Energy Efficient Management and Optimization

Strategies in Office Buildings

By implementing Simulation-based optimization control

By

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Abstract

This research presents a framework for using simulation-based optimization control approach in reducing primary energy consumption from a HVAC system in a Bosch office building in Schwieberdingen near Stuttgart, Germany. Two systems supplying heating energy to the building are investigated; the installed ventilation system and the static irradiative heating system. A building model is created using TRNSYS and calibrated to meet a satisfying agreement with the real building behavior. This model is used for fault detection and new control configuration investigations. However, the control parameters that influence the primary energy consumption are identified using a sensitivity analysis. Accordingly, it is found that the supply air temperature, the air volume flow rate, and energy required to heat coils are the main parameters that should be controlled to reduce the primary energy consumption.

Two optimization control approaches were conducted in this research. The 1st optimization method is applied using TRNSYS (a forward model) whereas the 2nd optimization method is applied using linear optimization with LINPROG algorithm in MATLAB (a data-driven model). The results show that 24% of primary energy savings is achieved by using appropriate control strategy.
Acknowledgement

I am heartily thankful to my parents, my sister, and my brother who always support me, especially to accomplish this work.

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Nomenclature

Abbreviations

- BEMS: Building Energy Management Systems
- BMS: Building Management System
- DMS: Distribution Management System
- FDD: Fault Detection and Diagnosis
- HVAC: Heating Ventilation and Air Conditioning
- O&M: Operation and Management
- VSD: Variable Speed Drive
- VNP: Virtual Private Network
- SQL: Structured Query Language

Symbols

- K: Degree Kelvin
- °C: Degree Celsius
- kJ: Kilo Joule
- Tamb: Ambient Temperature
- P_{nominal,fan}: Fan nominal power in [kW]
- Δp: Total pressure drop [Pa]
- η: Total fan efficiency [%]
- T_{supply,water}: Supply water temperature for the pumps [C°]
- T_{return,water}: Return water temperature for the pumps [C°]
- Q_P: Primary energy consumption in [kWh]
- P_{fan,elect,nominal}: Nominal electric Power from fan in [kW]
- P_{fan,actual (i)}: Actual electric power consumption from fan at time step (i) in [kW]
- V_{nominal}: Nominal air volume flow rate in [m³/hr]
- V_{air,fan}: Actual air volume flow rate in [m³/hr]
- P_{elec}: Primary energy factor for electricity
- P_{therm}: Primary energy factor for gas
- m: Mass [kg]
- C_P: Specific heat capacity [kJ/kgK]
- ρ: Density [kg/m³]
Chapter 1

1 Introduction

Energy use of buildings presents 40% of the total primary energy consumption in the United States [1]. Often, this energy is consumed inefficiently. By addressing ‘cause-and-effect’ relationships; most of the problems predominantly arise from the building technical operation and management. A study of 132 commercial buildings has found that 50% of the buildings have control problems. Savings of up to 77% have been achieved by correction of control problems [2]. This demonstrates that solving control-related problems contributes significantly in primary energy savings.

Building Energy Management Systems (BEMS) is one of the best known solutions in improving building operation. The BEMS are generally applied to the control of active systems, i.e. heating, ventilation, and air-conditioning (HVAC) systems, while also determining their operating times [3]. Although using BEMS has proved that it is one of the effective ways for building operation, it is still restricted to simple data measuring and metering for heating and cooling on a monthly basis. Furthermore, this method allows only for detection of high energy consumption without detecting the main reasons for faults in the system especially in complex systems such as the HVAC.

Simulation-based control is a key technology in next-generation building systems [4] where it can assist in more efficient operation for the Building Energy Management systems [5,6]. Moreover, it has the ability for fault detection and diagnosis. This requires creating a calibrated model that acts almost as the real building. The current researches revolve around control optimization using either forward model or data-driven model. Most of the researches adopted the data driven model for solving heating, ventilation and
cooling problems [7,8,9] which was successful for controlling some parts but it did not take into consideration the physical interactions of the whole building system. In this research, both approaches will be conducted to see which approach could fit better for solving control problems.

1.1 General Research Objectives

The objective of this work is to implement simulation-based control approach to reduce the primary energy consumption from the heating system in Bosch building. It also aims to present a guideline for calibration and validating of simulation models. Furthermore, two control optimization approaches (the forward model, and data driven model) are to be tested and evaluated in terms of accuracy, control optimization and primary energy reduction.

