrated into the landscape and orientation and shadings are optimized to adapt to the summer and winter sun. What made the concept unique was the integration of solar panels on the roof and south facade. “Haus Fischer” was the first solar house in Austria by that time (Nextroom 2017).

*Figure 1-2 External view "Haus Fischer" Grundlsee, 1975-77 (source: Nextroom 2017)*

“Haus Zankl” (Figure 1-3) marks a key project of “Grazer Schule” and is an early example of active and passive solar usage. With a strong sculptural approach the building was designed for a CERN scientist and works both as an experimental solar laboratory and a representative housing project (TU Graz 2017).

*Figure 1-3 External view "Haus Zankl" Geneve, 1976-85. (source: TU Graz 2017)*

### 1.3.2 Interview with Konrad Frey

Konrad Frey revealed key aspects of his career and approaches towards architecture in an interview with David Pasek and Bernhard Frodl recorded for “A Palaver” on June 4th, 2016. His works, especially “Kindergarten Pachern”, has to be seen in the context of his understanding of architecture, which is outlined in the following passage.

*“It is interesting that I - after spending my youth on utopian architecture - turned my focus of interest to the analysis of real building processes, especially the planning and construction process. As I learned from the very beginning that architecture is a teamwork process between various fields of science - especially concerning technical aspects - it is necessary to work in an interdisciplinary way to design a good "product", a comfortable house. I have always liked visiting construction sites. The experience with the building process has an impact on ready-made and prefabricated building parts as used in the field of the prefabricating housing industry. [...] The architect´s work is to design smart floor plans that can be realised with the use of prefabricated elements that are combined and planned in an innovative way. Time-effectiveness, which can be reached by using prefabricated elements is an important factor that is often demanded by the client. Cedric Price once mentioned that if a client wants to have a house designed, he first asks: “Do you really need a house? How do you live? Are there any alternatives besides a house?” [...] A house is a burden. It takes a long time to build it, it is often hard to sell, and it is a huge problem if the needs of the clients change in the course of time. That is a huge handicap and a disadvantage of the architect´s work. Therefore it is necessary to find an alternative way to build houses apart from those with massive, heavy concrete and stone walls that are built to last. We have to find a new way to design not only "houses" but light-weight and flexible "living spaces". Therefore a utopian approach that takes into account the user´s needs during a lifespan as for example changes in relationships, changes at work, changes in society, is a promising design strategy. [...] In the 1070s, it was interesting to deal with alternative forms of energy like solar energy. In terms of economical aspects it was much more efficient to cut down the energy demand of buildings by means of refurbishing existing buildings with thermal insulations than to only focus on renewable energy production. To my mind, state of the art products and technical details that exist on the global market should be examined and explored in on site experiments to*

*achieve further improvements. In this respect, even a cost limit is a challenge for me. It is much easier to design a building where costs do not matter, as for example the EZB building. To design low-budget, high-performance buildings is a challenging process. [...] A detailed and smart planning process should focus on producing a functional, satisfying building causing low costs and a minimum of efforts. [...] One huge disadvantage of the architectural process is that we always build prototypes. Every building starts from the very beginning over and over again in terms of size, materials, opening, and technical equipment. For example, for the automobile industry that would be a disaster. They build a dozen of prototypes before they start mass production. That makes the architectural process very complex. [...] The challenge is to adapt ordinary prefabricated elements that are available at the market, which is cost-efficient and time-efficient, and transform them into something sophisticated to design state of the art houses. The highest quality is always close to banality. A spectator is always impressed if something makes a strong and good impression but is made of simple and cheap elements that are usually being neglected. [...] A smart combination of existing elements, not inventions, is the key factor for a successful and satisfying building. [...] Architects should not only build for a small elite that can afford high budget projects."* [Interview with Konrad Frey, recorded on June 4$^{th}$, 2016, translated by the author.]

The interview can be re-listened in full length in German at: https://cba.fro.at/319671

# 2 BACKGROUND

The following parts will focus on relevant literature reviews in three main categories:

- Building thermal performance simulation
- Monitoring assisted thermal simulation
- Calibration of thermal simulation models

## 2.1 Building thermal performance simulation

Building performance simulation models play a significant role in design and optimisation processes of built environment. Simulation models can be used to define energy conservation methods at the design state as well as to propose various performance optimisation measures in the operational phase of a building. Therefore energy simulations are implemented frequently throughout the whole architectural process.

Building performance simulation (BPS) works with computer-based models that cover performance aspects such as energy consumption and thermal comfort in buildings. Crawly (2003) describes BPS as *"a powerful tool which emulates the dynamic interaction of heat, light, mass (air and moisture) and sound within the building to predict its energy and environmental performance as it is exposed to climate, occupants, conditioning systems, and noise sources"* (Hopfe 2009, p.1).

However *"the key issue of reproducing real-world processes with simulation models is the inaccuracy of results, if the model does not precisely represent the real world situation"* (Mahdavi et al. 2015, p.265).

In order to understand the building energy simulation process it is necessary to give an overview of scientific models in general. Coakley et al. (2014) distinguish between Law-Driven or Data-Driven models (see Figure 2-1).

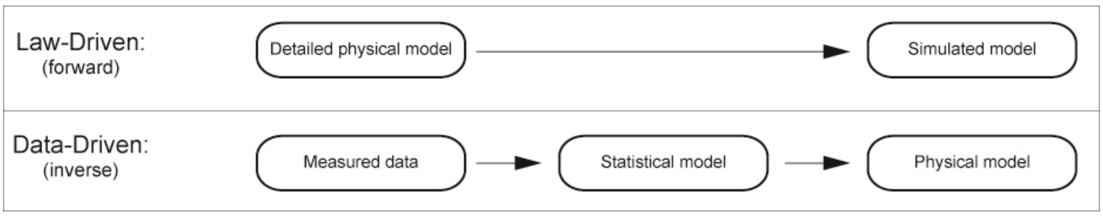


*Figure 2-1 Law-Driven vs. Data-Driven method according to Coakley et al. (2014)*

According to Coakley et al. (2014), BPS models, as used in building design, can generally be classified either as prognostic Law-Driven models that predict the behaviour of a complex system given a set of defined laws (e.g. gravity, heat/mass transfer etc.) or as Data-Driven models that are used in the context of building energy modelling. They refer to methods which are based upon monitored data from the building to design models which accurately predict system behaviour. A more detailed discussion of scientific modelling options would extend the framework of this master thesis.

Prognostic Law-Driven building energy simulation tools allow predictions about the buildings´ behaviour and energy consumption under the influence of external inputs such as weather, occupancy and equipment loads. In terms of thermal building simulations detailed heat balance calculations are carried out at discrete time steps according to the physical properties of the building (e.g. geometry, construction, etc.) as well as the dynamic inputs (e.g. occupancy behaviour) (Coakley et al. 2014).

A short historical overview of BPS in general and the foundation of ASHRAE (short for American Society of Heating, Refrigerating and Air-Conditioning Engineers) that plays an important role in establishing common standards in particular, provides better understanding of ongoing research projects.

Building thermal simulations were started in the early 1960s by gas and electric industries, initiating a process that led to the formation of the ASHRAE Task Group on Energy Requirements to develop a comprehensive hourly energy performance of buildings (Kusuda 1999). "*ASHRAE, founded in 1894, is a global society advancing human well-being through sustainable technology for the built environment. The Society and its members focus on building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the industry. Through research, standards writing, publishing and continuing education, ASHRAE shapes tomorrow's built environment today*" (ASHRAE 2017, frontpage). An essential aspect of ASHRAE is that it responds to the societal need to reduce energy use in buildings. The oil crisis in the early 1970s and the development of computer technology stimulated rapid improvements in calculation procedures to predict the thermal performance and energy requirements of buildings of all kinds. Besides peak-load and energy calculations the rising interest in solar energy applications played a major role in ASHRAE (Ayers & Stamper 1995).

As Mahdavi (2011) states, building performance simulation traditionally focuses on the design phase of a building; however, it can be implemented in the building operation phase as well. The potential of simulation routines is more and more tested in the building´s operation phase. A predictive system operation approach in particular has the potential to be incorporated in a building´s control system. In fact the quality of such systems depends on the reliability of the deployed simulation model. Therefore simulation models have to be calibrated and time dependent changes in building and boundary conditions (e.g. seasonal variation in climatic conditions or occupancy-dependent changes in use patterns) have to considered in the calibration process (Mahdavi and Tahmasebi 2012).

For generating an initial 3D model and carrying out simulations and calibrations for both design and operation phase, many different software tools are available. An updated list of various building energy simulation programs for calculating energy use in buildings is maintained by the U.S. Department of Energy (https://www.energy.gov/).

However, according to Oh and Haberl (2016) these programs often show significant differences in results for similar buildings.

Nevertheless, it is necessary to carry out energy simulations routinely during the design phase and to widen simulations on existing buildings more quickly to achieve ambitious and necessary energy saving targets. Especially in Central Europe refurbishing projects have to be carried out systematically because the huge amount of old building mass consumes a high amount of energy. In Austria, almost ¼ of energy consumed by private households is used for heating (Österreichs Energie 2017).

Performance simulations of existing buildings can, on the one hand, confirm the original design intents concerning energy demands and comfort, and on the other hand, can provide an outlook on further adaptations of the building to improve its performance. In fact, energy simulation represents a tool to assess the energy performance of buildings and to optimize the choice of different energy efficiency measures from an energetic and an economic point of view (Penna et al. 2015).

To carry out thermal performance simulations several types of parameters are required in advance. According to Heo et al. (2012), a short overview can be given as follows:

- Outdoor environment (weather data) due to its impact on indoor conditions
- Thermal properties of the construction components
- Specification of the ventilation and infiltration rate
- Heating and cooling systems

- Internal loads such as occupants, lightings, etc.

Due to the complexity of the stream of parameters involved in simulation processes an accurate representation of real-world behaviour can only be estimated more or less closely.

*“The built environment comprises a complex set of interactions of heat, mass and momentum transfers. These transfers interact dynamically under the action of occupant and system control. The problem of representing such time varying interactions in a manner suitable for prediction and evaluation of alternate designs has been addressed by many researchers”* (Macdonald 2012, p.1).

According to Heo et al. (2012), recent studies on building performance simulation show significant discrepancies between model predicted and actual metered building performance values. In current practice, building simulations are routinely performed with best guesses of input parameters that might more or less correspond to "real" values.

Assumptions, simplifications, lack of knowledge and modelling mistakes can cause inaccuracies. For example, building constructions might differ from plan material or simplification of geometry might lead to incorrectness of the simulation results. According to De Wit (2004), sources of uncertainty can be classified as first specification related, second modelling related and third scenario related.

Coakley et al. (2014) provide a compact overview of uncertainties and most influential input parameters that might lead to major errors in simulations:

- Specification uncertainty: arising from incomplete or inaccurate specification of the building or systems modelled.
- Modelling uncertainty: simplifications and assumptions of complex physical processes.
- Numerical uncertainty: errors introduced in the discretisation and simulation of the model.
- Scenario uncertainty: external conditions imposed on the building, including probabilistic (e.g. weather data) and stochastic (e.g. occupancy behaviour) elements.

According to Taheri (2013), controllable and uncontrollable sources of errors can be distinguished. To provide a better understanding, controllable errors would be for example inaccuracy in material properties due to the lack of information or the simplification of geometry and abstractions made during the modelling process.

Uncontrollable errors might result from the calculation methods or options provided by the simulation programme. Therefore the user should have a deep insight into the workflow, possibilities and limits of the software and should have detailed information about the building and site conditions of the building being investigated (Westphal and Lamberts 2005).

As we want to have a simulation model that is able to predict “real” performance data in the end it is one of the most critical points within the simulation process to estimate and capture the factors of inaccuracy and their impact on the simulation results.

According to Mahdavi and Tahmasebi (2012), an additional essential parameter to be considered in performance simulations is the “dynamic nature of the building operation”. Even in a short time span of one year there are changes in the factors effective on the building performance that might range from environmental conditions to occupants` behaviour.

Stochastic elements such as occupant behaviour are becoming more and more a topic of research as it is widely recognized as a major contributing factor to uncertainty of building performance simulations. However there are still many gaps in knowledge and limitations to current methodology concerning occupant behaviour (Yan et al. 2015).

As Mahdavi (2011) states, users affect the performance of buildings on the one hand due to their presence (e.g. internal gains) and on the other hand, due to their actions (e.g. user behaviour).

According to Royapoor and Roskilly (2015), an increasing body of research has come to recognize that occupancy related issues act as a more prominent source of uncertainty in model predictions than previously assumed, leading to efforts to develop case-specific stochastic models of occupancy.

Consequently this is a fact that has to be strongly considered when simulating an educational usage type such as a kindergarten because the children´s behaviour is much harder to predict and less documented than for example the occupants´ behaviour of an office building.

## 2.2 Monitoring assisted thermal simulation

To obtain reliable prediction from a simulation process, monitored field data can be deployed to calibrate the simulation model.

A standard monitoring setup consists of a four-layer model (Figure 2-2) namely management level, automation level, field bus level, and physical level (Schuss 2016).

- Management level: stores the measured data and can provide a graphical interface. Further processing and visualizations take place on this level.
- Automation level: the monitored data is passed to the control station. Automation levels handle higher data rates than the previous one (e.g. *Arduino YUN* based data logger recorded the collected sensor data locally at "Kindergarten Pachern" and forwarded it via UMTS-Modem to our central monitoring data repository at TU Wien)
- Field bus level: on that level the measured data is transferred to the automation level (e.g. *ENOcean* wireless transmitters at "Kindergarten Pachern")
- Physical layer: sums up the devices that are necessary for data collection (e.g. indoor air temperature sensors at "Kindergarten Pachern")

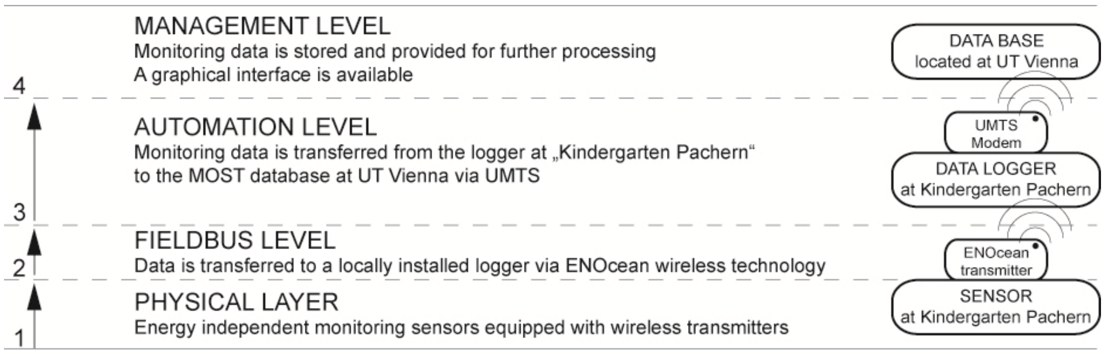


*Figure 2-2 Schematic description of data levels*

The monitored data fulfils two functions. On the one hand it defines a basis for the input parameters of the simulation model. On the other hand, measured data is necessary for the evaluation and calibration process to compare the simulated values with the measured values.

According to Taheri et al. (2013), the initial building model has to be populated with dynamic monitored data such as device states (window and door contacts), user behaviour (occupancy sensors), and internal loads (e.g. lights, radiators). The simulated model can be evaluated on the basis of the measurements by comparison (e.g. indoor temperature).

Validation of the simulation model by comparing the simulated and the measured values is a promising method according to Taheri (2013).

Furthermore, a local weather file needs to be created to carry out precis simulations. Local weather data is much more precis than a “typical year” weather file which can be obtained for bigger European cities (e.g. Graz) at the *Energy-Plus* website. Recorded weather data is needed to design a suitable local weather file.

As weather is one of the primary determinants of indoor conditions, Qingyuan et al. (2002) proposed that the least required information for generating a local weather data file are hourly records of the following parameters:

- outdoor temperature
- relative humidity
- wind speed
- direct and total solar radiation.

## 2.3 Calibration of thermal simulation models

Whenever using computer simulations, a validation process of the predicted results is necessary in order to assure accuracy, plausibility and consistency. The process of reconciling model outputs (results) with measured data is called calibration.

*“Calibrated simulation is the process of using a building simulation program for an existing building and “tuning” or calibrating the various inputs to the program so that predictions match closely with observed energy use. Historically, the calibration process has been an art form that inevitably relies on user knowledge, past experience, statistical expertise, engineering judgment, and an abundance of trial and error”* (Reddy et al. 2007, p221).

The level of accuracy and plausibility of simulation results (predictions) can always be judged by a comparison with measurements. Different types of statistical analysis are available.

At the beginning of the building simulation, simple percent difference was the primary method to define the quality of simulated and measured data. (Coakley et al. 2014) Nowadays standardized statistical indices which better represent the performance of a simulation model are available.

The Mean Bias Error *(MBE) and the* Coefficient of Variation of the Root Mean Square Error *CV(RMSE)*, presented in equation (1-3), allow to determine how well a model fits reality by capturing offsetting errors between measured and simulated data at any time step. Whereas *MBE* values provide an indication of errors averaged to the mean of measured values they suffer from a cancelation effect. *CV(RMSE)* values however are measurements of the accumulated error normalized to the mean of measured values. Therefore *CV(RMSE)* is a better indicator of the overall prediction accuracy of the simulation model (Royapoor and Roskilly, 2015).

$$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{\sum_{i=1}^{n}(m_i)} \quad [\%]$$ *eq. (1)*

whereas:

m = tm1, tm2, tm3, ..., tmn (monitored values, e.g. indoor air temperature)

s = ts1, ts2, ts3, ..., tmn (simulated values, e.g. indoor air temperature)

n = number of time steps (depending on the run time)

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \quad [°C]$$ *eq. (2)*

whereas:

m = $tm_1$, $tm_2$, $tm_3$, ..., $tm_n$ (monitored values, e.g. indoor air temperature)

s = $ts_1$, $ts_2$, $ts_3$, ..., tmn (simulated values, e.g. indoor air temperature)

n = number of time steps (depending on the run time)

$$CV(RMSE) = \frac{RMSE}{\bar{m}} \cdot 100 \quad [\%]$$ *eq. (3)*

whereas:

$\bar{m}$ is the mean of measured values

Building energy simulation models are generally considered ‘calibrated’ if they meet the criteria set out by ASHRAE Guideline 14. ASHRAE Guide 14 considers a building model calibrated if hourly *MBE* values fall within +/- 10% and hourly *CV(RMSE)* values are smaller than 30% (Royapoor and Roskilly 2015).

Calibration itself can take place in different types of methods.

Coakley et al (2014) propose four classes to calibrate a simulation model:

- Calibration based on manual, iterative and pragmatic intervention.
- Calibration based on a suite of informative graphical comparative displays.

- Calibration based on special tests and analytical procedures.
- Analytical / mathematical methods of calibration.

Furthermore, they distinguish between *manual* and *automated* calibration.

*Manual* means that this method depends on the modeller´s ability to carry out systematic calibration steps manually. No form of automation process is employed.

*Automated* means that there is an automated process (not user driven) involved to assist or complete model calibration (for deeper insight into these methods please see, for example Coakley et al (2014)).

As mentioned before, thermal performance simulation models are dependant on a complex and wide range of input factors. It is computationally expensive to spot all these variables. Therefore methods such as "sensitivity analysis" can be developed to find the most influencing set of parameters and cut down the number of variables in the optimization process. (Taheri et al. 2013)

In practice, it is important to identify a set of parameters of input factors that have a major impact on the simulation results. These input factors can be altered step by step (namely calibration steps) as long as the predictions of the simulation model reach a satisfying level.

To sum up the difficulties of Building Energy Performance Simulations (BEPS), Table 2-1 provides a summarized overview of difficulties in performance simulations and calibrations:

*Table 2-1 BEPS model development and calibration issues according to Coakley et al.(2014)*

| **BEPS modelling issues** | **BEPS calibration issues** |
|---|---|
| **Standards:** Lack of understanding and consistent use of standardized methods<br>**Expense:** The time, knowledge, expertise and cost required to develop accurate models of building geometry and HVAC systems | **Standards:** Lack of explicit standards for calibration criteria current guidelines only specify acceptable error ranges for yearly whole-building simulation, but do not account for input uncertainty, sub-metering calibration, or zone-level environmental discrepancies |
| **Integration:** Poor integration between various 3D modelling software packages (such as *Autodesk Revit* and *ArchiCAD*) and BEPS simulation packages (such as *Energy-Plus*, *TRNSYS* and *Modelica*) | **Expense:** The expense and time needed to obtain the required hourly sub-metered data, which is usually not available |
| | **Simplification:** Calibration is an over-specified and under-determined problem. There are thousands of model inputs but relatively few measurable outputs with which to assess the model accuracy |
| | **Inputs:** Lack of high-quality input data required for detailed models |
| | **Uncertainty:** There are currently few studies which account for uncertainty in model inputs and predictions, thus leading to a lack of confidence in BEPS outputs |
| | **Identification:** Problems identifying the underlying causes of discrepancies been model predications and measured data |
| | **Automation:** Lack of integrated tools and automated methods that could assist calibration |

# 3 METHODOLOGY

The following chapter describes the scientific method of the present work and steps that were taken. The chapter ends with a summary of key aspects that have to be verified or dismissed depending on the results.

## 3.1 Objective

In the wake of an ongoing nationally funded research project this master thesis deploys building simulation to asses the energy performance with the focus laid on designing a thermal performance model for an existing educational building in Hart, next to Graz, Austria. The case study of this thesis is “Kindergarten Pachern”, built in the late 1990s by the Austrian architect Konrad Frey, a pioneer of energy-efficient architecture (compare *Chapter 1*). To improve the accuracy of the thermal performance model a monitoring system was installed at the kindergarten in July 2016 by a research team of TU Wien to provide long-term monitored data for the simulations. Data streams which were incorporated as simulation input information were regularly collected over a period of one year with a variable frequency depending on the magnitude of changes in the relevant recordings. This study from modelling the initial model, over creating an accurate weather file, to calibrating and evaluating the thermal performance model is based on the recorded data stream, a detailed building documentation consisting of plan material and several on sight visits. Figure 3-1 schematically outlines the workflow to generate an accurate and stable simulation model that is suitable for practical purposes and marks a starting point for further optimization processes to improve the thermal performance of the case study.

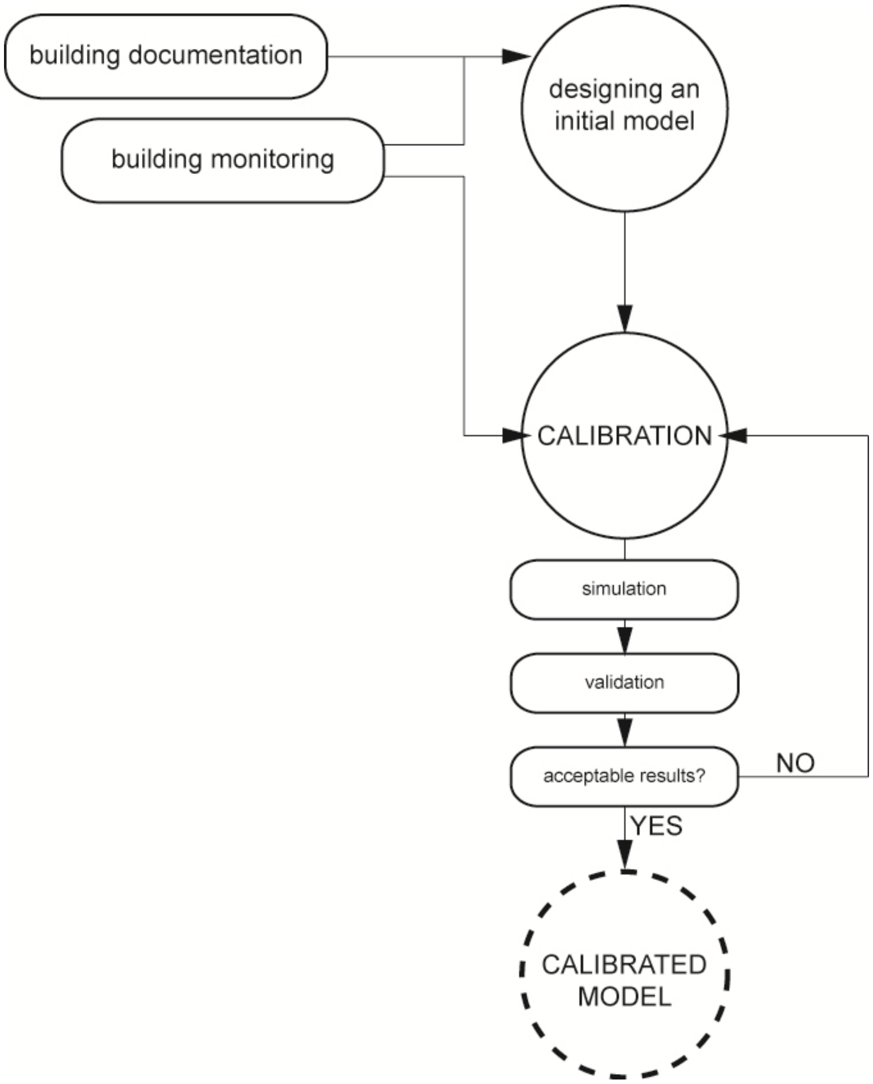


*Figure 3-1 Objective mind map for the simulation-calibration process of "Kindergarten Pachern"*

## 3.2 Modelling

The 3D modelling was done in *Sketch-Up Make 2015* provided by *Trimble* (https://www.sketchup.com/de). *Sketch-Up* is a user-friendly and intuitive tool for architects and engineers to quickly model and estimate building volumes and design surfaces. It provides a suitable Graphical User Interface (GUI) and allows to use plug-ins from other companies. *Energy-Plus* (EP) version 8.4.0 provided by the US Department of Energy (https://energyplus.net/) was the building simulation tool used for all thermal simulations. *Energy-Plus* is an open source and cross platform energy analysis and thermal load simulation programme (Energy-Plus 2015). To transfer all relevant data and geometry from *SketchUp Make 2015* to *EP* the *OpenStudio*

*SketchUp Plug-In* (version 1.9.0) provided by the US Department of Energy (https://www.openstudio.net/) was used as an interface. To handle the huge amount of data collected by the sensors *MATLAB R2014b* routines have been developed. *MATLAB* provided by *MathWorks* is a matrix-based programming language for solving technical-scientific problems which provides a graphical interface. (MATLAB 2017)

All mentioned tools are accurate and widely used. Except *MATLAB,* all applied tools are available for free.

To carry out thermal building performance simulations an accurate model which physically behaves as closely as possible to reality in terms of thermal performance has to be designed as mentioned in *Chapter 1*. The modelling process is characterized roughly by two main impact factors (Taheri 2013).

- First physical input data e.g. geometry, materials with their characteristic physical qualities and thermal properties, and constructions have to be defined.
- Second, dynamic input data like monitored data, a suitable weather file and occupants´ behaviour have to be implemented.

The more precis the modelling and assigning of properties is done, the better the CAD 3D-model will perform in simulations. Therefore extensive input data is necessary (Energy-Plus 2016).

### 3.2.1 The case study building - location and geometry

Konrad Frey´s “Kindergarten Pachern” built from 1995 to 1998 (see Figure 3-2 and Figure 3-3) is located in Hart next to Graz, Austria.


*Figure 3-2 Location "Kindergarten Pachern" (source: Google maps 2017)*

It is a single-storey building with a total floor area of 600m². As a fully functional solar house, it is integrated in the surrounding landscape. For passive solar gains it opens up towards the south whereas the north areas are embedded in the local landscape to utilize the benefits of reduced transmission losses via ground-adjacent building components (Schuss et al. 2016, Architektur Steiermark 2017).

*Figure 3-3 External view "Kindergarten Pachern"*

The roof is extensively green (Figure 3-4); therefore it offers a passive cooling strategy in the summer and it is used as a huge open air playground for the children including a slide from the upper level to the ground level.

*Figure 3-4 Rooftop playground at "Kindergarten Pachern"*

The building provides four group rooms (each approximately $60m^2$), an office space (approximately $40m^2$) and rooms like wardrobe and sanitary rooms situated alongside a generous corridor (see Figure 3-5, Figure 3-6 and Figure 3-7).

