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An envelope retrofit for an existing building

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ABSTRACT

Building envelope retrofits by adding insulation is an ongoing approach for improving the thermal performance of buildings and reducing annual heating demand.
Retrofitting is the process of modifying the systems inside buildings or the structure itself after the initial construction and occupation. It is a common approach to improve energy efficiency in existing buildings. Retrofits can involve diverse energy technologies. As example they can be concentrated on climate control strategies or alternatively improve the building envelope by adding insulation and/or changing window constructions.
Using the example of an existing dormitory building in Vienna, the present thesis explores different design options (energy conservation measures) through a calibration effort, to retrofit the building envelope to reach low-energy standards.
For this purpose, a simulation model was generated based on assumptions of the building characteristics and collected information of the building.
To improve the reliability of the simulation results, the simulated model was calibrated using inside air temperature measured with data loggers. To make it possible to identify the best retrofit measure, the calibrated model was used to define a set of scenarios which involved glazing and insulation in roof and walls.
The simulation results in this retrofit approach seem to suggest that relying on the assumptions of the building characteristics may lead to inaccurate simulation models; therefore, calibrated models may show relatively good agreement between simulated data and measurements. Moreover, by using alternative energy conservation measures (such as better windows and insulation) the building indicates to reach a low-energy standard which demonstrates the significant effect on building envelope retrofits.

ZUSAMMENFASSUNG

Die Nachrüstung einer Gebäudehülle durch Hinzufügen einer Isolierung ist ein kontinuierlicher Ansatz zur Verbesserung der Wärmeeffizienz von Gebäuden und die Verringerung des jährlichen Wärmebedarfes.
Eine Nachrüstung ist der Prozess der Veränderung der Anlagen innerhalb von Gebäuden oder der Struktur selbst nach Ersterbauung und Benutzung. Es ist ein gebräulicher Ansatz um die Energieeffizienz in bestehenden Gebäuden zu verbessern. Dabei koennen unterschiedlichste Energietechnologien mit einbezogen werden. Als Beispiel kann einerseits ein Fokus innerhalb eines Gebäudes auf eine Klimatisierungsstrategie gelegt werden oder andererseits auf die Verbesserung der Gebäudehülle durch Hinzufügen einer Isolierung und/oder Austausch von Fensterkonstruktionen ausgerichtet sein.
Die Masterarbeit untersucht am Beispiel eines bestehenden Gebäudes - einem Personalunterkunft in Wien - verschiedene Designoptionen (Energiesparmaßnahmen) mittels einer Kalibrierung zur Nachrüstung der Gebäudehülle um den Standard eines Niedrigenergiehauses zu erreichen.
Zu diesem Zweck wurde ein Simulationsmodell basierend auf Annahmen der Gebäudeeigenschaften erstellt, sowie Informationen zum Gebäude gesammelt.
Um die Zuverlässigkeit der Simulationsergebnisse zu verbessern, wurde das simulierte Modell mit Innenlufttemperatur mit Datenloggern gemessen, kalibriert.
Um die bestmoegliche Auswahl einer geeigneten Nachrüstung zu ermitteln wurde dieses kalibrierte Modell verwendet um unterschiedliche Szenarien, die sowohl Verglasung als auch Isolierung am Dach und den Wänden beinhalteten, zu definieren.
Die Simulationsergebnisse in diesem Ansatz lassen vermuten, dass die Konzentration auf die Annahmen der Gebäudeeigenschaften zu ungenauen Simulationsmodellen führen, daher koennen kalibrierte Modelle relativ gute Übereinstimmungen zwischen simulierten Daten und Messungen zeigen. Durch den den Einsatz alternativer Energiesparmaßnahmen (wie z.B bessere Fenster und Isolierung) lässt sich beim betroffenen Gebäude ein Niedrigenergie–Standard erzielen, was die bedeutsame Auswirkung von Nachrüstungen einschlägig demonstriert.

ACKNOWLEDGEMENT

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ABREVIATIONS

OIB	Österreichisches Institut für Bautechnik
ECMs	Energy Conservation Measures
SBCI	Sustainable Buildings & Climate Initiative
EPBD	Energy Performance of Buildings Directive
UNFCCC	United Nations Framework Convention on Climate Change
EEB	Energy Efficiency in Buildings
WBCSD	World Business Council for Sustainable Development
NRMSD	Normal Root Mean Square Deviation
R^2	Coefficient of determination
DG	Double Glazing windows
TG	Triple Glazing windows
ECM	Energy Conservation Measure
HWB	Heizwärmebedarfs (annual heating demand)
ACH	Hourly Air Change rate

CHAPTER 1

INTRODUCTION

1.1 Objective

About two-thirds of the residential buildings in Austria were built before 1980. The majority of these buildings were built between 1961 and 1970. Approximately 129.952 housing buildings were built between a period registered from 1961 to 1970 and other 99.77 units in a period between 1945 and 1960 in Vienna. The number of the housing buildings constructed during the period between 1945 and 1960 represents just one part of the 450.080 units built around Vienna in Austria during that period of time. Table 1 provides a description of the number of housing units constructed since 1919.
Some of the buildings that were built after the Second World War to the 80s are still greater consumers of energy as they operate in an inefficient way that demands more energy. According to the Austrian statistics, buildings that were built between 1945 and 1960 have the highest heating demand. This means that some of these buildings have not yet been renovated or retrofitted following the current Austrian regulations imposed by the OIB (Österreichisches Institut für Bautechnik 2011).

Table 1
Residential units in Austria constructed between 1919 and 2009

ÖSTERREICH	Wohneinheiten (Hauptwohnsitz)								
	Zeitraum vor 1919	1919 – 44	1945 – 60	1961 – 70	1971 – 80	1981 – 90	1991 – 00	2001 – 09	Summe
Bundesland									
Burgenland	7.392	7.952	15.904	16.912	19.936	15.792	15.904	12.208	**112.000**
Kärnten	21.676	13.577	37.159	42.876	39.541	29.537	35.254	18.580	**238.200**
Niederösterreich	91.729	58.494	70.458	89.735	106.352	89.735	99.040	59.158	**664.700**
Oberösterreich	69.270	40.747	81.494	94.300	93.136	68.106	88.479	46.568	**582.100**
Salzburg	15.645	12.069	32.855	38.666	41.348	28.832	35.760	18.327	**223.500**
Steiermark	58.605	39.571	60.609	80.144	90.663	60.108	69.625	41.575	**500.900**
Tirol	27.379	17.868	35.449	47.265	47.265	35.737	45.536	31.702	**288.200**
Vorarlberg	15.481	7.214	16.383	20.291	23.447	19.389	26.603	21.493	**150.300**
Wien	238.106	96.416	99.770	129.952	86.355	65.395	72.941	49.466	**838.400**
Hauptwohnsitze	**545.283**	**293.909**	**450.080**	**560.140**	**548.042**	**412.629**	**489.142**	**299.076**	3.598.300
ges. Österreich	15 %	8 %	13 %	16 %	15 %	11 %	14 %	8 %	100 %

Anzahl der errichteten Wohneinheiten (Hauptwohnsitz) nach Bauperiode in den Bundesländern Österreichs

There are around 3 million residential buildings in Austria which 78% of their area was built before 1981. These buildings are still performing with specific annual heating energy demand of 150 to 250 kWh / m².a (Old buildings with passive house practice 2013).
This specific annual heating energy demand of 150 to 250 kWh/m².a per unit greatly contributes to the degeneration of the environment and excessive consumption of energy.
Around 25% of the buildings in Vienna date back to the period between 1945 and 1980 or even before it. Some of these buildings still remain without any significant

rehabilitation or renovation that could reduce energy consumption and thus operate in an efficient way. The shortage of economic resources assigned to rehabilitate existing buildings delays updates in retrofitting. Thus, they carry on contributing to the degradation of the environment and squander of non-renewable energy sources.

The base case model presented in this study represents an example of one of the housing buildings in Vienna that has not yet been updated. In Austria, even allowing for the ongoing accreditation of regulations, methodological approaches for energy-efficient improvement of buildings are still insufficient. In this framework, elemental envelope retrofits significantly contribute to decrease heating and cooling energy consumption.

The high-level objective of this thesis effort is to carry out an assessment of thermal building performance aimed to retrofit the existing building envelope. A principal goal of this analysis is to evaluate the building envelope and identify the best retrofit measure for future energy savings; moreover, it is also important to scrutinize in this analysis the reliability of the simulation approach.

The study also focuses on the analysis, visualization and interpretation of the results obtained from the simulated model which is based on collected data and assumptions pertaining the building characteristics. Comparing the simulation model with temperature measurements allow to obtain a calibrated model which improves the accuracy and feasibility of the digital model. Furthermore, after the calibrated model is generated, it enables the assessment of alternative retrofit measures to meet low-energy standards.

1.2 Motivation

In an energy consumption time and shortage of natural resources, buildings significantly contribute to the shortage of resources and ultimately, therefore, to global climate change. The world faces the challenge of maximizing energy efficiency and minimizing energy consumption. Today, in this present time, existing buildings represent a burden for the energy sector as they are not efficient energy consumers. The building sector significantly contributes to the consumption of non-renewable energy sources due to employments such as room heating, water heating, lighting, among other utilities.

Approximately 40% of world energy consumption is in buildings; about 60% of this usage is attributed to the consumption in residential buildings. In the specific case of residential buildings in Vienna, approximately 25% of them still perform without any updates.

Necessity to minimize fossil fuel consumption and CO_2 emissions from residential buildings induce to energy-efficient improvements of existing buildings and regulations for new building designs. These attempts lead into research areas such as monitoring, energy performance in existing buildings, thermal building performance, and further into retrofitting (Gücyeter et al. 2012).

In this context, retrofit measures offer a means of reducing energy inefficiencies; however an incorrect measure may constrain the effectiveness.

Therefore, it is necessary to assess energy performance of existing buildings through the use of dynamic models, and calibrated simulation approach (Mahdavi et al. 2007). This research aims to show an approach to optimize the building envelope through a calibrated simulation model.
To achieve this, an existing dormitory building in Vienna, which was approximately built in 1960, is analyzed and monitored for a short period of 5 months. This analysis includes on site climatic data such as indoor and outdoor temperature, and energy consumption. The research aims to utilize a building energy simulation tool in order to reproduce the base-case energy performance of the existing building and use this simulated model to test different energy conservation measures to identify the best retrofit measure.

To support this approach, the research sets out the following questions:

How accurate are the simulation model assumptions in this base-case model?

Which energy conservation measure (ECM) is the most suitable to retrofit the building?

1.3 Structure

This thesis is structured in terms of 7 sections. Section 2 provides general information regarding the thesis topic. Section 3 describes the methodology of the analysis. Section 4 describes the main results and the discussion of the pertain results. Section 5 includes the conclusions. Section 6 provides the compilation of research information and section 7 gives extra information of the research.

CHAPTER 2

BACKGROUND

2.1 Buildings contribution to climate change

The earth’s climate is changing day by day as the earth its being partly affected by greenhouse gas emissions which are produced from the building sector and human activity.
Today, the concentration of the main greenhouse gas, carbon dioxide, is 20% higher than at any other time in the past 400,000 years, having risen rapidly over the past 50 years.
The continuous growth in fossil fuel used over the past 50 years has also contributed to increase the global temperature. Gases, which damage the environment, are generated in part from derivations of the built environment such as transportation systems, infrastructure, building construction and buildings´ operation.
The building sector contributes as much as one third of total global greenhouse gas emissions which are primarily through the use of fossil fuels during their operational phase. Thus, the building sector contributes up to 30% of global annual greenhouse gas emissions and consumes up to 40% of all global energy. According to the Sustainable Buildings & Climate Initiative (SBCI), if nothing is done against the massive growth in new construction, and the inefficiencies of existing building stock worldwide, greenhouse gas emissions from buildings will be more than double in the next 20 years (Buildings and Climate Change 2013).

2.2 Energy and Buildings

On 19th May 2010, the European Union (EU) adopted the Energy Performance of Buildings Directive (EPBD) which is the main legislative agent to reduce the energy consumption of buildings.
According to the EPBD, buildings are responsible to 40% of the total energy consumption and 36% of EU CO_2 emissions. These emissions are even more than those emitted in other sectors, such as the transportation sector and industry. The necessity to increase energy demand grows with the increasing size of the building sector.
The use of energy from renewable sources and reduction of energy consumption are important measures to decrease greenhouse emissions. So, if energy from renewable sources increases, measures for reducing energy consumption in the EU would assist it to conform to the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The main goal of this protocol is to maintain the global temperature rise below 2 °C, and to reduce, by 2020, overall greenhouse gas emissions to at least 20% below 1990 levels and by 30% being reached. The Directive (EPBD) indicates to the Member States the application of minimum energy performance requirements for new and existing building and ensures the certification of building energy performance. Furthermore, it requests to the Member States to meet the nearly zero building standards for all new buildings by 2021 (Eur-Lex. 2013).

In addition to the preceding regulations, according to the World Business Council for Sustainable Development (WBCSD) energy consumption in buildings is projected to rise around the world and even more obvious in developing countries, such as China and India.
A study on energy efficiency in buildings (EEB) indicates that the global building sector needs to reduce energy consumption in buildings to 60 percent by 2050 in order to meet global climate change projections. According to the World Business Council for Sustainable Development, the building sector must achieve greater energy efficiency through a combination of public policies, technological innovation, informed customer choices and smart business decisions. Some of the recommendations from the organization are that governments start to drastically reduce energy use in new and existing buildings.
The building sector represents a threat to the environment due to use of non-renewable energy sources, thus, it is indispensably to decrease the use of non-renewable energy consumption in buildings.
Necessity to reduce CO2 emissions and fossil fuel consumption to decrease the use of non-renewable energy consumption encourages energy-efficient improvements of existing buildings and new regulations. Attempts to improve building performance in new and existing buildings grew into investigation areas such as monitoring and assessment of energy performance. These areas are leaded to retrofits through the implementation of possible energy conservation measures to reach low-energy standards. Improving energy performance of buildings by retrofitting represent a cost effective way of discharge on climate change and improve the environment for present and future generations.

2.3 Retrofitting in Buildings

Maintenance and new technologies need to continually deal with the building sector to update it. According to the Energy Efficient and Renewable Energy Department, retrofit, renovation and refurbishment of existing buildings represent an opportunity to improve energy performance in buildings for their ongoing life.
Retrofitting of buildings refers to the implementation of some internal or external changes to buildings over a certain period of time. These changes can result into the alteration of the structure in the building or the systems inside it (The built environment, climate change and health 2013).
Although retrofitting implicates the alteration of the existing building, it also has the effect of enhancing energy efficiency, reduce future and present operation costs in energy and improve user comfort.
Thereby, upgrading existing buildings by retrofitting not only contributes to decrease the heat demand but also to reduce costs and preserve the character of the existing building stock in Vienna.

CHAPTER 3

METHODOLOGY

3.1 Process

The study of this thesis addresses in particular the thermal performance of the building to retrofit an envelope that lead to reach low-energy standards. In this context, to obtain close results similar to actual performance levels, it is essential to validate an assessment methodology with real data. Toward this end, we follow a strategy documented in previous publications (Mahdavi et al. 2007) where part of this study considers the following: "i) Collect local climatic data as well as data pertaining to indoor conditions; ii) Collect data concerning the construction methods, building materials, and building systems; iii) Collect data regarding heating and ventilation regimes and occupancy patterns; iv) Analyze and interpret the collected data in view of the buildings' salient design features (location, massing, apertures, thermal mass, etc.); v) Create a digital performance simulation model of the building; vi) Calibrate the digital models using collected indoor climate data."

The simulation process applied to this methodology bases on collected information. The main purpose of this process is to analyze the performance of the building by reproducing the digital model. Based on assumptions, the simulation results enable to assess indoor conditions. The simulated model is bound to the domain of thermal performance which excludes in this study other possible aspects of building controls such as acoustics and lighting.

For better understanding of the building performance outdoor and indoor temperature is monitored. This monitoring mainly relates to the thermal performance of the building. Moreover, data pertaining to building materials, building systems, occupancy, heating and ventilation regimes is collected.

The collected data is initially analyzed and then interpreted in order to evaluate the thermal performance of the building. For the evaluation of the building, the monitored data is used to calibrate the performance simulation model. Specifically; thermal performance simulation model is generated for the calibration purpose. In this case, the thermal performance simulation process allows predicting alternative strategies (scenarios) to retrofit the building envelope. The intended process for the generation and application of calibrated simulation model for the selected building is illustrated in Figure 1 (Mahdavi et al. 2007).

In Figure 1 we can see that the process involves the generation of the simulated model which is based on collected geometry, construction, and operation data. The simulated model needs for running a weather file which is based on data obtained from the locally installed weather station.

Subsequent to the previous step, initial simulation results (e.g. indoor air temperature values) are compared to measurements (indoor air temperature values monitored), leading to a calibrated version of the simulation model. Then using such a calibrated model, alternative scenarios are explored and evaluated for the thermal improvement of the building.

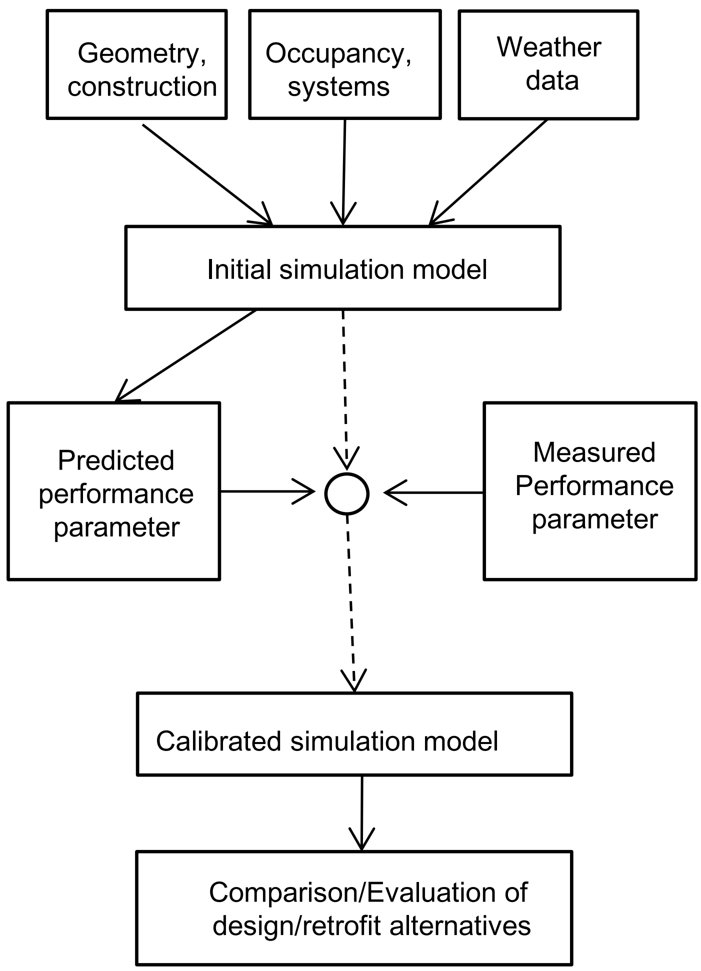

Figure 1
Illustrative depiction of the process of simulation model generation, calibration, and application (Mahdavi et al. 2007)

3.2 Sample Building

As mentioned before, an existing dormitory building in Vienna, Austria was selected for this analysis. The building accommodates staff of a renowned train company in Austria since approximately 50 years ago (1960). The building selected is a good sample of one of the old housing buildings in Vienna that represents a burden for the energy sector due to the continuous years of use without any significant renovation or restoration.