*Figure 3-5 Internal view "Kindergarten Pachern", internal corridor*

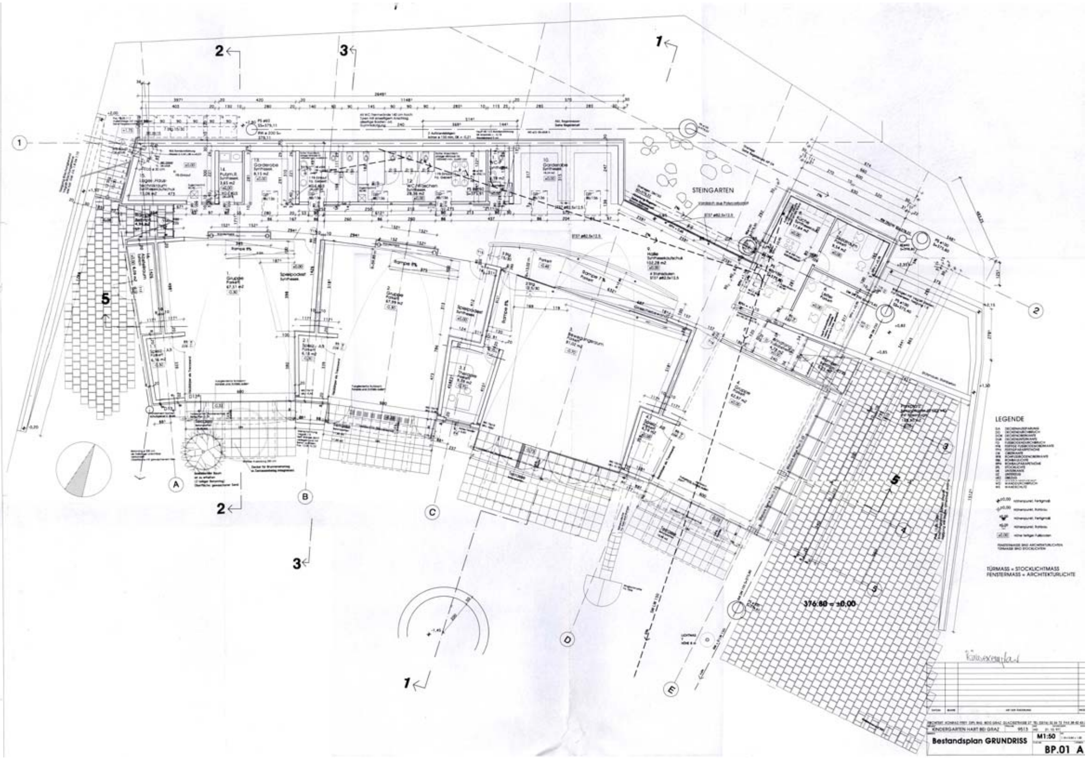


*Figure 3-6 Historical floor plan of "Kindergarten Pachern" (source: Municipality Hart)*

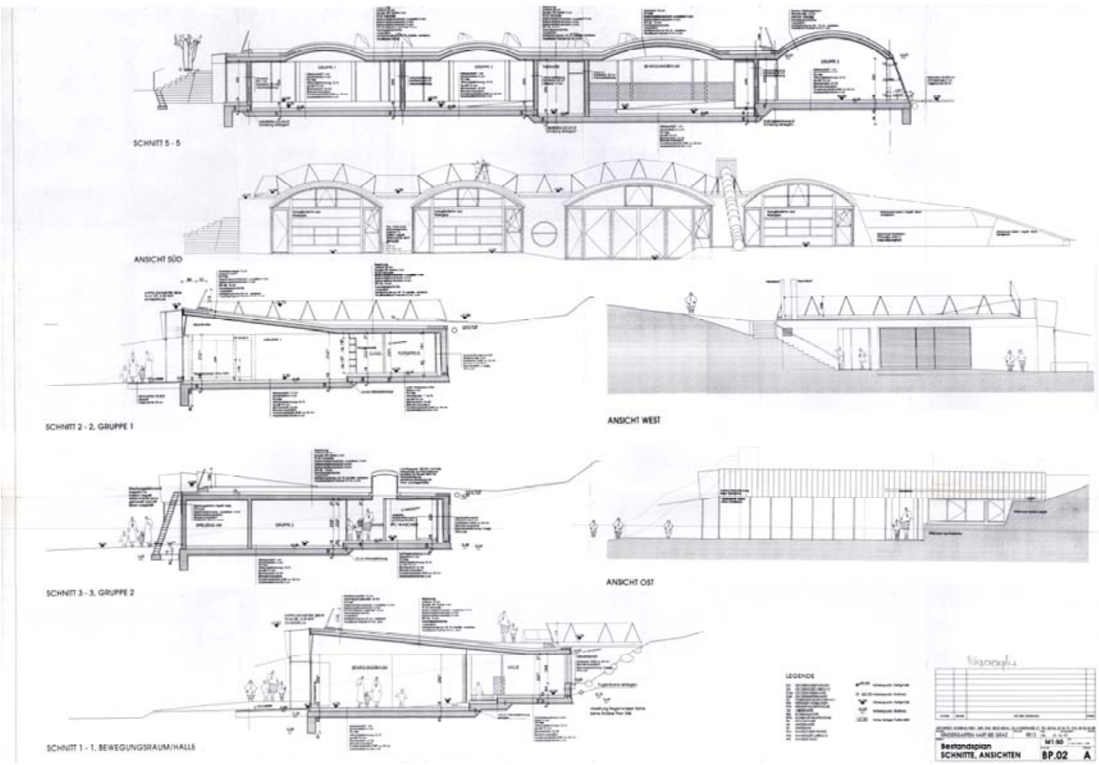


*Figure 3-7 Sections and views of "Kindergarten Pachern" (source: Municipality Hart)*

Note that, “Kindergarten Pachern” was built with simple and cheap material and building elements that are assembled in a smart way to design a low-budget as well as low-tech building. In his late works, Konrad Frey tried to use ordinary, cheap and prefabricated mass production elements that are combined in a smart way to be used for building these elements were not intended for originally (compare: interview with Konrad Frey by David Pasek 2016, *Chapter 1*). For example, ordinary garage rolling doors are used as facade panels for “Kindergarten Pachern” as shown in Figure 3-8. These industrial rolling doors fulfil two functions: On the one hand, they offer the opportunity to open up large parts of the south facade and therefore allow daylight and shortwave radiation to penetrate the building. On the other hand, the open doors create a seamless transition from the inside to the outside from an architectural point of view.

*Figure 3-8 Garage rolling door at a group room*

To gather all necessary data for modelling the geometry of “Kindergarten Pachern” (Figure 3-9) in *Sketch-Up*, the floor plans and sections provided by the Municipality Hart, on-site measurements and observations were put together.

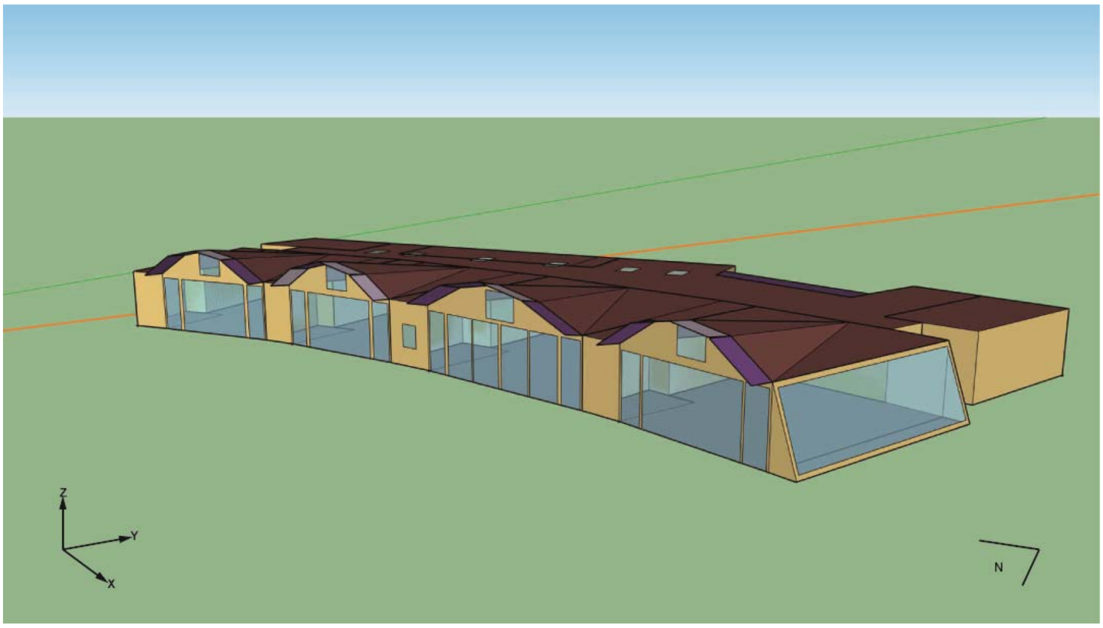


*Figure 3-9 3D CAD model of "Kindergarten Pachern"*

### 3.2.2 Thermal properties of the constructions

Every material has specific properties that define the quality of a construction in terms of, for instance, thermal performance, visual performance, and acoustic performance. If a construction is built with different layers in a certain order we speak of a "multi-layered" component. Almost all building parts in contemporary buildings are multi-layered components because the advantages of single materials can be combined in the most satisfying way for a specific building demand in a specific region and climate zone.

Thermal building performance simulation programs have to be filled with information about every material that is used in the model at the very beginning of the simulation process. All further calculations and simulations are based on that information. The more precis this information can be provided, the more accurate the results of the simulation will be in the end.

In the second step, constructions for building components are defined. Each material plays a different role within a construction. Therefore, it is necessary that each construction combines the materials in the right order with sufficient strength.

If we take a look at an outside wall for example, we would use material that is stable enough to carry all loads (horizontal and vertical), material that servers as a thermal envelope, material that acts as vapour barrier and material that covers the construction at the outside and if wished at the inside. To give an example, a typical construction (Figure 3-10) for an outside wall in Central Europe would be as follows (Neufert 2016).

(listing from outside layer to inside layer)

- exterior plaster (1cm) = outside cover / protection
- XPS panel (12cm) = thermal envelope
- PE membrane ( - ) = vapour barrier
- concrete wall (15cm) = statics / load carrier

optional: interior plaster as an inside (visual) cover of the construction.

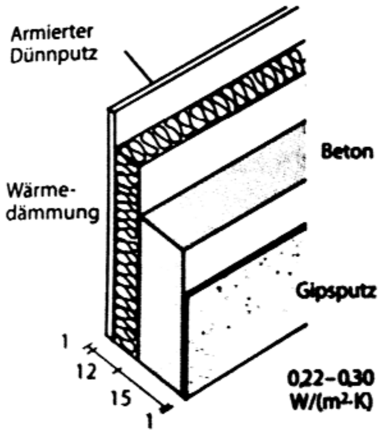


*Figure 3-10 Examplary outdoor wall construction (source: Neufert 2016)*

Properties of materials can be found at various sources. For this work, exclusively *Baubook* (BB) material definitions were used. *Baubook* is a library for ecological building- and refurbishment materials. It is an information and communication platform for sustainable eco-friendly and energy efficient building projects. (Baubook 2016)

Information about building parts and constructions of “Kindergarten Pachern” was provided by the Municipality of Hart. Additional information about window and door constructions was either gathered through on site surveys or taken from product catalogues of manufacturers. All thermal properties of the constructions were set according to the real, existing setup.

Table 3-1 and Table 3-2 give an overview of all applied material properties and constructions of the simulation model.

*Table 3-1 Constructions and Properties of the enclosure elements*

| **Building Component** | **Layers** outside to inside | **Thickness** [m] | **Conductivity** [W/mK] | **Density** [kg/m³] | **Specific heat** [J/kgK] | **Source** |
|---|---|---|---|---|---|---|
| **ROOF Green** (flat) | Substrate | 0,25 | 1,5 | 1200 | 1670 | BB |
| | Polyester membrane | 0,03 | 0,5 | 300 | 792 | BB |
| | PE membrane | 0,001 | 0,5 | 980 | 1260 | BB |
| | Bitumen sheeting | 0,015 | 0,17 | 1200 | 1250 | BB |
| | EPS panel | 0,14 | 0,035 | 28 | 1450 | BB |
| | Vapour barrier | 0,001 | 0,5 | 650 | 1260 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Reinforced concrete floor | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Acoustic plaster | 0,025 | 0,15 | 500 | 1000 | BB |
| **ROOF Green** (tons) | Substrate | 0,1 | 1,5 | 1200 | 1670 | BB |
| | PE membrane | 0,001 | 0,5 | 980 | 1260 | BB |
| | Bitumen sheeting | 0,01 | 0,17 | 1200 | 1250 | BB |
| | EPS panel | 0,14 | 0,035 | 28 | 1450 | BB |
| | Vapour barrier | 0,001 | 0,5 | 650 | 1260 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Reinforced concrete floor | 0,2 | 2,3 | 2300 | 1000 | BB |
| | Acoustic plaster | 0,025 | 0,15 | 500 | 1000 | BB |
| **ROOF** (standard) | Metal decking | 0,1 | 1,5 | 1200 | 1670 | BB |
| | Mineral wool | 0,14 | 0,035 | 50 | 1030 | BB |
| | Vapour barrier | 0,001 | 0,5 | 650 | 1260 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Reinforced concrete floor | 0,2 | 2,3 | 2300 | 1000 | BB |
| | Acoustic plaster | 0,02 | 0,15 | 500 | 1000 | BB |
| **FLOOR** (groups, office) | Wooden parquet | 0,01 | 0,16 | 740 | 1600 | BB |
| | Cement screed | 0,06 | 1,33 | 2000 | 1080 | BB |
| | PE membrane | 0,001 | 0,5 | 980 | 1260 | BB |
| | Mineral wool | 0,095 | 0,035 | 50 | 1030 | BB |
| | Bitumen sheeting | 0,005 | 0,17 | 1200 | 1250 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Reinforced concrete floor | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Blinding | 0,06 | 1,35 | 2000 | 1000 | BB |
| **FLOOR** (corridor) | PVC surface | 0,04 | 0,17 | 1200 | 1400 | BB |
| | Cement screed | 0,06 | 1,33 | 2000 | 1080 | BB |
| | PE membrane | 0,001 | 0,5 | 980 | 1260 | BB |
| | Mineral wool | 0,095 | 0,035 | 50 | 1030 | BB |
| | Bitumen sheeting | 0,005 | 0,17 | 1200 | 1250 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Reinforced concrete floor | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Blinding | 0,06 | 1,35 | 2000 | 1000 | BB |
| **FLOOR** (wet cells) | PVC surface | 0,04 | 0,17 | 1200 | 1400 | BB |
| | Heated cement screed | 0,06 | 1,33 | 2000 | 1080 | BB |
| | PE membrane | 0,001 | 0,5 | 980 | 1260 | BB |
| | Mineral wool | 0,095 | 0,035 | 50 | 1030 | BB |
| | Bitumen sheeting | 0,005 | 0,17 | 1200 | 1250 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Reinforced concrete floor | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Blinding | 0,06 | 1,35 | 2000 | 1000 | BB |
| **WALL ext_1** (exterior) | Reinforced concrete | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Bitumen sheeting | 0,005 | 0,17 | 1200 | 1250 | BB |
| | XPS panel | 0,06 | 0,035 | 38 | 1450 | BB |
| **WALL ext_2** (exterior) | Particleboard coated | 0,01 | 0,13 | 650 | 1700 | BB |
| | Mineral wool | 0,095 | 0,035 | 50 | 1030 | BB |
| | Reinforced concrete | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Priming coat | 0,001 | 0,17 | 1050 | 960 | BB |
| | Bitumen sheeting | 0,005 | 0,17 | 1200 | 1250 | BB |
| | XPS panel | 0,06 | 0,035 | 38 | 1450 | BB |
| **WALL ext_3** (exterior) | Outside plaster | 0,01 | 0,27 | 900 | 1000 | BB |
| | XPS panel | 0,06 | 0,035 | 38 | 1450 | BB |
| | Reinforced concrete | 0,3 | 2,3 | 2300 | 1000 | BB |
| | Particleboard | 0,01 | 0,13 | 650 | 1700 | BB |
| **WALL int_1** (interior) | Reinforced concrete | 0,3 | 2,3 | 2300 | 1000 | BB |
| **WALL int_2** (interior) | Plaster board (2 layers) | 0,03 | 0,19 | 600 | 1000 | BB |
| | Mineral wool | 0,08 | 0,035 | 50 | 1030 | BB |
| | Plaster board (2 layers) | 0,03 | 0,19 | 600 | 1000 | BB |
| **DOOR ext.** (exterior) | Particleboard | 0,018 | 0,13 | 650 | 1700 | BB |
| | Mineral wool | 0,06 | 0,035 | 50 | 1030 | BB |
| | Particleboard | 0,018 | 0,13 | 650 | 1700 | BB |
| **DOOR int.** (interior) | Particleboard | 0,024 | 0,13 | 650 | 1700 | BB |

*Table 3-2 Properties of the window components*

| **Glazing** | | Solar transmittance [-] | Solar reflectance [-] |
|---|---|---|---|
| | Clear 6mm | 0,78 | 0,07 |
| | Clear 10mm | 0,75 | 0,083 |
| | Coated Poly | 0,18 | 0,74 |
| Blind | | Slat width [m] | Slat separation [m] |
| Blind with medium reflectivity slats | | 0,025 | 0,019 |
| Gas | | Thickness [m] | |
| | Air | 0,006 | |

### 3.2.3 Thermal zoning

Zones in *Energy-Plus* are thermal concepts which define air volumes at a uniform temperature plus every heat transfer and heat storage surface bounding or inside these volumes. (Energy-Plus 2016). Creating the right zoning requires experience and a proper knowledge of the building including all HVAC (Heating, Ventilation and

Air Conditioning) systems. Different approaches to design zonings are described in the *Energy-Plus* user manual (Energy-Plus 2016).

For “Kindergarten Pachern” the focus for designing an appropriate zoning lays on the four group rooms (see Figure 3-11; zones marked in *dark blue*, *red*, *green*, and *pink*) and the corridor (marked in *dark red*) connecting these rooms. Table 3-3 shows detailed information on areas and volumes of the relevant zones for this project. To obtain sufficient data for the simulation process, these four rooms and the corridor were monitored for almost one year. Moreover, four non-monitored zones are included in the *Energy-Plus* model.

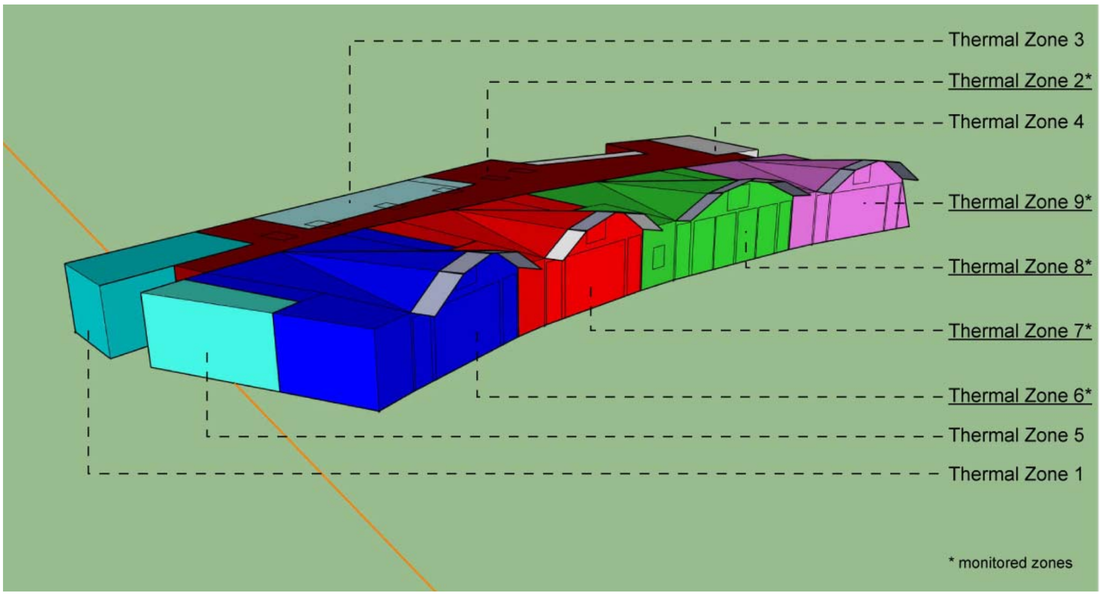


*Figure 3-11 Zoning for “Kindergarten Pachern”*

*Table 3-3 Detailed zone information for the monitored zones*

| **Thermal Zones** | **Area** [m²] | **Floor Height** [m] | **Volume** [m³] |
|---|---|---|---|
| Zone 6 = Group 1 (dark blue) | 77 | 2,7 - 4 | 224 |
| Zone 7 = Group 2 (red) | 76 | 2,7 - 4 | 220 |
| Zone 8 = Group 3 (green) | 96 | 2,7 - 4 | 280 |
| Zone 9 = Group 4 (pink) | 81 | 2,7 - 4 | 223 |
| Zone 2 = Corridor (dark red) | 170 | 2,7 | 459 |

## 3.3 Monitoring

As the building performance simulation focuses on the four group rooms situated next to the corridor, all group rooms and the corridor have been equipped with the essential monitoring system required for this work to gather all necessary input data information.

### 3.3.1 Monitoring-based simulation

The data stream that is provided by a long-term monitoring of “Kindergarten Pachern” fulfils three functions (see Table 3-4). First, it is used to feed the simulation model with relevant input data (e.g. internal gains); second, it is necessary to create a local weather file, and third, it forms a basis for the calibration process (compare *Chapter 1*) where simulated data is compared with measured data (e.g. indoor air temperature).

*Table 3-4 Use of monitored data in the calibration process (source: Mahdavi and Tahmasebi 2012)*

| Use of data | Data point | Unit |
|---|---|---|
| Creating a local weather file | Global horizontal radiation | W/m² |
| | Diffuse horizontal radiation | W/m² |
| | Outdoor dry bulb temperature | °C |
| | Outdoor air relative humidity | % |
| | Wind speed | m/s |
| | Wind direction | degree |
| | Atmospheric pressure | Pa |
| Creating the initial model | Electrical loads | W |
| | State of openings (open/closed) | - |
| | State of the lights (on/off) | - |
| | Occupancy (presence/absence) | - |
| | Radiators´ surface temperature | °C |
| Calibration | Indoor air dry bulb temperature | °C |

### 3.3.2 Monitoring equipment

All sensors used for the monitoring process are standard wireless energy independent sensors equipped with *EnOcean* transmitters. They are characterized by a very low energy use. A data logger based on *Arduino YUN* recorded the collected data locally and forwarded it via UMTS-Modem to a central database at TU Wien (for more details also see: Schuss et al. 2016).

A detailed documentation of the sensor equipment and calibration of the sensors is provided in Table 3-5.

*Table 3-5 Deployed monitoring devices*

| Device | Range / Accuracy |
|---|---|
| Davis Vantage Pro2 wireless weather station | Temperature: -40 to +65°C +/- 0,5K |
| | Humidity: 0 to 100% +/- 3% |
| | Solar radiation: 0 to 1800W +/-- 5% |
| | Wind speed: 1 to 67m/s +/-1m/s or 5% |
| | Wind direction: 0 to 360° +/- 4° |
| Pressac $CO_2$ temperature and humidity sensor | Temperature: 0 to +51°C +/- 0,5K |
| | Humidity: 0 to 100% +/- 5% |
| | $CO_2$: 0 to 2550ppm +/- 125ppm |
| Thermokon SR-MDS Solar | Occupancy / Motion: 0 / 1 |
| | Light level: 0 to 510 lx |
| Thermokon SRW01 Window contact | Status: 0/1 |

### 3.3.3 Monitoring setup

As mentioned before, the case study of this thesis focuses on the four group rooms of “Kindergarten Pachern” and the connecting corridor. The group rooms as well as the corridor were equipped with sensors in July 2016 by a research team of TU Wien. The data acquisition focuses on air temperature, humidity, and carbon dioxide concentration in the group rooms, the gym, and the corridor. Two motion detection sensors were installed in each group room to capture occupancy patterns and illumination levels. The states of doors and windows were recorded with contact sensors. All thermal sensors were positioned 2,5m above floor level away from direct sunlight to avoid misleading measurements. Prior to deployment, all sensors were calibrated in a climate box at TU Wien.

The monitored data is necessary for carrying out the simulation, calibration, and validation process (compare *Chapter 1*). To create a simulation model of “Kindergarten Pachern” the monitored data was used both to generate the local weather file and schedules for the physical behaviour of the simulation model such as the state of windows/doors (open/closed), occupancy (absence/presence), light (on/off). To calibrate and validate the initial model, monitored data such as indoor temperature was compared with simulated data. Figure 3-13 provides an overview of all sensors that were mounted at “Kindergarten Pachern”. Figure 3-12 shows mounting details of the sensor equipment. Numbers and IDs off the applied sensors are shown in Table 3-6.

Temperature sensor, Thermal Zone 7, #TB2

Occupancy sensor, Thermal Zone 6, #MA2

Contact sensor, garage door, Thermal Zone 6, #CA2

Contact sensor, top window, Thermal Zone 6, #CA3

Contact sensor, door to outside, Thermal Zone 7, #CB1

Contact sensor, door to corridor, Thermal Zone 6, #CA6

*Figure 3-12 Exemplary mounting details of monitoring sensors*

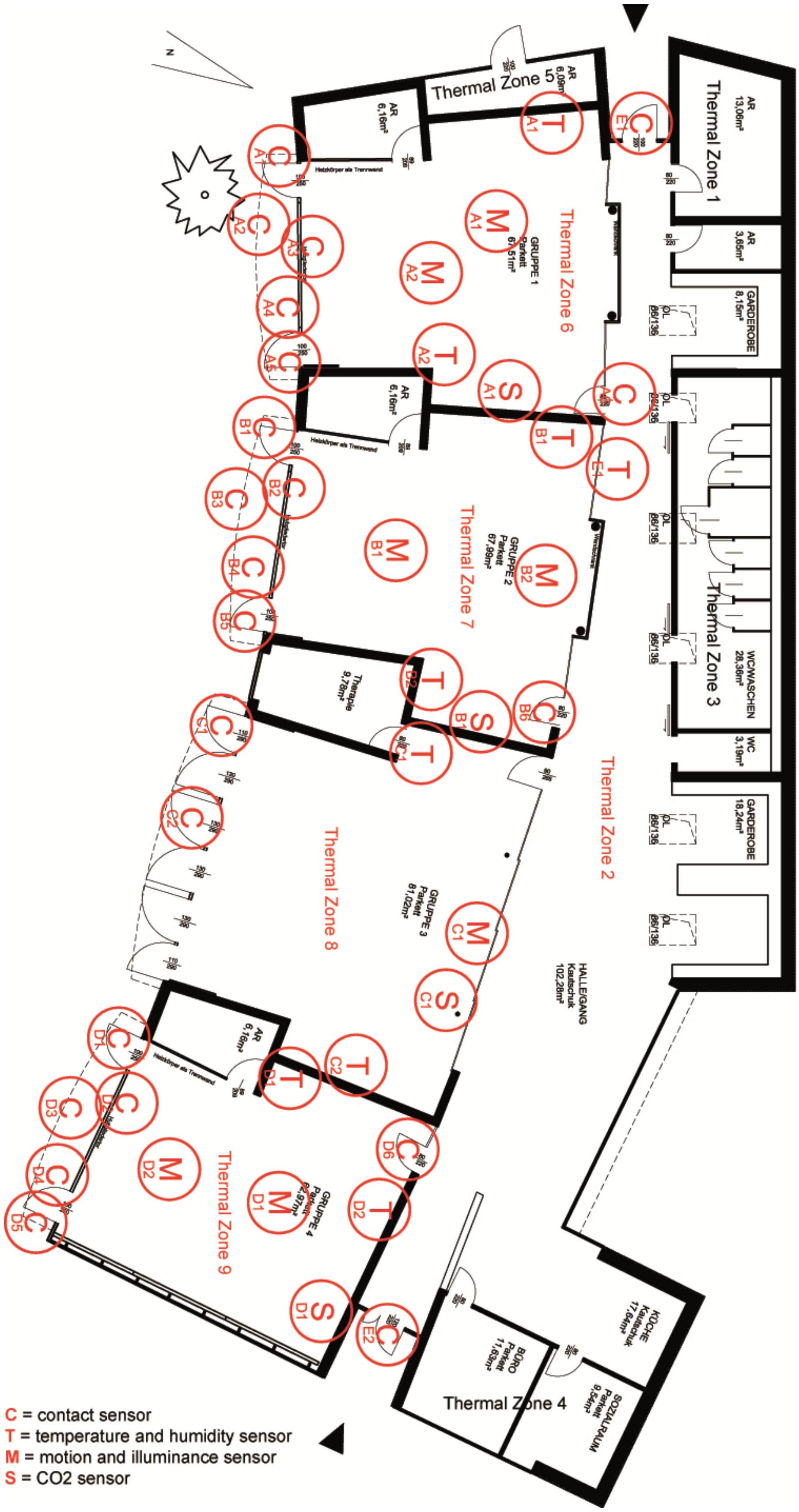


*Figure 3-13 Floor plan of the building including thermal zones and installed sensors*

*Table 3-6 Monitoring sensors at "Kindergarten Pachern"*

| Zone | Description | Amount | ID |
|---|---|---|---|
| 2 | Indoor air temperature and humidity sensor | 1 | TE1 |
| | Contact sensor | 1 | CE1 |
| 6 | Indoor air temperature and humidity sensor | 2 | TA1, TA2 |
| | Contact sensor | 6 | CA1, CA2, CA3, CA4, CA5, CA6 |
| | Motion and illuminance sensor | 2 | MA1, MA2 |
| | Carbon dioxide sensor | 1 | SA1 |
| 7 | Indoor air temperature and humidity sensor | 2 | TB1, TB2 |
| | Contact sensor | 6 | CB1, CB2, CB3, CB4, CB5, CB6 |
| | Motion and illuminance sensor | 2 | MB1, MB2 |
| | Carbon dioxide sensor | 1 | SB1 |
| 8 | Indoor air temperature and humidity sensor | 2 | TC1, TC2 |
| | Contact sensor | 2 | CC1, CC2 |
| | Motion and illuminance sensor | 1 | MC1 |
| | Carbon dioxide sensor | 1 | SC1 |
| 9 | Indoor air temperature and humidity sensor | 2 | TD1, TD2 |
| | Contact sensor | 6 | CD1, CD2, CD3, CD4, CD5, CD6 |
| | Motion and illuminance sensor | 2 | MD1, MD2 |
| | Carbon dioxide sensor | 1 | SD1 |

Relevant input parameters obtained from the monitoring process are incorporated in the simulation model.