The case building is located in the South-West (12th district) of Vienna; address Kerschensteinergasse 32a 1120 Vienna, Austria. The following map (Figure 2) shows the location of the building selected.

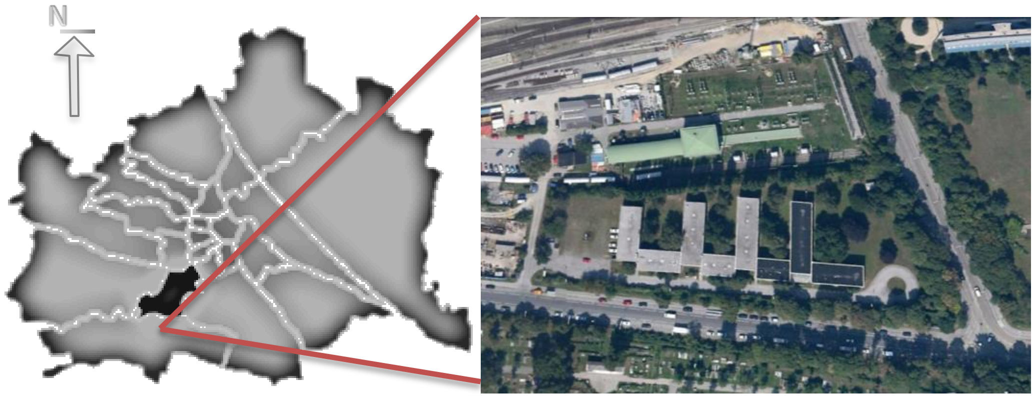

Figure 2
Location of the building in the 12th district in Vienna

3.3 Building Information

Basic data regarding building characteristics such as orientation, location, environmental factors, envelope characteristics, and dimensions was collected in order to reproduce a digital model with real properties. Table 2 shows building information.

Table 2
Base case building information

Location	48◦10’28.54”N latitude 16◦20’26.82” E longitude
Orientation	8.09◦ (CW normal angle of north facade)
See (m)	190
Environment	No shadow effect of close structures but tall trees.
Floor height (m)	2.62
Gross wall area (m^2)	1150.11
Total building area (m^2)	1471.41
Glazing area (m^2)	356.84
Glazing ratio (%)	11.73

The case building is divided in 4 tracks which are connected by operable doors (track A, track B, track C and track D). The tracks which are currently accommodating are track A, and track B. Track C and track D are not currently in use due to the elevated expenses such as energy expenses, gas, electricity, and maintenance that the whole construction entails for the correct operation

Construction elements such as walls are constructed of reinforced concrete with a plaster finish. Likewise, the roof surface is constructed of reinforced concrete but with a membrane finish. Thermal characteristics of the building envelope are based on assumptions regarding U-values. Table 3 shows thermal characteristics of the building envelope.

Glazing components are defined by a double-pane clear glass with an air cavity in between and wood tight frames. Approximately 90% of the window area is glass with a U-Value of 2.51 W/m²․K.

The case building operates with a central heating system to acclimatize the indoor environment in winter. The centralized system uses gas as the energy source. Cooling and ventilation systems are not in existence in the building, therefore, excessive heat may remain trapped inside during the summer season.

Comfort average temperatures for heating periods in bedrooms fluctuate between 22 ◦C and 24 ◦C, and for circulation spaces 20 ◦C and 24 ◦C, respectively. User's occupancy schedule varies to different hours through the whole day on weekdays and weekends, however a general schedule was set for the simulation model. Bedrooms schedule was set from 19:00pm to 6:00am for weekdays and weekends. Lounge room schedule was set from 9:00am to 18:00pm for all days.

Table 3

Thermal characteristics of the building envelope

Envelope component	***Thickness (mm)***	***U-value (W.m⁻².K⁻¹)***	***Heat flow direction***
Exterior reinforced concrete wall	200	0.50	Horizontal
Floors Concrete floor on ground	300	2.50	Down
Concrete flat roof	300	0.40	Up
Windows (Double glazing) **Clear** **Argon** **Clear**	 3 13 3	2.51	Horizontal

3.4 Measurements

3.4.1. Thermal Parameters

Some outdoor and indoor measurements are collected for a better understanding of the building performance. Indoor parameters such as temperature and relative humidity are collected in this monitoring stage. Outdoor parameters including, dry bulb temperature, relative humidity, global radiation, wind speed and wind direction are taken from a local weather station.

3.4.2. External Parameters

In the case of the outdoor parameters**,** weather stations installed on site could not be used at the building due to budget constraints. Therefore, outdoor temperature was taken from the closest local weather station in the TU Wien main building, which is located approximately 5 kilometers from the base case building.
The registered period of this weather data was from 1^{st} January 2013 to 23^{th} May 2013 for the simulation.

3.4.3. Internal Parameters

The indoor conditions in the building such as air temperature, and relative humidity were monitored with data loggers (HOBO). The data was measured every five minutes during the period between March, 2013 and July, 2013. Eight data loggers were installed in different zones according to the different orientations and room usage. The location of the installed data loggers in the building are marked in the respective floor plans (see Figure 4 and Figure 5). The data loggers (HOBO) stored measurements of air temperature, relative humidity, voltage (CO2) and light intensity from which just temperature was needed. Furthermore, the monitored data was downloaded and stored every week in order to avoid future data loses. Figure 6 to Figure 10 show the position of the sensors on the plan.

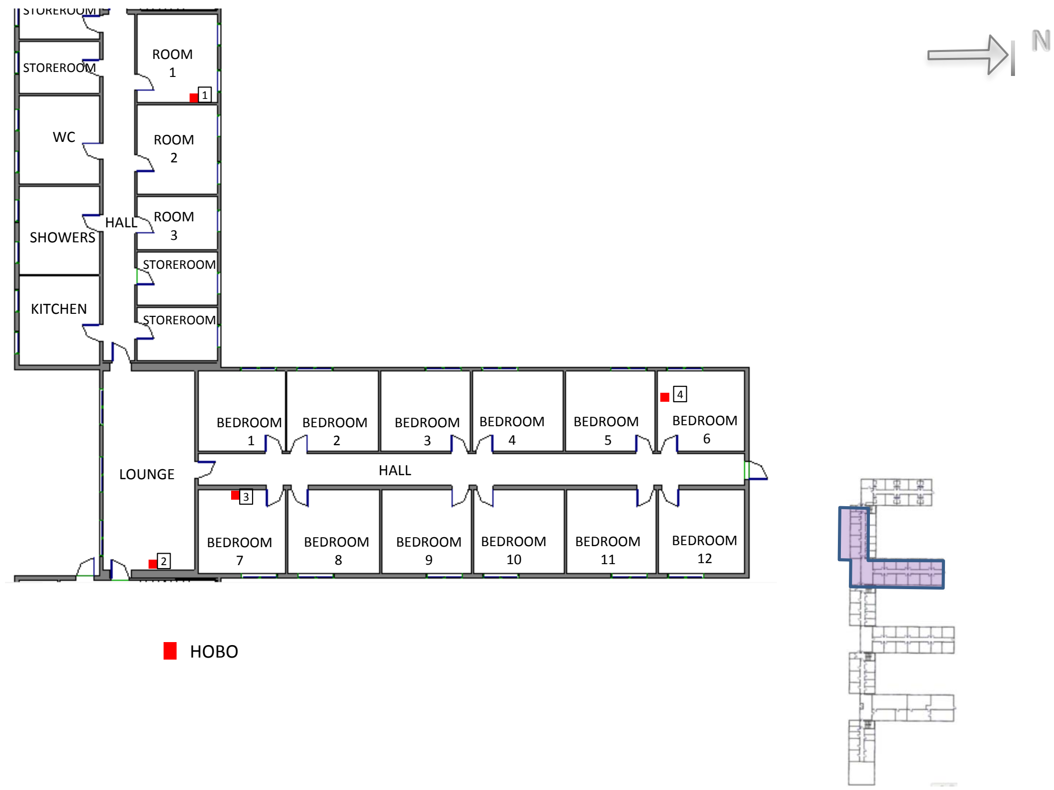

Figure 3
Data loggers (HOBO) on the Ground Floor

Figure 4
Data loggers (HOBO) on the First Floor

3.5 Performance Simulation

3.5.1 Weather Data

Typical weather files for building performance simulation require air temperature, humidity, wind speed, and wind direction (Meteotest 2012).
The weather information used for the simulation was generated using the Meteonorm 6.1 software tool, based on measured data provided by the weather station installed in the Technical University of Vienna, including dry-bulb outdoor temperature, outdoor relative humidity, atmospheric pressure, global horizontal radiation, and wind speed/direction.

3.5.2 Modeling

A thermal simulation application (EnergyPlus) was used to simulate the thermal performance of the building in operation and analyze measures that could make the building operate in an efficiency way. EnergyPlus is a building simulation software tool which its main function is to dynamically simulate the thermal performance of buildings and their systems (EnergyPlus 2013). As the EnergyPlus package does not include a graphical user interface, the geometry of the building was created in the OpenStudio plugin for Sketchup, which works smoothly as a third-party interface for EnergyPlus. OpenStudio plugin is a graphical energy-modeling tool from Sketch up software. By using OpenStudio tool the geometry is rapidly created with minor complications in comparison to other thermal simulation applications. Therefore, this tool was chosen due to its facility to create the geometry and to assign space attributes to different zones (OpenStudio 2013).

For the creation of the geometry, only track A and track B were considered in the graphical model. The reason for representing these tracks in isolation within the graphical model is due to the location of the data loggers which were located in these zones. In building performance simulations is important to take into account adjacent constructions and objects such as trees or buildings, tracks C and track D. In the geometry, adjacent objects were represented with 2 simple shading surfaces. Thus, an adiabatic boundary condition was assigned to the surfaces where the adjacent tracks were connected. Figure 5 shows the geometry of the building modeled by OpenStudio plug-in. The shading surfaces have been highlighted in this figure. Thermally, the building was modeled in terms of twenty four distinct zones. In the present thesis, only 8 thermal zones from a total of 24 thermal zones were explored as the data loggers were located there. Figure 6 illustrates the 24 zones with different colors. Figure 7 and Figure 8 illustrate the location of the eight different explored zones for building performance simulations.