Figure 3-14 shows mounting details of the local weather station which was necessary to create the local weather file. Table 3-7 illustrates the observed data points:

*Figure 3-14 Installed weather station at "Kindergarten Pachern"*

*Table 3-7 Necessary monitored data for generating a local weather file (source: Taheri 2013)*

| **Data point** | **Unit** |
|---|---|
| Global horizontal radiation | W/m² |
| Diffuse horizontal radiation | W/m² |
| Outdoor dry bulb temperature | °C |
| Outdoor air relative humidity | % |
| Wind speed | m/s |
| Wind direction | degree |
| Atmospheric pressure | Pa |

## 3.4 Data analysis and generation of simulation input

The quantity of data acquisition and the quality of measurements in building simulations are of utmost importance. For this thesis, long-term monitoring was the basis for the whole simulation process. The monitored data was both used to populate the initial simulation model and to maintain its fidelity through a systematic calibration process.

### 3.4.1 Local weather file

According to Tauber et al. (2015), typical year weather data cannot be used to represent the outdoor conditions. To carry out accurate simulations it is necessary to have a local weather file that is based upon real weather data of the region where the building is situated. Therefore the case study of this thesis was equipped with a weather station (Figure 3-14) in July 2016. This monitored data was used to create a local weather file. Text based weather files can be read in in *Energy-Plus*.

### 3.4.2 Simulation schedules

According to Tauber et al. (2015), a promising way to create reliable simulation schedules is to populate the simulation model with time dependent values (=schedules) such as the state of a window/door for specific points in time.

For door and window contacts, indoor air temperature, motion and illuminance, data from the monitoring database is used to design schedules that are assigned to the corresponding schedules in the *Energy-Plus* simulation model. This helps to make the simulation model as precis as possible because assumptions are reduced and are involved only in cases that no monitored data is available. To minimize the source of errors related to data gaps, user behaviour interviews (e.g. about the usage of blinds) that were carried out in December 2016 with the head and staff of “Kindergarten Pachern” are used to fill gaps in the measured data and to design realistic occupants´ behaviour dependant schedules. For the average distribution of the children number within the groups during one day a typical design day was selected that represents the daily routine at “Kindergarten Pachern" (Table 3-8), according to the interviews.

*Table 3-8 Occupancy schedules at "Kindergarten Pachern"*

| **Group room** | **occupied hours** | **number of children** |
|---|---|---|
| 1 | 7am – 1pm | 26 |
| 2 | 7am – 3pm | 25 |
| 3 | 9am – 12am | 26 |
| 4 | 7am – 17pm | 26 |

According to Mahdavi and Tahmasebi (2012), it is a time-consuming and error-prone process to write schedules manually in *Energy-Plus*. Therefore a simple program was written in *MATLAB* to generate an event-based “compact schedule” for each data class.

A CSV-file containing all variable data points that can be scheduled was assigned to all related input variables in the *Energy-Plus* model. Where data gaps occur, interview-based simulation schedules were taken to fill the gaps.

### 3.4.3 Internal gains

Internal gains consist of all internal elements and devices that consume energy and produce heat. Due to the absence of electrical devices such as computers in the group rooms internal gains only result from people and artificial lighting in this case study.

#### 3.4.3.1. People

“Kindergarten Pachern” consists of three groups of children of approximately 26 children in each group. A typical metabolic heat generation of the children was assumed for type “walking about” (100W/m²) according to ASHRAE standard 55-2010 (ASHRAE.org 2017). As that metabolic heat generation is dependent on the total body envelope surface, the following equation (4) (Schuss et. al 2015, p. 30) can be used to obtain a reasonable value for a child:

$$A_D = 0.202 m^{0.425} l^{0.725} \qquad \text{eq. (4)}$$

whereas:
$A_D$ = DuBois surface area, m²
m = mass, kg
l = height, m

A child of 35kg and 1.28m, which is asumed to be an average child at “Kindergarten Pachern”, has a total body envelope of 1.1m². In combination with the metabolic heat rate for “walking about” a total metabolic heat rate factor of 110W is assigned to each child.

As mentioned above, the distribution of the children within different zones was set according to occupancy and behaviour interviews carried out in December 2016.

#### 3.4.3.2. Lights

A huge number of single light bulbs (Figure 3-15) are installed at “Kindergarten Pachern” to provide sufficient luminance within all group rooms. The initial model is based on the total installed light power and the daily occupied hours.

As the amount of watts consumed by the light bulbs differs depending on the product (Table 3-9), the total consumption per group room was calculated based on an on-sight visit in July 2016. Figure 3-16 provides an overview of the light bulb positions and shading devices for all four group rooms.

*Figure 3-15 Artificial lighting design at "Kindergarten Pachern"*

*Table 3-9 Overview of light bulbs installed at "Kindergarten Pachern"*

| Zone | Description | Amount | Watts total |
|---|---|---|---|
| 6 | Light bulb 23W<br>Light bulb 15W | 15<br>17 | 600 |
| 7 | Light bulb 23W<br>Light bulb 15W | 23<br>9 | 664 |
| 8 | Light bulb 23W<br>Light bulb 15W | 25<br>13 | 770 |
| 9 | Light bulb 23W<br>Light bulb 15W | 10<br>13 | 425 |


*Figure 3-16 Positions of light bulbs and shading devices in group rooms*

### 3.4.4 Air change rates

As it was not possible to carry out tracer gas measurements to precisely define the infiltration rate (e.g. “blower door test”), it was estimated by analysing the decay of $CO_2$ values during the night (unoccupied hours) (see Figure 3-17). For this purpose, a suitable date during the winter period where all openings (doors and windows) were closed was chosen.

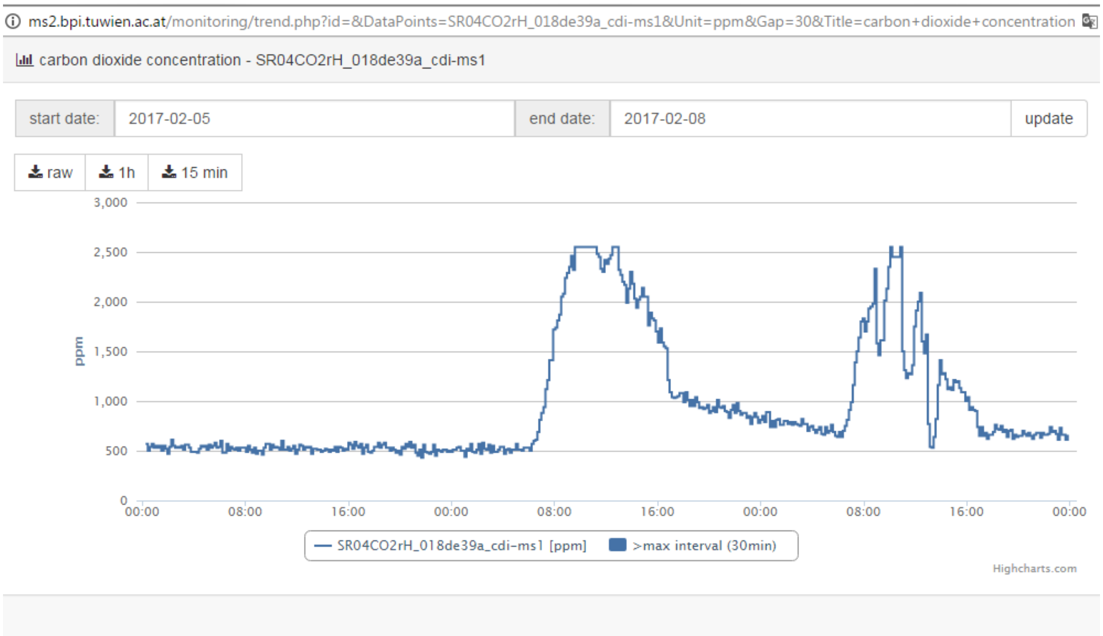


*Figure 3-17 $CO_2$ concentration in Group room 1, 05.02 - 07.02.2016. (source: ms2.bpi.tuwien.ac.at)*

To obtain satisfying infiltration rates from the above illustrated $CO_2$ decay curve, the following equation can be used:

$$Infiltration = \frac{lnC_0 - lnC_{end}}{h} \quad [1/h] \qquad \text{eq. (5)}$$

whereas:

| | |
|---|---|
| h | total decay time [h] |
| $C_0$ | max. $CO_2$ value |
| $C_{end}$ | average $CO_2$ value |

Ventilation rates were defined based on user interviews (occupancy behaviour) and measurements (window and door contact sensors).

### 3.4.5 The heating system model

Two types of heating devices are installed at “Kindergarten Pachern”. All group rooms are equipped with flat wall mounted heating panels. The height of the panels is 2,5m and the length varies according to the given room geometry (Figure 3-18 and Figure 3-19). *Group room 4* is additionally equipped with floor convectors.

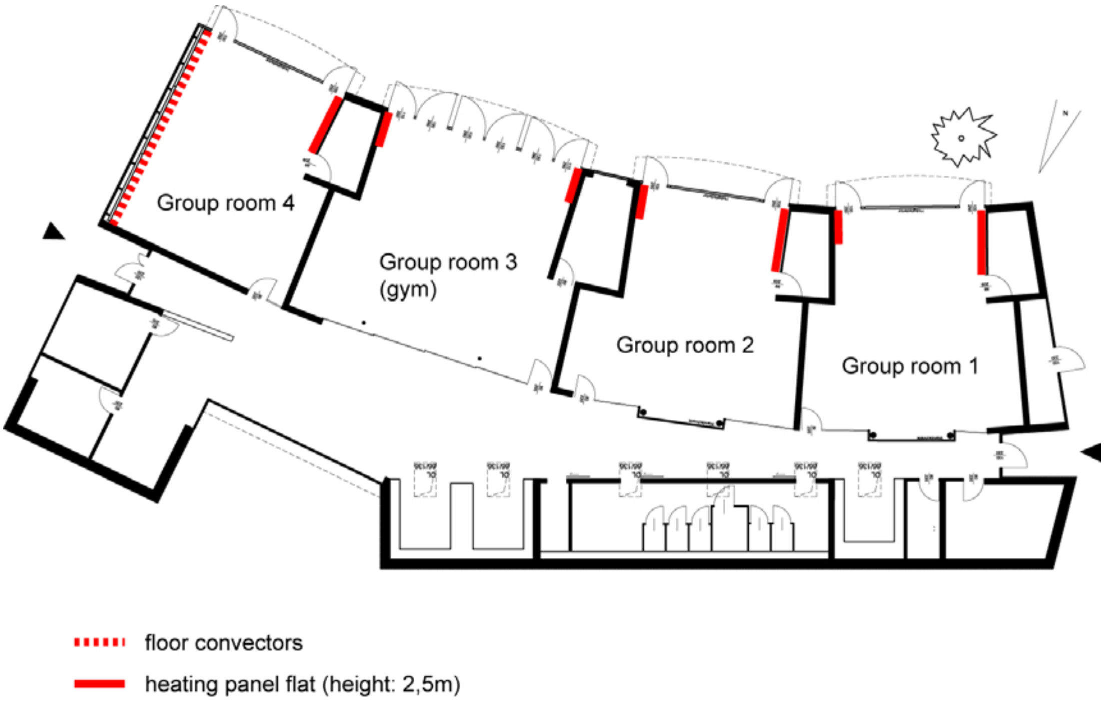


*Figure 3-18 Layout of the heating system at "Kindergarten Pachern"*

*Figure 3-19 Heating panels at "Kindergarten Pachern"*

Each radiator has been equipped with contact temperature sensors to monitor the heating system during the winter period. Figure 3-20 shows a typical heating operating day in February.


*Figure 3-20 Operating temperature of a heating panel (24hours) (source:ms2.bpi.tuwien.ac.at)*

To evaluate the building´s thermal performance during the heating season, the heat delivery rate of the heating system that is necessary as input information can be calculated (eq. 6-9) according to Mahdavi and Tahmasebi (2012) as follows:

$$q = q_R + q_C \qquad \text{eq. (6)}$$

$$q_R = \varepsilon \cdot \sigma \cdot A_R \cdot (T_S^4 - T_R^4) \qquad \text{eq. (7)}$$

$$q_C = h_C \cdot A_C \cdot (\theta_S - \theta_R) \qquad \text{eq. (8)}$$

$$h_C = 2 \cdot |\theta_S - \theta_R|^{0.25} + 4\varepsilon \cdot \sigma \cdot \left(\frac{T_S + T_R}{2}\right)^3 \qquad \text{eq. (9)}$$

whereas:

q heat delivery rate of radiators [W]

$q_R$ radiative component of heat delivery [W]

| | |
|---|---|
| $q_C$ | convective component of heat delivery [W] |
| $\varepsilon$ | emissivity of the radiator [-] |
| $\sigma$ | constant ($5{,}67 \cdot 10^{-8}\ W/m^2K^4$) |
| $A_R$ | effective radiator area for radiation [m²] |
| $T_S$ | surface temperature of radiators [K] |
| $T_R$ | room temperature [K] |
| $h_C$ | convective heat transfer coefficient [W/m²K] |
| $A_C$ | effective radiator area for convection [m²] |
| $\theta_S$ | surface temperature of radiator [°C] |
| $\theta_R$ | room temperature [°C] |

### 3.4.6 Run periods

The long-term monitoring started in July 2016 and was carried out for one year to obtain representative data for hot summer days as well as cold winter days (see Table 3-10). In general, it has to be said that long-term monitoring provides more data that can be used for different simulation conditions and therefore the design and calibration of the simulation model can be done more precisely. As there is no mechanical cooling system installed at “Kindergarten Pachern” and the heating system is only relevant during the winter period, we have a “free-running-period” in the summer, which eliminates the inaccuracies that are related to the heating/cooling system during the summer period.

*Table 3-10 Specification of  run periods*

| Run period | **Start date** | **End date** | **run period** |
|---|---|---|---|
| summer period | 13th of August 2016 | 03th of September 2016 | 3 weeks |
| winter period | 20th of January 2017 | 10th of February 2017 | 3 weeks |

Figure 3-21 and Figure 3-22 illustrate the outdoor air temperatures during both simulation periods.

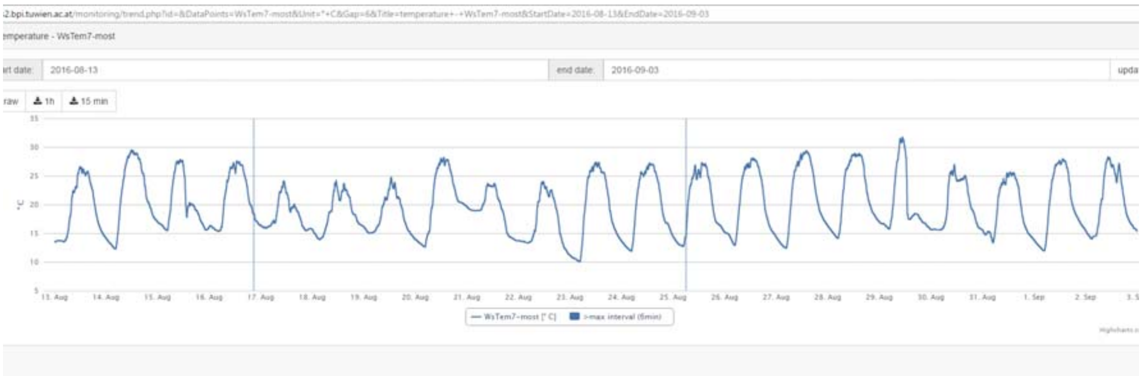


*Figure 3-21 Illustration of the outdoor air temperatures during the summer period (source:ms2.bpi.tuwien.ac.at)*


*Figure 3-22 Illustration of the outdoor air temperatures during the winter period (source:ms2.bpi.tuwien.ac.at)*

## 3.5 Calibration of the simulation model

Calibration (compare *Chapter 2*) is an iterative process starting with an initial simulation model that is adapted step by step and evaluated systematically to represent reality as closely as possible at the end of the simulation process.

In order to reliably predict a building´s behaviour, simulation models have to be calibrated as mentioned in *Chapter 2*. As to the "dynamic nature" of building operation, some input factors of the model that have a major impact on the outcome of the simulations have to be subjected to calibration processes on a recurrent basis. Therefore the calibration process does not work as a "one-time activity" but needs to be repeated on a systematic basis (Taheri et al. 2013).

In case of “Kindergarten Pachern”, the calibration process is done mostly manually The variables that can be altered (e.g. occupancy behaviour) are based on user interviews and on sight observations.

According to Figure 3-23, the initial model has to be calibrated based on the monitored data from the first scenario ($1^{st}$ calibration). The resulting model of that $1^{st}$ calibration ($1^{st}$ calibrated model) has to be evaluated by comparing the predicted values with the monitored results (e.g. indoor air temperature). Furthermore, the results have to be compared with the predictions of the initial model, to see if the calibrated results fit reality better. Systematically this calibration process has to be repeated *n*-times. If the results of the $n^{th}$ calibration are acceptable, the model can be considered as calibrated.

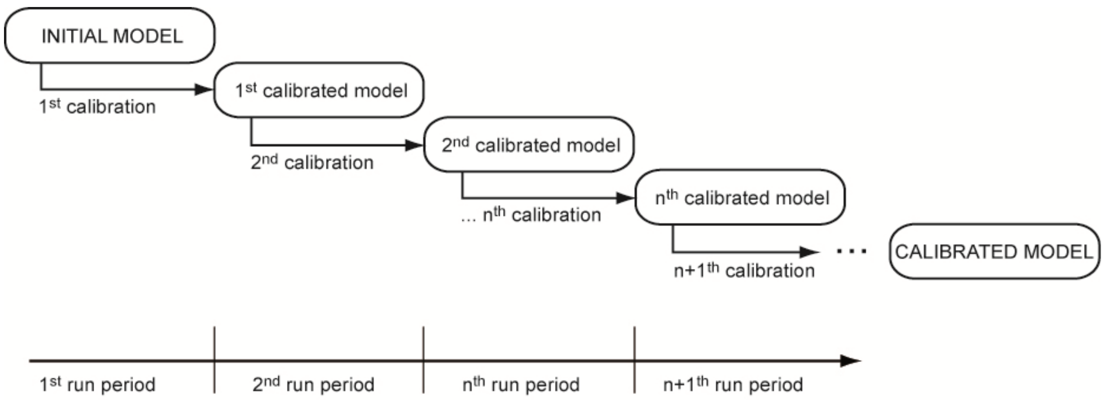


*Figure 3-23 The process of recurrent calibration*

To minimize the potential sources of errors, a step by step simulation approach was chosen for this thesis. According to Taheri et al. (2013), the following procedure was carried out successfully in previous case studies:

1. A single-zone model based on available information about the building and monitored data has to be generated. The measured indoor air temperature of the adjacent zones can be used as boundary conditions for the simulated zone.
2. That “one-zone model” has to be evaluated by comparing the measured and the simulated indoor mean air temperature within the calibration process. All input variables chosen for adaption can be altered to fit as well as possible.
3. A “multi-zones model” has to be developed that is filled with the optimized values obtained from the previous calibration of the “one-zone model”.
4. The model has to be re-calibrated several times according to Figure 3-23.

### 3.5.1 Calibration variables

As discussed in *Chapter 2,* there is a huge and complex variety of input parameters that have a more or less relevant impact on simulation results. For this thesis previous research presented in *Chapter 2* provides reasonable guidance for the selection of possible calibration variables and their variation ranges. Parameters were selected based on the author´s experience and their impact on the outputs shown in Table 3-11:

*Table 3-11 Calibration variables and fixed input parameters for "Kindergarten Pachern"*

| **Variables** | **Source** |
|---|---|
| Direct solar gains | on sight visits / user interviews by the author |
| Internal gains | interviews about user behaviour carried out by the author / measurements |
| Infiltration rate | CO2 decay calculation |
| Ventilation rate | interviews about user behaviour carried out by the author / measurements |
| **Fixed input parameters** | **Source** |
| Thermal conductivity of construction details | according to plan material |
| Geometry | according to plan material |

The first variable "Direct solar gains" addresses uncertainties related to user behaviour (e.g. state of blinds) and surroundings of the building that have a shading impact on the facade (e.g. trees). The second variable "Internal gains" addresses uncertainties such as movement and interaction producing body heat. The fact that this educational building kindergarten is not as well documented as for example an office building concerning occupants´ behaviour constitutes a major factor of inaccuracy regarding assumptions of the internal gains. To narrow down uncertainty about the children´s behaviour, interviews about the children´s daily routine have been carried out with the staff at "Kindergarten Pachern" as mentioned before. As the behaviour of children is hard to predict (e.g. *"How many children are in a room at a certain time?"* or *"What types of activities do they perform?"*) this variable was of paramount interest. The third and fourth variables address infiltration and ventilation rates in the building. User interviews and sensor data form the basis for these variables as it was not possible to carry out measurements (e.g. "blower door test").

After defining the calibration variables, they were systematically varied within specified ranges in order to minimize the difference between simulated and measured data. A detailed overview on that topic is provided in the following chapter.

## 3.6 Improvement options

Proposals to improve the thermal performance of “Kindergarten Pachern” are developed based upon the calibrated model. The goal of this thesis was to design the basis for a "user manual" that addresses user behavioural aspects and provides hints for the staff at “Kindergarten Pachern” on how to improve the thermal building performance by adapting their daily routine. Methods such as "free cooling" (cooling without any mechanical ventilation system) are proposed depending on the outcome of the simulation results.

## 3.7 Key aspects

By means of computational simulations based on the calibrated model of Konrad Frey´s "Kindergarten Pachern” it has to be tested whether the original intentions of Konrad Frey in terms of thermal performance and comfort are met. Virtual improvements of the building´s thermal performance are going to be analysed and discussed. As there have been some changes in design compared to the original building of the 1990s, previous states of the building can be virtually reconstructed and evaluated.

# 4 RESULTS

After a comprehensive description of the methodology (see previous chapter “Methodology”) I would like to continue with presenting the results. The results are illustrated with relevant figures and tables and are accompanied by analysis and comments where necessary. To illustrate the iterative “step by step” calibration process, different simulation scenarios are going to be presented.

## 4.1 Overview

In order to reduce possible errors throughout the simulation process, the initial model was designed based on accurate, detailed and comprehensive information about geometry, material properties and constructions (compare *Chapter 3*). In the current case study the thermal performance of four thermal zones (*Group rooms 1-4*) is evaluated within an iterative calibration process. A summer period of three weeks as well as a winter period of three weeks are deployed for the calibration process as mentioned in *Chapter 3*. To illustrate the “goodness of fit” between the measured indoor air temperature and the simulated values line charts and tables with indicators to judge the accuracy of the simulation model such as *MBE, RMSE* and *CV(RMSE)* values are going to be presented.

For S*cenario 1* a single-zone model of *Group room 2* was deployed. Therefore the monitored temperatures in the adjacent group rooms can be used as boundary conditions of *Group room 2*. The extent of assumptions is therefore reduced.

The obtained input settings were aligned to the other group rooms that are also used to verify the simulation results.

*Scenarios 2* and *3* continue the iterative “step by step” calibration process. Variables such as internal gains and air change rates are subjected to optimization.

*Scenario 4* incorporates a heating system during the winter period in the simulation model.

The last scenario should underline the necessity to create a local weather file for accurate simulations. *Group room 2* is picked out as an example to demonstrate the huge impact of the weather file on the simulation results.

To improve the thermal performance of “Kindergarten Pachern” so-called “improvement options” were designed after a successful calibration. These patterns are going to be summed up in a kind of “user-manual” that might give hints to the user how to improve the thermal performance of the building by simple means such as “free cooling”. These improvement options are described later on in this chapter.

Table 4-1 sums up the calibration variables explored in the present thesis to optimize the simulation model.

*Table 4-1 Calibration variables linked to calibration steps*

| **Calibrat-ion #** | **simul. period** | **Weather file** | **Solar gains** | **Internal gains** | **Air change rates** | **HVAC design** | **CV(RMSE) [%]** |
|---|---|---|---|---|---|---|---|
| 0 initial m. | summer | local | assumption | assumption | assumption | - | 17,37 |
| 1 | summer | local | user interview based | assumption | assumption | - | 13,17 |
| 2 | summer | local | derived from scenario # 2 | user interview based | assumption | - | 5,51 |
| 3 | summer | local | derived from scenario # 2 | derived from scenario # 3 | $CO_2$ decay analysis | - | 4,92 |
| 4 | winter | local | derived from scenario # 2 | derived from scenario # 3 | derived from scenario # 4 | schedule controlled | - |

Table 4-2 provides an overview of all modelling assumptions throughout the calibration process at “Kindergarten Pachern”.

*Table 4-2 Modelling assumptions with regard to the calibration variables and shedules*

| | Scenario | initial model | calibr. step 01 | calibr. step 02 | calibr. step 03 | validation |
|---|---|---|---|---|---|---|
| **Weather-file** | | local weatherdata Hart | local weatherdata Hart | local weatherdata Hart | local weatherdata Hart | local weatherdata Hart |
| **Solar gains** | | for weekdays: 11am to 1pm shading on | for weekdays: 9am to 3pm shading on | for weekdays: 9am to 3pm shading on | for weekdays: 9am to 3pm shading on | for weekdays: until 24:00 shading off |
| **Internal gains** | Occupancy | for weekdays: 7am to 5pm | for weekdays: 7am to 5pm | for weekdays: 7am to 10am and 1pm to 3pm | for weekdays: 7am to 10am and 1pm to 3pm | for weekdays: 7am to 5pm |
| | Lights | for weekdays: 7am to 5pm | for weekdays: 7am to 5pm | for weekdays: 4pm to 5pm | for weekdays: 4pm to 5pm | for weekdays: 3pm to 5pm |
| **Air change rates** | Infiltration rate [$h^{-1}$] | for alldays: until 24:00 1 | for alldays: until 24:00 1 | for alldays: until 24:00 1 | for alldays: until 24:00 0.2 | for alldays: until 24:00 0.2 |
| | Ventilation rate [$h^{-1}$] | for weekdays: 10am to 2pm 10 | for weekdays: 10am to 2pm 10 | for weekdays: 10am to 2pm 10 | sheduled according to sensor data | sheduled according to sensor data |
| **HVAC design** | Heating set-point | X | X | X | X | sheduled according to sensor data |
| | Heating availability shedule | X | X | X | X | for alldays: 3am to 3pm |

Building geometry, construction elements, and material properties are given in all simulations according to plan material, descriptions and on-sight visits (compare chapter “Methodology”). User behaviour dependant schedules such as ventilation rates and occupancy are derived from measurements (e.g. contact sensors and occupancy sensors) and user interviews as described in chapter “Methodology” in detail.

## 4.2 Initial simulation model

The initial model (see Figure 4-1 and Table 4-3) was designed based on the collected input information available (e.g. geometry and constructions) and general assumptions for the operational design as described in detail in chapter "Methodology".

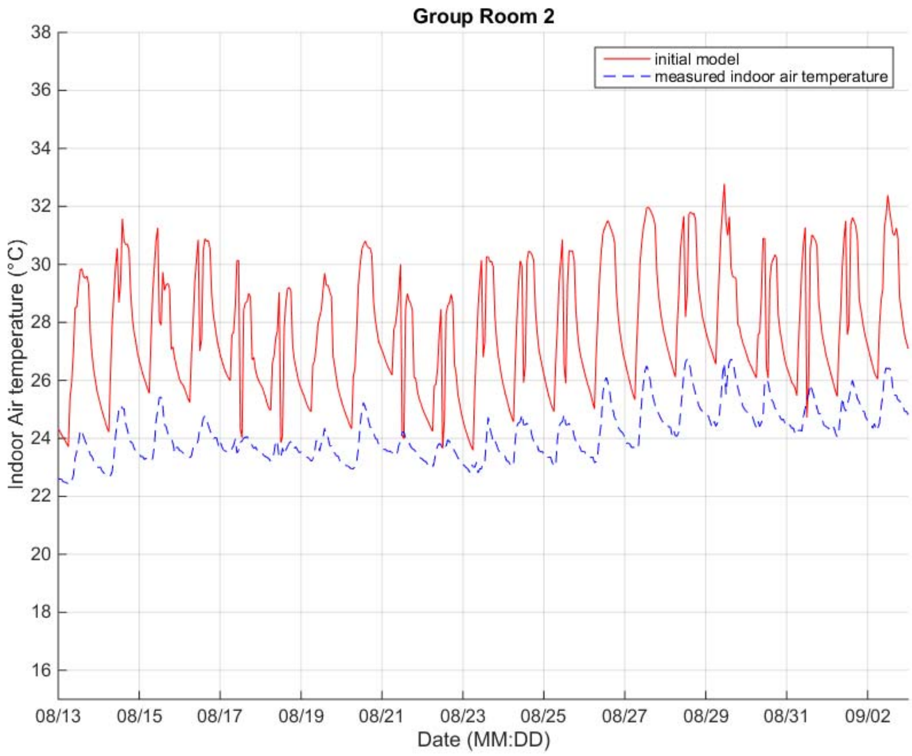


*Figure 4-1 Initial simulation model of "Kindergarten Pachern"*

*Table 4-3 Simulation data – initial model, Group room 2*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous simulation step | - | - | - |
| initial model | 14,93 | 3,96 | 16,39 |

### Analysis of simulation results

There is an enormous overheating problem and a huge offset of the simulated temperature curve compared to the measured temperatures. The following variables that might contribute to overheating such as solar gains and internal gains have to be examined more closely. Construction elements that might contribute to overheating problems as well due to a low heat storage capacity are not going to be examined because these elements are considered to be fixed according to plan material as mentioned before.