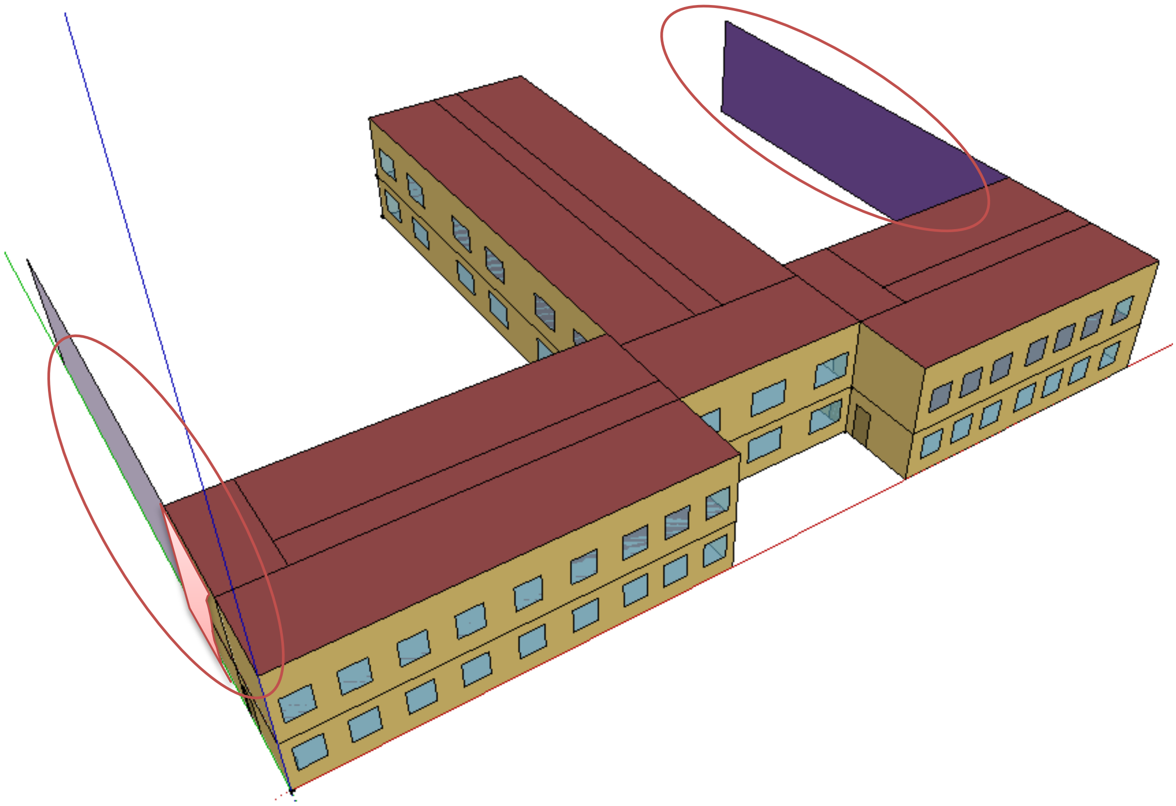

Figure 5
Geometry of the model generated by OpenStudio plug-in for Sketchup

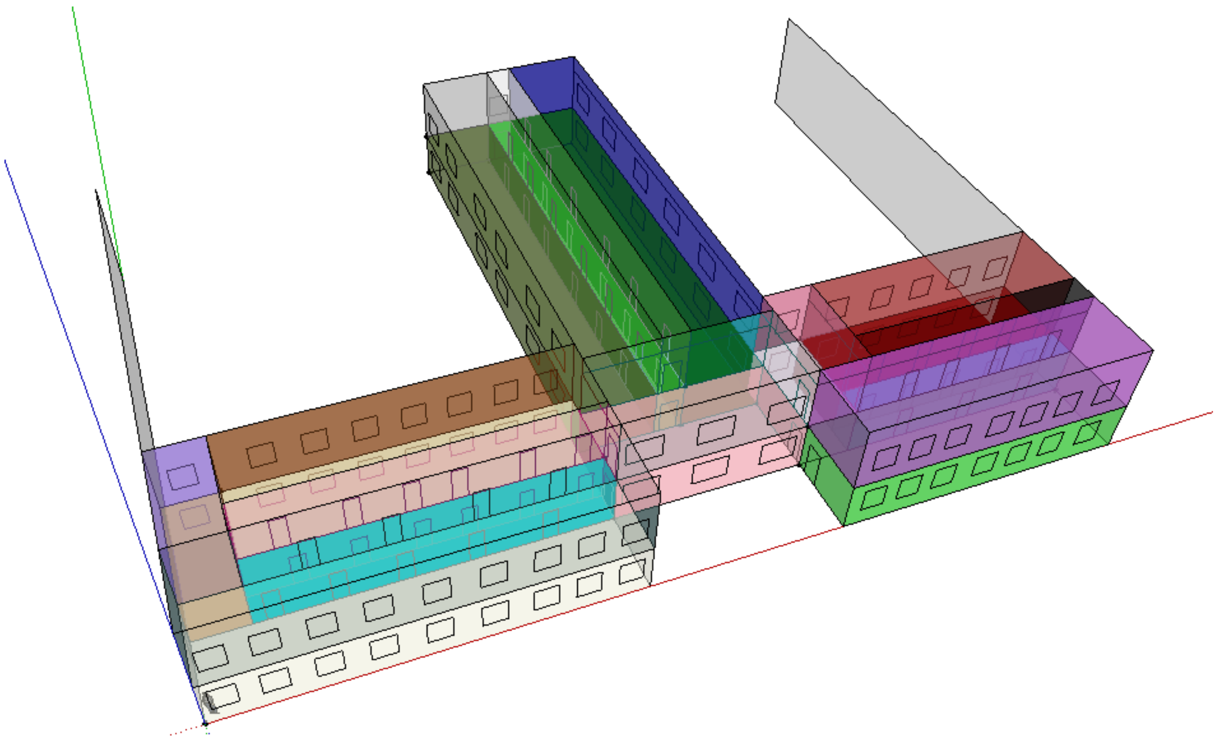

Figure 6
Location of the 24 distinct zones

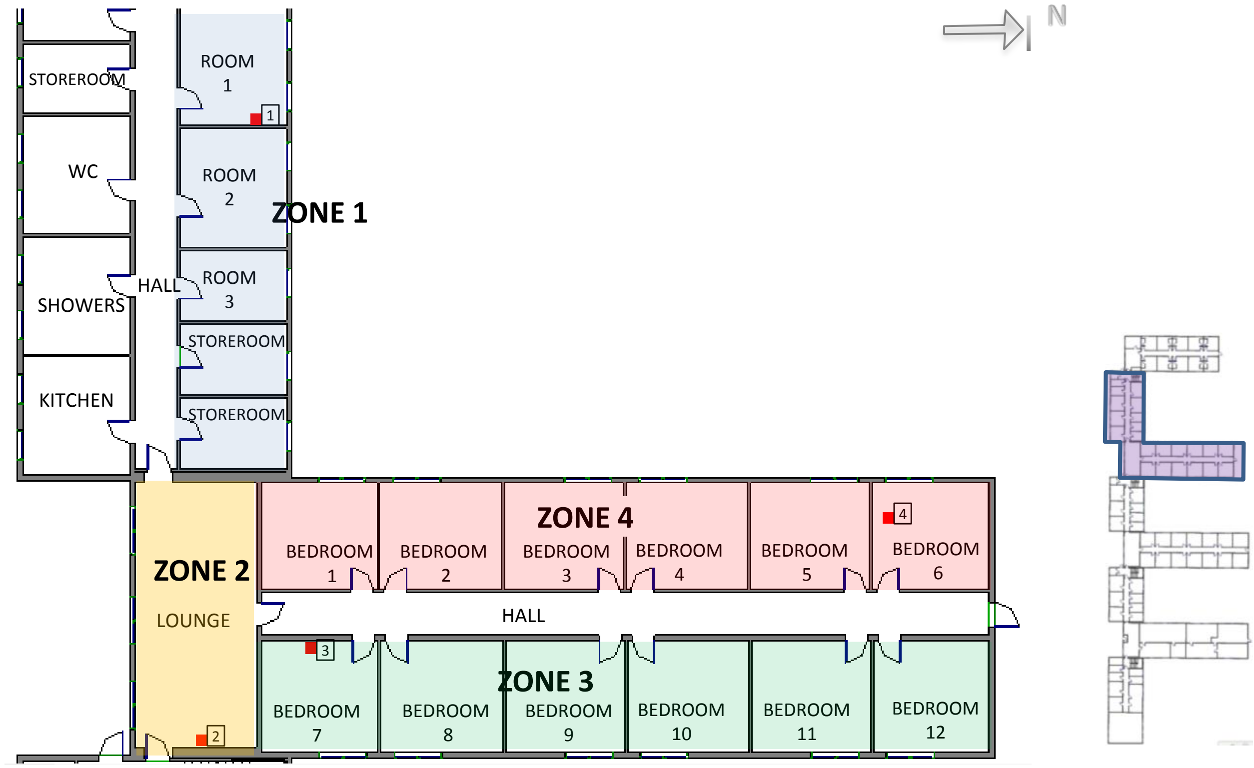

Figure 7
Location of thermal zones 1, 2, 3, and 4 on the ground floor

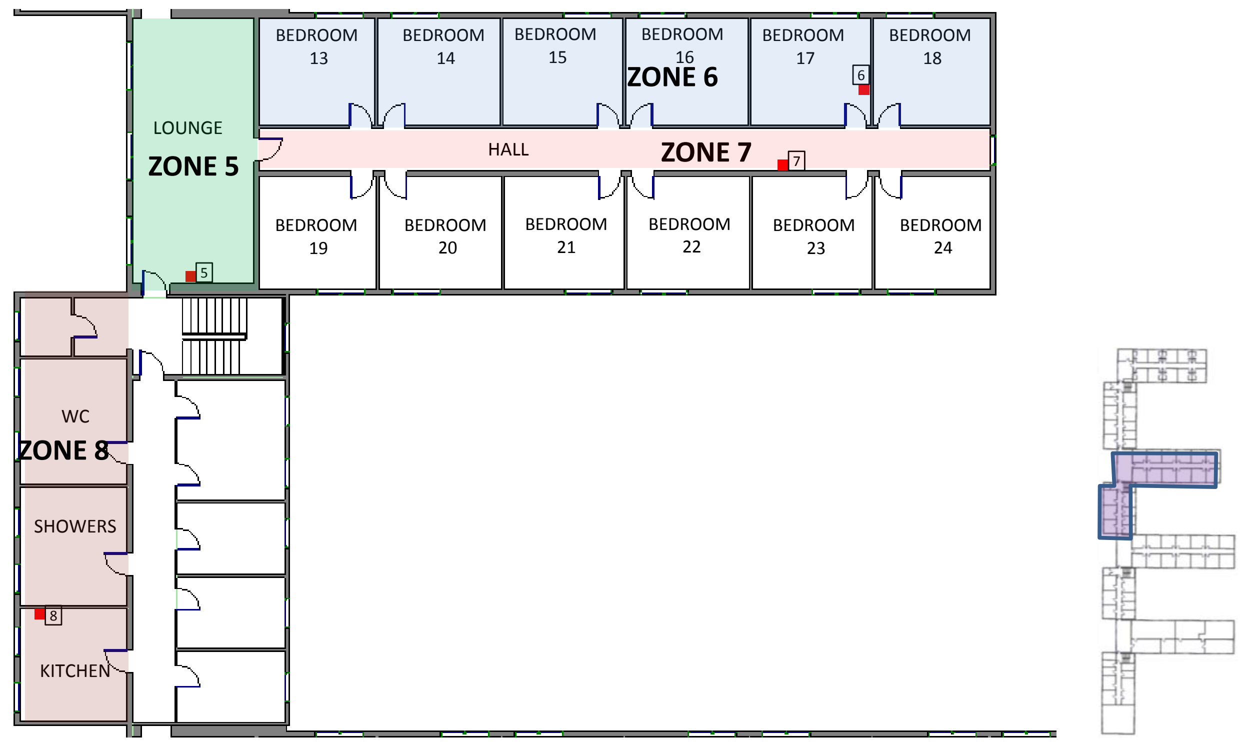

Figure 8
Location of thermal zones 5, 6, 7, and 8 on the first floor

3.5.3 Simulation: Initial simulation model

After generating the geometry, the building simulation model was populated with input data regarding building envelope physical properties and internal gains. This initial simulated model was generated based on assumptions of the available data as the documentation pertaining construction elements and properties was not available. Occupancy hours for the dormitories were set from 19:00pm to 6:00am for all days and the occupancy hours for the lounge were set from 9:00 to 18:00pm for all days. Hourly air change rate (ACH) was set to 1.30 h^{-1} in summer.

Construction materials with physical values such as thickness, conductivity, density and specific heat, were assigned to all construction elements; walls, floors, ceilings, and windows.

The approach is to achieve the thermal state of the building with the building assumptions to demonstrate the feasibility of building performance simulations for retrofitting. The following Table 4 provides a description of simulation assumptions regarding construction data for walls, floor, roof and windows and the pertain u-values. Table 5 provides information regarding the areas and volumes from the 24 zones in OpenStudio.

Table 4
Simulation assumptions regarding construction data

Envelope component	*Thickness (mm)*	*U-value ($W.m^{-2}.K^{-1}$)*	*Heat flow direction*
Exterior reinforced concrete wall	200	0.50	Horizontal
Concrete floor on ground	300	2.50	Down
Concrete flat roof	300	0.40	Up
Windows (Double glazing) **Clear** **Argon** **Clear**	 6 13 6	2.51	Horizontal
Exterior door	50	1.0	Horizontal

Table 5
Modeled zones in Openstudio

Zone Number	***Zone Name***	***Floor area in m^2***	***Volume in m^3***
1	Bedrooms	79.29	355.07
2	Hall	50.82	129.48
3	Bedrooms	130.01	379.50
4	Lounge	121.56	148.39
5	Stairs	50.82	50.38
6	Bedrooms	121.56	169.27
7	Hall	44.31	62.55
8	Kitchen and Toilettes	72.41	211.32
9	Stairs	17.25	50.38
10	Bedrooms	79.28	231.50
11	Hall	29.29	85.54
12	Kitchen and Toilettes	94.21	275.11
13	Bedrooms	121.60	480.32
14	Hall	44.34	175.16
15	Bedrooms	129.96	513.34
16	Lounge	50.82	200.73
17	Stairs	17.25	68.13
18	Bedrooms	57.97	228.98
19	Hall	21.42	84.60
20	Kitchen and Toilettes	72.37	285.86
21	Stairs	17.25	68.13
22	Bedrooms	79.28	313.15
23	Hall	29.29	115.69
24	Kitchen and Toilettes	94.21	372.12

3.5.4 Heating assumptions

The building only uses a central heating system which operates in winter seasons. This is a centralized system which uses gas as the energy source.
For the purpose of this study, calculating the heating load of the building was sufficient. Therefore, the heating system of the building was modeled as an ideal heating system which provides the required heating energy to meet the heating set point.
Based on the measurements on a short cold period we defined the heating set point of 20 ◦C for all zones (dormitories, lounge, and circulation zones).
The building simulation model does not consider any cooling or mechanical ventilation systems as it only has natural ventilation. Therefore, cooling load calculations were not taken into consideration in this study.

3.5.5 Internal gains

Model input assumptions regarding internal gains such as equipment, lighting and people were based on information collected on site. Table 6 provides a description of internal gains (people) for each of the eight zones. Table 7 describes simulation assumption regarding internal gains (lights).

Table 6
Simulation assumption regarding internal gains (people)

Zone	***Number of people***	***Schedule Hours/Week (hr)***	***Internal Gains People* (W.m^{-2})**
1	5	63	10.6
2	4	105	5.6
3	4	77	29.3
4	4	77	30.0
5	2	105	5.6
6	1	2	4.2
7	2	5	1.2
8	1	2	4.2

Table 7
Simulation assumption regarding internal gains (lights)

Zone	***Lighting (W/m^2)***	***Total power (W)***	***Schedule Hours/Week (hr)***
1	4.54	360.00	17
2	5.66	288.00	17
3	12.92	1680.00	17
4	14.14	1720.00	168
5	5.66	288.00	59
6	13.82	1680.00	17
7	1.21	54.00	27
8	2.98	216.00	8

3.6 Evaluation: Calibration

To improve the reliability of the simulation results, the simulation model was calibrated using short-term continuous measurements on environmental conditions (air temperature). For the calibration model, from all the 24 zones generated in OpenStudio, only the first eight zones were taken into consideration as the data loggers were located there.
This calibration process is based on the comparison of the simulated indoor temperatures with the corresponding monitored data.
The resolution of data used for calibration depends on the data retrieved from measurements. In this case study, hourly measurements are used to calibrate the model. Benchmarks which define calibration procedures are ASHRAE Guideline 14, IPMVP Volume I (ASHRAE Guideline 14., 2002).
The calibration of thermal performance simulation models is a complex process due to underdermined nature of the model and the limitations in information about the building, such as occupancy schedules, envelope characteristics, outdoor conditions and internal gains. Thereby, it is expected to obtain certain deviation in the evaluation process as it is a challenging process to exactly reproduce the thermal behavior of the building. In the initial simulation results, when the simulated base-model is compared with the monitored measurements (temperatures) a large deviation from the simulated model is noticed. Discrepancies of up to 45% of variation are marked between the simulation results and the monitored measurements. This disagreement in the simulation results is unacceptable when predicting the effects of energy conservation measures in retrofitting models. Therefore, it is necessary to define an acceptable error margin in comparison to monitoring data via calibration of the building simulation model.
Two model evaluation statistics were used to evaluate the accuracy of the simulation model results: the NRMSD (normalized root mean squared deviation) and the R^2 (coefficient of determination).

The following equation depicts the formula used to calculate the NRMSD, where, N is number of observations, Tma is the average measured temperatures for N observations, Ts is the simulated hourly temperatures, and Tm is the measured hourly temperatures.

$$\text{NRMSD (\%)} = \frac{[(\sum(Ts-Tm)^2]^{0.5}}{Tma} \qquad (1)$$

3.6.1 Evaluation of results

When doing a comparative analysis between the predicted results with corresponding measurements via evaluation of the NRMSD and the R^2 , we can affirm the following statements:

a) Over the observed period, simulation results from the first three zones (zone 1 to 3) underestimate indoor temperature 3◦C to the corresponding measurements. The inconsistency in air temperatures for zones 1 and 2 may correspond to the detection of the active heating system during this period which was identified when collecting the measurements at the pertain zones (see Figure 9 and Figure 10).
b) In zone 3 a different flaw was detected. The inconsistency in air temperatures for zone 3 corresponds to a flaw detected in the data logger. In Figure 11 we can see the flaw in the data logger, where the air temperature seems to remain the same (22◦C) over the course of all the 20 observed days.
c) Regarding the evaluation statistics in zones 1, 2 and 3 show inconsistent results as it was detected lower r-square (R^2)and significant higher NRMSD (see Table 8). This discrepancy is unacceptable as a satisfactory coefficient of determination should be close to 1 to show good correlation between simulation results and measurements. Thus, it demonstrates a noticeable deviation that cannot be considered acceptable in simulation models. Scatter charts show the lack of correlation between simulation results and measurements in zones 1, 2, and 3 (see Figure 17 to Figure 19).
d) Zone 4 seems to have better correlation between simulated heating loads and measurements; however some notorious fluctuations are observed in the graph (see Figure 12). The fluctuations detected correspond to the detection of the active heating system which was operating at its maximum capacity. In the graph we can see that air temperature rises till 25◦C. In contrary to the firsts 3 zones (zone 1, 2 and 3) zone 4 shows higher r-square (R^2) and lower NRMSD (see Table 8). However, even that the results in this zone seem to have more correlation between simulation results and measurements, it was not taking into consideration as the heating system was still active.
e) According to the aforementioned results from zones 1 to 4 it is concluded that the discrepancies identified in the simulation model and measurements are not acceptable as they limit the effectiveness and efficiency of future measures in simulation models. Therefore these zones were not taking into consideration.
f) Contrary to zones 1, 2, 3 and 4, the obtained results in zones 5, 6 7, and 8 seem to suggest better agreement between simulation temperatures and measurements (see Figure 13 to Figure 16). They show a lower NRMSD and higher r-squared which are considered acceptable (see Table 8). Moreover, it seems to suggest that zone 5,6,7 and 8 in contrast to the first four zones show better agreement between measured and simulated temperature; nevertheless, we can see a discrepancy in temperature that varies between 2 ◦C and 4◦C as the scatter chats show (see Figure 21 to Figure 24).
g) It can be concluded by this initial evaluation that discrepancies of the simulated model are due to the use of inaccurate information, as documentation pertaining construction elements and properties was not available. Thus, a large deviation was obtained as result of inaccurate assumptions which differ from the real surface properties.

Table 8

Model evaluation statistics of the initial model

Zones	***Zone 1***	***Zone 2***	***Zone 3***	***Zone 4***	***Zone 5***	***Zone 6***	***Zone 7***	***Zone 8***
Coefficient of determination (R^2)	0.02	0.19	0.001	0.37	0.31	0.57	0.20	0.38
NRMSD(%)	15.6	13.8	9.9	5.4	9.6	5.6	5.4	6.9

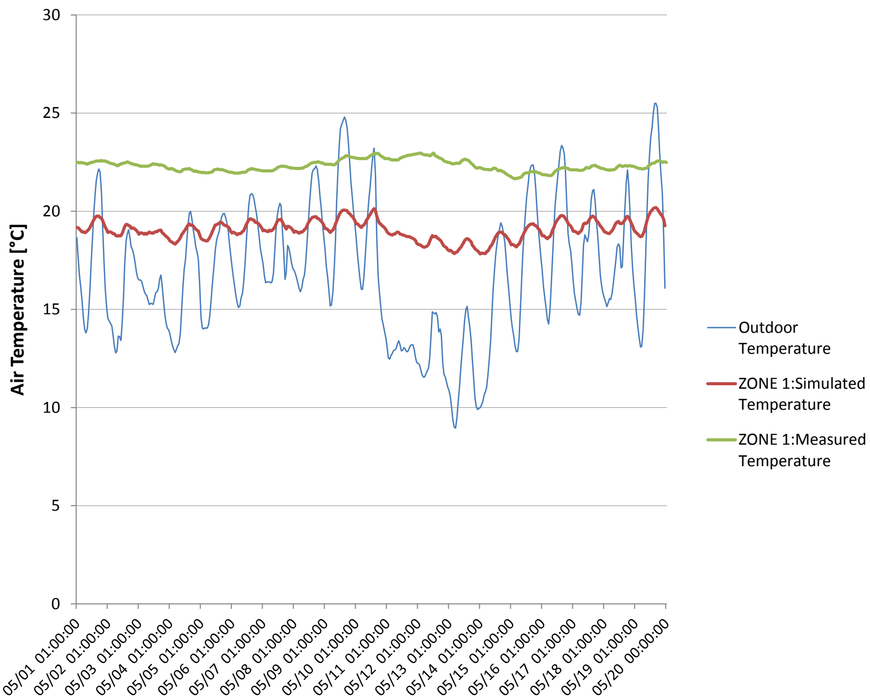

Figure 9

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 1- over the course of 20 days)

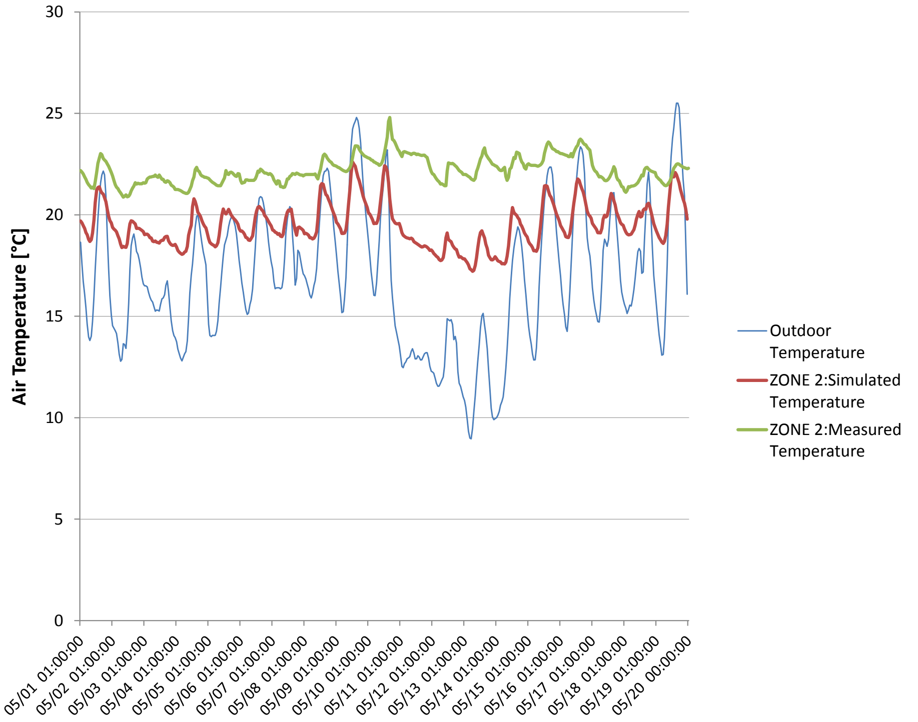

Figure 10

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 2- over the course of 20 days)

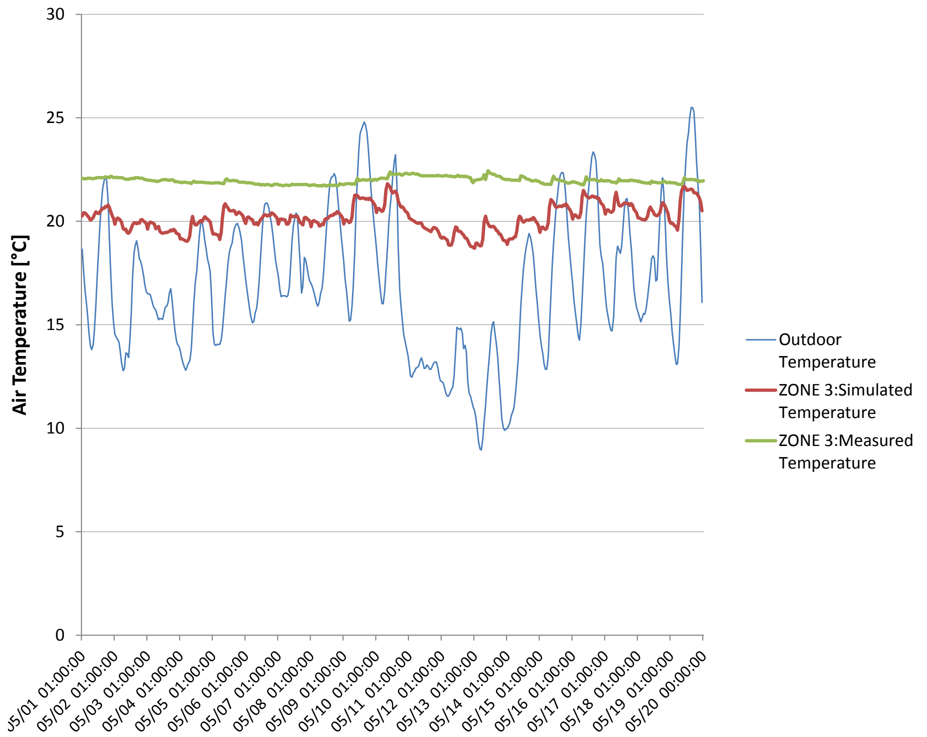

Figure 11

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 3- over the course of 20 days)

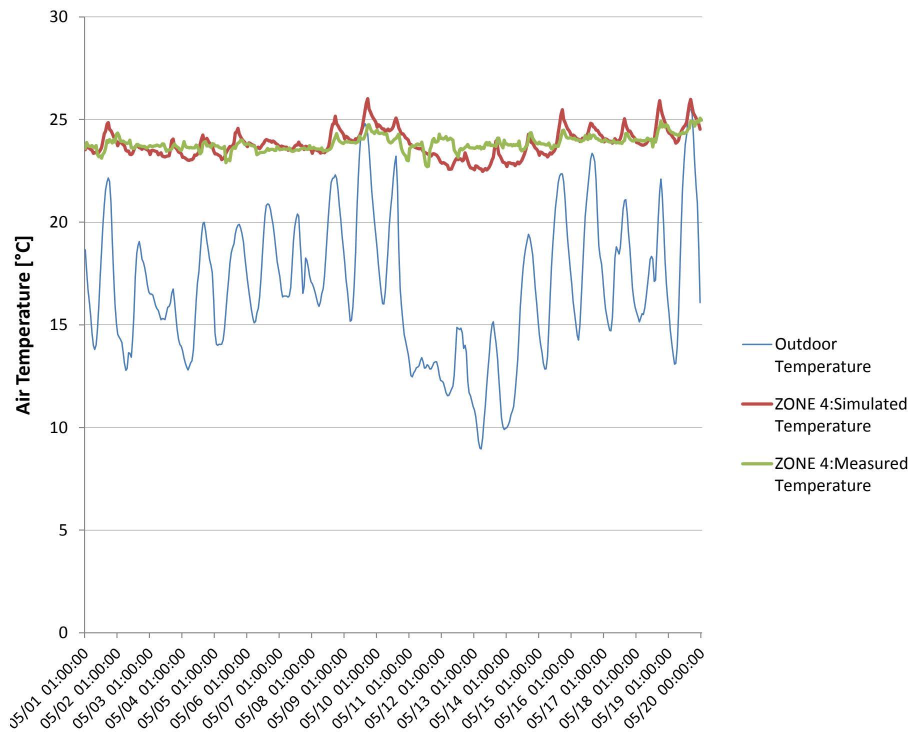

Figure 12

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 4- over the course of 20 days)

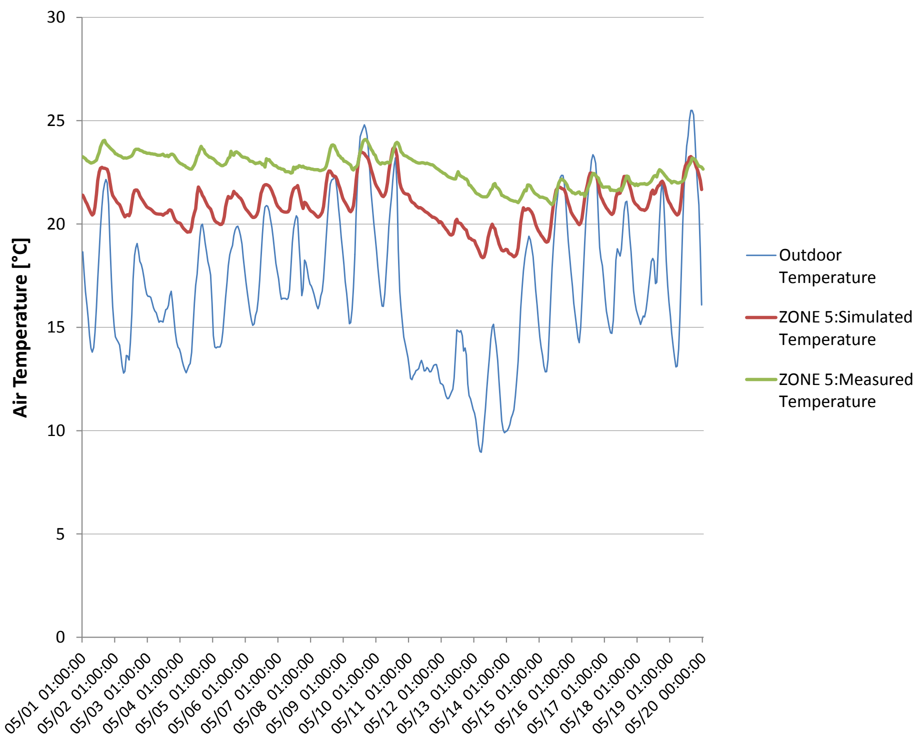

Figure 13

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 5- over the course of 20 days)

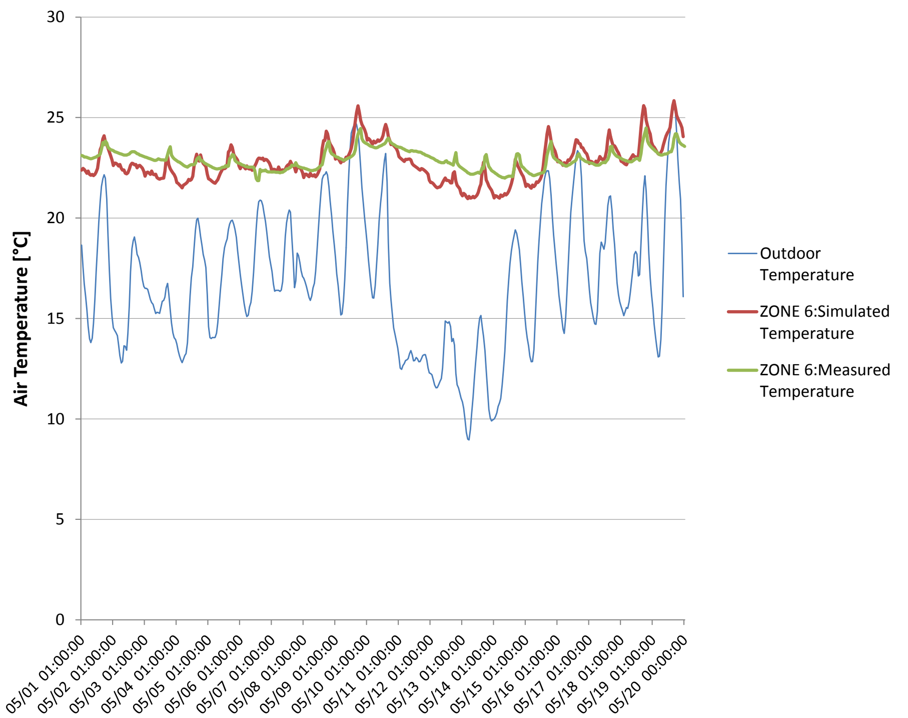

Figure 14

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 6- over the course of 20 days)

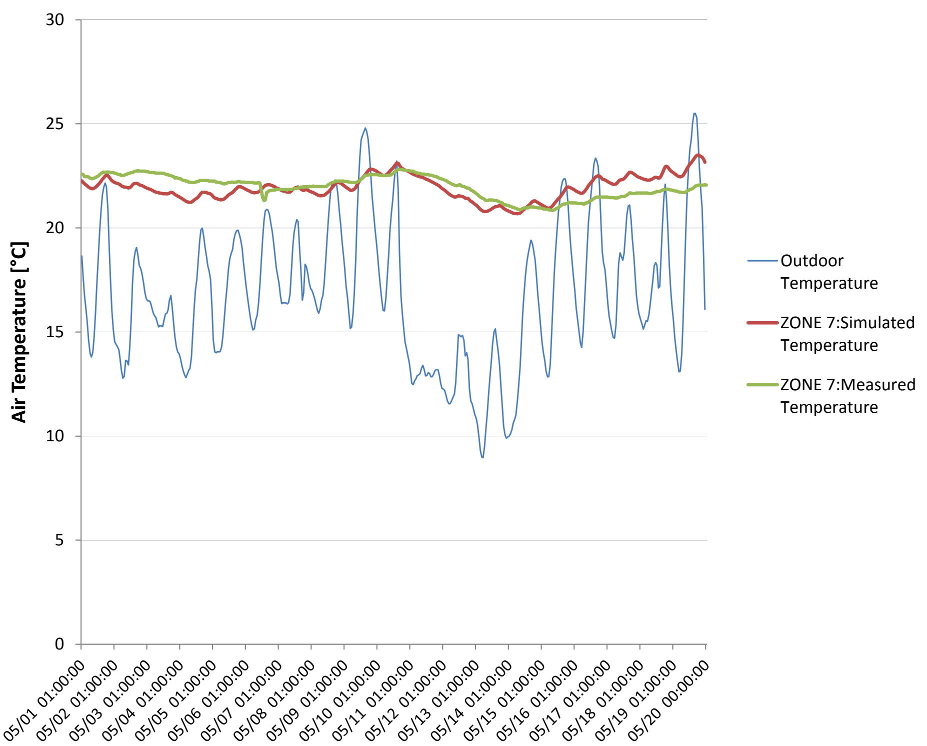

Figure 15

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 7- over the course of 20 days)

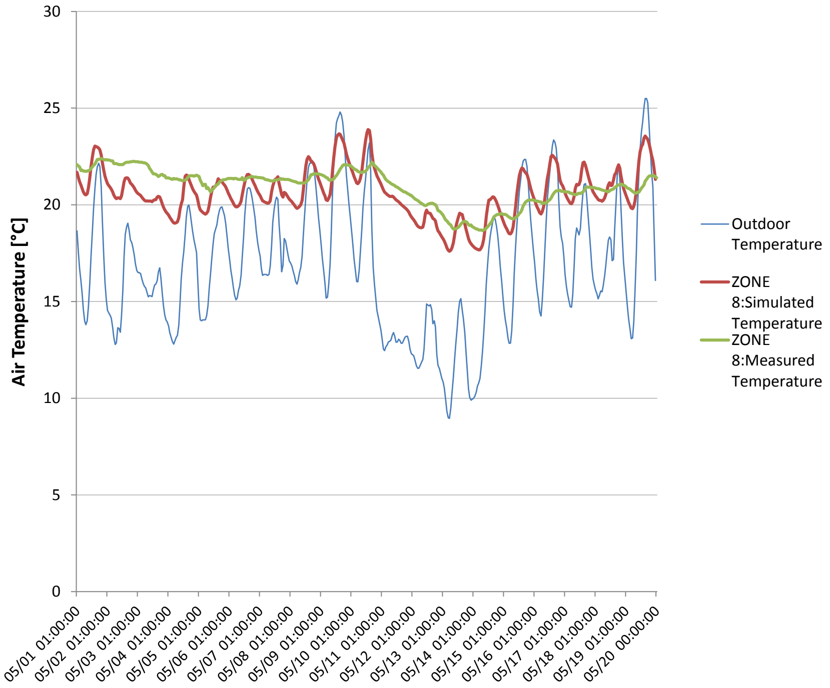

Figure 16

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 8- over the course of 20 days)