**Hypothesis first calibration step**

Solar gains have to be examined to lower and flatten the simulated temperature curve. The assumptions of shadings have to be replaced by user dependant schedules that were designed according to user interviews at “Kindergarten Pachern” (compare chapter “Methodology”)

## 4.3 First scenario – calibration of the solar gains assumptions

To limit the number of uncertainties and focus on defining solar gains more precisely a “one-zone-simulation” will focus on the thermal performance of *Group room 2.* The measured indoor air temperature values of the adjacent zones can be set as boundary conditions by adding predefined thermostats for these zones in the simulation model. The measured indoor air temperature data sheet for the *EP* inputs of *Group room 1* and *4* was created automatically with a script written in *MATLAB*.

The results after adapting the shading devices are illustrated in Figure 4-2. Furthermore, *CV(RMSE), RMSE* and *MBE* were calculated with a *MATLAB* script to make a more objective comparison of the different scenarios possible (see Table 4-4).

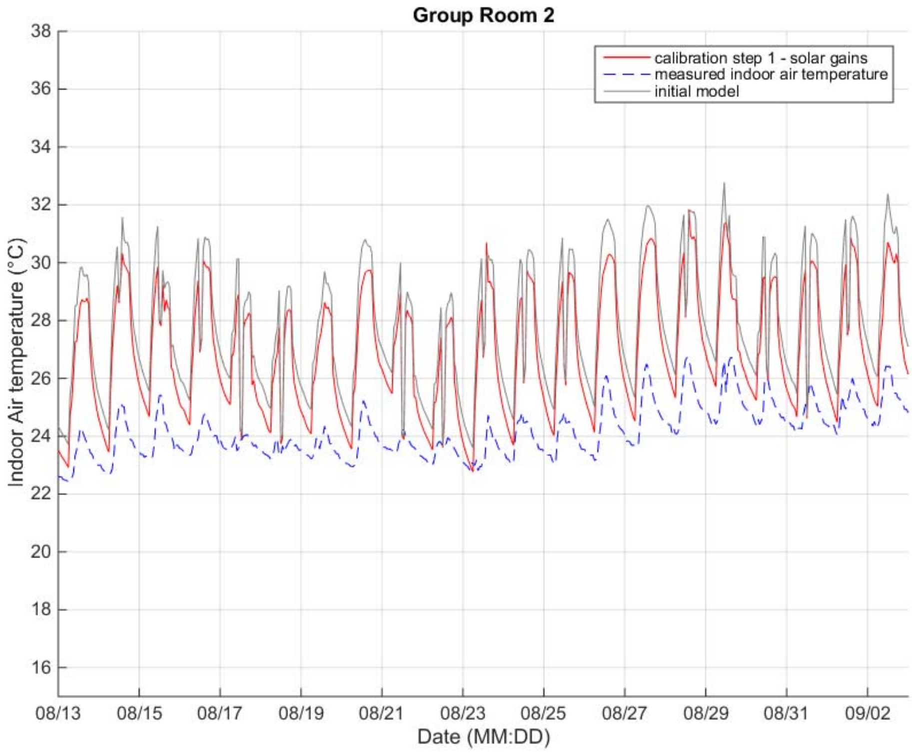


*Figure 4-2 First calibration step - optimizing solar gains*

*Table 4-4 Simulation data – first calibration, Group room 2*

| simulation run | MBE [%] | RMSE [K] | CV(RMSE) [%] |
|---|---|---|---|
| initial model | 14,93 | 3,96 | 16,39 |
| first calibration | 11,37 | 3,14 | 13,02 |

### Verification of simulation results

To verify and evaluate the obtained simulation results the other group rooms *(1, 3* and *4)* serve as reference objects.

Figure 4-3 to Figure 4-5 and Table 4-5 to Table 4-7 show the simulation results of *Group rooms 1, 3,* and *4*.

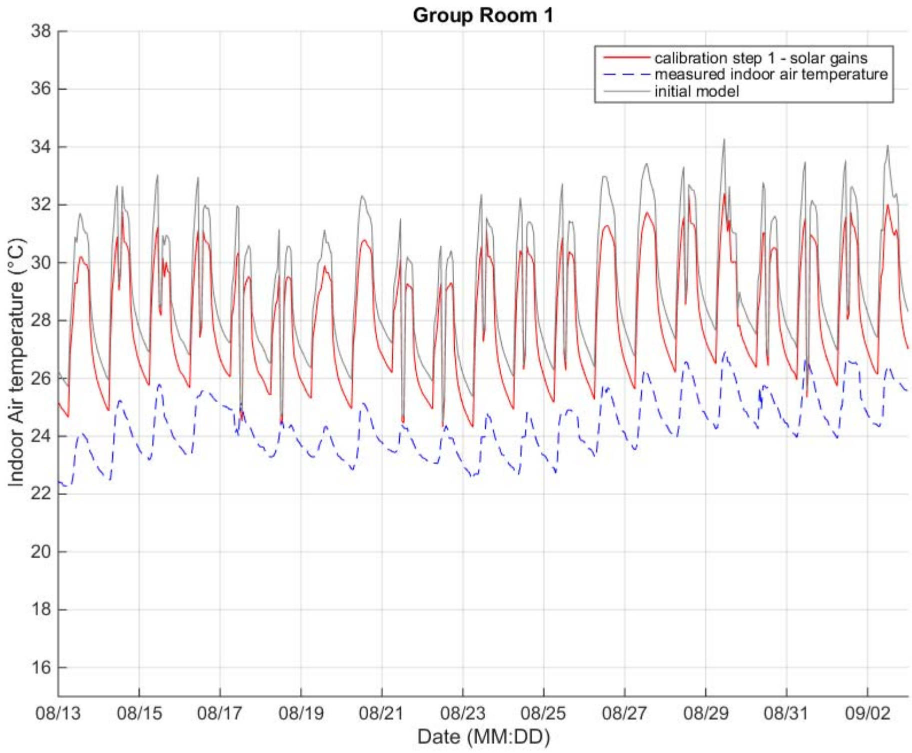


*Figure 4-3 Validation of first calibration step of Group room 1*

*Table 4-5 Simulation data – first calibration, Group room 1*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| initial model | 19,81 | 5,12 | 21,08 |
| first calibration | 15,12 | 4,00 | 16,45 |

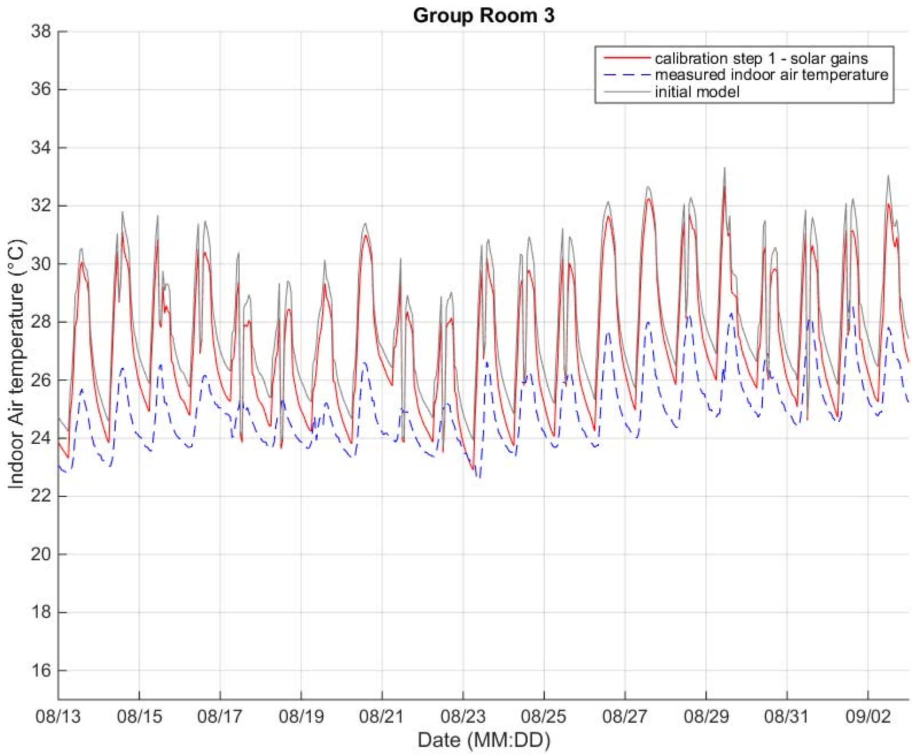


*Figure 4-4 Validation of first calibration step of Group room 3*

*Table 4-6 Simulation data – first calibration, Group room 3*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| initial model | 12,13 | 3,38 | 13,55 |
| first calibration | 8,91 | 2,67 | 10,72 |

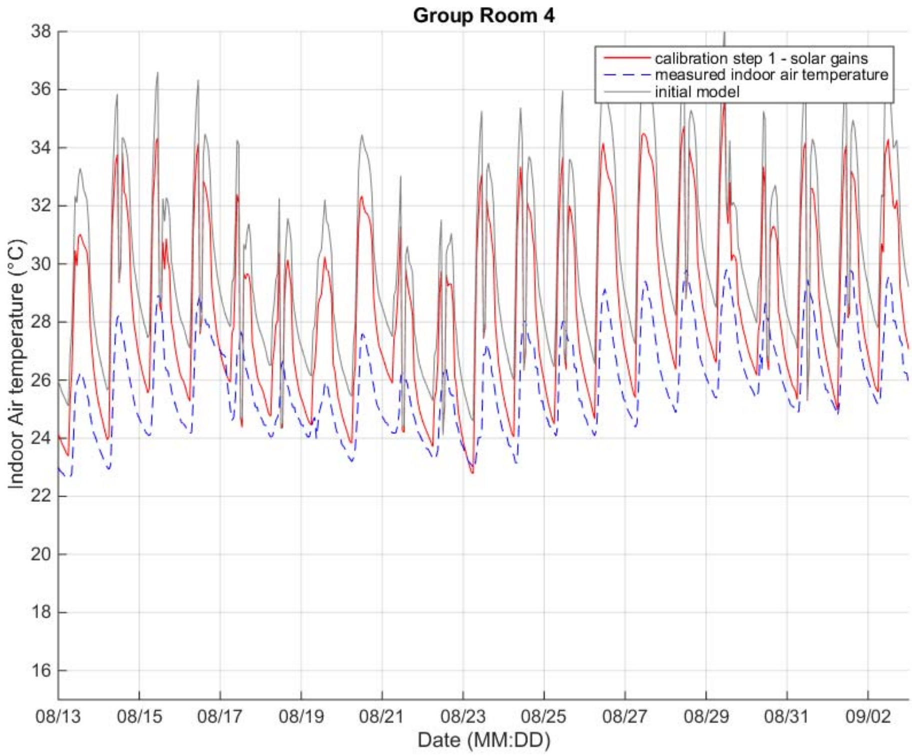


*Figure 4-5 Validation of first calibration step of Group room 4*

*Table 4-7 Simulation data – first calibration, Group room 4*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| initial model | 16,39 | 4,78 | 18,48 |
| first calibration | 9,73 | 3,23 | 12,49 |

As can be seen, there is an improvement of the thermal simulation results in all group rooms. Still, the overheating is a major problem to be examined.

**Hypothesis second calibration step**

Internal gains have to be adapted in the next calibration step to match reality more closely.

## 4.4 Second scenario – calibration of the internal gains assumptions

To adapt internal gains such as occupancy and the usage of artificial lights, user dependant schedules derived from user behaviour interviews (described in chapter "Methodology" in details) and sensor data (occupancy sensors, illumination sensors) are going to be implemented in the simulation model. Assumptions can therefore be narrowed down in this calibration step. Figure 4-6 and Table 4-8 show the results of *Group room 2* after calibration.

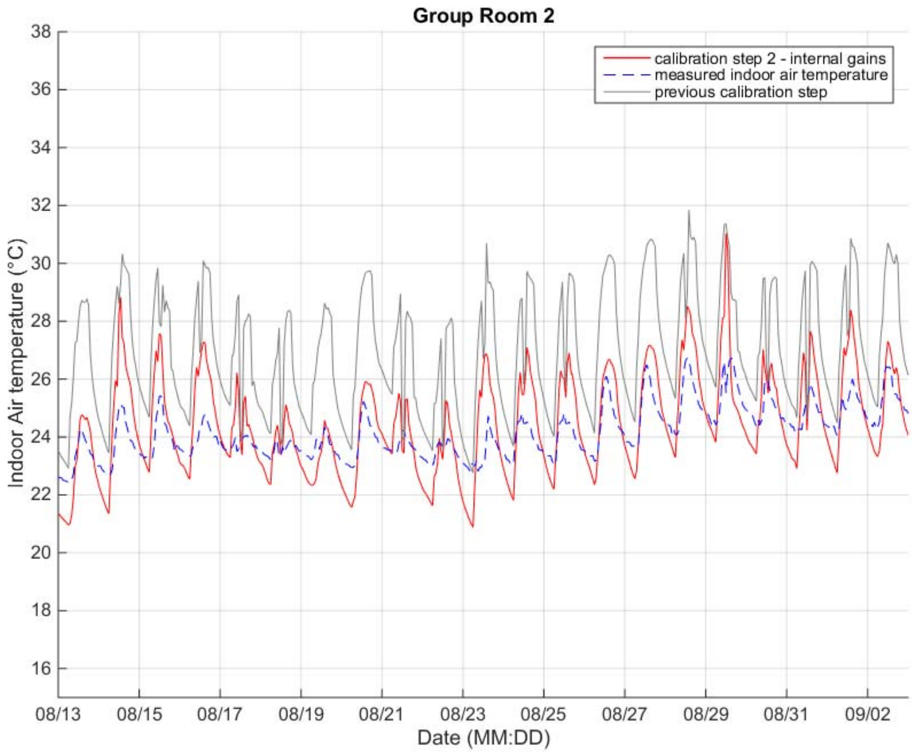


*Figure 4-6 Second calibration step - optimizing internal gains*

*Table 4-8 Simulation data – second calibration, Group room 2*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous calibration | 11,37 | 3,14 | 13,02 |
| second calibration | 3,48 | 1,29 | 5,37 |

### Analysis of simulation results

As can be seen, internal gains had a huge impact on the simulation results. As the behaviour and occupancy of children is hard to predict, the daily routine in an educational building has to be taken into account in detail to create occupancy schedules close to reality (compare chapter “Methodology”). On-sight visits, documentation of the daily routine and interviews are a promising way to obtain necessary information for scheduling occupancy behaviour.

### Verification of simulation results

Figure 4-7 to Figure 4-9 and Table 4-9 to Table 4-11 illustrate the results of the simulation in *Group rooms 1, 3* and *4*.

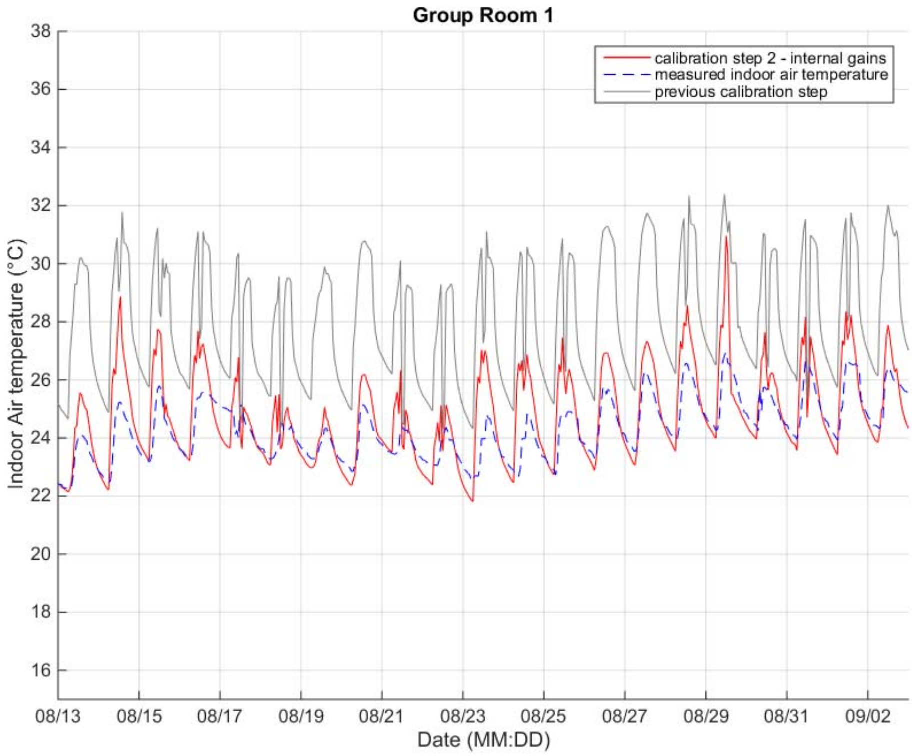


*Figure 4-7 Validation of second calibration step of Group room 1*

*Table 4-9 Simulation data – second calibration, Group room 1*

| simulation run | MBE [%] | RMSE [K] | CV(RMSE) [%] |
|---|---|---|---|
| initial model | 15,12 | 4,00 | 16,45 |
| first calibration | 2,85 | 1,16 | 4,79 |

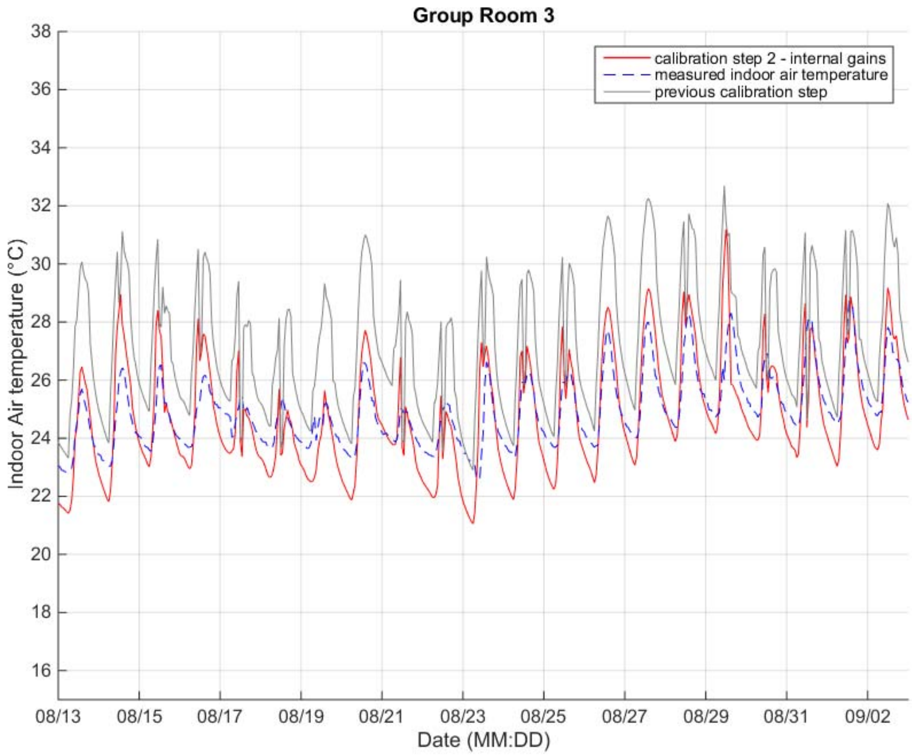


*Figure 4-8 Validation of second calibration step of Group room 3*

*Table 4-10 Simulation data – second calibration, Group room 3*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| initial model | 8,91 | 2,67 | 10,72 |
| first calibration | 1,93 | 1,06 | 4,28 |

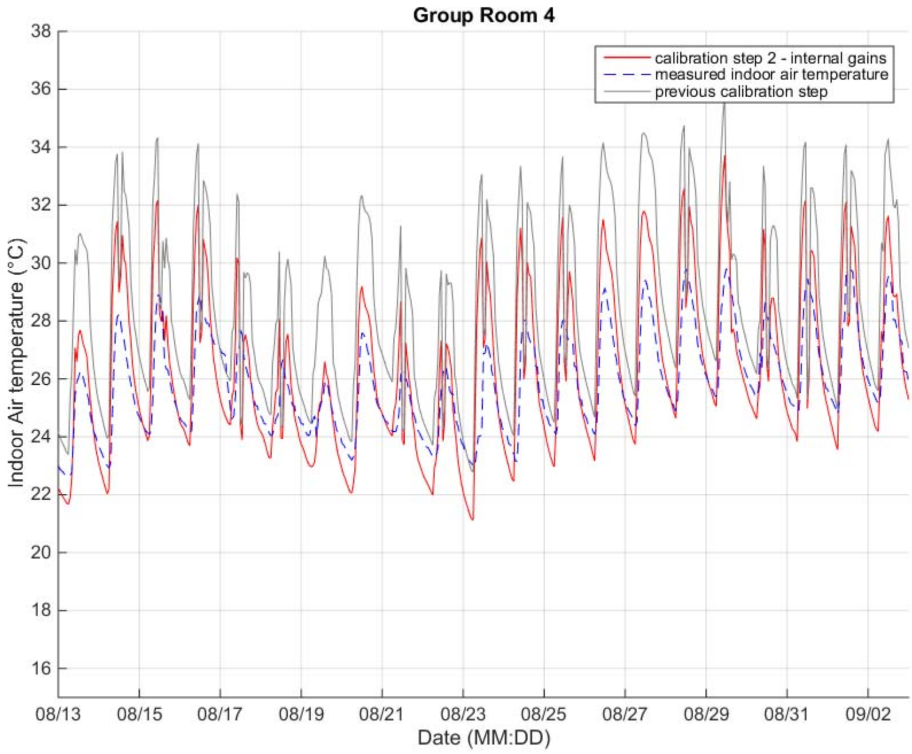


*Figure 4-9 Validation of second calibration step of Group room 4*

*Table 4-11 Simulation data – second calibration, Group room 4*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| initial model | 9,73 | 3,23 | 12,49 |
| first calibration | 4,46 | 1,96 | 7,6 |

As can be seen, there is a considerable improvement of the thermal simulation results in all group rooms. Still the overheating and the offset of the temperature have to be examined more closely.

**Hypothesis third calibration step**

As the temperature curve shows an offset compared to measured values, the air change rates - namely ventilation and infiltration - have to be defined more closely in the next calibration step.

## 4.5 Third scenario – calibration of the air change rate assumptions

As described in chapter “Methodology”, the ventilation rate was set according to measurements (e.g. contact sensors) and occupancy behaviour interviews. For the infiltration rate the $CO_2$ decay during the night (winter period) can be deployed to obtain a guideline for realistic infiltration rates if measurements (e.g. tracer gas measurements) are not possible. Figure 4-10 and Table 4-12 show the simulation results of the current calibration step.

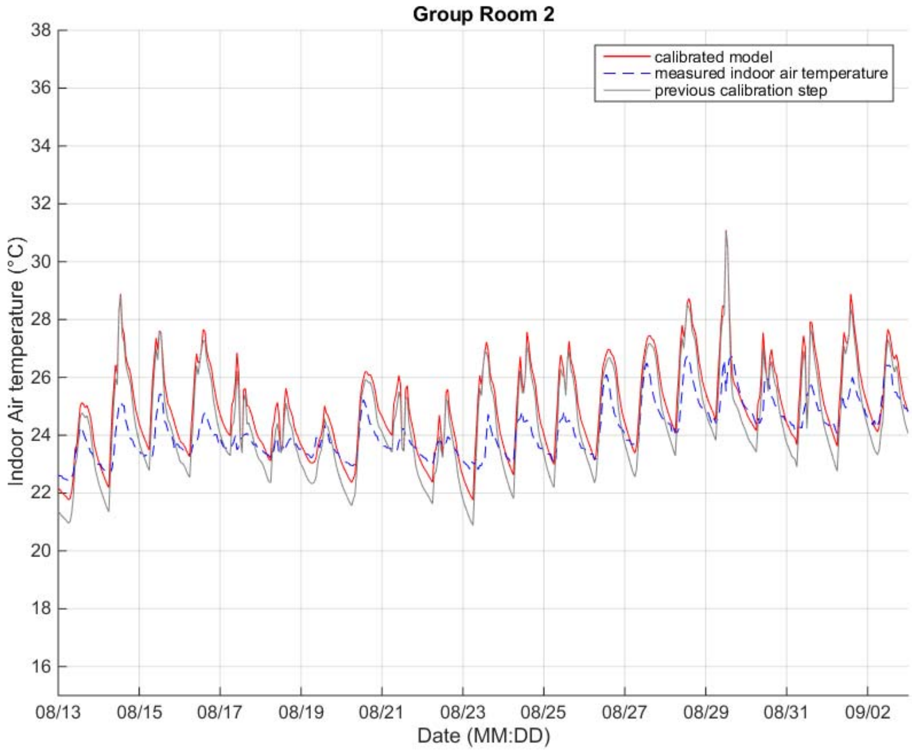


*Figure 4-10 Third calibration step - optimizing air change rates*

*Table 4-12 Simulation data – third calibration, Group room 2*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous calibration | 3,48 | 1,29 | 5,37 |
| third calibration | 1,16 | 1,15 | 4,78 |

### Analysis of simulation results

The simulated temperature curve has improved in terms of matching the measured results. The results can be considered as acceptable, however a slight overheating still occurs.

### Verification of simulation results

Figure 4-11 to Figure 4-13 and Table 4-13 Table 4-15 illustrate the results of the simulation in *Group rooms 1, 3* and *4*.