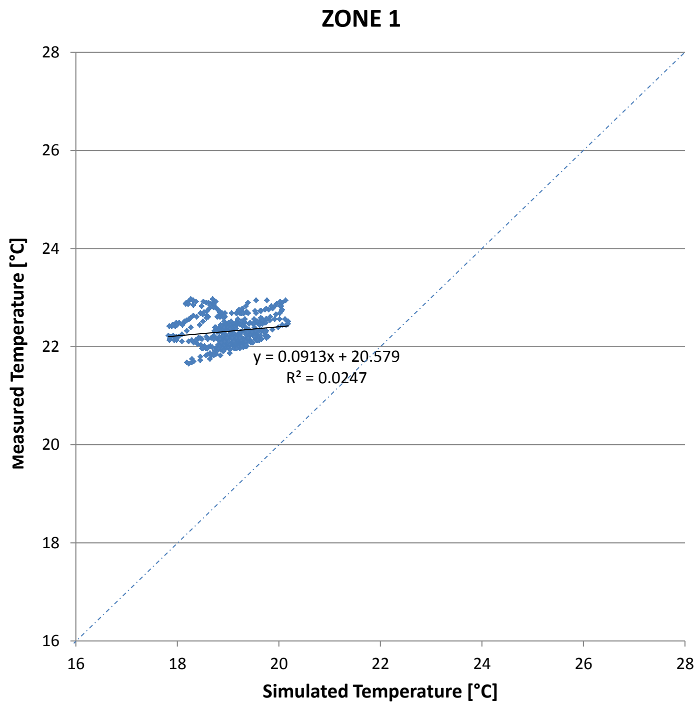

Figure 17

Correlation between simulated data and monitored data zone 1- initial model

Figure 18

Correlation between simulated data and monitored data zone 2- initial model

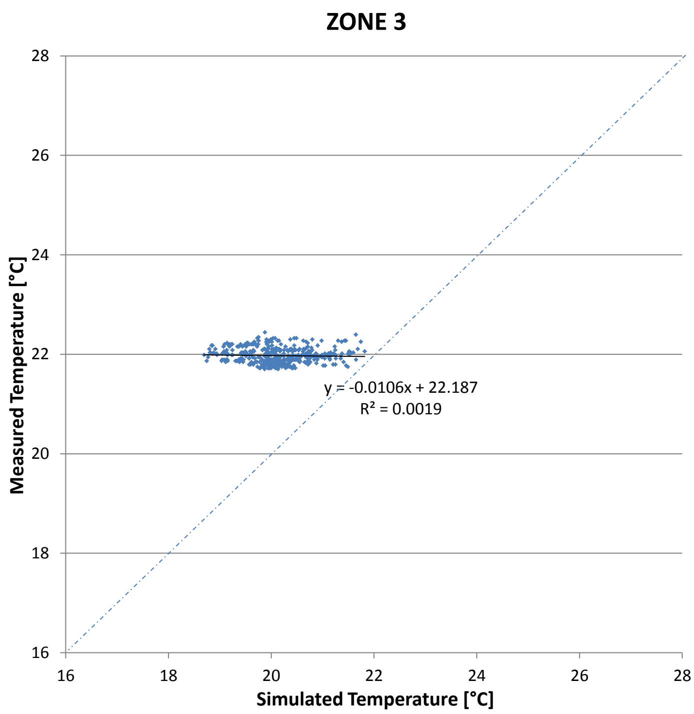

Figure 19

Correlation between simulated data and monitored data zone 3- initial model

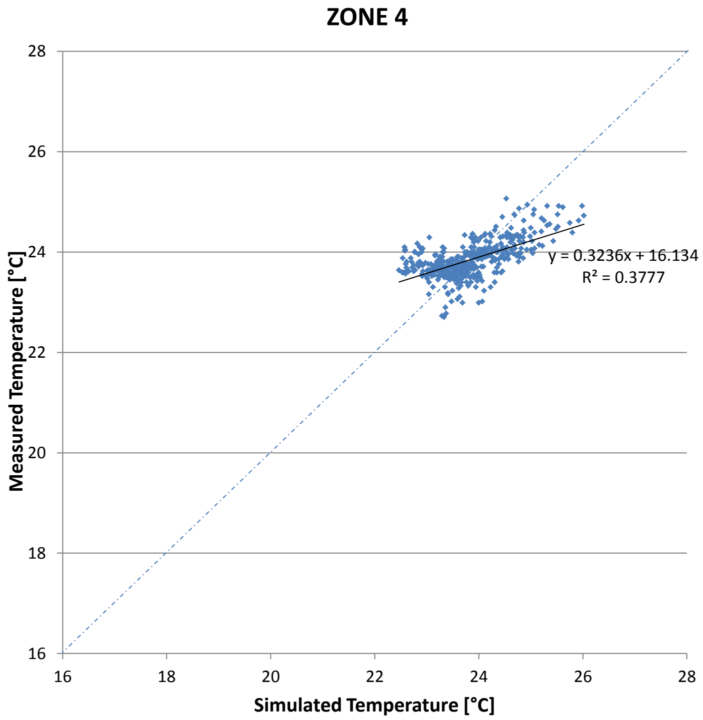

Figure 20

Correlation between simulated data and monitored data zone 4- initial model

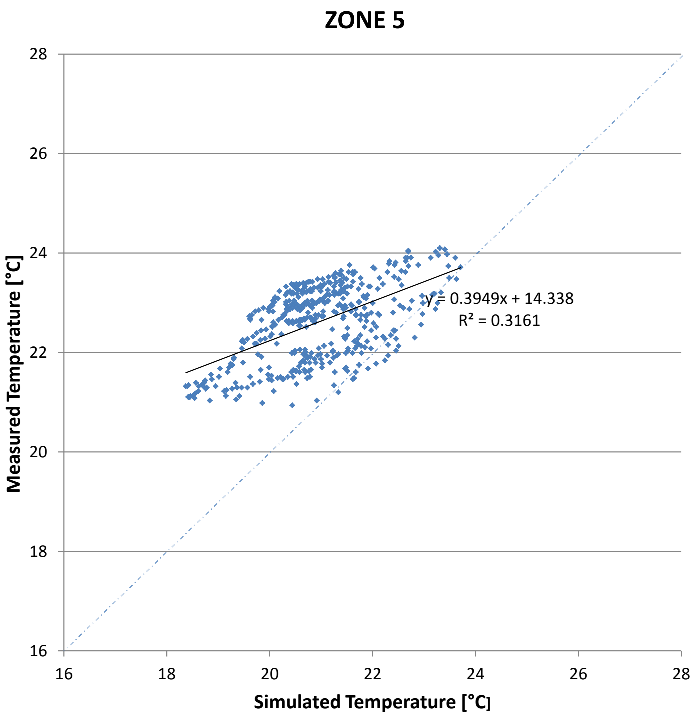

Figure 21

Correlation between simulated data and monitored data zone 5- initial model

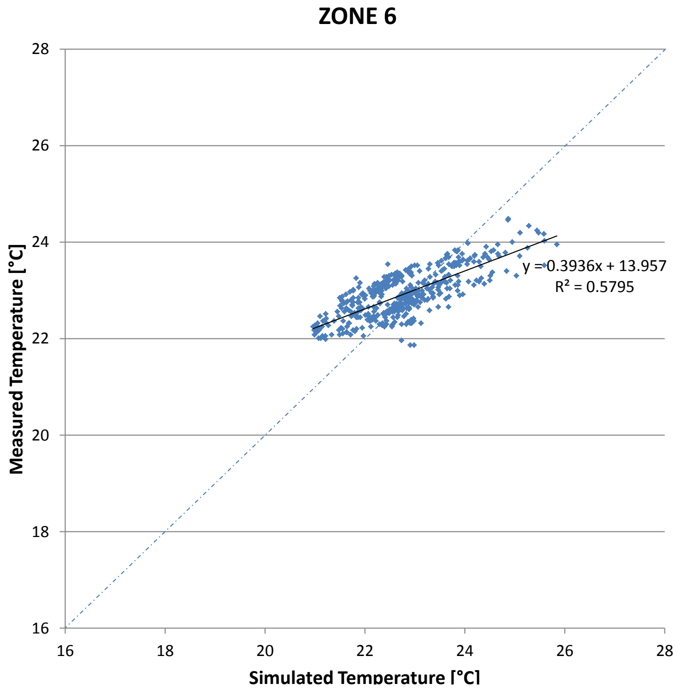

Figure 22

Correlation between simulated data and monitored data zone 6- initial model

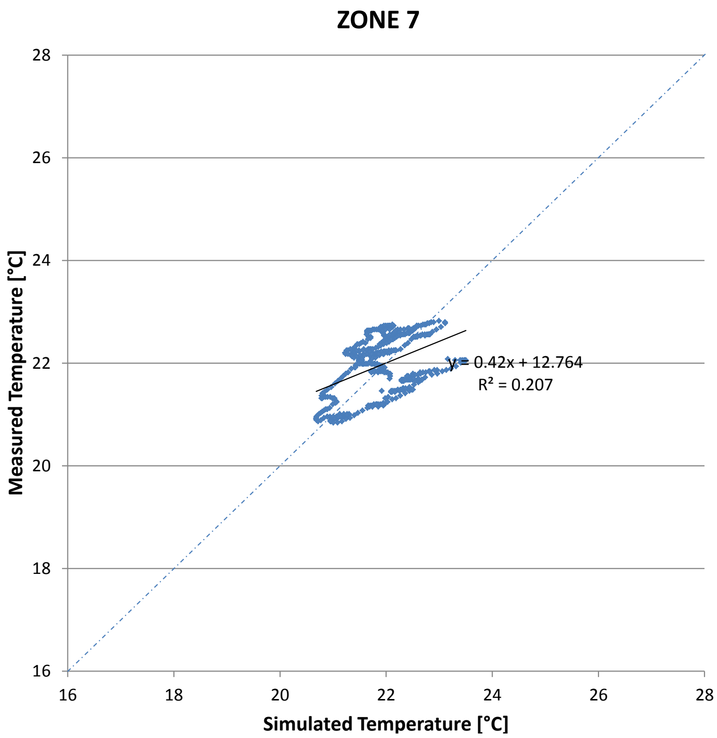

Figure 23

Correlation between simulated data and monitored data zone 7- initial model

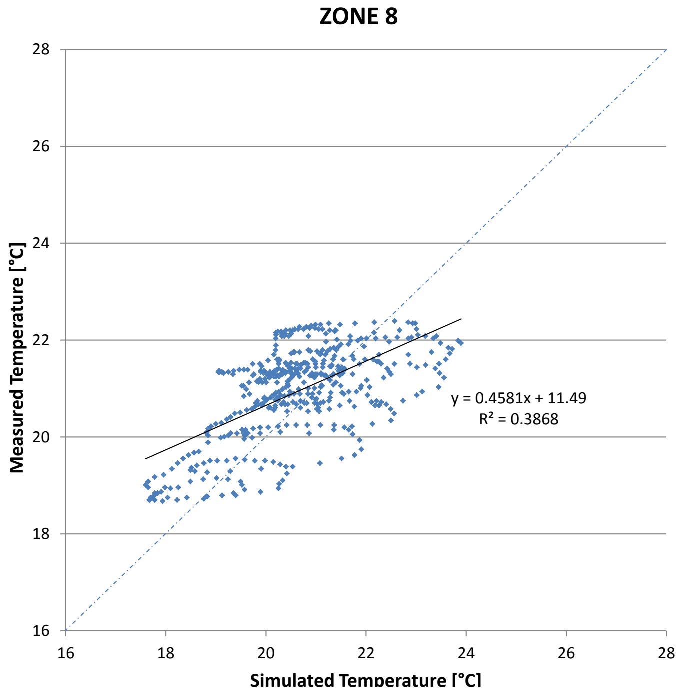

Figure 24

Correlation between simulated data and monitored data zone 8- initial model

For the purpose of model calibration, we only used the results from zones 5 to 8 as not sufficient information was available to accurately model the occupancy and other dynamic features of the first 4 zones. To increase the accuracy of the model, we performed some adjustments on a number of input parameters such as schedules, equipment, internal mass ventilation and hourly air change rate (ACH in h^{-1}). The following adjustments were made to the initial model:

a) Internal mass was increased in zones 5 to 8.
b) Lighting and equipment schedule was modified to different occupancy hours (e.g. a constant schedule was considered for zone 8 which counts with a refrigerator that is active the 24 hours).
c) Hourly air change rate (ACH) was set to 0.70 h^{-1}.

When running a second simulation with the previous adjustments to the simulated model, the comparative analysis of this new calibrated model affirm the following:

a) Zone 5, 6, 7 and 8 show higher r-square but lower NRMSD. Table 9 depicts the evaluation statistics of this new calibrated model. These values are acceptable as they show better correlation between simulation results and measurements. (see Figure 25 to Figure 28).
b) The obtained results in zones 5 seem to suggest better agreement between simulation temperatures and measurements (Figure 29).

c) The results indicate lower NRMSD and higher r-square (see Table 9); however we can still see a slight discrepancy between the simulation model and measurements. In the scatter chart we can see that 1 ◦C is underestimated to the corresponding measurements (see Figure 25).
d) The coefficient of determination (R^2) in zone 6 does not vary in comparison to the initial r-square but increases the NRMSD to 7.5% (see Table 9). The scatter chat shows the deviation between simulated data and monitored data in this zone (see Figure 26). We can see a slightly discrepancy of around 2 ◦C with the measurements. This means that the simulated model underestimates 2 ◦C the monitoring data (Figure 30).
e) Results in zones 7 and 8 suggest better agreement between measured and simulated temperatures. Scatter charts indicate better correlation between simulated data and monitored data for zones 7, and 8 (see Figure 27 and 28).
f) Temperature fluctuations represented in the graphs reveal a close correlation between measured and monitored temperature (see Figure 29 to Figure 32). Furthermore, when using a reference day to asses hourly temperature for all the monitored days we can see a promisingly approach in measured temperature versus simulation (see Figure 33 to Figure 36).
g) This calibration effort seems to suggest that the significant improvement in these zones is due to the changes in schedules (occupancy hours), internal mass and hourly air change rate (ACH). Given the considerable uncertainties involved in simulating air change rates in buildings, these results are considered valid.

Table 9

Model evaluation statistics of the calibrated model - comparison with the initial model

Zones	***Zone 5***	***Zone 6***	***Zone 7***	***Zone 8***
Coefficient of determination (R^2) (Initial model)	0.31	0.57	0.20	0.38
Coefficient of determination (R^2) (Calibrated model)	0.49	0.57	0.32	0.51
NRMSD (%) (Calibrated model)	5.5	7.5	7.3	6.5

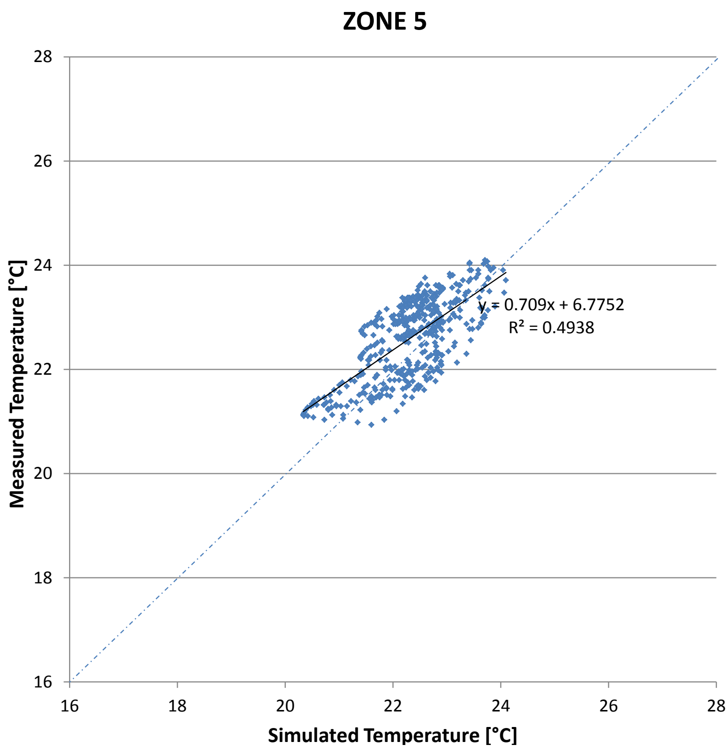

Figure 25
Correlation between simulated data and monitored data Zone 5- calibrated model

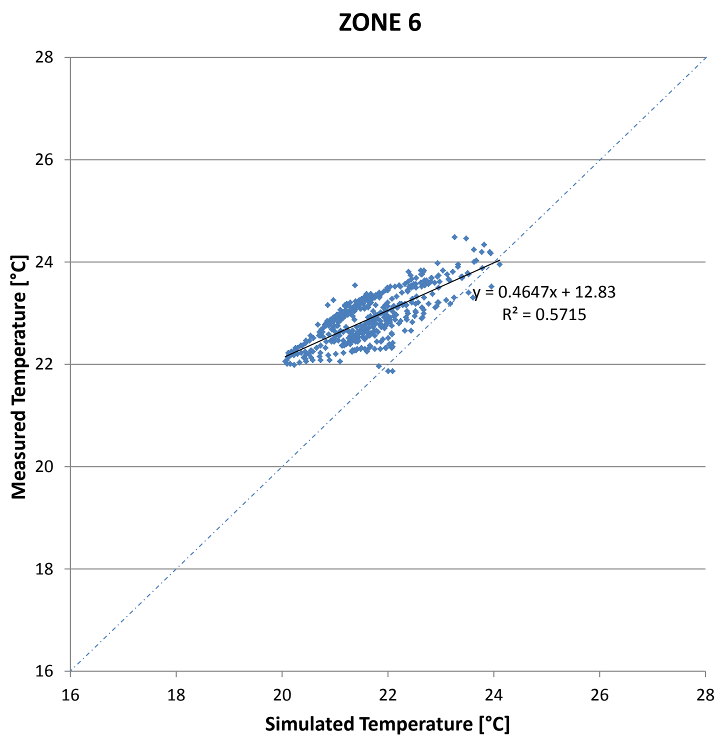

Figure 26
Correlation between simulated data and monitored data Zone 6- calibrated model

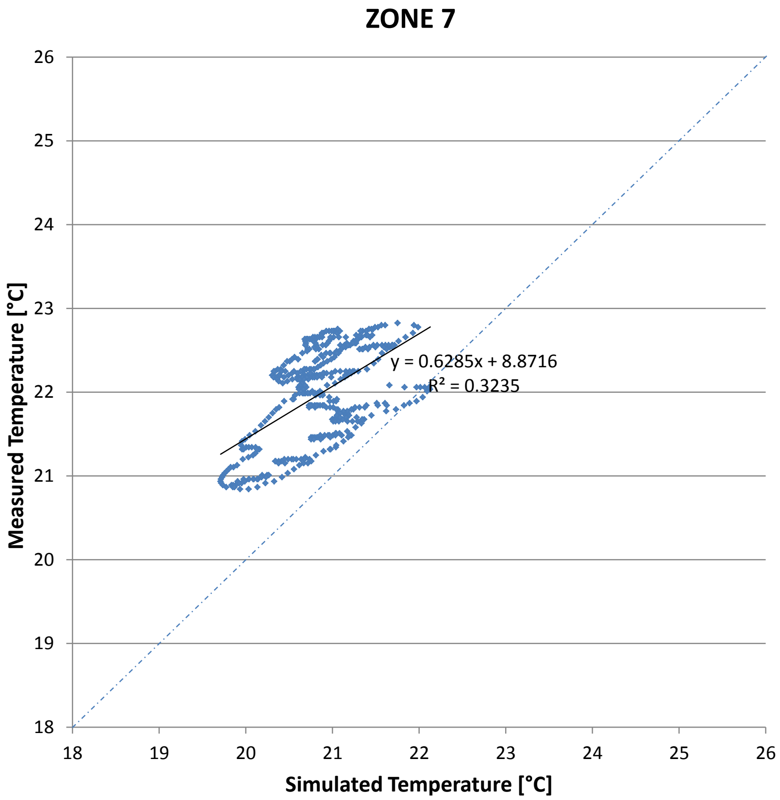

Figure 27

Correlation between simulated data and monitored data Zone 7- calibrated model

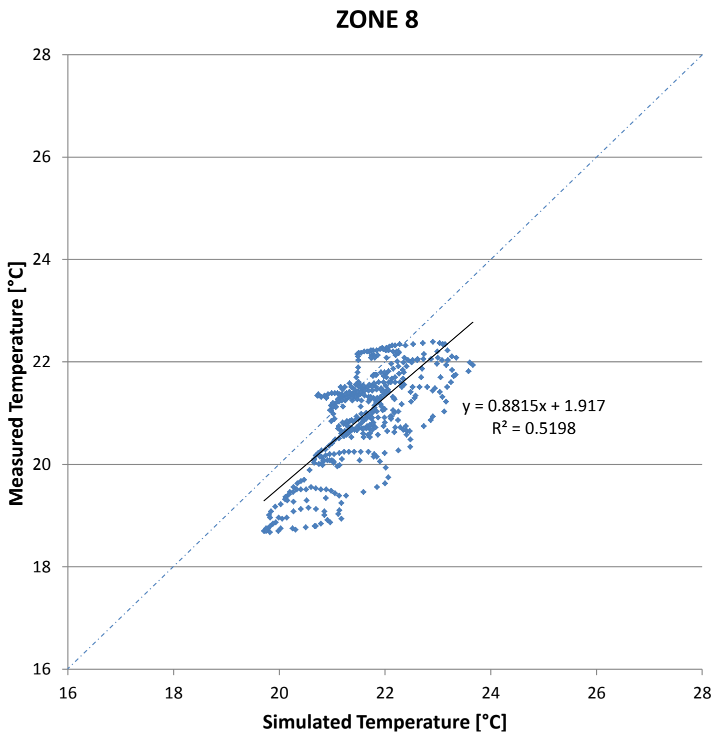

Figure 28

Correlation between simulated data and monitored data Zone 8- calibrated model

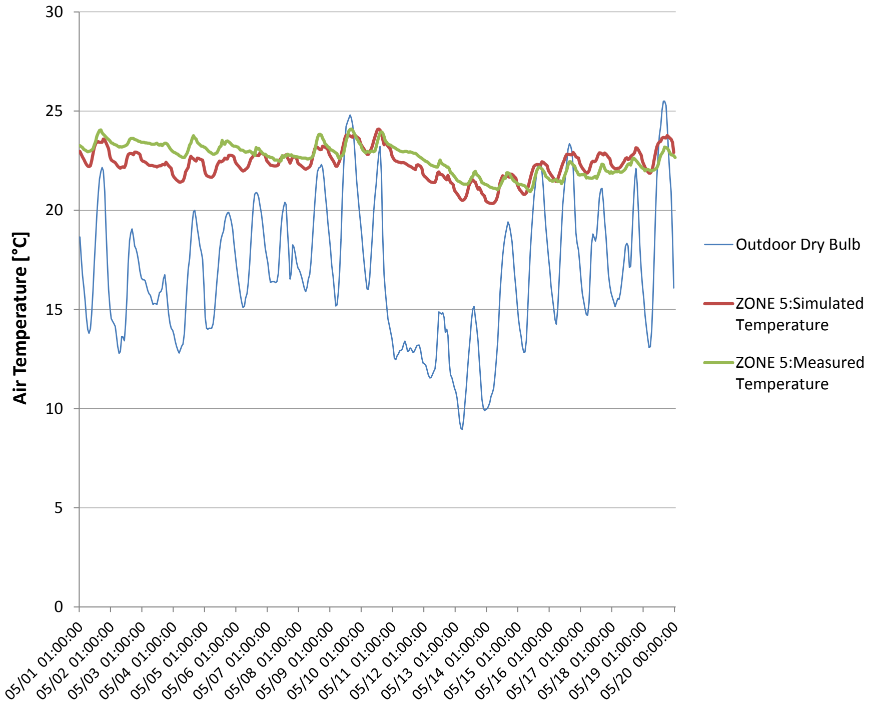

Figure 29

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 5- calibrated model)

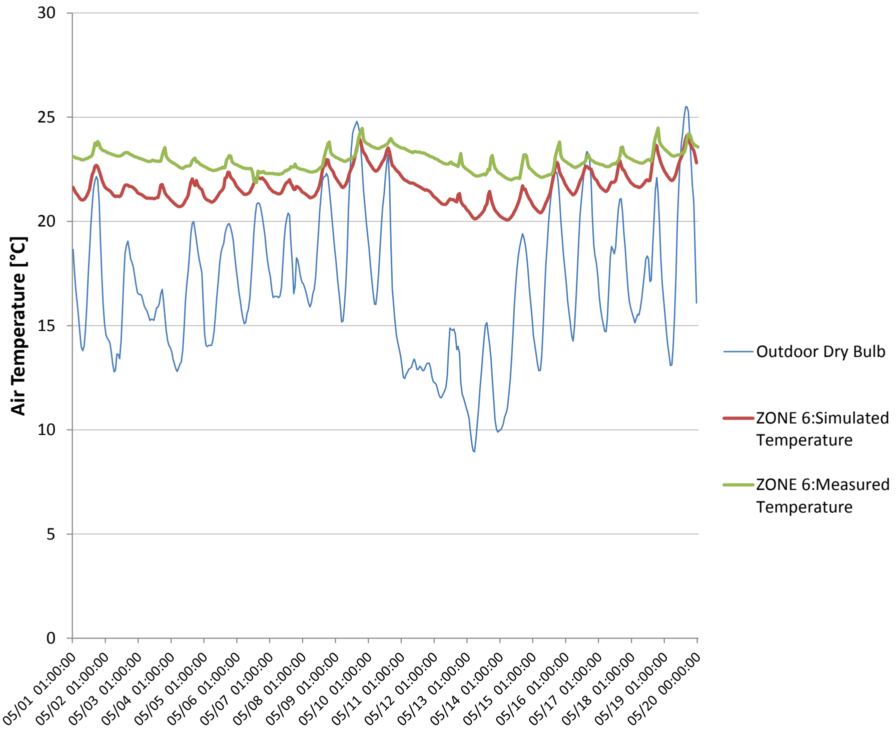

Figure 30

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 6- calibrated model)

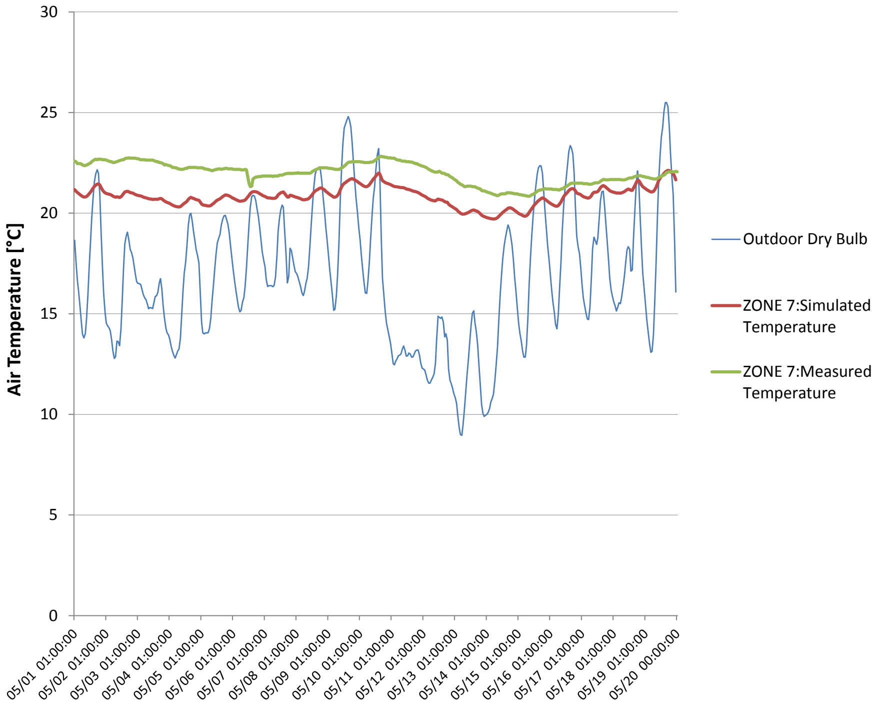

Figure 31

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 7- calibrated model)

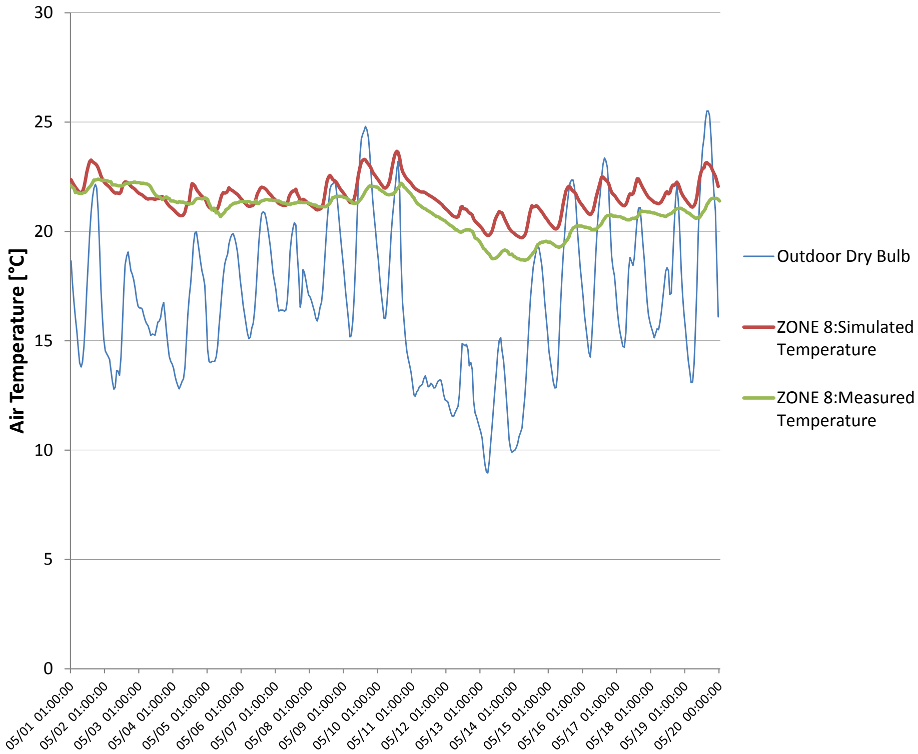

Figure 32

Comparison of the predicted results with corresponding measurements (indoor temperature in zone 8- calibrated model)

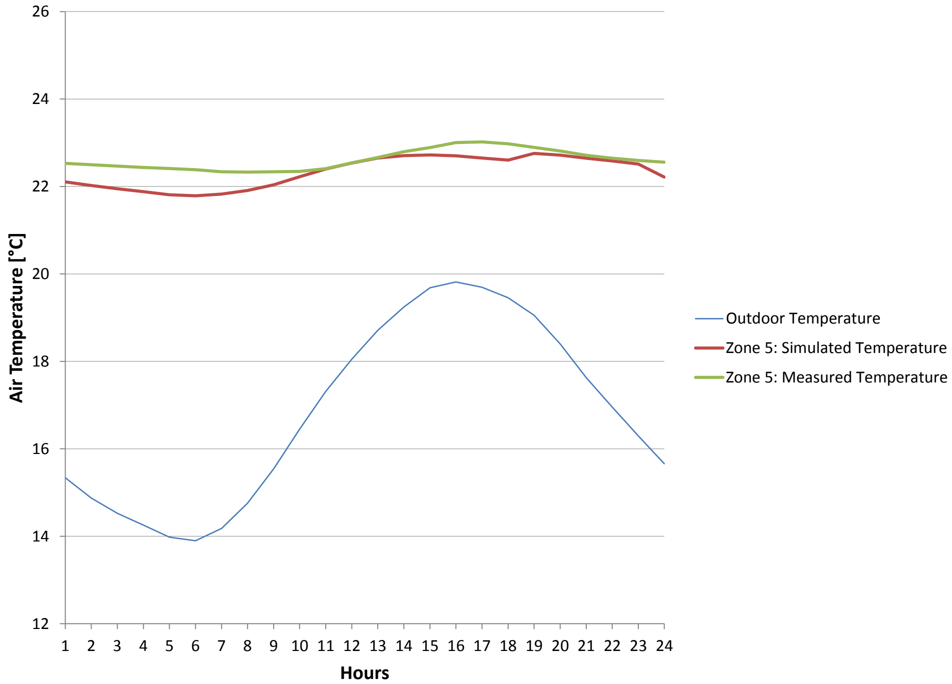

Figure 33

Measured versus simulation indoor air temperatures and outdoor temperatures for a reference day-zone 5

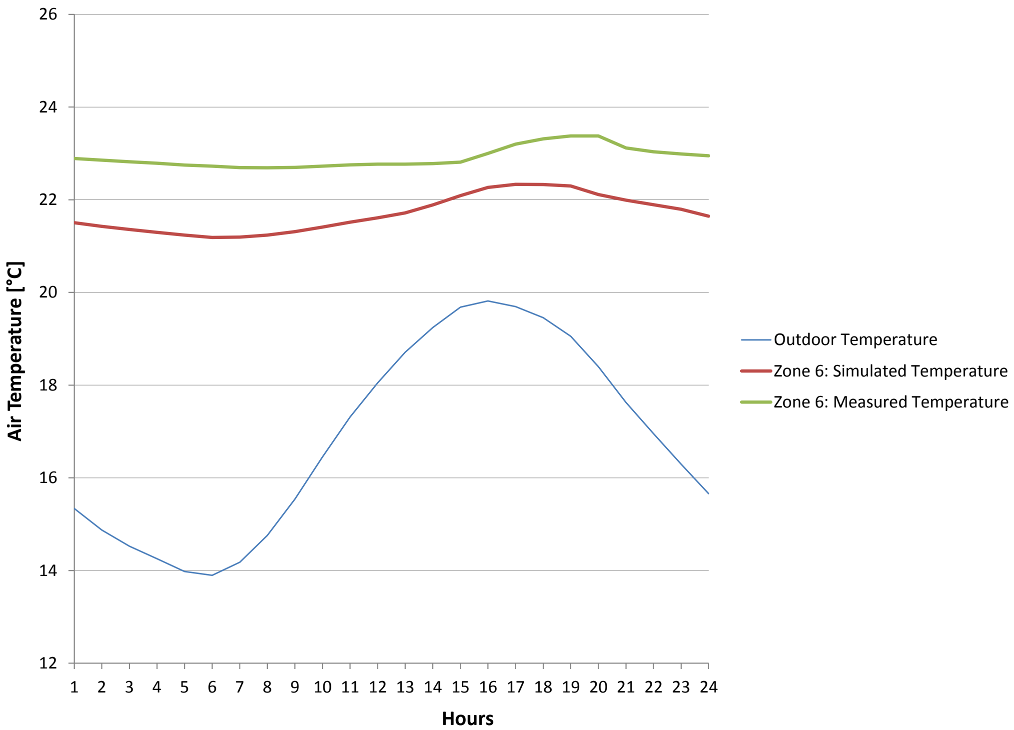

Figure 34

Measured versus simulation indoor air temperatures and outdoor temperatures for a reference day-zone 6

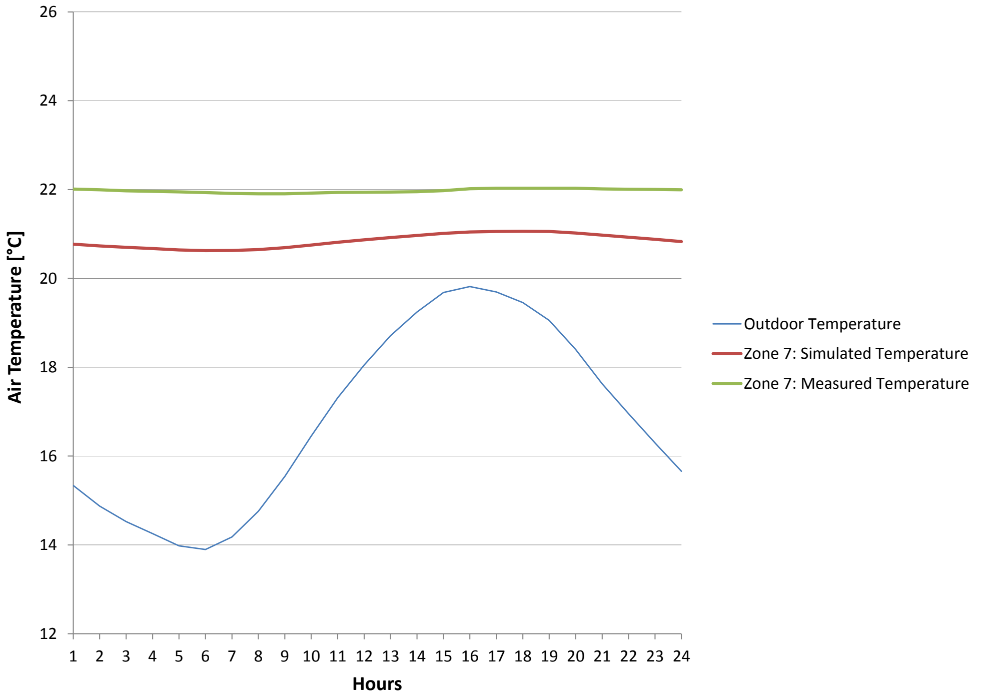

Figure 35

Measured versus simulation indoor air temperatures and outdoor temperatures for a reference day-zone 7

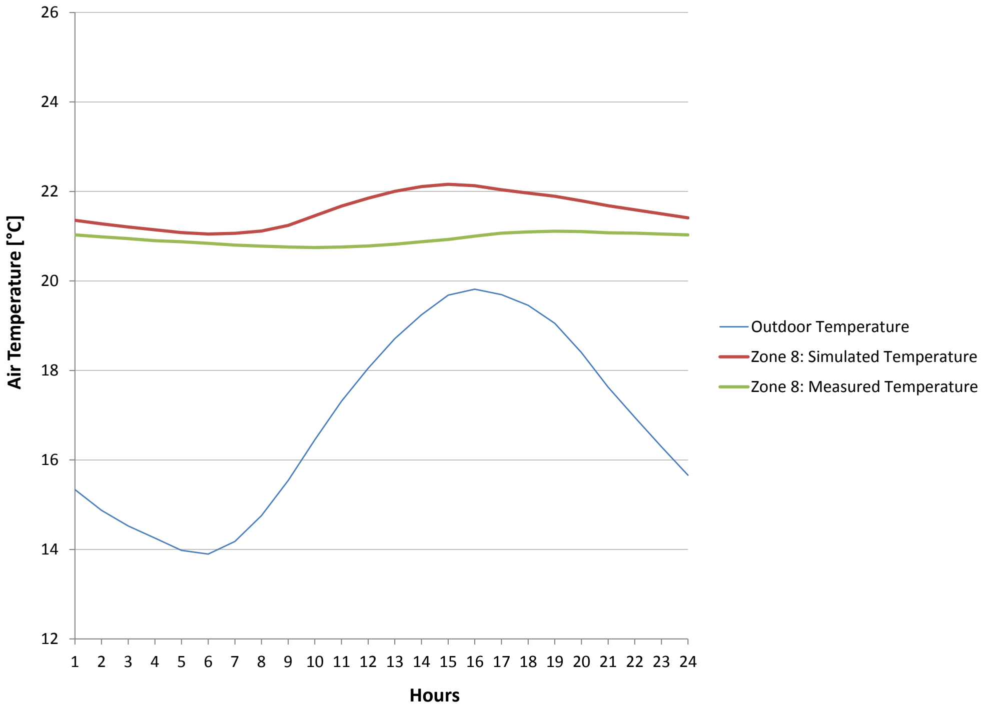

Figure 36

Measured versus simulation indoor air temperatures and outdoor temperatures for a reference day-zone 8

3.7 Improvement Scenarios

To illustrate the utility of the calibrated simulated model toward comparison of thermal improvement possibilities for retrofitting the building envelope; five scenarios were considered.
According to revised literature, “it is emphasized that an efficient building envelope retrofit scenario requires to control one combination or all of the following thermal characteristics: (a) reduction of transmission, (b) reduction of infiltration and ventilation losses and (c) reduction or increase of solar gains through the envelope. Retrofit strategies demand decisive criteria based on insufficiencies determined via building performance audit and/or analysis of the existing building. Nevertheless, it is necessary to define an approach in generating retrofit strategies, due to the numerous alternatives where the main concern is to identify the strategies or measures which are expected to be efficient in long term” (Gücyeter et al. 2012).
Given the great number of possibilities of retrofit measures we considered the most feasible measures. When considering measures it is important to take into account environmental, energy, financial and social factors to attain the most reliable solution. In this framework, five different improvement options (concerning glazing and insulation alternatives) were analyzed to illustrate the utility of the simulation model toward comparisons of thermal improvements to the building envelope. Information regarding improvement alternatives is summarized in Table 10.

The first scenario (ECM1) involves the improvement of the thermal insulation of the roof construction. This alternative option adds 25 cm of polystyrene with lower thermal conductivity value to 0.033W/mK. The second scenario (ECM2) involves the improvement of the thermal insulation of the walls. This alternative option adds 25 cm of glass fiber - organic bonded insulation. The third scenario (ECM3) involves the use of triple-glazing (instead of the existing double-glazing) for windows. The four scenario (ECM4) involves the combination of the three scenarios (ECM1, ECM2, ECM3).
As one of the goals was to reduce energy demand, a higher-level scenario 5 (ECM5) was generated to attain a higher classification that could reach better energy efficiency standards. The fifth scenario (ECM5) involves, in addition to the triple-glazing improvement in ECM3, the incremented of the thermal insulation of the roof and walls (same material properties used for ECM1 and ECM2) to 40 cm from the original 5 cm in roof and 10 cm in walls. Moreover, hourly air change rate (ACH) was set to 0.40 h^{-1} as the windows were almost considered tightly shut. Table 11 provides information regarding scenario 5.
Heating set point remained in 20 ◦C. Hourly air change rate (ACH) was set to 0.70 h^{-1} for all scenarios with the exception to the fifth scenario (ECM5) that we wanted to reach a higher classification in energy efficiency.

Table 10 Overview of simulated improvement scenarios

CODE	*SCENARIO*	*DESCRIPTION*
ECM1	Improved roof insulation (25 cm)	U_{roof} = 0.098 W.m^{-2}.K^{-1}; Insulation material: Expanded polystyrene-molded beads-32kg/m^3 density Tickness 0.25 Conductivity 0.033 Density 32 Specific heat 1210 Hourly air change rate (ACH) set to 0.70 h^{-1}
ECM2	Improved wall insulation (25 cm)	U_{walls}= 0.11 W.m^{-2}.K^{-1}; Insulation material: Glass fiber - organic bonded Tickness 0.25 Conductivity 0.036 Density 140 Specific heat 960 Hourly air change rate (ACH) set to 0.70 h^{-1}
ECM3	Improved windows	$U_{windows}$= 0.78 W.m^{-2}.K^{-1}; -Replacing double glazing windows to triple glazing -SHGC=0.579 Clear 3mm Argon 13mm Clear 3mm Argon 13mm LoE Clear 3mm Rev Hourly air change rate (ACH) set to 0.70 h^{-1}
ECM4	Combined improvements ECM1, ECM2, ECM3	-Increasing roof insulation from 10 cm to 25 cm U_{roof} = 0.098 W.m^{-2}.K^{-1}; -Increasing walls insulation from 5 cm to 25 cm U_{walls}= 0.11 W.m^{-2}.K^{-1}; -Replacing double glazing windows to triple glazing $U_{windows}$= 0.78 W.m^{-2}.K^{-1} SHGC=0.474 Hourly air change rate (ACH) set to 0.70 h^{-1}

Table 11
Overview of simulated improvement scenario 5

CODE	***SCENARIO***	***DESCRIPTION***
ECM5	Using combined improvements + increasing the thickness of the insulation to meet low-energy standards	-Increasing roof insulation 40 cm U_{roof} = 0.068 $W.m^{-2}.K^{-1}$; -Increasing wall insulation 40 cm U_{walls}= 0.077 $W.m^{-2}.K^{-1}$; -Replacing double glazing windows to triple glazing $U_{windows}$= 0.78 $W.m^{-2}.K^{-1}$ SHGC=0.474 Hourly air change rate (ACH) set to 0.40 h^{-1} (windows tightly shut)

CHAPTER 4

RESULTS AND DISCUSSION

Retrofit measures were simulated via calibrated model by integrating to the envelope the improved measures. Simulation results were evaluated according to annual energy consumption.