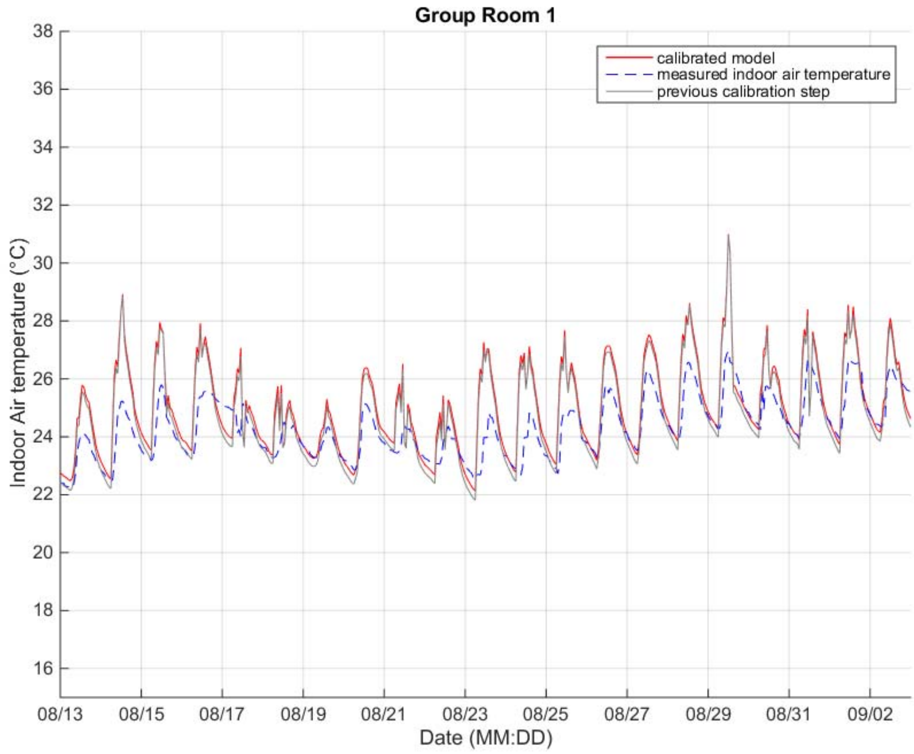


*Figure 4-11 Validation of third calibration step of Group room 1*

*Table 4-13 Simulation data – third calibration, Group room 1*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous calibration | 2,85 | 1,16 | 4,79 |
| third calibration | 1,85 | 1,06 | 4,36 |

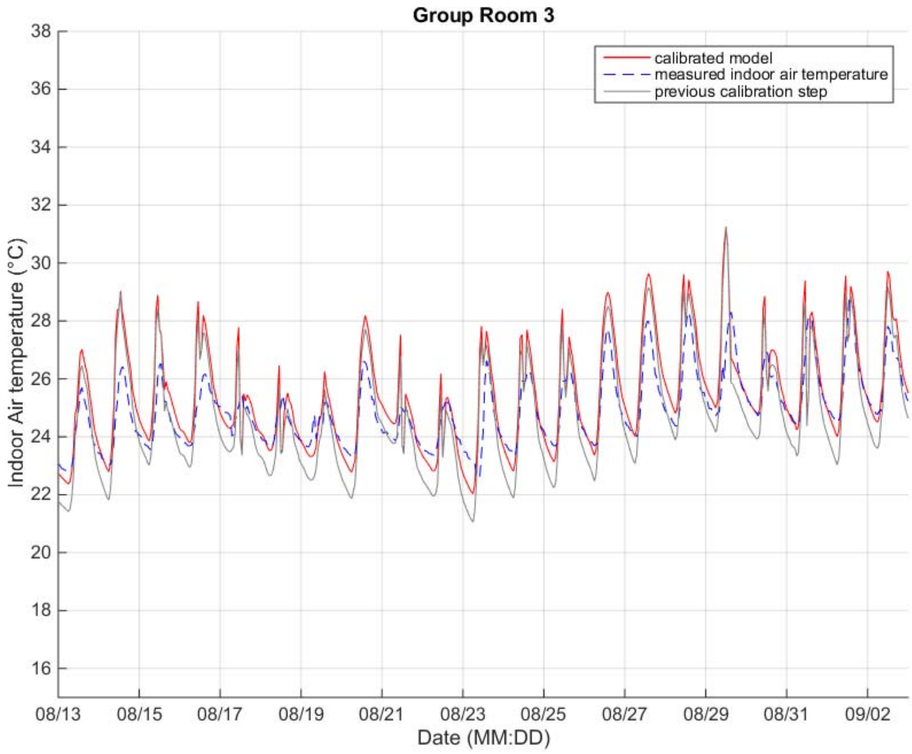


*Figure 4-12 Validation of third calibration step of Group room 3*

*Table 4-14 Simulation data – third calibration, Group room 3*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous calibration | 1,93 | 1,06 | 4,28 |
| third calibration | -0,75 | 1,05 | 4,23 |

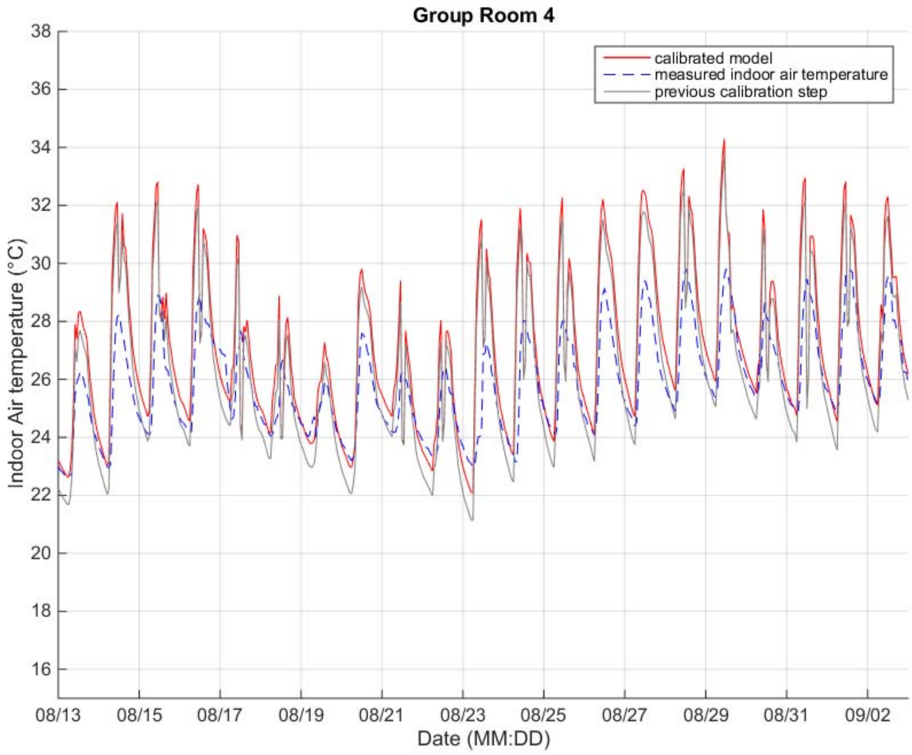


*Figure 4-13 Validation of third calibration step of Group room 4*

*Table 4-15 Simulation data – third calibration, Group room 4*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| previous calibration | 4,46 | 1,96 | 7,60 |
| third calibration | 1,65 | 1,63 | 6,32 |

## 4.6 Fourth scenario – implementing a heating system

To implement an accurate heating system a winter simulation period is chosen for this scenario. According to the equations in chapter "Heating system model" the performance of the simulated heating system can be evaluated. The heating thermostat set points are scheduled and linked to the measurements. *Group room 2* is exemplary for all other group rooms. Figure 4-14 illustrates the simulation results.

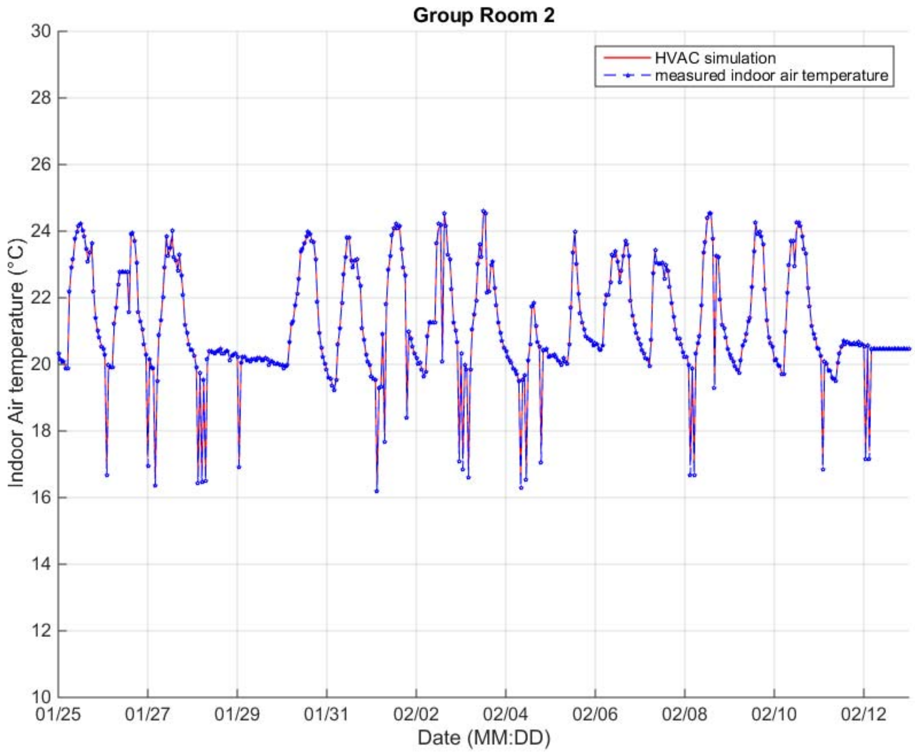


*Figure 4-14 Fourth calibration step - Implementing a HVAC system*

### Analysis of simulation results

As the heating system is coupled to the measured indoor air temperature, one temperature graph is resulting that is of course identical with the measured values. The negative peaks mark mechanical ventilation (opening of windows and doors) produced by the user. These peaks can be seen clearly as the temperature difference between indoor and outdoor air temperatures is high in the winter (compare outdoor temperatures in Figure 3-21 and Figure 3-22 in *Chapter 3*).

### Verification of simulation results

To evaluate the simulation model the performance of the heating system is compared with the calculated heating demand of “Kindergarten Pachern” (Table 4-16) according to the equations (eq. 6 to eq. 9) in chapter “Heating system model”.

*Table 4-16 Energy demand of the heating system*

| heating demand* | **Group 1 [kWh]** | **Group 2 [kWh]** | **Group 3 [kWh]** | **Group 4 [kWh]** | **Total [kWh]** |
|---|---|---|---|---|---|
| calculated | 46 | 46 | 30 | 42 | 164 |
| simulated | 35 | 50 | 49 | 40 | 174 |

* The heating demand is calculated and simulated for an average winter day (24h) within the simulation period.

The heating demand has to be further examined as the simulation values of the group rooms do not match satisfyingly with the calculated ones. The author also expected the outer group rooms (*1* and *4*) to have a higher heating demand due to their being exposed to outer climate factors, which was not the case in the simulation. Internal gains might play an important role for creating the difference between calculated and simulated heating demands.

## 4.7 Calibrated model

The performance of the calibrated model is illustrated in Figure 4-15 to Figure 4-18 and Table 4-17 to Table 4-20.

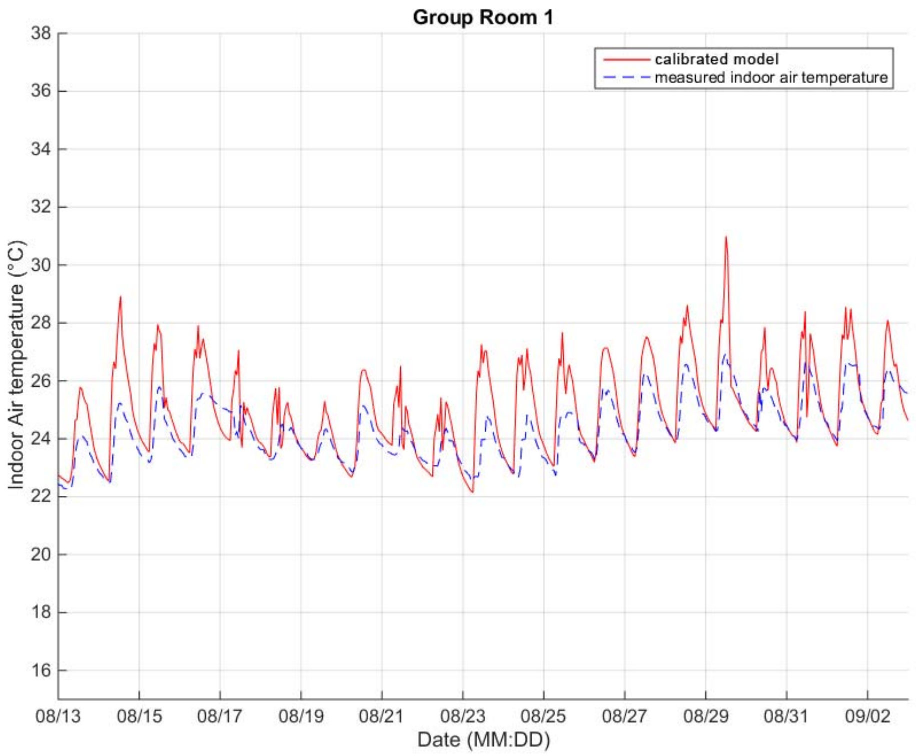


*Figure 4-15 Calibrated model of "Kindergarten Pachern", Group room 1*

*Table 4-17 Simulation data – calibrated model, Group room 1*

| calibrated model | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| | 2,85 | 1,16 | 4,79 |

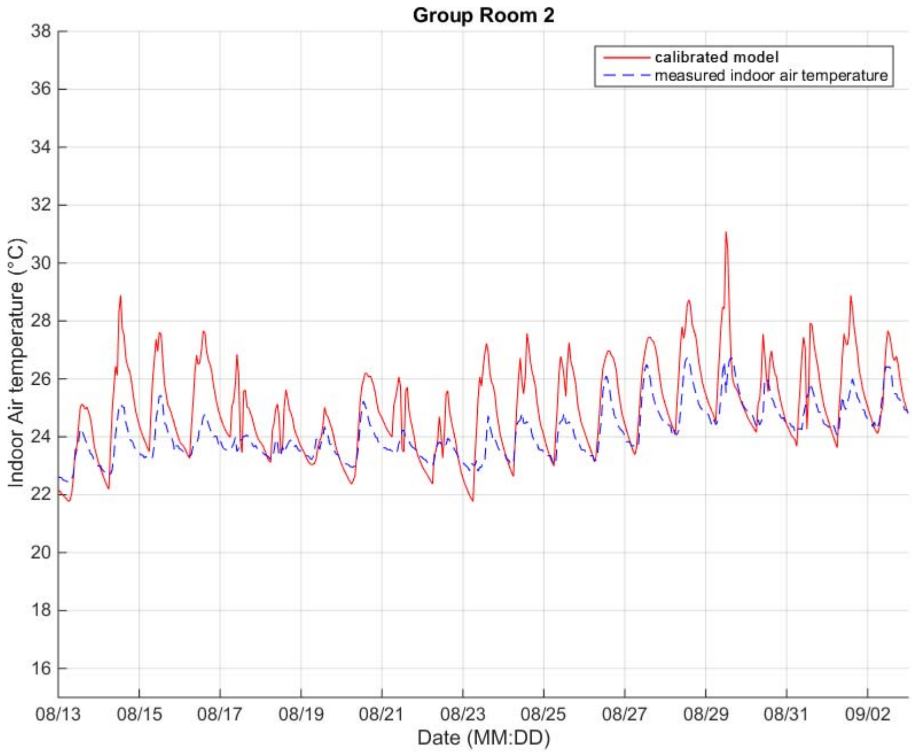


*Figure 4-16 Calibrated model of "Kindergarten Pachern", Group room 2*

*Table 4-18 Simulation data – calibrated model, Group room 2*

| calibrated model | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| | 3,48 | 1,29 | 5,37 |

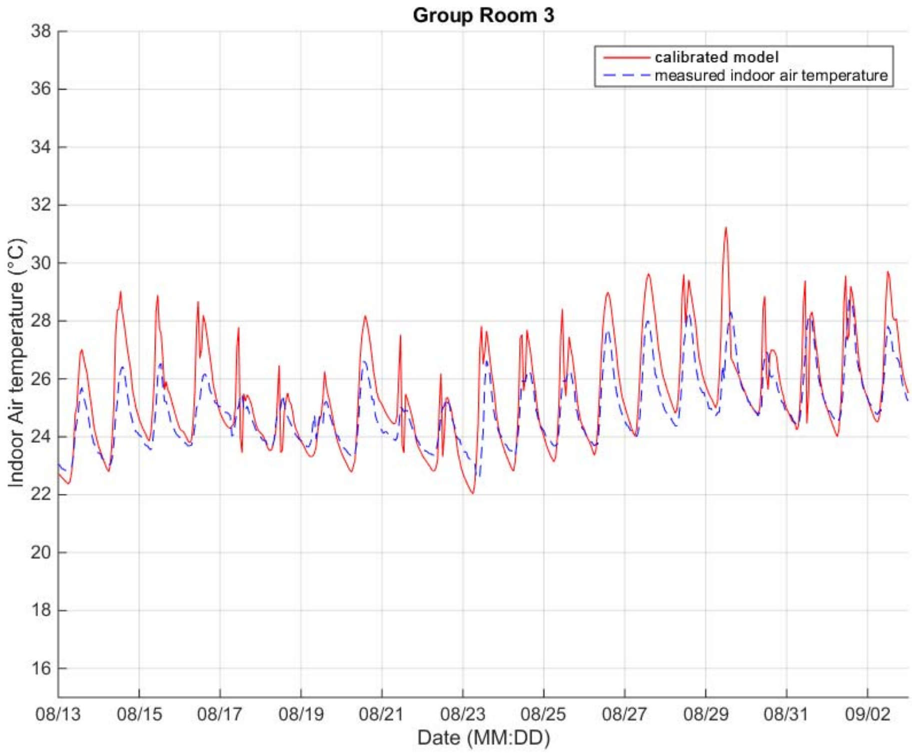


*Figure 4-17 Calibrated model of "Kindergarten Pachern", Group room 3*

*Table 4-19 Simulation data – calibrated model, Group room 3*

| calibrated model | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| | 1,93 | 1,06 | 1,96 |

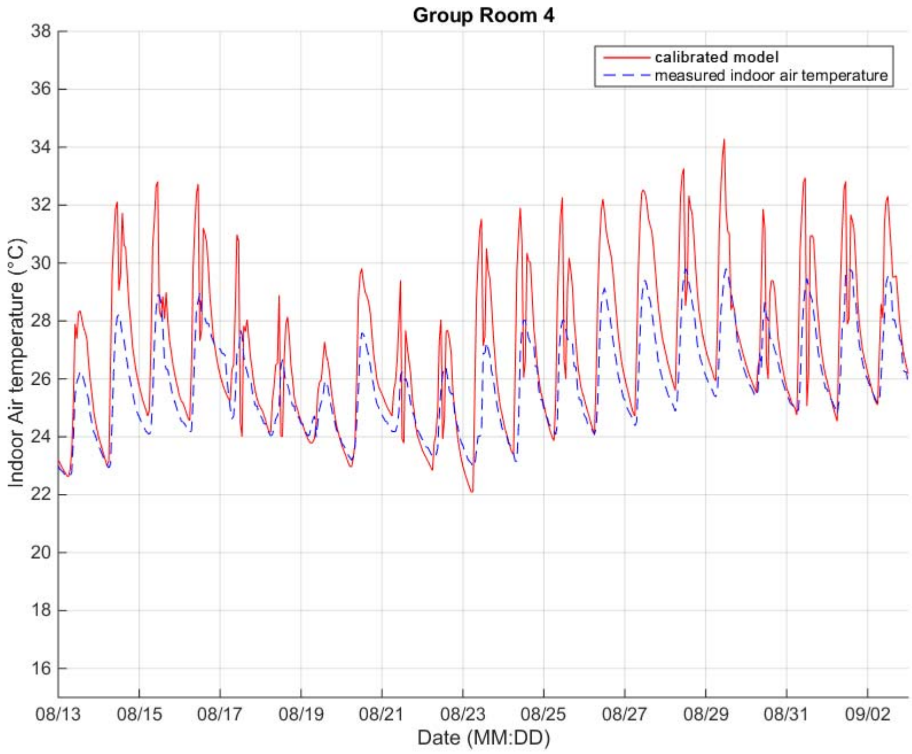


*Figure 4-18 Calibrated model of "Kindergarten Pachern", Group room 4*

*Table 4-20 Simulation data – calibrated model, Group room 4*

| calibrated model | MBE [%] | RMSE [K] | CV(RMSE) [%] |
|---|---|---|---|
| | 4,46 | 1,96 | 7,6 |

Based on this calibrated model, so-called improvement options to improve the building´s thermal performance are going to be designed and discussed in the chapter “Improvement options”.

## 4.8 Impact of local weather data

To demonstrate the significance of using a local weather file, the simulation model of “Kindergarten Pachern” is both simulated with a standard design weather file “Graz” that is available at the *Energy-Plus* website and a local weather file. The local weather file was designed based on local measurements described in *Chapter 3*.

As the building is in free run mode (no HVAC system installed) during the summer, a summer period of three weeks (13$^{th}$ of August – 3$^{rd}$ of September) was chosen to simulate this scenario to cut down the parameters that might have an impact on the simulation. *Group room 2* is exemplary for all other group rooms.

Figure 4-19 compares the simulation results of the simulation model of “Kindergarten Pachern” using a standard weather file “Graz” (grey line) and a local weather file “Hart” based on local measurements (red line).

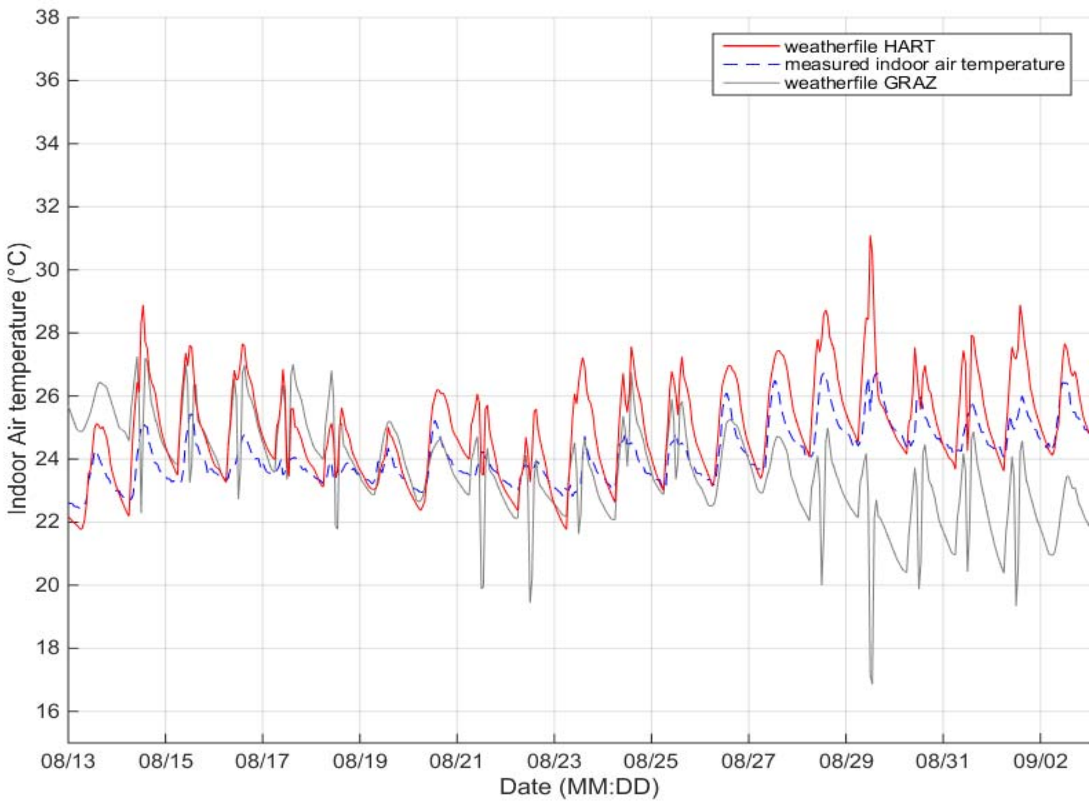


*Figure 4-19 Scenario #1: Simulation results weather file "Hart" vs. weather file "Graz”*

As can be seen, there is a strong impact of the weather file on the accuracy of the simulation. The simulation model is the same in both cases but the simulated values (red) correspond much better with the measured ones (blue/dashed) when using a local weather file (see Table 4-21).

*Table 4-21 Impact of the local weather file on the simulation results, Group room 2*

| simulation run | **MBE [%]** | **RMSE [K]** | **CV(RMSE) [%]** |
|---|---|---|---|
| Weather data Graz | -2,13 | 1,98 | 8,21 |
| Weather data Hart | 2,48 | 1,29 | 5,37 |

## 4.9 Improvement options – building performance optimization scenarios

On the basis of the calibrated model, the effectiveness of the improvement scenarios (*improvement options*) can be examined objectively. The results of these *improvement options* might give hints how to improve thermal conditions and limit summer overheating by simple and cheap methods such as "free cooling" or adding additional shadings in the summer.

### 4.9.1 *Improvement option #1* – additional shadings

The facade of "Kindergarten Pachern" opens up generously towards the south to profit from solar gains during the winter; on the other hand, to create a seamless transition from the inside to the outside from an architectural point of view (compare *Chapter 3*). However, the high amount of transparent building components in the facade contributes to a summer overheating problem.

If there were additional shading devices that can react to the seasons of the year such as leaf trees or large bushes, the problem of summer overheating could be reduced. At the same time, the benefit of solar gains during the winter would not be affected. Therefore, this improvement option was designed to evaluate the impact of natural shading devices. Figure 4-20 illustrates what this proposal could look like.

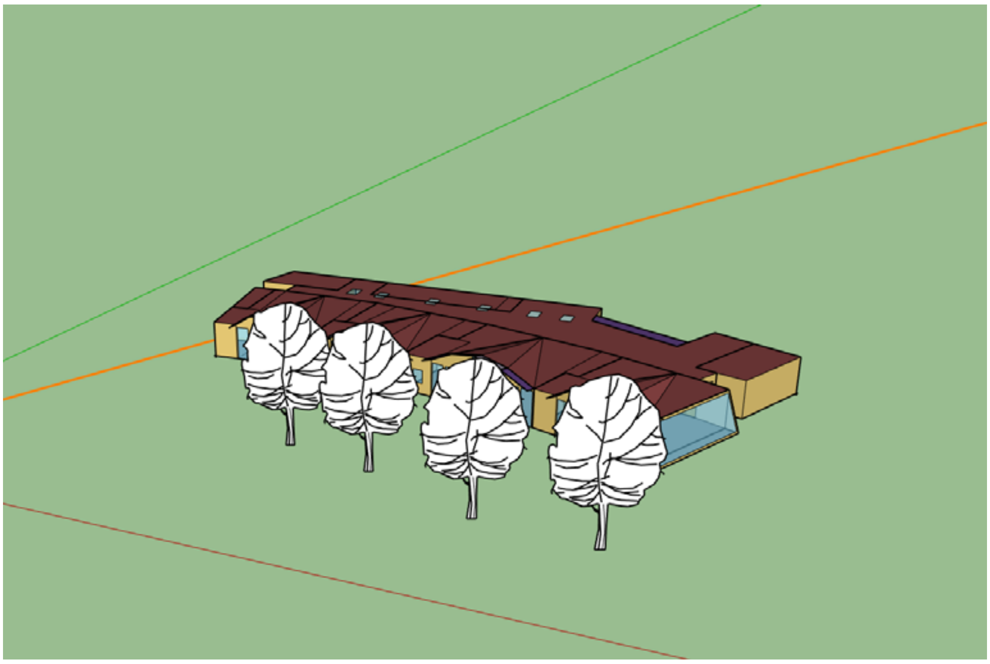

*Figure 4-20 Natural shading devices for "Kindergarten Pachern"*

Figure 4-21 to Figure 4-24 show the results of the thermal performance improvement simulation.

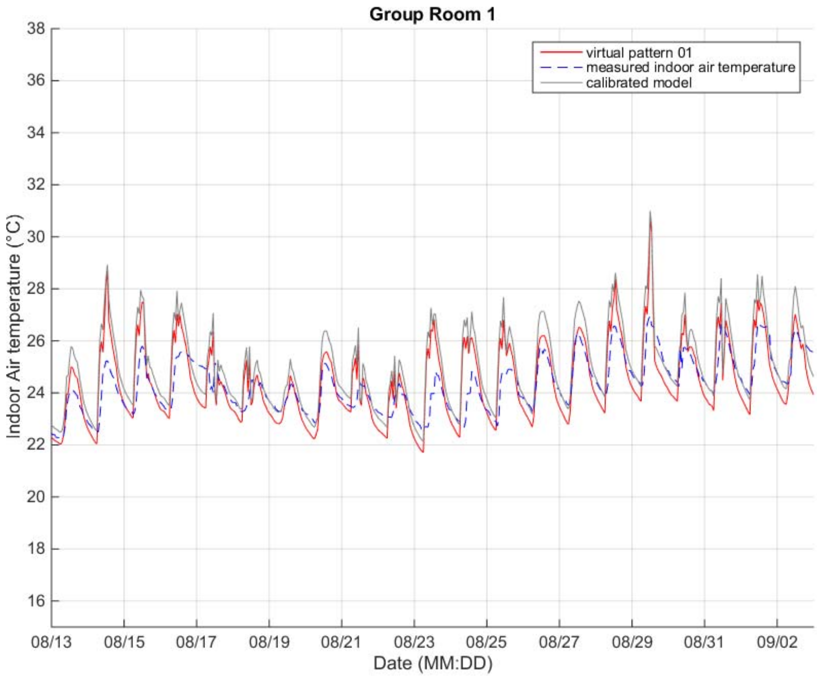


*Figure 4-21 Simulation result with additional shadings, Group room 1*

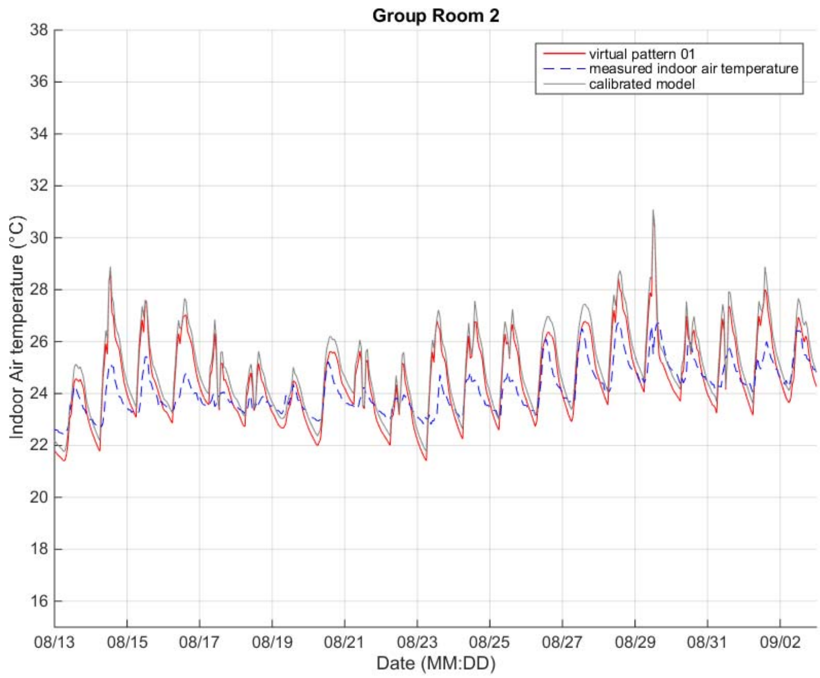


*Figure 4-22 Simulation result with additional shadings, Group Room 2*

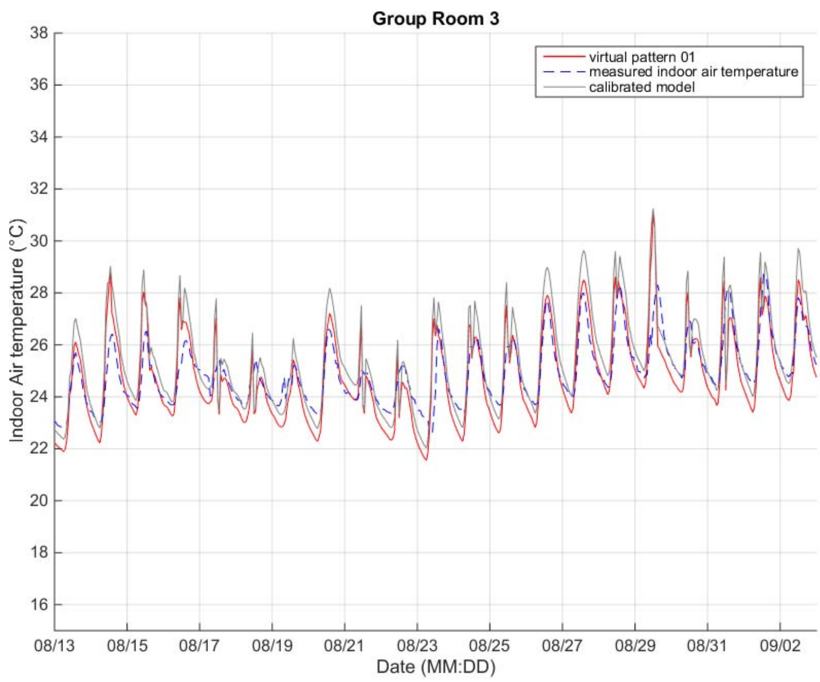


*Figure 4-23 Simulation result with additional shadings, Group Room 3*

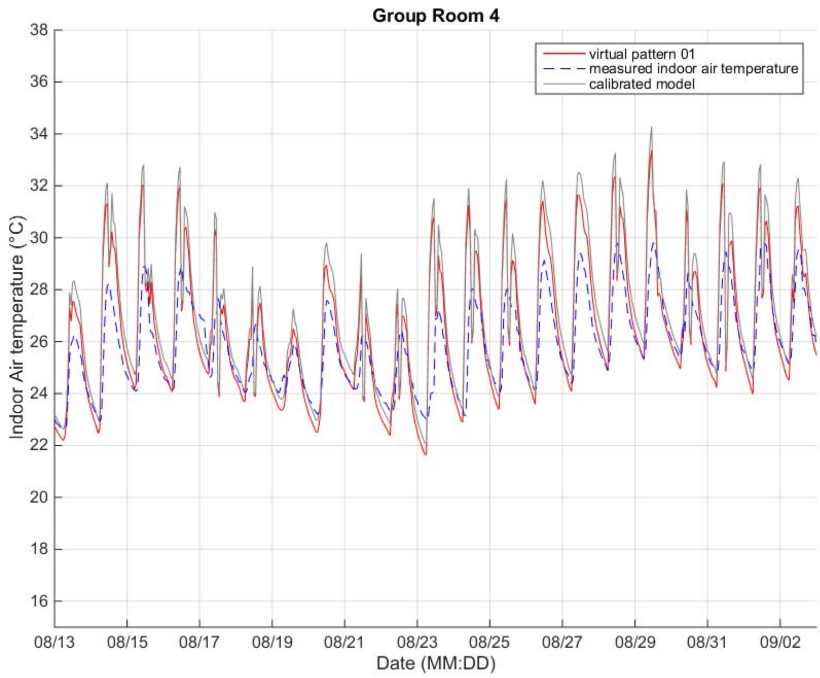


*Figure 4-24 Simulation result with additional shadings, Group Room 4*

As can be seen there is a noteworthy improvement of the thermal performance of the building addressing summer overheating in *Group rooms 1-3*. *Group room 4* does not benefit to the same amount from this suggestion. The reason might be found in the circumstance that there is a large transparent opening in the side facade of *Group room 4*.

### 4.9.2 *Improvement option #2* – free cooling

To further improve the thermal performance of "Kindergarten Pachern" the second suggestion is adding "free cooling" measures to the improvement option described above. "Free cooling" means that cross ventilation (depicted blue in Figure 4-25) effects can be achieved to ventilate the building effectively without any technical ventilation equipment. For the following simulation run (*improvement option #2*), a schedule has been created that opens the rolling doors and the doors to the corridor during the night (6am to 7am every day).

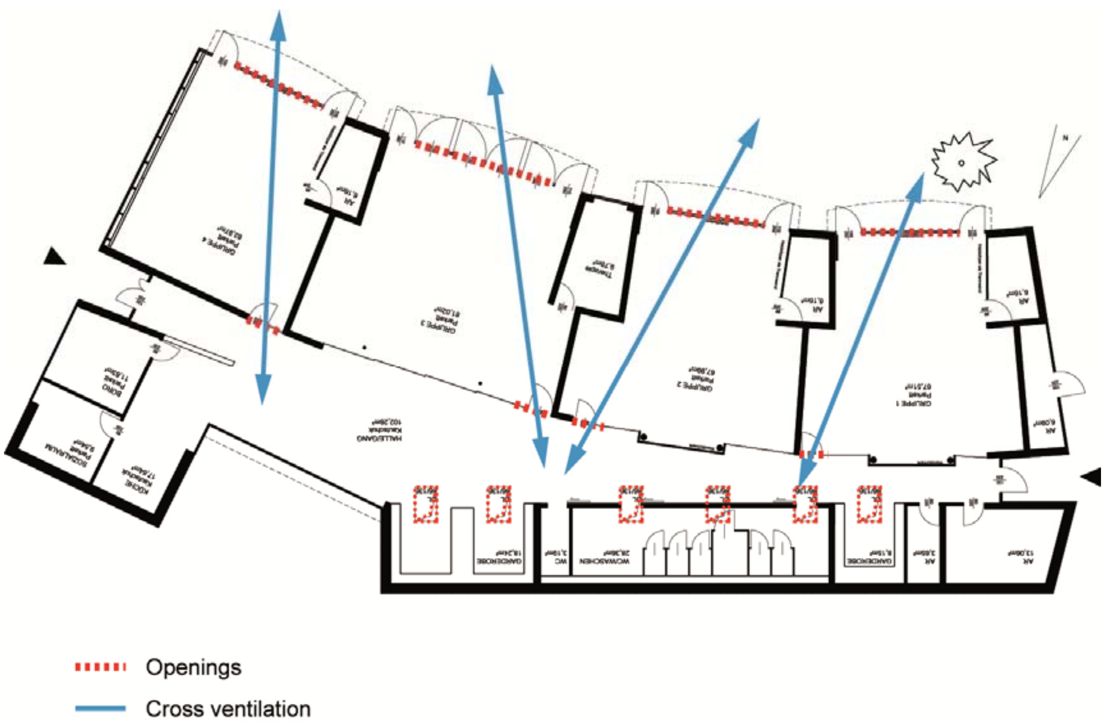


*Figure 4-25 Schematic illustration of free cooling through cross ventilation*

The thermal benefits of free cooling are illustrated in Figure 4-26 to Figure 4-29.

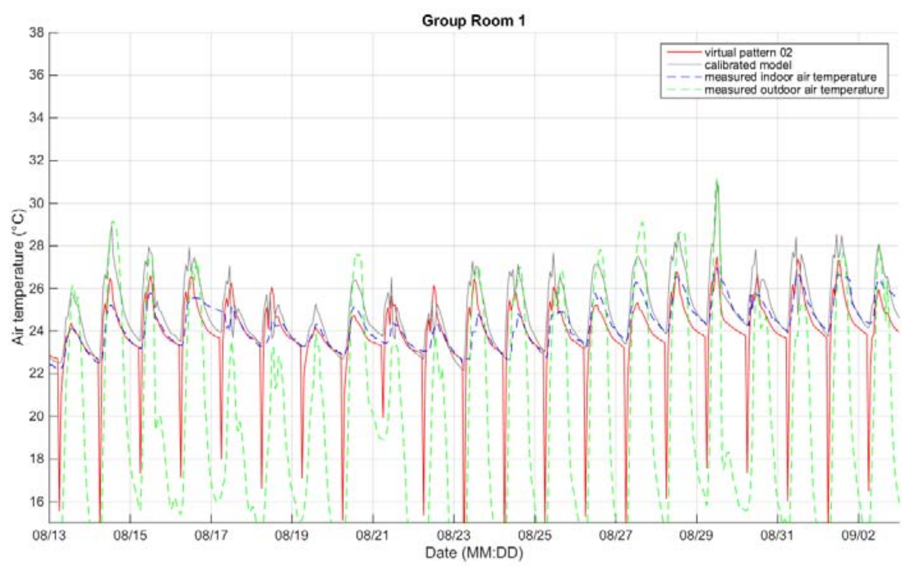


*Figure 4-26 Improvement of thermal performance through free cooling, Group room 1*

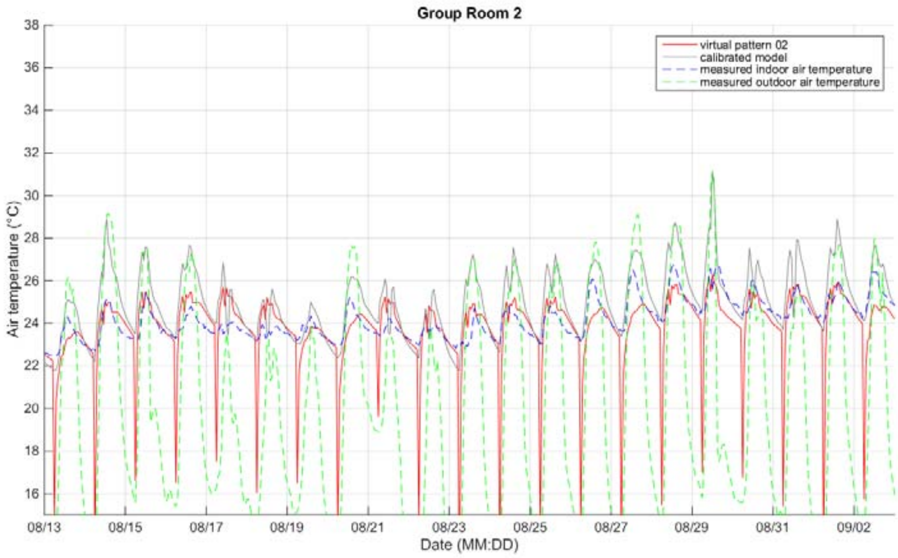


*Figure 4-27 Improvement of thermal performance through free cooling, Group room 2*

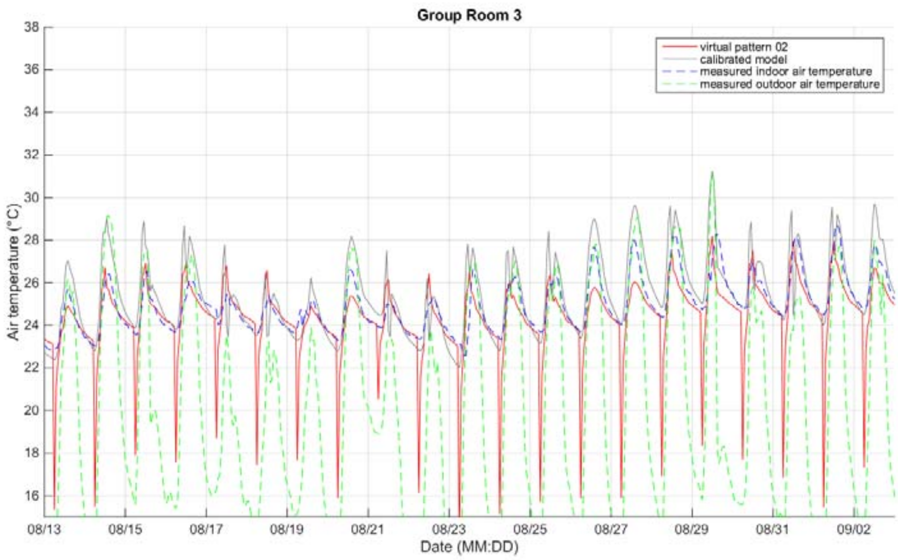


*Figure 4-28 Improvement of thermal performance through free cooling, Group room 3*

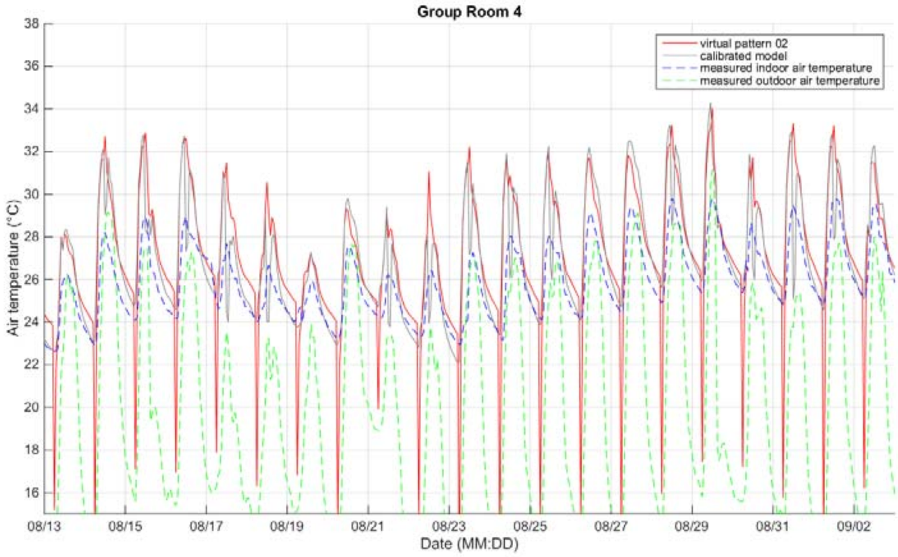


*Figure 4-29 Improvement of thermal performance through free cooling, Group room 4*

The thermal performance of *Group rooms 1-3* has improved and summer overheating problems are reduced noteworthy. The indoor air temperatures of *Group room 4* hardly show any changes. The negative peaks visible in the figures mark the ventilation process during the night.

In practice, this suggestion can either be realised by implementing technical opening devices (automatic e-motors) or can be carried out by cleaning staff that has to work at “Kindergarten Pachern” every morning anyway; who opens doors and ceiling-windows manually.

### 4.9.3 *Improvement option #3* – original design intentions

Konrad Frey´s intention was to create a rough and cheap but well-working building. (compare *Chapter 1*) Therefore the interior concrete walls did not have any cover in the original design. The acoustic plaster has been added recently to the ceilings to improve the acoustical building performance. *Improvement option #3* analyses the impact of the acoustic plaster that was not part of the original design in terms of thermal performance. The results of the simulation are shown in Figure 4-30 to Figure 4-33.

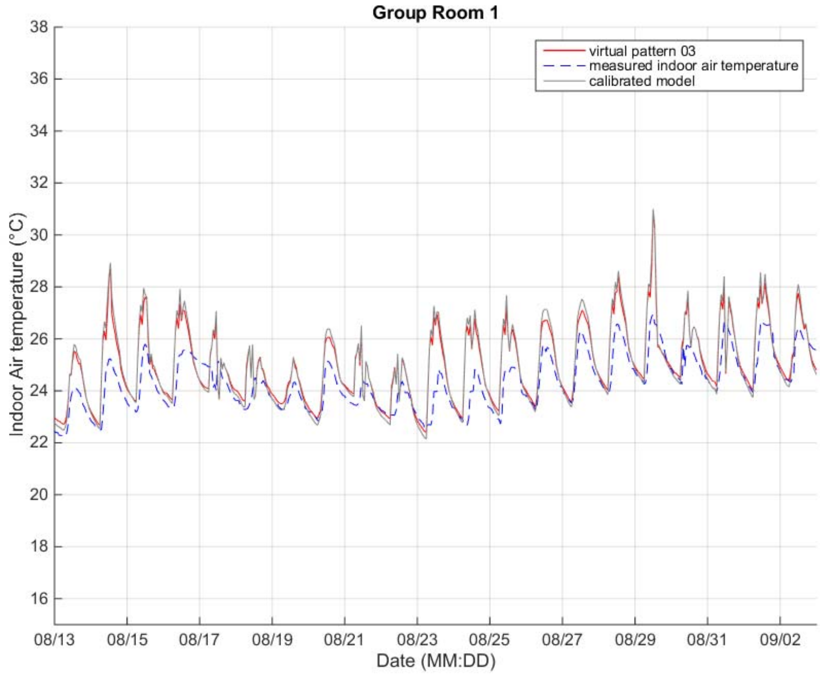


*Figure 4-30 Original design intent; Thermal performance of Group room 1*

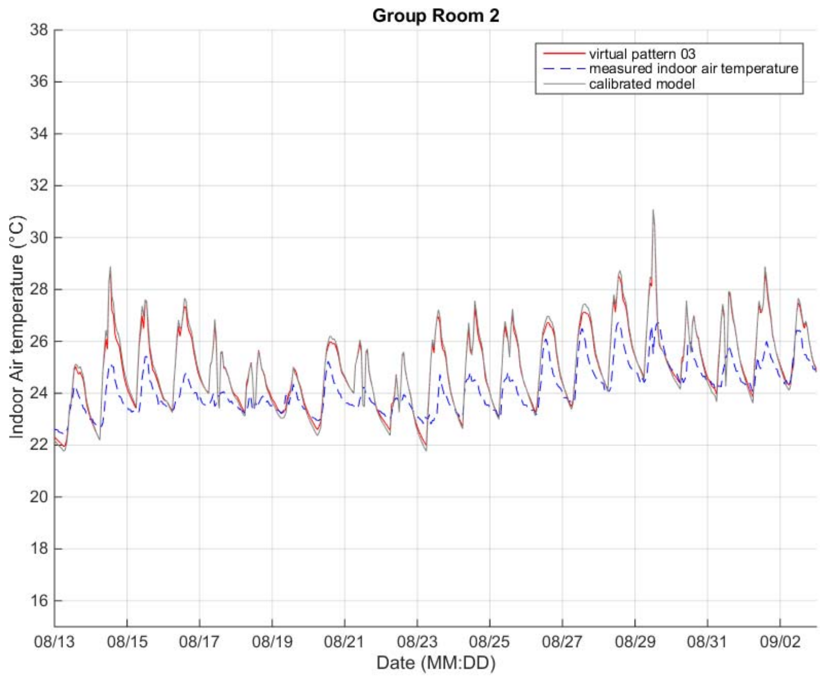


*Figure 4-31 Original design intent; Thermal performance of Group room 2*

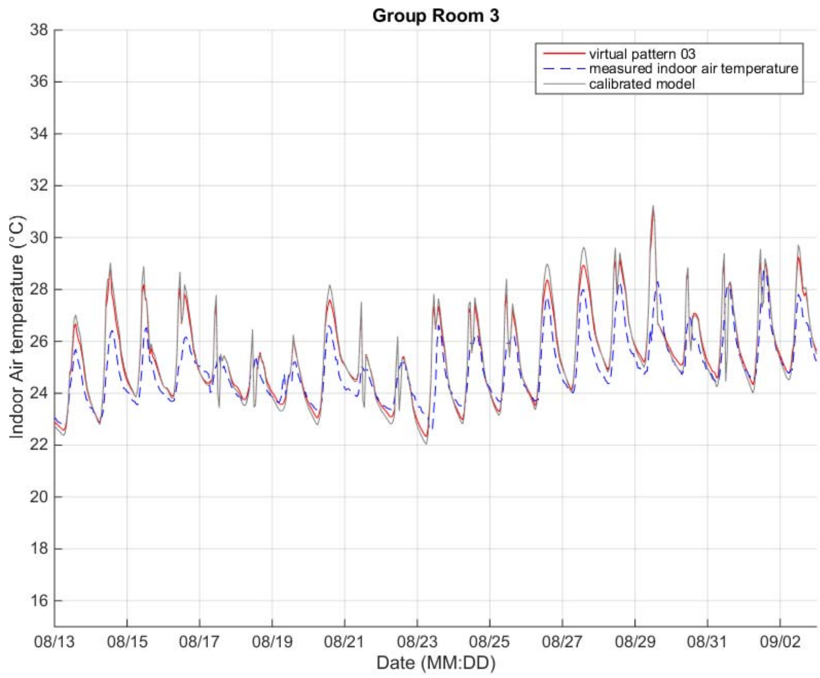


*Figure 4-32 Original design intent; Thermal performance of Group room 3*

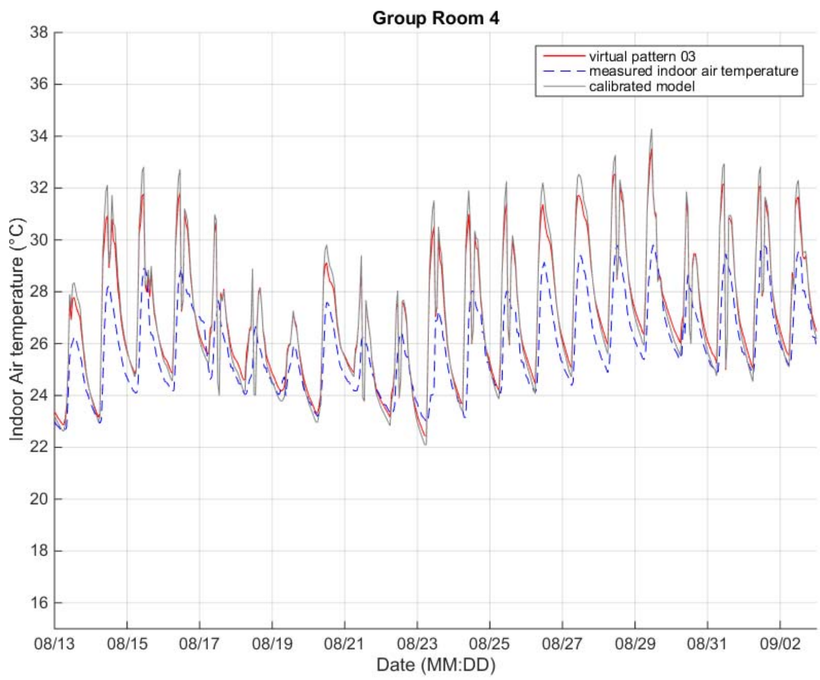


*Figure 4-33 Original design intent; Thermal performance of Group room 4*

The removal of the acoustic plaster slightly flattens the simulated temperature curve compared to the measured values. All in all, the effect is very small and therefore can be neglected. In practice, the acoustic benefits outweigh the thermal disadvantages. Therefore removing the acoustic plaster from the ceilings is not recommended.

# 5 DISCUSSION

The following chapter is divided into two parts. It starts with a presentation of the summary of the calibration results focusing on the summer period when the building is operated in “free run mode” to analyse summer overheating issues. In the second part, the proposed thermal performance improvements, the so-called *improvement options*, are going to be discussed.

## 5.1 Calibration process

Figure 5-1 to Figure 5-4 sum up the results of the calibration process. All simulation results of the calibration steps, the initial model and the measured indoor air temperatures are overlayed graphically.

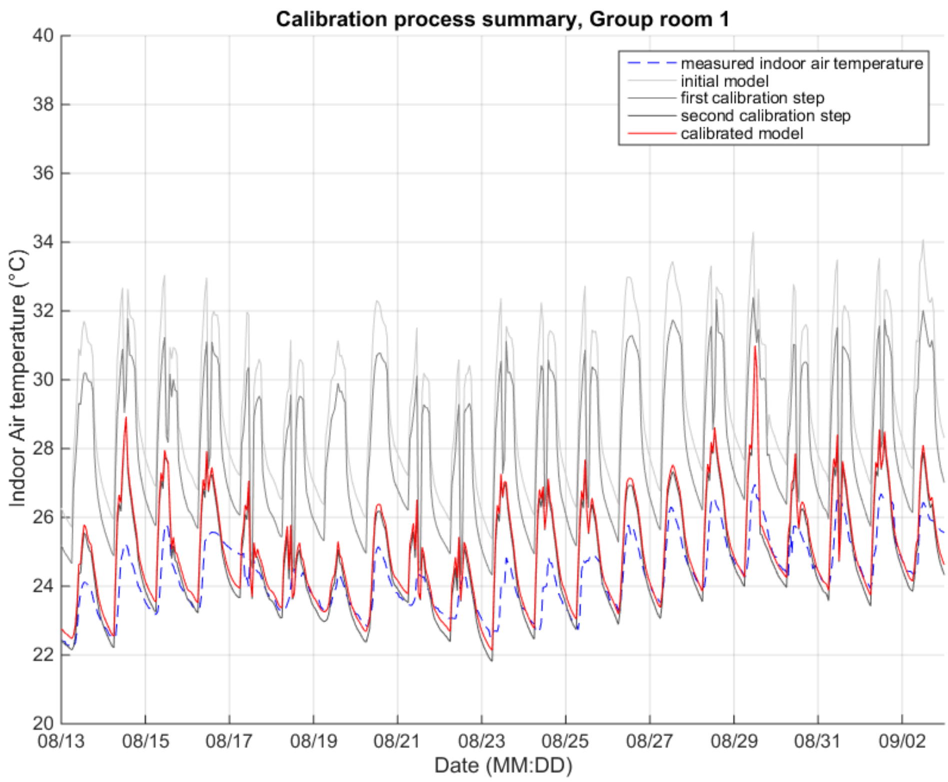


*Figure 5-1 Summary of the calibration process, Group room 1*

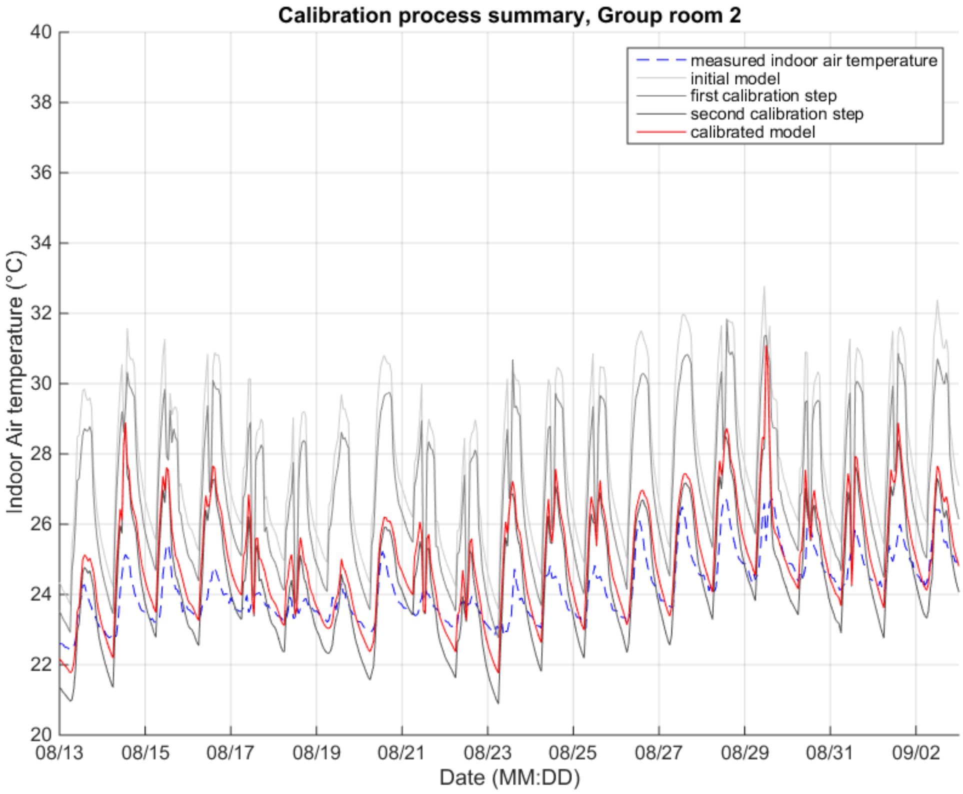


*Figure 5-2 Summary of the calibration process, Group room 2*

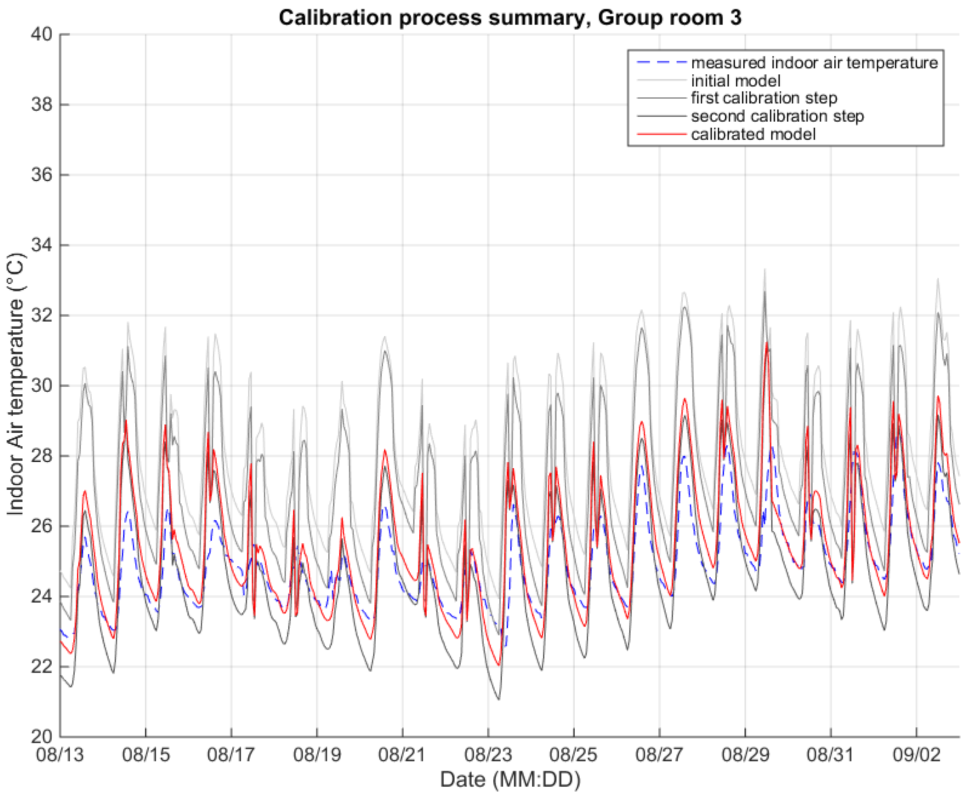


*Figure 5-3 Summary of the calibration process, Group room 3*

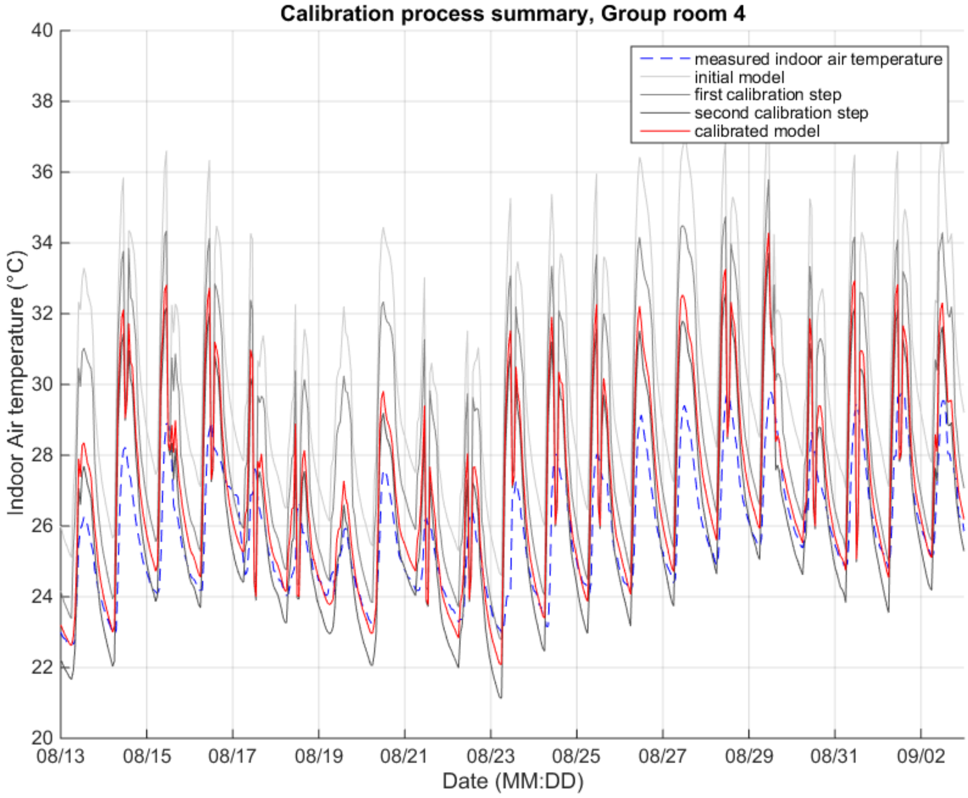


*Figure 5-4 Summary of the calibration process, Group room 4*

The initial model (with general operation schedules based on working hours and maximum internal gains) showed significant deviations from the monitored results. A strong trend towards overheating can be seen. The first calibration (optimizing solar gains, e.g. shadings) has been adapted based on user interviews. The second simulation run after the first calibration still shows trends towards overheating. The second calibration (internal gains have been adapted, based on user interviews) limits down the summer overheating problem and results in a noteworthy higher agreement with the measured values. After a third calibration step (adapting air change rates), which did not improve the model in a noteworthy manner, the simulation model was considered to be calibrated. As can be seen graphically, an improvement of the simulation model took place in each calibration step, a fact that is also expressed in the comparison of *MBE, RMSE* and *CV(RMSE)* values which are graphically presented in Figure 5-5 to Figure 5-7.