The results obtained indicate a number of observations and conclusions:

- The case study presented suggests that the calibration of thermal performance simulation models of existing buildings via monitoring may improve the reliability of the simulation analysis in the implications of retrofit measures of existing buildings.
- Results in scenario 1 (ECM1) indicate a low heat load reduction of 10.5 kWh/m².a. It means that this improvement, which only enhances 8.89% of the annual heating demand, does not reduce in a noteworthy manner the heating load; thereby this measure does not have a significant effect in retrofitting the building envelope (see Table 13).
- Almost the same result, similar to the one in ECM1, is seen in scenario 3 (ECM3) with a heat load reduction of 7.6 kWh/m².a. This output represents a minor degree of improvement in energy efficiency for retrofitting measures.
- Scenario 2 (ECM2) increases the effectiveness of retrofit with higher improvement (13.5%). The heat load decreases of 15.9 kWh/m².a. Even that it is not considered a promisingly good result; it can be contemplated as the best result when we compare it with the results obtained in ECM1 and ECM3. Therefore, it is possible to assert that the improvement in scenario 2 (ECM2) is due to the lower thermal conductivity of the thermal insulation of the wall construction.
- The fourth scenario, which involves the combination of the three first scenarios (ECM1, ECM2, and ECM3), has an important effect in retrofitting the building envelope. We can see that it leads to an important heat load reduction of 35.1 kWh/m².a (see Table 13).
- The higher improved scenario 5 (ECM5) indicates a promisingly good effect of retrofitting existing buildings. The significant improvement, which enhances 58.5% of the annual heating demand, is due to the increment of the thermal mass and lower infiltration rate (hourly air change rate to 0.40 h^1); thereby, it demonstrates that by combining all the improved scenarios (ECM1, ECM2 and ECM3) along with an increment of the thermal mass and lower infiltration rate, a significant heat load reduction up to 47.2 kWh/m².a can be obtained (see Table 11).
- For comparison reasons in the energy efficiency scale, the Austrian Energy efficiency guideline, which is emitted by the Austrian Institute for Building Technology, OIB (Österreichisches Institut für Bautechnik 2011) was taken as a benchmark. Using the scale in energy efficiency we can compare the base-case model (no retrofitted) and the highest improvement scenario ECM5 (retrofitted). Based on the Austrian energy standards, the base-case model (no

retrofitted) is classified in a category C with an annual heating demand of 118.0kWh/m².a (see Figure 39).

- In contrast to the base-case model, the highest classification in energy efficiency reaches a superior category B with an annual heating demand of 49.0 kWh/m².a. (see Figure 40). Table 13 shows the annual heating loads in kWh/m².a for each simulated scenario and the resulted improvement. Simulated heating loads of the different scenarios over the observation period are shown in Figure 37.

The aforementioned results seem to suggest that some improvements to the building envelope such as improvement of the thermal insulation in walls and roof and the use of triple-glazing for windows with a low thermal emissivity film can bring about better performance of the building envelope leading to an important heat load reduction up to 47.2 kWh/m².a.

By using this last measure (ECM 5) the building can attain a better energy efficiency category from C to B which is based on the Austrian Energy efficiency guideline. Thereby, it is likely to assert that the highest category in energy efficiency arises as the most effective retrofit measure for this case building which demonstrates the significant effect of retrofitting existing buildings.

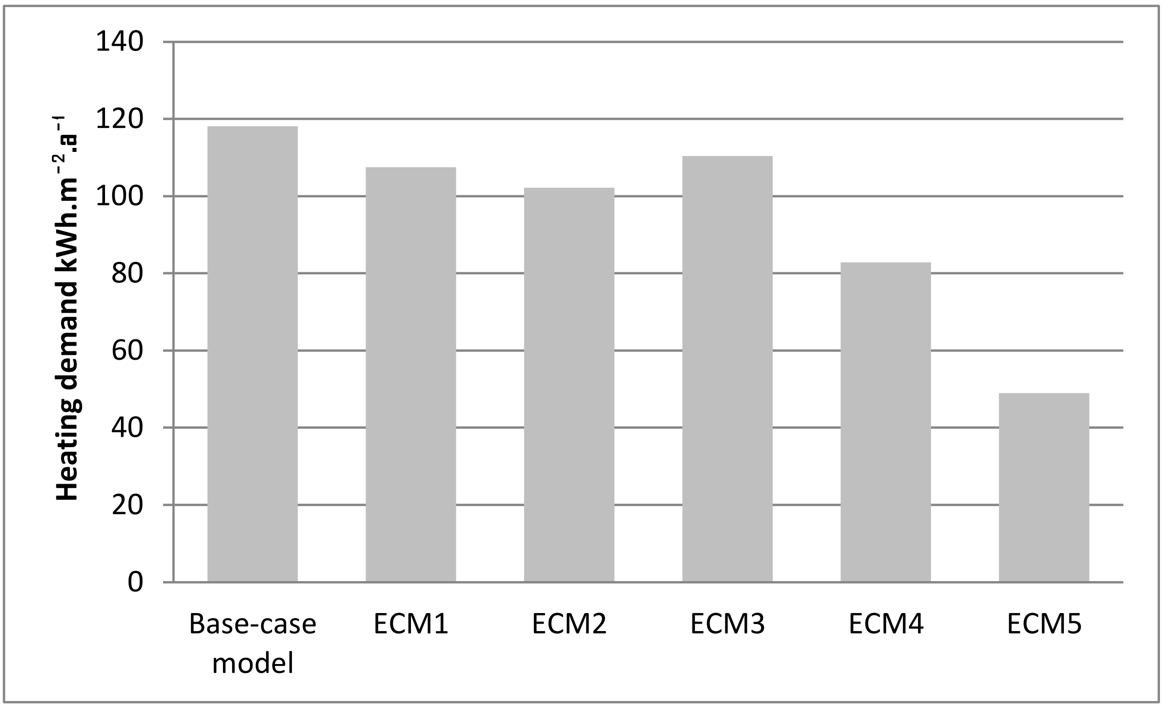

Figure 37

Predicted heating loads for the different scenarios over the observed period

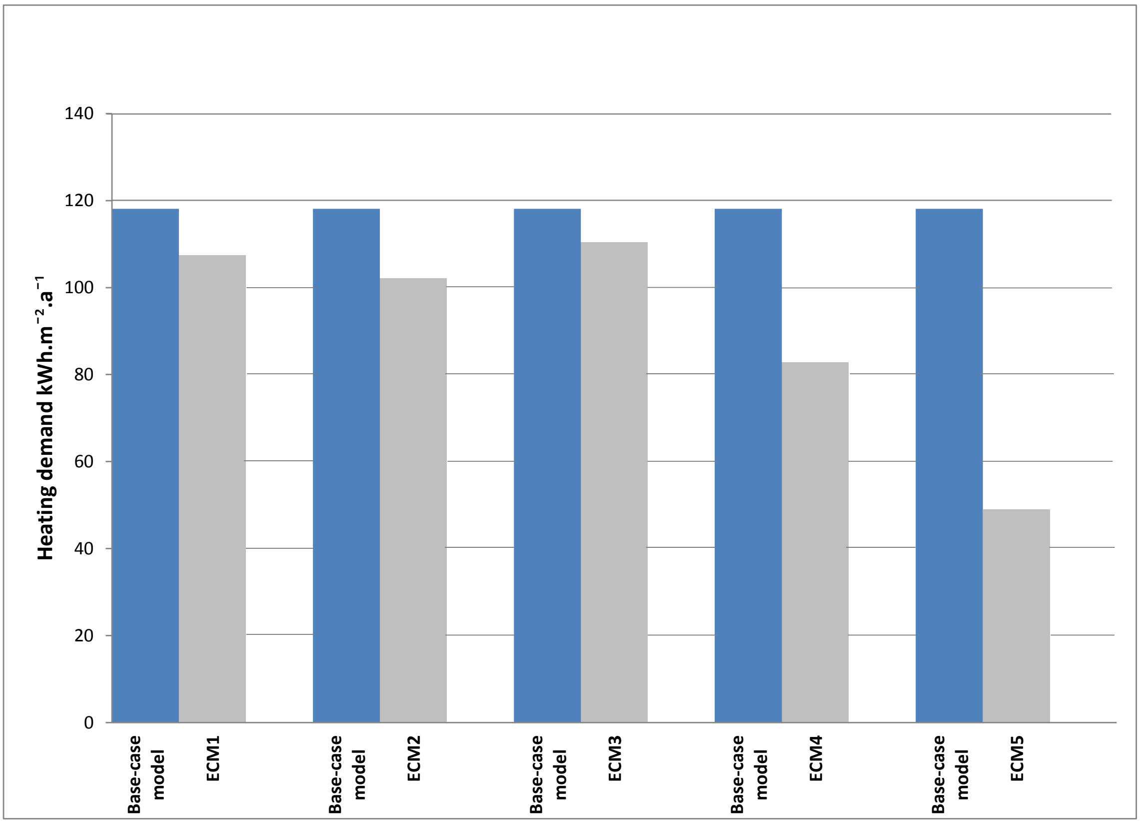

Figure 38

Predicted heating loads for the different scenarios versus monitored values

Table 12

Energy Conservation Measures (ECMs)

	WALLS INSULATION (cm)	***ROOF INSULATION (cm)***	***WINDOWS***	***INFILTRATION***	***ENERGY DEMAND ($kWh.m^{-2}.a^{-1}$)***
ECM 1	-	25	DG	0.7	107.5
ECM 2	25	-	DG	0.7	102.1
ECM 3	-	-	TG	0.7	110.4
ECM4	25	25	TG	0.7	82.9
ECM5	40	40	TG	0.4	49.0

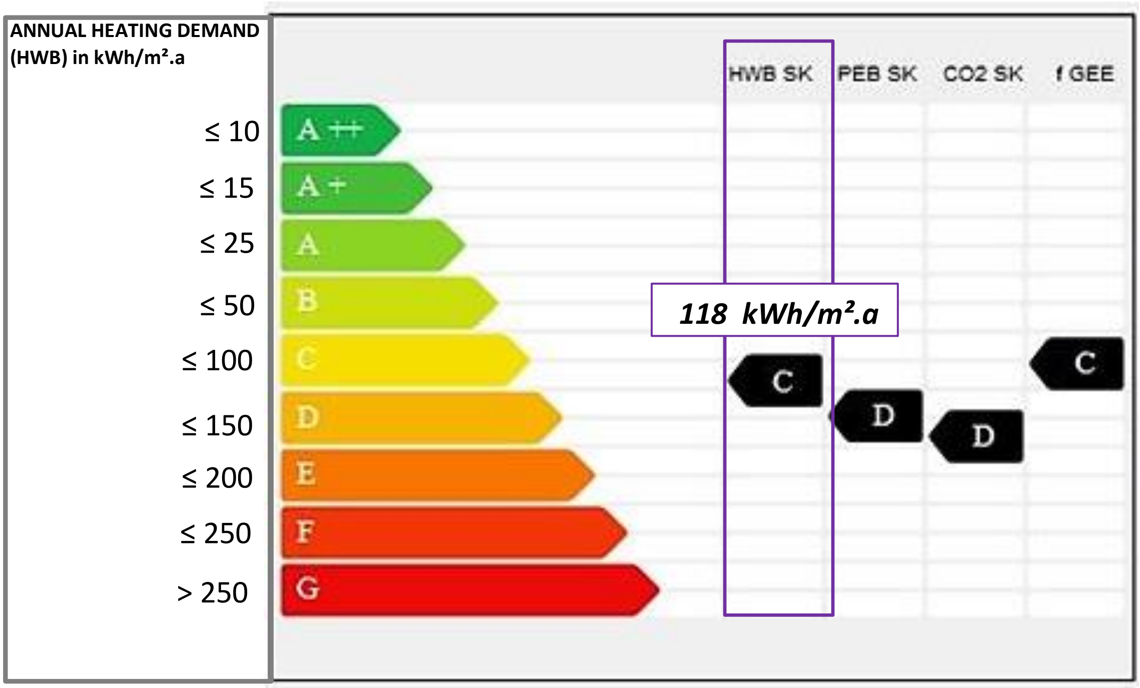

Figure 39
Energy standards according to the Austrian Energy efficiency guideline and the pertain category before the retrofit

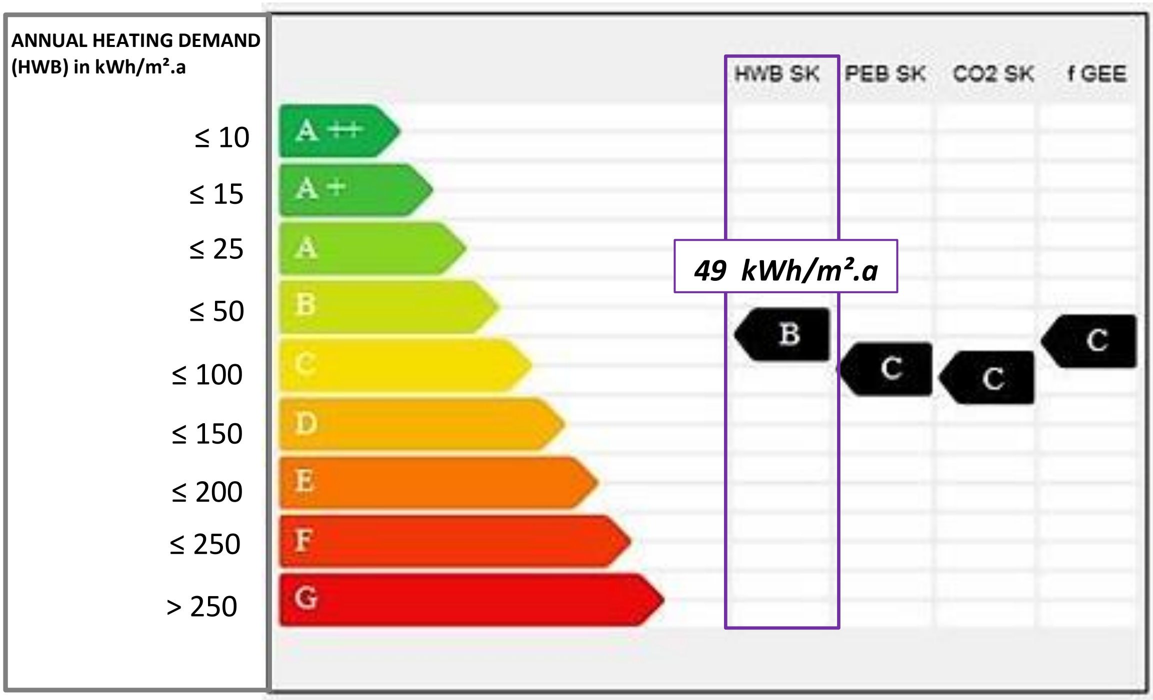

Figure 40
Energy standards according to the Austrian Energy efficiency guideline and the highest category after the retrofit (ECM 5)

Table 13

Annual heating demand in $kWh.m^{-2}.a^{-1}$ and improvement

	BASE-CASE MODEL	***ECM1***	***ECM2***	***ECM3***	***ECM4*** ALL ECMs	***ECM5*** MEASURE TO MEET LOW-ENERGY STANDARDS
Annual heating load ($kWh.m^{-2}.a^{-1}$)	*118.0*	*107.5*	*102.1*	*110.4*	*82.9*	*49.0*
Improvement	0.0%	-9.0%	-13.5%	-6.5%	-29.8%	-58.5%

CHAPTER 5

CONCLUSSION

5.1 Contribution

In this analysis, we examined the use of calibrated dynamic simulation and energy performance measurements to retrofit the building envelope by exploring different alternative improvement options that could enhance the thermal performance of the building.

The simulation results in this retrofit approach seem to suggest that relying on assumptions may lead to inaccurate simulation models. As we could see, the simulation results obtained via the initial non calibrated simulation model displayed significant large errors. The errors were mainly due to the uncertainties in the assumptions pertaining construction materials, ventilation and occupancy hours. As mentioned in the initial simulation process, the documentation pertaining construction elements and properties was not available. Thereby, we can see that large deviations may result from the assumptions which differed from the real surface properties.

An approach to improve the reliability of the simulation-base results, which are based on the assumptions, is to use the monitoring data (indoor temperature) towards calibration of the simulation models. By comparing the simulation temperatures with the measurements the calibrated process adds accuracy to the simulation-based results. Thus, it is possible to assert that evaluations on improvements to retrofit existing buildings rely on accurate calibrated models.

Concerning energy conservation measures, given the great diversity of retrofit measures, we conclude that the most effective retrofit measure in this base-case involves the combination of alternative design measures (such as improvement of the thermal insulation in walls and roof and the use of triple-glazing for windows with a low thermal emissivity film) .The effectiveness to consider alternative retrofit measures relies on the efficacy to reduce heating loads to attain higher standards in annual heating demand.

5.2 Future research

In this analysis, only the thermal performance of the building was evaluated; however for a complete assessment of the building performance would be interesting to evaluate acoustic and visual parameters in future studies.

Another future effort could also focus on determining payback costs regarding each of the measures applied to see the financial effect of retrofitting existing buildings.

Apart from that, future efforts dealing with energy efficiency improvements would also be helpful to consider different retrofit technologies in buildings such as in mechanical ventilation, artificial lighting, and cooling installations with renewable energy technologies.