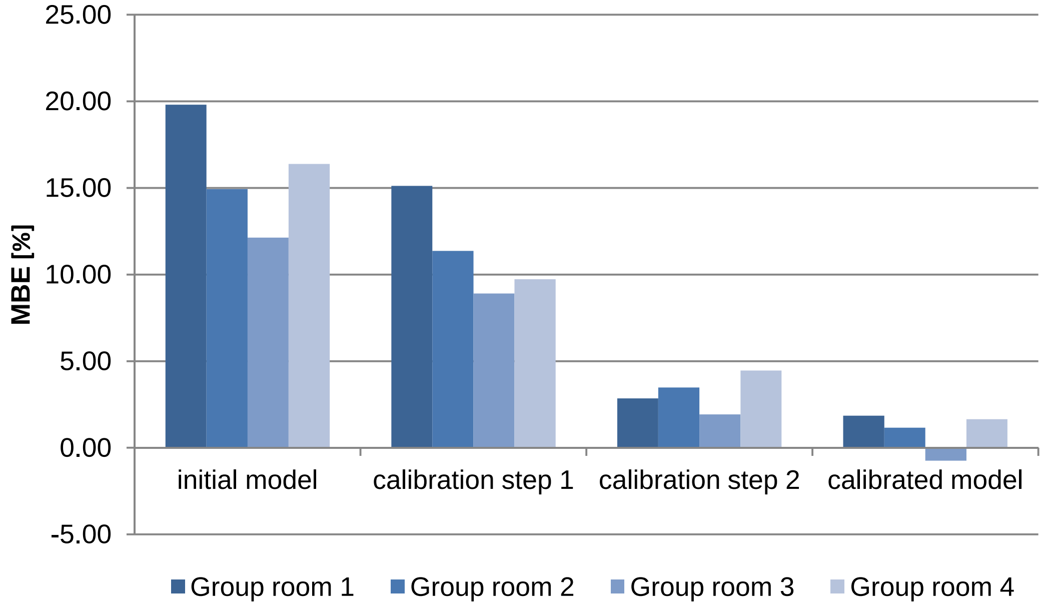


*Figure 5-5 Compact summary of MBE values*

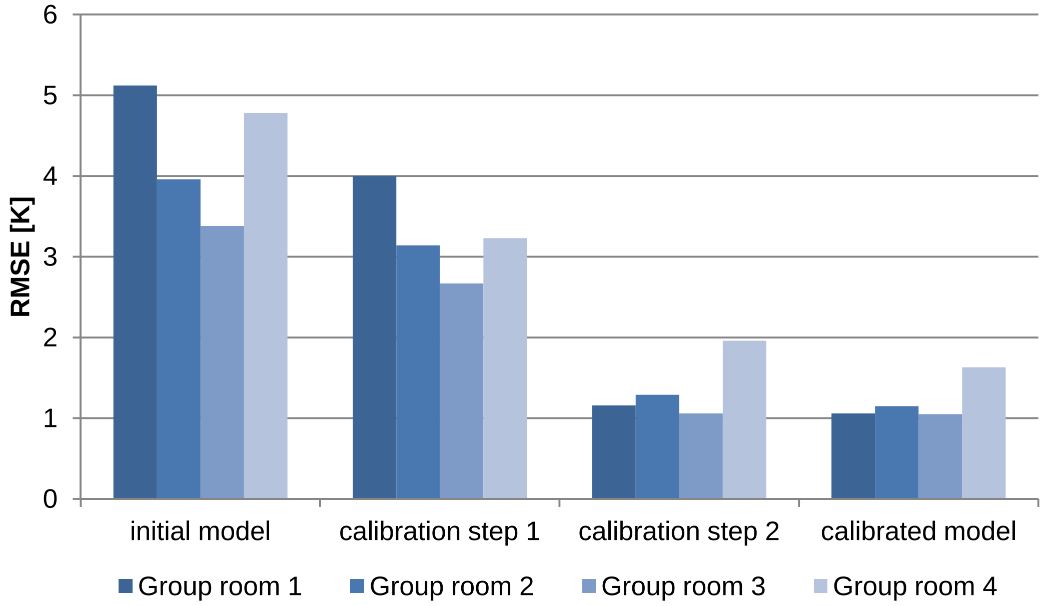


*Figure 5-6 Compact summary of RMSE values*

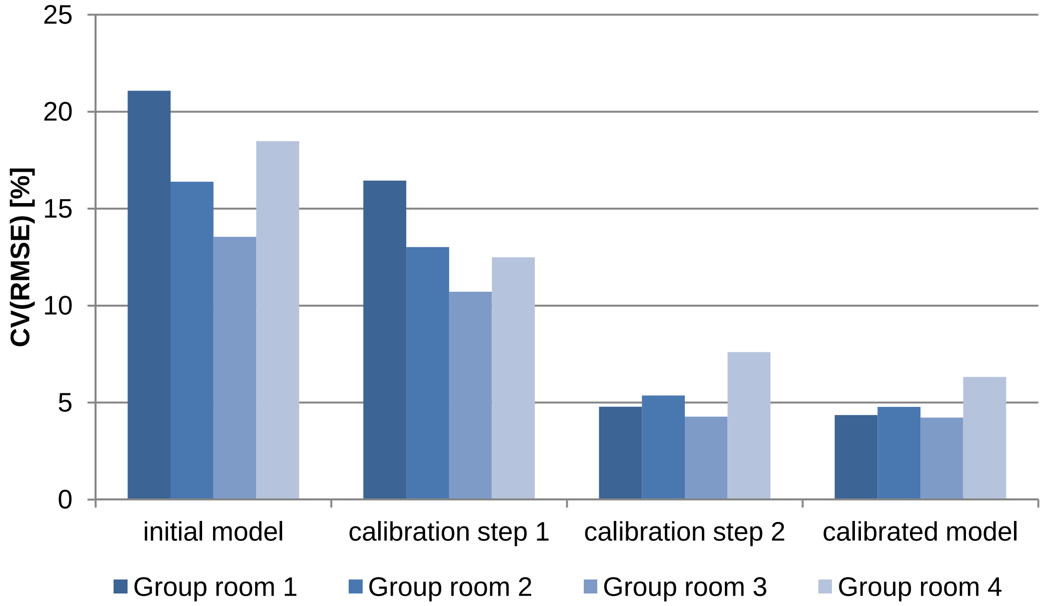


*Figure 5-7 Compact summary of CV(RMSE) values*

All values improve continuously throughout the calibration process. As the figures illustrate, solar gains (calibration step 1) and internal gains (calibration step 2) had a huge impact on the simulation results whereas adaptations in air change rates (final calibration step) hardly improved the simulation model. The *CV(RMSE)* values of the calibrated model for *Group rooms 1-3* fall within 5%. *Group room 4* stays slightly behind at around 6%.

As mentioned in *Chapter 2*, ASHRAE Guide 14 considers a building model calibrated if *MBE* values fall within +/- 10% and *CV(RMSE)* values are smaller than 30%. As the results stay within these limits, the simulation model of “Kindergarten Pachern” can be considered as calibrated.

By comparing the simulated and calculated heating demands during the winter simulation period, the accuracy of the simulation model was verified during the heating season in an indirect way as well.

## 5.2 Improvement options

By simple methods such as “night cooling” through cross ventilation during the night or adding additional shadings it is possible to reduce the indoor air temperature during the summer. If both proposals are combined, indoor air temperature peaks can be limited as demonstrated in Figure 4-26 to Figure 4-29.

The use of “free cooling” effects was an original intent of Konrad Frey. The building geometry allows cross ventilation via the ceiling openings above the corridor if operated properly.

Although *Improvement option #3* was not too effective, it points out the impact on building performance that refurbishment measures might have. Therefore building simulation should always be deployed to simulate the refurbishment proposals in advance (compare: Penna et al. 2015, *Chapter 2*).

Figure 5-8 to Figure 5-11 present a graphical overlay of the *improvement options #1, #2* and *#3*. To point out the benefits of the virtual improvements the measured indoor air temperature curve and the results of the calibrated model are displayed as well.

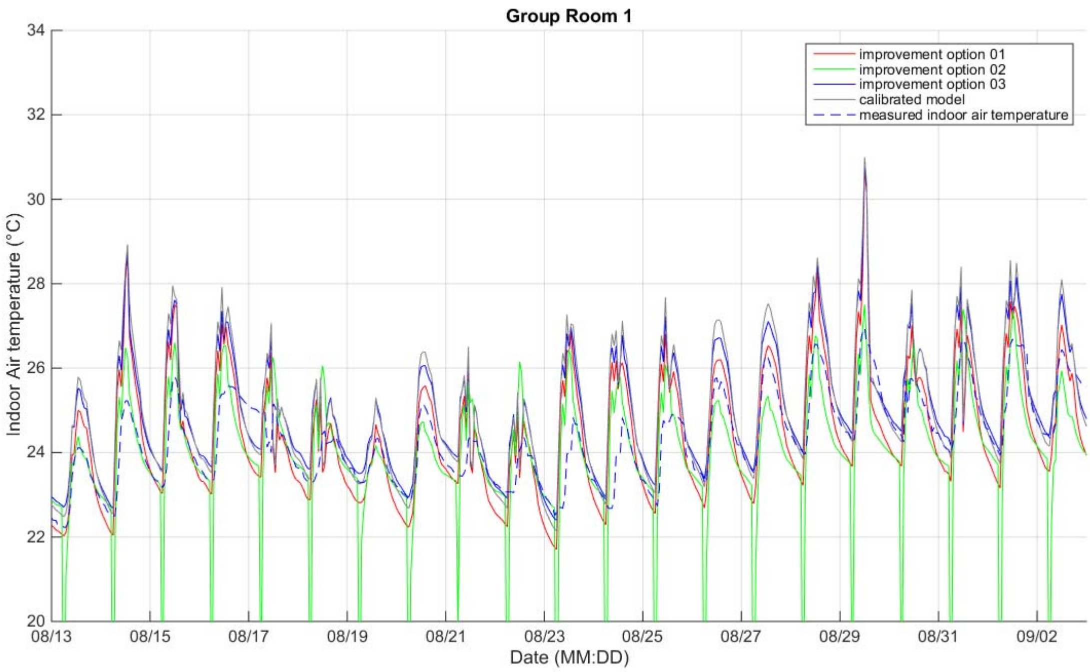


*Figure 5-8 Comparison of the improvement options, Group room 1*

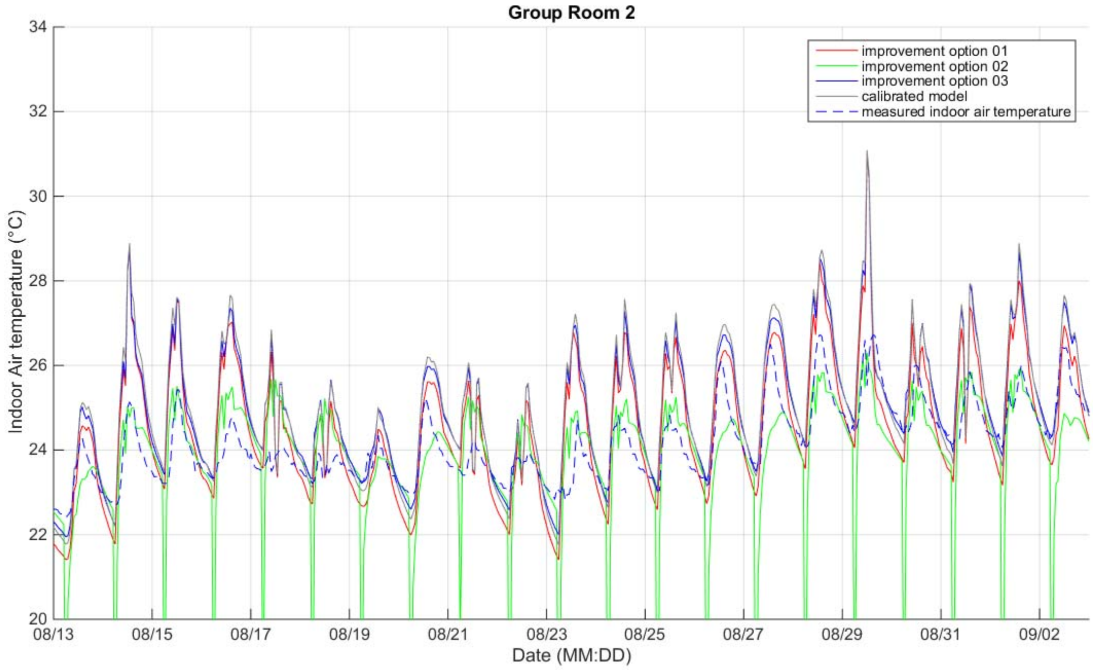


*Figure 5-9 Comparison of the improvement options, Group room 2*

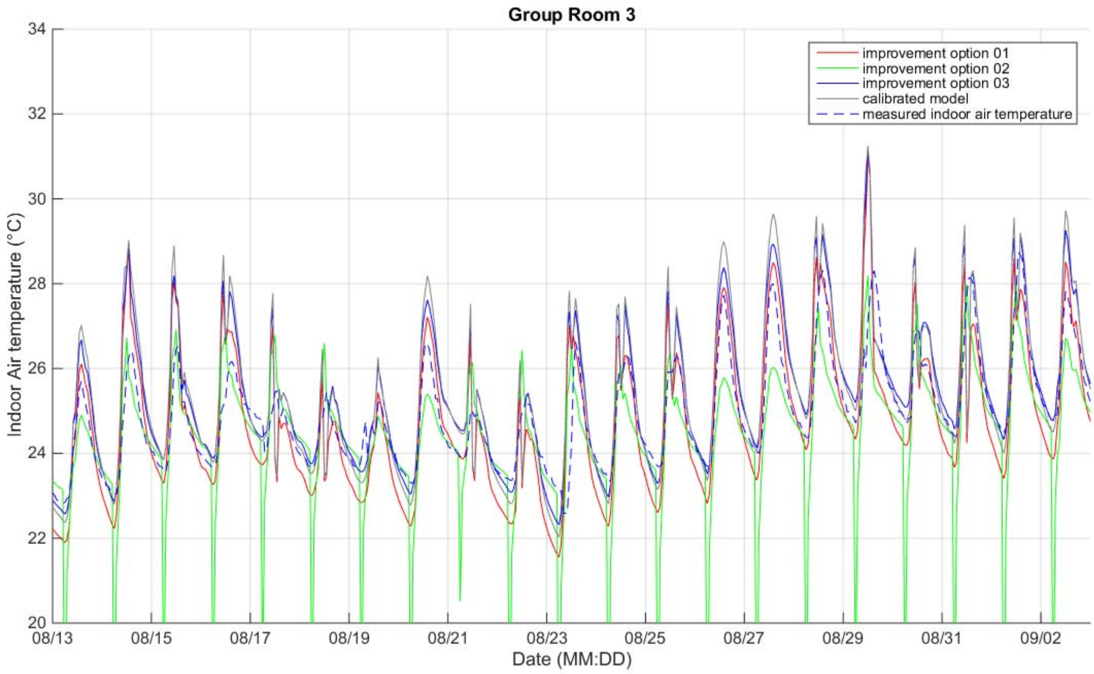


*Figure 5-10 Comparison of the improvement options, Group room 3*

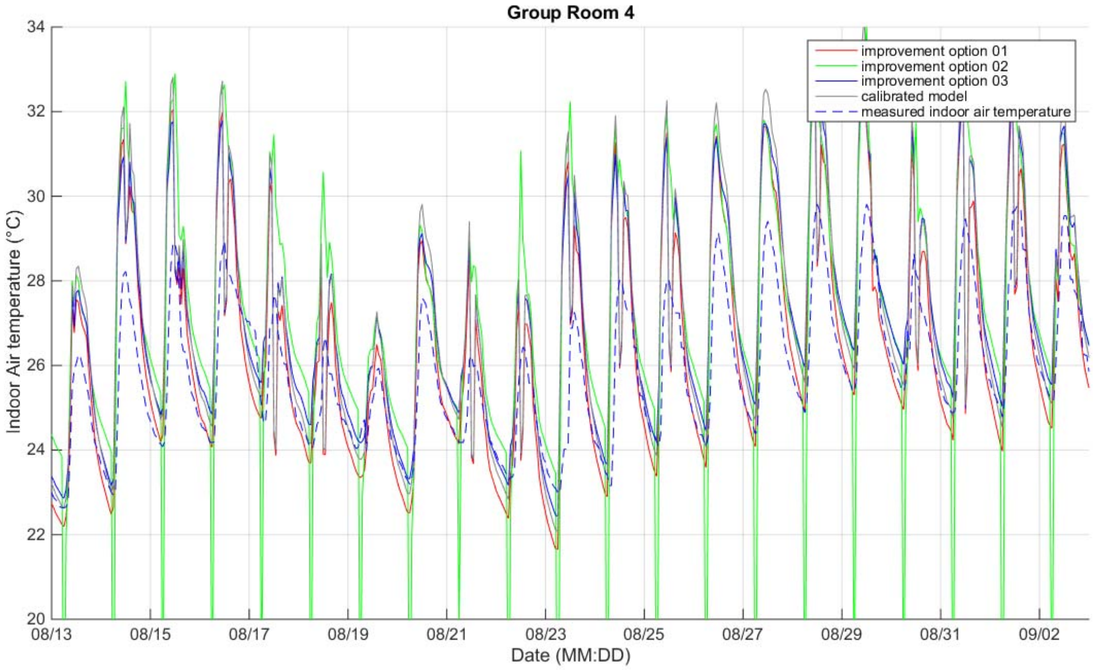


*Figure 5-11 Comparison of the improvement options, Group room 4*

In a follow-up step, proposals for the improvement of the thermal performance, the so-called "improvement options", can be summed up and presented as a "user manual" that can be handed over to the staff of "Kindergarten Pachern". On the basis of the calibrated model, the effectiveness of the improvement scenarios (*improvement options*) can be examined objectively. The user manual might give hints how to improve thermal conditions by simple and cheap methods such as "free cooling" or adding additional shadings in the summer. Table 5-1 provides an overview of the indoor air temperatures > 25°C in the summer simulation period. Group rooms 1 to 3 show a thermal performance improvement and a noticeable reduction of summer overheating in the *improvement option* simulations.

*Group room 4,* which shows the poorest simulation results (in all simulation cases) compared to the measured data, has to be examined in further research in a single-zone simulation. As *Group room 4* was not intended to be built originally, there might be inaccuracies in the construction and material properties of the simulation model.

*Table 5-1 Summer overheating during the summer simulation period of three weeks (528 hours); in group rooms 1, 2, 3 and 4, respectively*

| **Scenario** group room 1/2/3/4 | **# of hours indoor temp. >25°C** | **# of hours indoor temp. >26°C** | **# of hours indoor temp. >27°C** | **# of hours indoor temp. >28°C** | **# of hours indoor temp. >29°C** | **# of hours indoor temp. >30°C** |
|---|---|---|---|---|---|---|
| calibrated model | 237/249/ 292/408 | 140/147/ 178/315 | 71/60/ 112/233 | 12/11/ 60/172 | 3/2/ 22/127 | 2/2/ 3/90 |
| impr. option 01 | 172/198/ 206/355 | 90/98/ 120/256 | 23/26/ 68/193 | 6/7/ 24/142 | 2/2/ 3/100 | 2/2/ 2/65 |
| impr. option 02 | 111/78/ 184/439 | 32/2/ 60/358 | 5/0/ 10/259 | 0/0/ 1/194 | 0/0/ 0/139 | 0/0/ 0/89 |
| impr.option 03 | 240/249/ 303/427 | 132/132/ 178/331 | 48/53/ 104/239 | 8/12/ 46/170 | 2/2/ 12/119 | 2/2/ 3/79 |

Figure 5-12 to Figure 5-15 illustrate the summer overheating at "Kindergarten Pachern" for all group rooms for the summer simulation period of three weeks (528 hours). *Improvement option 1* and *2* show major improvements compared to the calibrated simulation model. The total number of hours, where the indoor air temperature exceeds the limits of 25°C, 26°C, 27°C, 28°C, 29°C and 30°C can be reduced by adding additional shadings (*Improvement option 1*) and providing cross ventilation during the night (*Improvement option 2*).

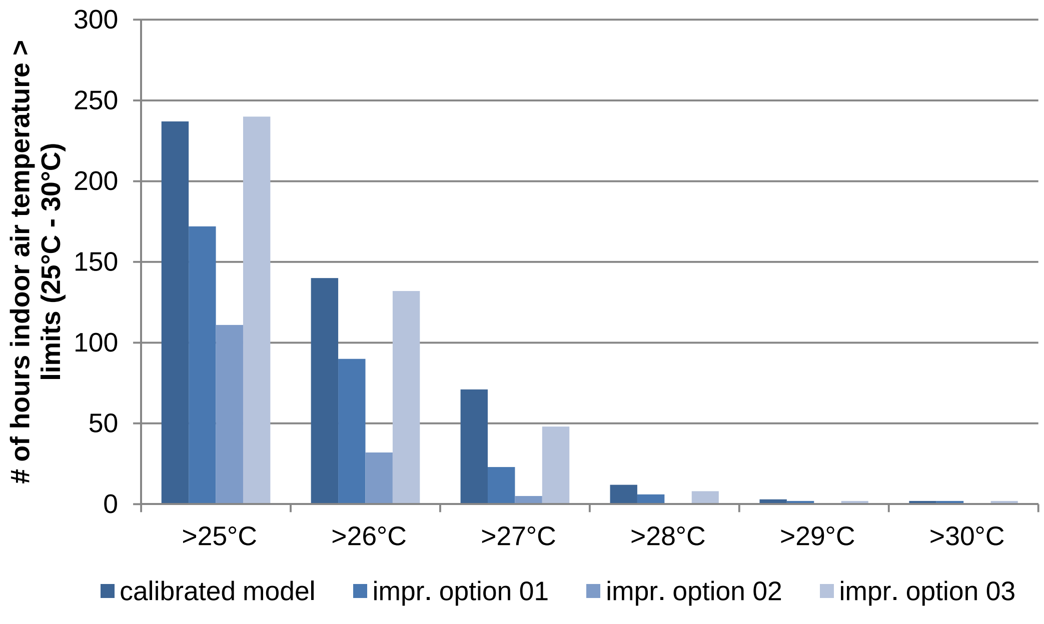


*Figure 5-12 Number of hours of the indoor air temperature > limits (25°C-30°C); Group room 1*

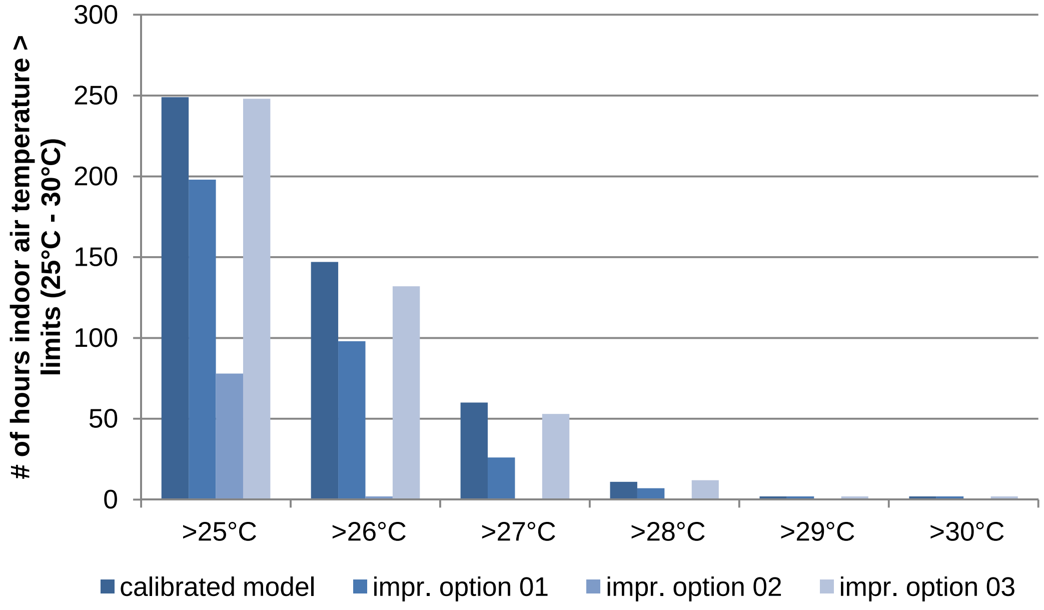


*Figure 5-13 Number of hours of the indoor air temperature > limits (25°C-30°C); Group room 2*

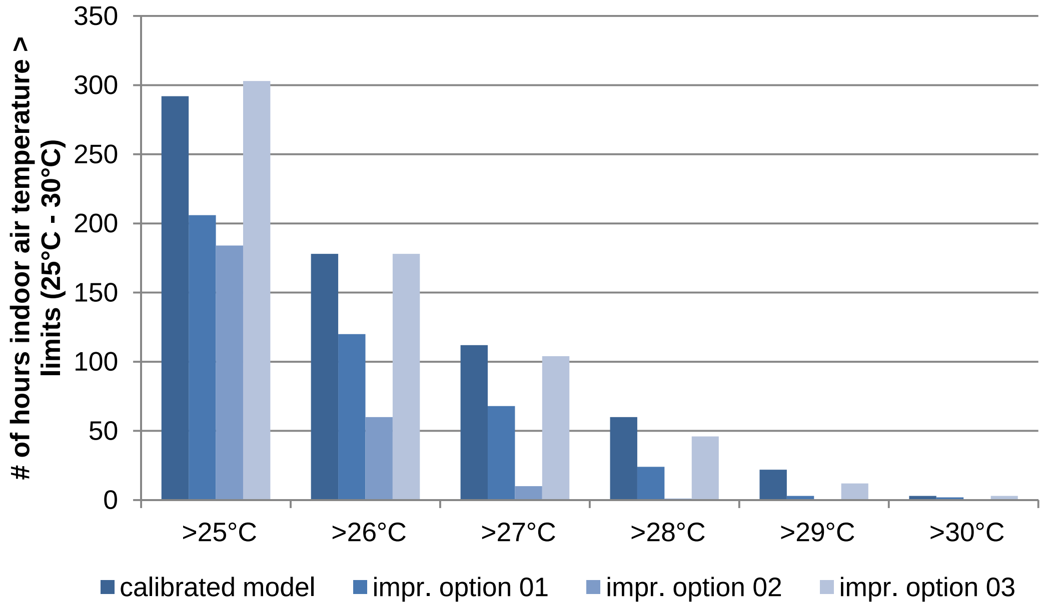


*Figure 5-14 Number of hours of the indoor air temperature > limits (25°C-30°C); Group room 3*

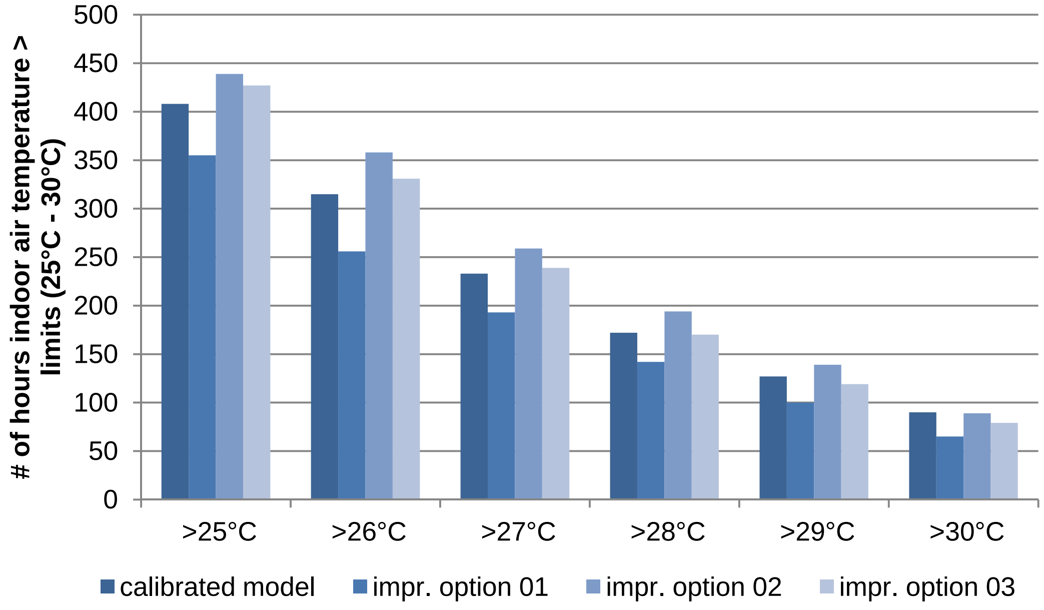


*Figure 5-15 Number of hours of the indoor air temperature > limits (25°C-30°C); Group room 4*

Table 5-2 and Figure 5-16 to Figure 5-19 provide a percentage overview of the indoor air temperatures > 25°C in the summer simulation period of three weeks. All group rooms show a thermal performance improvement and a noticeable reduction of summer overheating in the *improvement option* simulations.