CHAPTER 6

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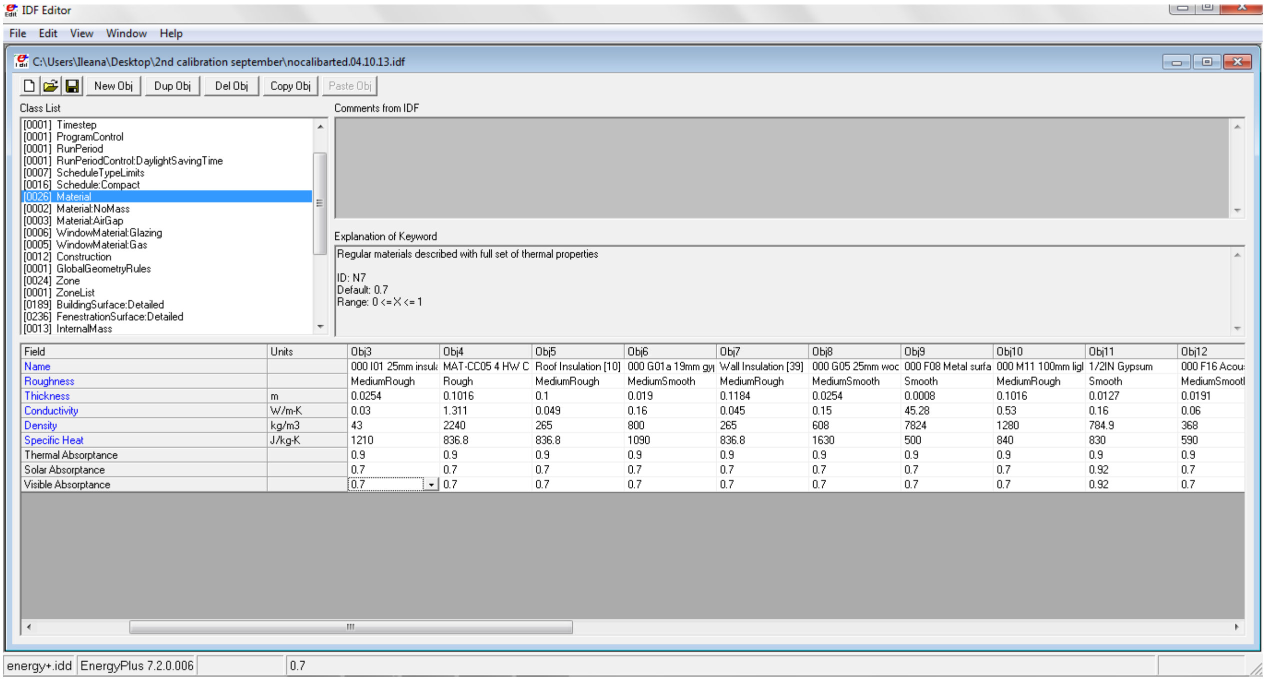
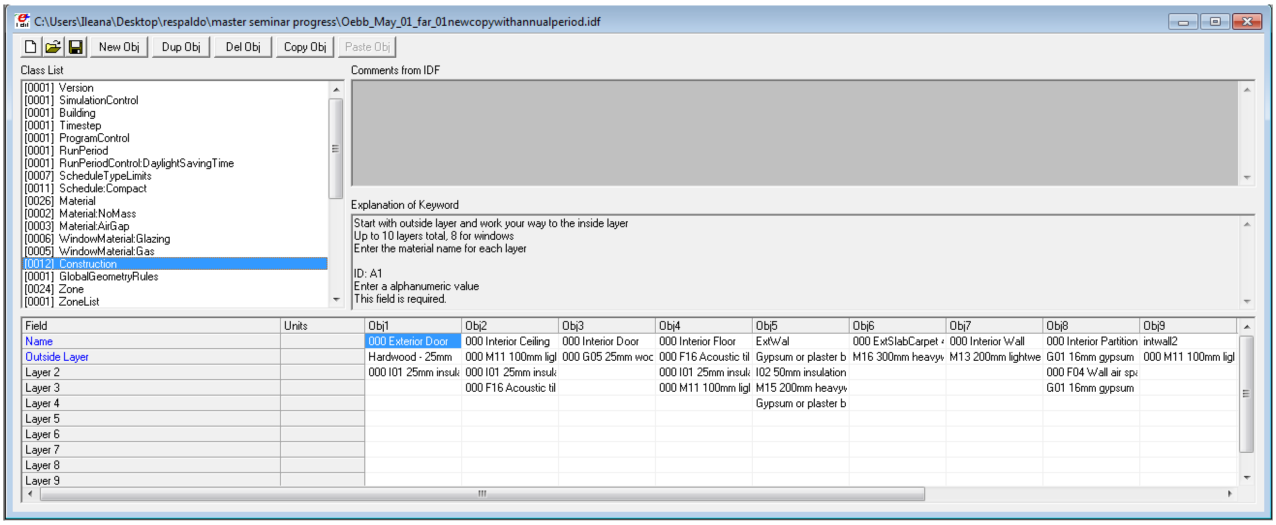
CHAPTER 7

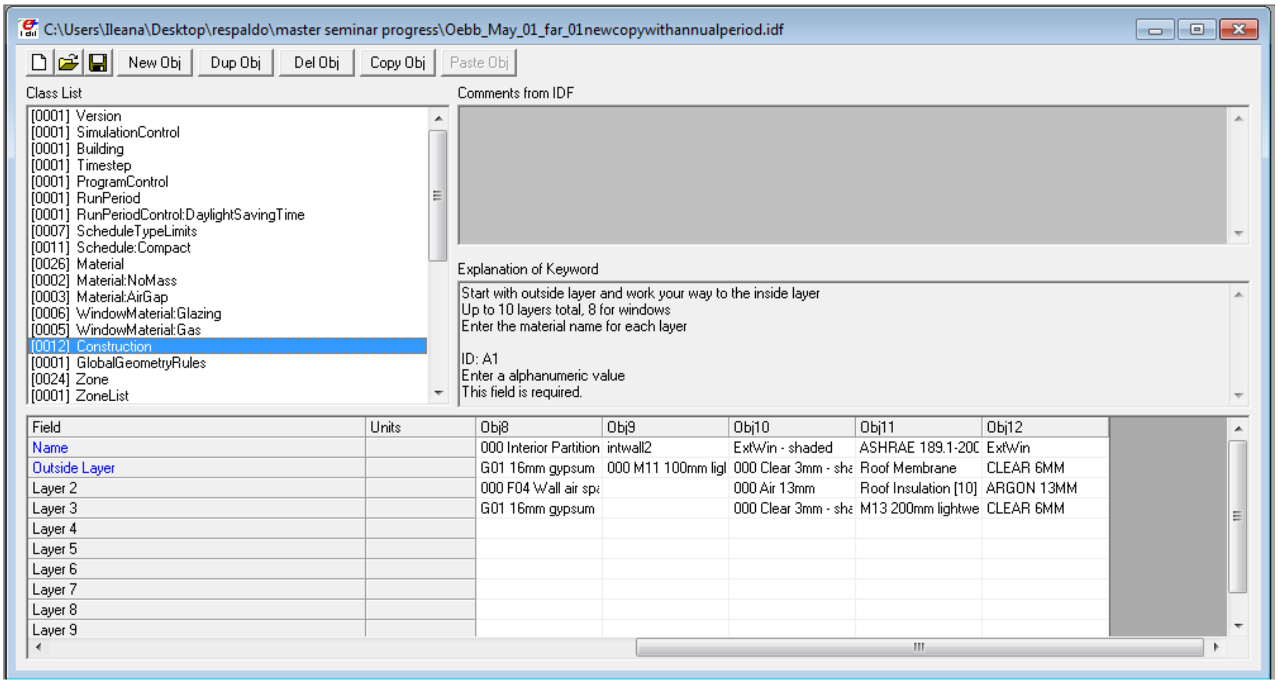
APPENDIX

Assumptions regarding materials in EnergyPlus simulation



Constructions in EnergyPlus simulation

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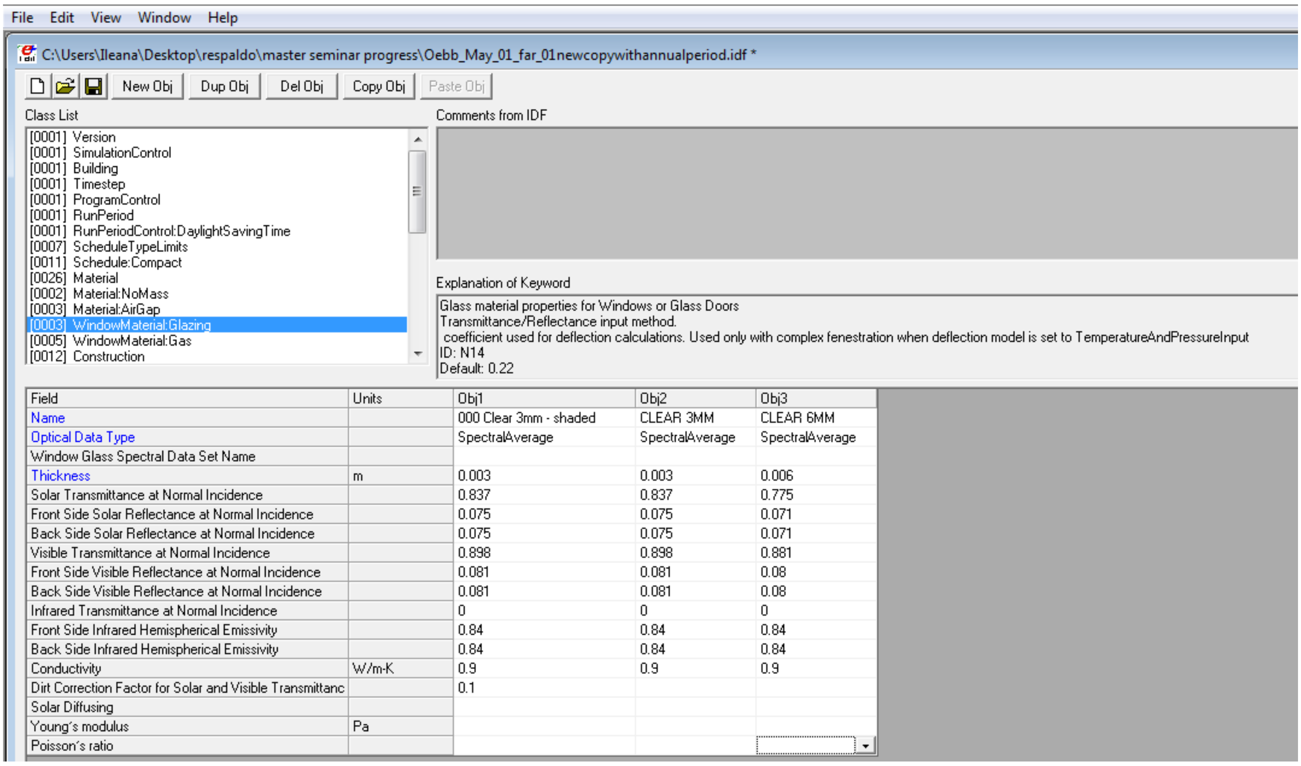
[0001] ZoneList
Comments from IDF
Explanation of Keyword
Start with outside layer and work your way to the inside layer
Up to 10 layers total, 8 for windows
Enter the material name for each layer
ID: A1
Enter a alphanumeric value
This field is required.
Field | Units | Obj8 | Obj9 | Obj10 | Obj11 | Obj12
Name | | 000 Interior Partition | intwall2 | ExtWin - shaded | ASHRAE 189.1-200 | ExtWin
Outside Layer | | G01 16mm gypsum | 000 M11 100mm ligl | 000 Clear 3mm - sha | Roof Membrane | CLEAR 6MM
Layer 2 | | 000 F04 Wall air spa | | 000 Air 13mm | Roof Insulation [10] | ARGON 13MM
Layer 3 | | G01 16mm gypsum | | 000 Clear 3mm - sha | M13 200mm lightwe | CLEAR 6MM
Layer 4
Layer 5
Layer 6
Layer 7
Layer 8
Layer 9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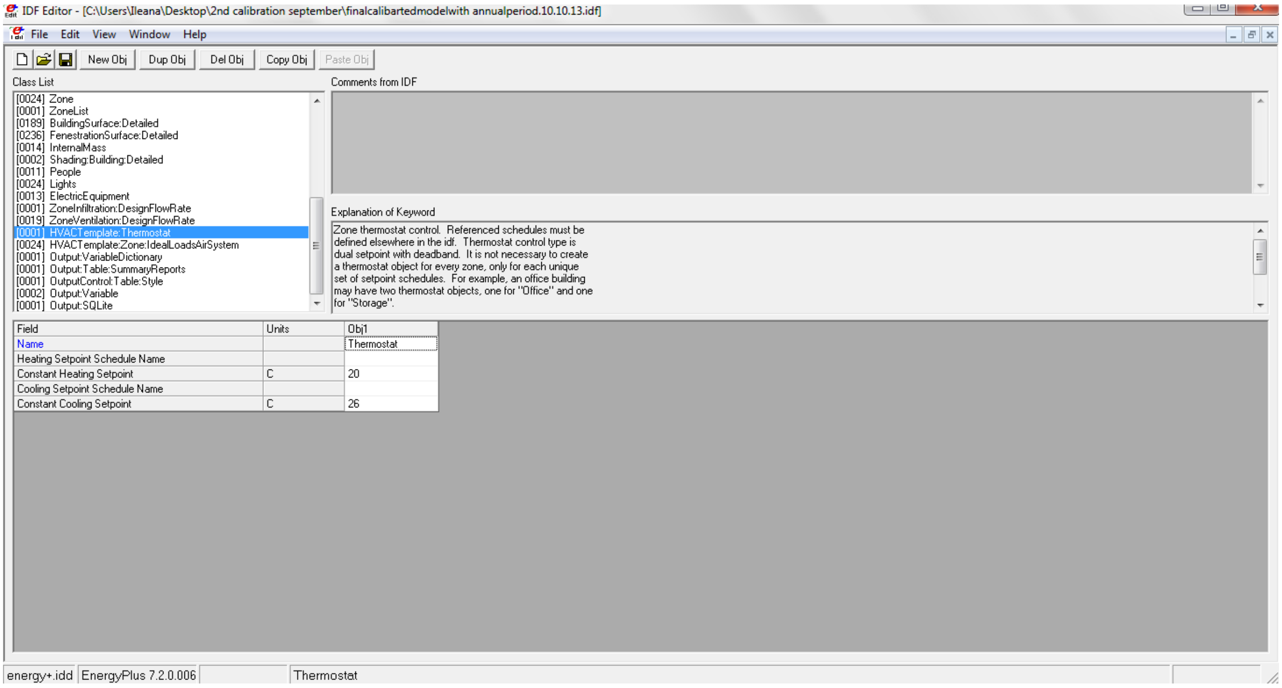
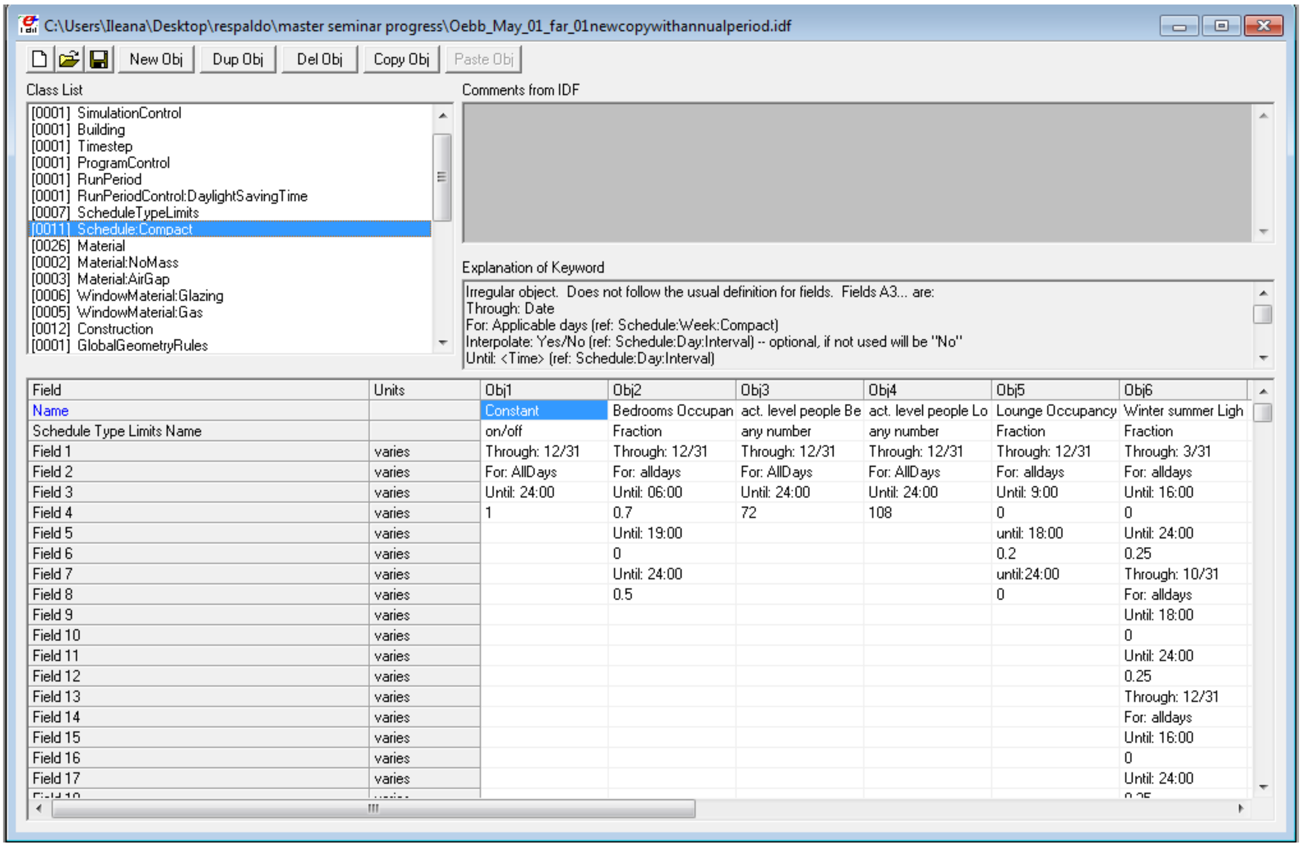
[0012] Construction
Comments from IDF
Explanation of Keyword
Glass material properties for Windows or Glass Doors
Transmittance/Reflectance input method.
coefficient used for deflection calculations. Used only with complex fenestration when deflection model is set to TemperatureAndPressureInput
ID: N14
Default: 0.22
Field | Units | Obj1 | Obj2 | Obj3
Name | | 000 Clear 3mm - shaded | CLEAR 3MM | CLEAR 6MM
Optical Data Type | | SpectralAverage | SpectralAverage | SpectralAverage
Window Glass Spectral Data Set Name
Thickness | m | 0.003 | 0.003 | 0.006
Solar Transmittance at Normal Incidence | | 0.837 | 0.837 | 0.775
Front Side Solar Reflectance at Normal Incidence | | 0.075 | 0.075 | 0.071
Back Side Solar Reflectance at Normal Incidence | | 0.075 | 0.075 | 0.071
Visible Transmittance at Normal Incidence | | 0.898 | 0.898 | 0.881
Front Side Visible Reflectance at Normal Incidence | | 0.081 | 0.081 | 0.08
Back Side Visible Reflectance at Normal Incidence | | 0.081 | 0.081 | 0.08
Infrared Transmittance at Normal Incidence | | 0 | 0 | 0
Front Side Infrared Hemispherical Emissivity | | 0.84 | 0.84 | 0.84
Back Side Infrared Hemispherical Emissivity | | 0.84 | 0.84 | 0.84
Conductivity | W/m-K | 0.9 | 0.9 | 0.9
Dirt Correction Factor for Solar and Visible Transmittanc | | 0.1
Solar Diffusing
Young's modulus | Pa
Poisson's ratio



Schedules in EnergyPlus simulation



Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		Constant	Bedrooms Occupan	act. level people Be	act. level people Lo	Lounge Occupancy	Winter summer Ligh
Schedule Type Limits Name		on/off	Fraction	any number	any number	Fraction	Fraction
Field 1	varies	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 12/31	Through: 3/31
Field 2	varies	For: AllDays	For: alldays	For: AllDays	For: AllDays	For: alldays	For: alldays
Field 3	varies	Until: 24:00	Until: 06:00	Until: 24:00	Until: 24:00	Until: 9:00	Until: 16:00
Field 4	varies	1	0.7	72	108	0	0
Field 5	varies		Until: 19:00			until: 18:00	Until: 24:00
Field 6	varies		0			0.2	0.25
Field 7	varies		Until: 24:00			until:24:00	Through: 10/31
Field 8	varies		0.5			0	For: alldays
Field 9	varies						Until: 18:00
Field 10	varies						0
Field 11	varies						Until: 24:00
Field 12	varies						0.25
Field 13	varies						Through: 12/31
Field 14	varies						For: alldays
Field 15	varies						Until: 16:00
Field 16	varies						0
Field 17	varies						Until: 24:00

Hourly air change rate (ACH) set to 0.70 h^1 for all zones in EnergyPlus simulation