*Table 5-2 Percentage comparison of summer overheating during the summer simulation period of three weeks (528 hours); in group rooms 1, 2, 3 and 4, respectively*

| **Scenario** group room 1/2/3/4 | **percentage of indoor temp. >25°C [%]** | **percentage of indoor temp. >26°C [%]** | **percentage of indoor temp. >27°C [%]** | **percentage of indoor temp. >28°C [%]** | **percentage of indoor temp. >29°C [%]** | **percentage of indoor temp. >30°C [%]** |
|---|---|---|---|---|---|---|
| calibrated model | 45/47/ 55/77 | 27/27/ 33/59 | 13/11/ 21/44 | 2/2/ 11/32 | 0/0/ 4/24 | 0/0/ 0/17 |
| impr. option 01 | 33/37/ 39/67 | 17/18/ 22/48 | 4/5/ 13/37 | 1/1/ 5/27 | 0/0/ 0/19 | 0/0/ 0/12 |
| impr. option 02 | 21/15/ 35/83 | 6/0/ 11/68 | 1/0/ 2/49 | 0/0/ 0/37 | 0/0/ 0/26 | 0/0/ 0/17 |
| impr. option 03 | 45/47/ 57/80 | 25/25/ 34/63 | 9/10/ 20/45 | 2/2/ 9/32 | 0/0/ 2/25 | 0/0/ 0/15 |

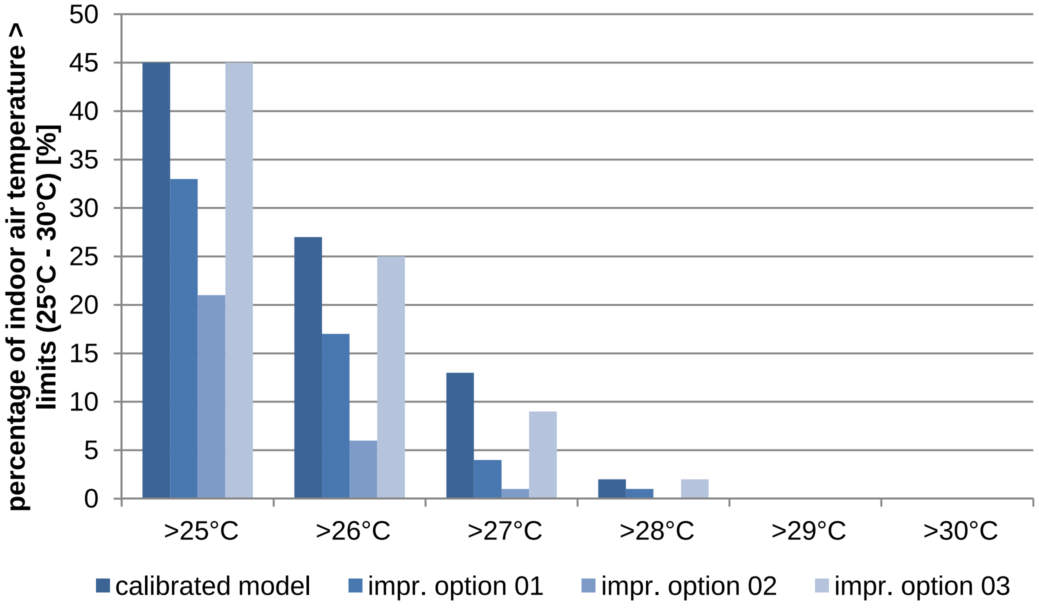


*Figure 5-16 Percentage comparison of the indoor air temperature > limits (25°C-30°C); Group room 1*

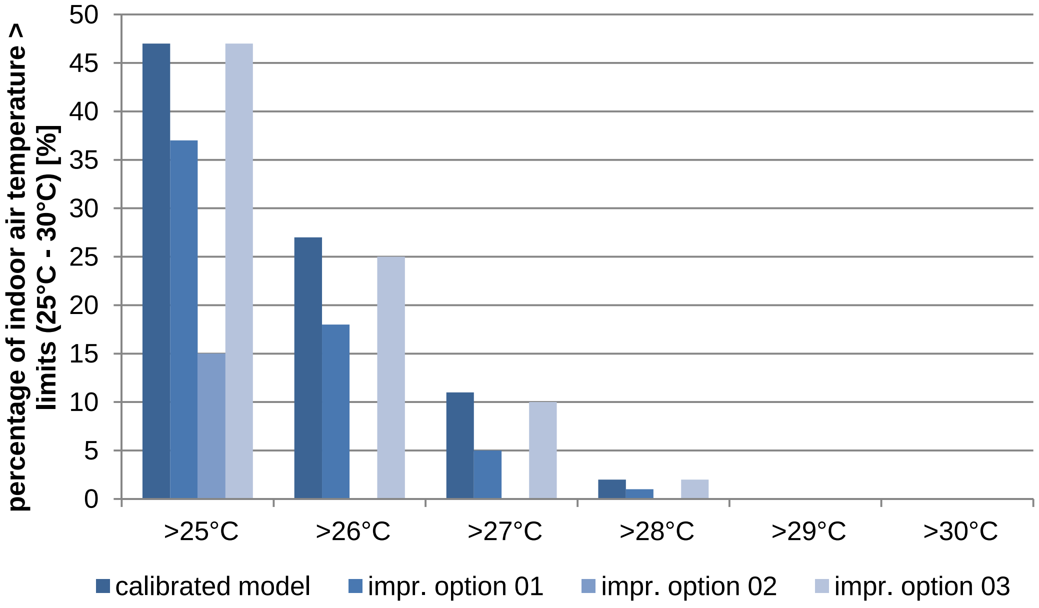


*Figure 5-17 Percentage comparison of the indoor air temperature > limits (25°C-30°C); Group room 2*

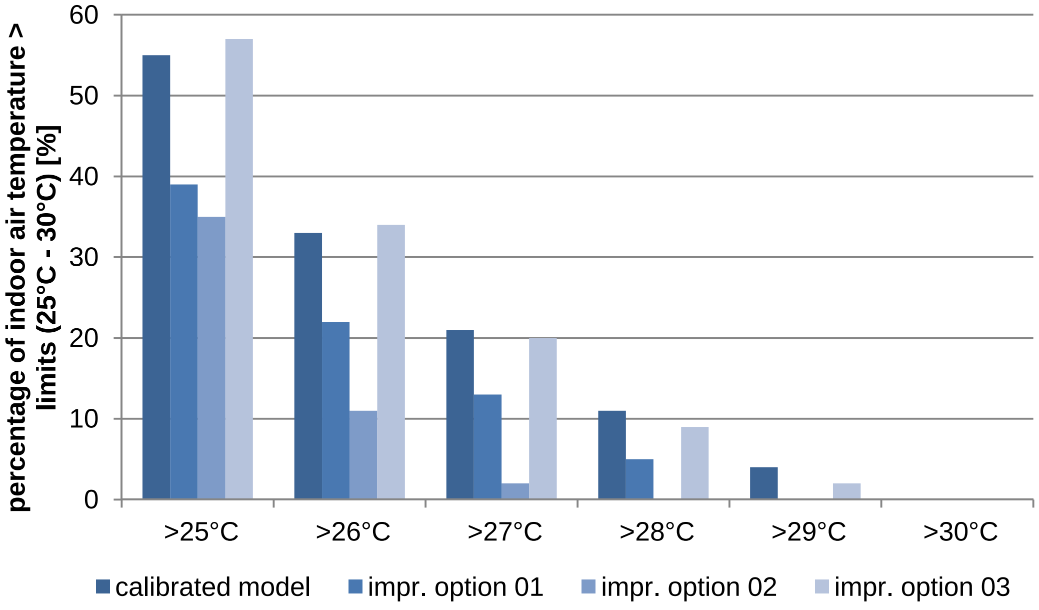


*Figure 5-18 Percentage comparison of the indoor air temperature > limits (25°C-30°C); Group room 3*

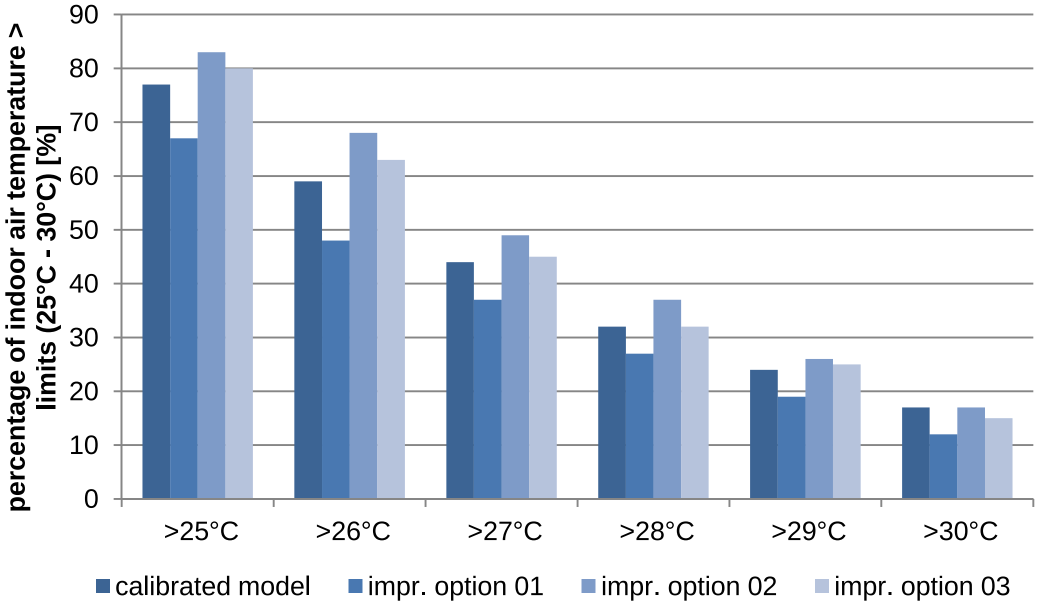


*Figure 5-19 Percentage comparison of the indoor air temperature > limits (25°C-30°C); Group room 4*

To provide another illustration of the trend towards summer overheating Table 5-3 and Figure 5-20 show the mean indoor air temperature for all group rooms if the indoor air temperature rises above 25°C during the summer simulation period.

The following equation can be used to calculate the mean overheating temperature:

$$T_{overheating} = \frac{\theta_i - 25}{n} \quad [K] \qquad \text{eq. (10)}$$

whereas:

$\theta_i > 25$

n = number of hours indoor air temperature > 25°C

*Table 5-3 Mean overheating temperature if the indoor air temperature rises above 25°C for all group rooms during the summer simulation period*

| **Scenario** | Group room 1 [K] | Group room 2 [K] | Group room 3 [K] | Group room 4 [K] |
|---|---|---|---|---|
| **calibrated model** | 1,53 | 1,47 | 1,85 | 3,07 |
| **improvement option 01** | 1,31 | 1,31 | 1,70 | 2,83 |
| **improvement option 02** | 1,00 | 0,73 | 0,97 | 3,13 |
| **improvement option 03** | 1,36 | 1,37 | 1,68 | 2,87 |

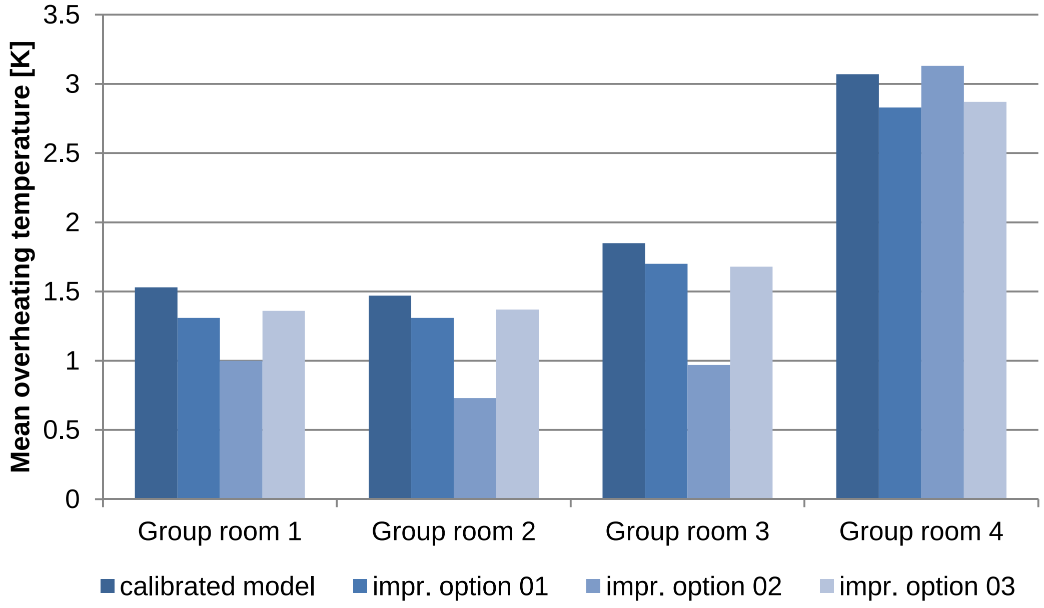


*Figure 5-20 Mean overheating temperature >25°C if the indoor air temperature rises above 25°C*

According to Table 5-3 and Figure 5-20 summer overheating can be limited without using any mechanical cooling systems. This seems to be a promising eco-friendly and sustainable solution not only for “Kindergarten Pachern”. This fact represents the main finding of this master thesis.

# 6 CONCLUSION

*"Given the diverse and varied nature of underlying uncertainties in simulation attempts, building performance results can at best rest within a small allowable error margin"* (Royapoor and Roskilly, 2015, p117).

This master thesis illustrates the use of monitored data to design a more accurate simulation model compared to standard design assumptions for operation schedules and external climate. The monitored data was both used to populate the initial simulation model and to maintain its fidelity through a systematic calibration process. The variation of the indoor air temperature in the different calibration steps highlights the importance of realistic operation schedules and internal gains. In the course of multiple simulation and calibration steps, several variables were selected for calibration based upon measured data and user interviews. Step by step, calibrations were performed in a systematic manner to adjust the building´s physical properties (e.g. shadings, infiltration) and the occupants´ interactions (occupancy, ventilation) in different environmental conditions (local weather data).

Building performance simulation is a powerful tool to predict the "behaviour" of a building. If the input factors of the simulation are accurate enough, it is possible to reach a precision level of around 5% for *CV(RMSE)* values (Figure 5-7) and *MBE* values within a range of 2% (Figure 5-5) as demonstrated in this thesis.

Note that, the quantity of data acquisition and the quality of measurements in building simulations are of utmost importance. For this thesis, long-term monitoring was the basis for the whole simulation process. As shown in C*hapter 3,* the impact of a local weather file based on local measurements has a tremendous impact on the simulation results. The same holds true for an extensive indoor monitoring (e.g. contact sensors, occupancy sensors) to obtain all relevant input variables as precisely as possible.

A major topic that influenced the simulation results of "Kindergarten Pachern" noteworthy was occupancy behaviour. By conducting user interviews the sources of error were narrowed down in this field.

Another notable point is that detailed building documentation was strongly relevant for this thesis. Detailed plan material (sections, floor plans) formed the basis for designing the building geometry and defining material properties and constructions.

Overall *Energy-Plus* provided an acceptable simulation for the case study of this thesis, a fact which underlines that virtual computer simulations remain an indispensable tool for performance analysis of buildings both pre- and post-constructional. Therefore building simulation should always be deployed to simulate the refurbishment proposals in advance (compare: Penna et al. 2015).

## 6.1 Main findings

The main findings of this work can be summarized as follows:

- Detailed building information such as geometry and properties of the constructions form the basis for acceptable simulation results.
- Probabilistic elements such as local weather data play a significant role in the accuracy of simulation results.
- Stochastic processes such as occupancy behaviour have a major impact on simulation results.
- The quality and quantity of measured data are of high importance for accurate simulations. Gaps and errors in measurements lead to significant uncertainties.
- The impact of lighting and small electrical power devices was originally overestimated in this master thesis.
- The levels of tolerated errors strongly depend on primary data available.
- An accurate and reliable building simulation model is able to predict the impact of further refurbishment and forms the basis for further performance improvements of the building.
- Summer overheating can be limited without using any mechanical cooling systems according to the simulation results of the "*improvement options*" simulations.

## 6.2 Further research

Building performance simulation remains an interesting field for the author. Apart from pointing out the strength and reliability of building simulation tools by providing acceptable *CV(RMSE)* values and line charts, this master thesis raises the following questions that have to be examined in further research:

- Further variables that were not taken into account for these simulations have to be spotted to improve the thermal performance. For instance,

- Summer overheating and temperature overestimation still occurs in the calibrated model. Therefore, material properties and constructions which are modelled according to plan material have to be verified.
- A more detailed documentation of the heating system would bring benefits to the winter period simulations. Data of gas and electricity metering of “Kindergarten Pachern” would be helpful to make accurate calculations of the power consumption. Therefore, the cooperation and exchange of information between the user and the simulation engineer have to be improved.
- Long-term data collection is the basis for accurate simulations. Therefore the quality of measured data (especially avoiding data gaps) is important. Due to user behaviour (e.g. unplugging of devices) data gaps occured, a fact which makes it hard to produce seamless simulation patterns.
- As fluent data transfer was checked manually over a period for almost one year, it is worth considering improving automatic data back-up systems and alert systems that inform the simulation team automatically in case data gaps occur. Projects like MOST (TU Wien) and the development of a flexible and interactive user-interface seems to be a promising and important way to improve data collection and data handling (http://most.bpi.tuwien.ac.at/).

# 7 INDEX

## 7.1 List of Figures

*All figures that are not labeled explicitly are designed by the author.*

## 7.2 List of Tables

*All tables that are not labeled explicitly are produced by the author.*

# 8 LITERATURE

All sources (books, journals, internet documents...), which were used in this work, are listed below:

A Palaver, 2017. *http://www.apalaver.com/blog_apalaver/2016/07/a-palaver-161-konrad-frey/* Accessed 18.03.2017

Architektur Aktuell, 2017. *https://www.architektur-aktuell.at/termine/veranstaltungen-vortraege/sprechen-ueber-architektur-konrad-frey.* Accessed 14.02.2017

Architektur Steiermark, 2017. *http://www.gat.st/news/konrad-freys-well-tempered-environment.* Accessed 14.02.2017

ASHRAE, 2016. *https://www.ashrae.org/File%20Library/.../55_2010_g_Final.pdf* Accessed 02.01.2017

ASHRAE, 2017. https://www.ashrae.org/about-ashrae. Accessed 14.02.2017

Ayres, J.M. and Stamper, E., 1995. *Conference*: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) winter meeting and exhibition. 28 Jan - 1 Feb 1995, Chicago

BAUBOOK, 2016. *https://www.baubook.info/* Accessed 06.10.2016

Bellinger, G., 2004. *Simulation is not the answer.* http://www.systems-thinking.org/simulation/simnotta.htm. Accessed 15.02.2017

Coakley, D., Raftery, P. and Keane, M., 2014. A review of methods to match building energy simulation models to measured data. Renewable and Sustainable Energy Reviews, Elsevier 2014

Crawley, D.B., 2003. *Conference*: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) winter meeting. In: ASHRAE Annual Winter Meeting, 25-29 January 2003, Chicago

De Wit, S., 2004. Uncertainty in Building Simulation. In: Malkawi, A.M. and Augenbroe, G. (Eds), Advanced building simulation. New York, USA: Taylor & Francis, pp. 25-60

ENERGY-PLUS, 2016. *http://apps1.eere.energy.gov/buildings/energyplus/* Accessed 06.09.2016

ENERGY-PLUS, 2017. *https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.3.0/EMS_Application_Guide.pdf* Accessed 25.02.2017

GOOGLE Maps, 2017. *https://www.google.at/maps/place/Volkshilfe+Kindergarten+Hart+bei+Graz/@47.0463381,15.5207227,207m/data=!3m1!1e3!4m8!1m2!2m1!1shart+bei+graz+kindergarten+pachern!3m4!1s0x476e4b6c1a1b5441:0x60e01bd7965ae971!8m2!3d47.046221!4d15.520802* Accessed 18.03.2017

Green, H.L. 2009. *High-performacne buildings, Innovations: Technology, Governance, Globalization.* MIT Press Journals 4(4), pp. 235-239. DOI: 10.1162/ itgg.2009.4.4.235

Hensen, L.M. and Lamberts, R. (Eds.), 2011. *Building performance simulation for design and operation.* London and New York: Spon Press.

Heo, Y., Choudhary, R. and Augenbroe, G. A., 2012. *Calibration of building energy models for retrofit analysis under uncertainty.* Energy and Buildings, Volume 47, pp. 550-560

Hopfe, C.J., 2009. *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization.* Dissertation: UT Eindhoven

Kusuda, T., 1999. *Early history and future prospects of building system simulation.* Proceedings of Building Simulation '99, Volume 1: 3-16.

Macdonald, I.A., 2002. *Quantifying the Effects of Uncertainty in Building Simulation.* Dissertation: University of Strathclyde

Mahdavi, A., 2011. *People in building performance simulation.* In: Hensen, L.M. and Lamberts, R. (Eds.), 2011. Building performance simulation for design and operation. London and New York: Spon Press, pp. 56-83.

Mahdavi, A. and Tahmasebi, F., 2012. *An optimization-based approach to recurrent calibration of building performance simulation models.* Conference: ECPPM2012 eWork and eBusiness in Architecture, Engineering and Construction. DOI: 10.1201/b12516-24

Mahdavi, A. and Tahmasebi, F., 2012. *Monitoring-based optimization-assisted calibration of the thermal performance model of an office building.* 1st International Conference on Architecture & Urban Design, Proceedings 19-21 April 2012, Epoka University

MATLAB 2017. *https://de.mathworks.com/products/matlab.html?s_tid=hp_ff_p_matlab Accessed 17.02.2017*

Neufert, E., 2016. *Bauentwurfslehre: Grundlagen, Normen, Vorschriften.* Wiesbaden: Springer.

Nextroom, 2017. *http://www.nextroom.at/event.php?_q=n,160607&id=19089 http://www.nextroom.at/building.php?id=29880* Accessed 14.02.2017

Oh, S. and Haberl, J.S., 2016. *Origins of analysis methods used to design high-performance commercial buildings: Whole-building energy simulation.* Science and Technology for the Built Environment, 22:1, 118-137, DOI: 10.1080/23744731.2015.1063958

Österreichs Energie, 2017. *http://oesterreichsenergie.at/daten-fakten/statistik/verbrauch.html* Accessed: 17.02.2017

Penna, P., Gasparella, A., Cappelletti, F., Tahmasebi, F. and Mahdavi, A. 2015. Automated simulation model calibration based on runtime building monitoring. In: *Optimization-based calibration of a school building based on short-term monitoring data.* In: Mahdavi. A., Martens. B. and Scherer. R., (Eds.) 2015*. ECPPM 2014 eWork and eBusiness in Architecture, Engineering and Construction.* London: Taylor&Francis Group

Polly, B., Kruis, N. and Roberts, D., 2011. *Assessing and Improving the Accuracy of Energy Analysis for Residential Buildings*. U.S. Department of Energy. http://www.nrel.gov/docs/fy11osti/50865.pdf. Accessed 15.02.2017

Qingyuan, Z., Huang, J. and Siwei, L., 2002. Development of typical year weather data for Chinese locations. ASHRAE Transactions 2002, Honolulu, USA

Reddy, T.A., Maor, I. and Panjapornpon, C., 2007. *Calibrating Detailed Building Energy Simulation Programs with Measured Data — Part I: General Methodology*. HVAC&R Research,Vol. 13, No. 2, March 2007

Royapoor, M., Roskilly and T., 2015. *Building model calibration using energy and environmental data.* Energy and Buildings, Elsevier 2015

Schuss, M., Pont, U., Taheri, M., Lindner, C. and Mahdavi, A., 2016. Simulation-assisted monitoring-based performance evaluation of a historically relevant architectural design. Paper funded by the Austrian Science Fund (Grant No. P28677-G26)

Schuss, M., Glawischnig, S. and Mahdavi, A., 2016. *A flexible and scalable approach to building monitoring and diagnostics.* In: Proceedings of the 11th European Conference on Product and Process Modelling.

Schuss, M., 2016 *Building Monitoring and Diagnostics.* Lecture at TU Wien, Departement of building physics and building ecology. Summerterm 2016.

Schütte Lihotzky, M., 2004. *Warum ich Architektin wurde. Erinnerungen und Betrachtungen.* Salzburg: Residenz Verlag

Taheri, M., 2013. *Optimization-based calibration of a building thermal performance simulation model.* Case Study: Vienna. Master Thesis: TU Wien

Taheri, M., Tahmasebi, F. and Mahdavi, A., 2013. A case study of optimization-aided thermal building performance simulation calibration. In: Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association, August 26-28, Chambéry, France

Tauber, C., Tahmasebi, F., Zach, R. and Mahdavi, A. 2015*. Automated simulation model calibration based on runtime building monitoring.* In: Mahdavi. A., Martens. B. and Scherer. R., (Eds.) 2015*. ECPPM 2014 eWork and eBusiness in Architecture, Engineering and Construction.* London: Taylor&Francis Group

TU Graz, 2017*. http://akk.tugraz.at/veranstaltung/ausstellung-frey-denken/ http://akk.tugraz.at/website_zankel/startseite.html* Accessed 14.02.2017

Wagner, A. and Böck, I., 2013 *Konrad Frey: Haus Zankel. Experiment Solararchitektur.* Berlin: architektur + analyse 2

Westphal, F. S. and Lamberts, R., 2005. Building simulation calibration using sensitivity analysis. In: Ninth International IBPSA Conference, Montreal, Canada.

Yan, D., O'Brien, W., Hong, T., Feng, X., Gunay, H.B., Tahmasebi, F. and Mahdavi, A., 2015. *Occupant behavior modelling for building performance simulation: Current state and future challenges.* In: Energy and Buildings, Elsevier.

Zach, R. et al., 2012. *MOST: An Open-Source, Vendor and Technology Independent Toolkit for Building Monitoring, Data Processing, and Visualization. http://most.bpi.tuwien.ac.at/* Accessed 15.02.2017