1.2 The Thesis Structure

This thesis is divided into eight chapters. Chapter 2 gives an overview for the state of art in simulation-based control in general and its potential to solve control problems. Chapter 3 demonstrates the methodology followed in this research; highlighting the research framework organizational layer. Chapter 4 is devoted to describe the case study by focusing on the installed HVAC system and analyzing the current control configuration. Chapter 5 explains the procedures for modeling the whole building system and the heating supply systems using TRNSYS 17. Moreover, it tackles the model validation process. This model will be used later for the fault detection analysis in the system. Chapter 6 presents a detailed analysis for identifying the building control problems. A graphical analysis using carpet plots will be used for fault detection and diagnosis, and a sensitivity analysis to indicate the main parameters that should be controlled to reduce
primary energy. Chapter 7 discusses the control optimization process. Two approaches are to be conducted: the 1st is optimization using physical model (TRNSYS) and the 2nd is optimization using data-driven model (MATLAB). Chapter 8 is a discussion and conclusion for the research.
Chapter 2

2 Literature Review

Simulation-based optimization control is one of the growing fields in the last years. Several researches addressed the potential of using this approach. In this chapter this method will be tackled and the work of other researchers will be reviewed.

2.1 Building Energy use and Control problems relationship

To address the relationship between the energy consumption and control problems, a deeper look has been made on the literature review mentioning this point. A study carried out on 60 buildings by the Lawrence Berkeley National Laboratory found that the frequency of common problems in percentage are as following: 50% of the buildings had controls problems, 40% had HVAC equipment problems, 25% had energy management systems, economizers, and/or variable speed drives (VSD) that were not functioning properly and 15% had missing equipment [10]. An analysis for commercial buildings in the US performed on 132 buildings showed; up to 77% savings could be achieved from control system re-commissioning as shown in Figure 2.1 22% potential savings from operation and management (O&M) and 1% from delamping with estimated potential energy savings of nearly $4,000,000 per year [2].

Ardehali & Smith [11] made a review on 67 case studies covering 118 building. It reported that over 384 control-related problems were identified in which the problems were divided into three main categories; hardware, software and human factors. This appears as problems in programming, communication between devices, problems in data management or in controllers. This indicates that most of the problems occurred were predominantly control related problems which need to be detected and diagnosed. In this
context, Building Energy Management System (BEMS) is believed to have high contribution for solving control problems since it depends on continuous management to achieve high operational performance [3].

![Potential Savings]

Energy management and control functions can be broadly classified into three groups: basic, intermediate, and advanced [12]. Basic and intermediate functions seek measuring and control energy in simple way. It varies from using sensors, energy metering, alarm settings, scheduling and load shifting. It follows a simple process, from data collected by sensors, which gives signals for controllers that takes decision according to the signal given. Advanced functions could be identified as “intelligent” energy management systems. A number of studies [13,14] presented these types of intelligent systems and its
potential in efficient building control. This type of BEMS has the ability to track the energy use from different building components, automated fault detection and diagnoses. On the other hand, a simulation model fed with forecast data could be encapsulated within the BEMS where it performs a whole-building control evaluation and optimization according to a given control algorithm. This process is called simulation assisted control [5]. Figure 2.2 illustrates how the simulation assisted control proceeds. This process proceeds by creating a building model that acts as the real building, where new control configuration analysis takes place. Then optimize the parameters that could achieve the best control configuration. Implement the results using a control algorithm. This model should be connected to a forecast data. This helps in prediction for the best control strategy within the next days. The system simulation models that belong to this category are expected to predict system performance accurately [15].

![Simulation assisted control process](image-url)
2.2 Simulation-based optimization control approach

Simulation-based optimization control approach is one of the major topics that are the researchers’ main focus in the last years. This approach depends on creating a model that is able to act almost as the real building, track its physical behavior and have the ability to understand the system dynamics under certain boundary conditions. Several simulation tools are available for this purpose as Energy Plus, ESP-r, TRNSYS, MATLAB, SIMBAD, etc.

Modeling approaches could be classified as; Forward (classical) and Driven (inverse) approaches [16]. The application of the two model types depends on the availability of data and the purpose of the investigation [17]. Although both approaches are substantially different, the main principle behind them is to provide reference values for optimal building operations. Therefore, modeling plays an important role in detecting errors and in the optimization process.

2.2.1 The Forward (classical) approach

The objective of forward modeling is the prediction of the output variables with prior knowledge for the parameters and inputs of the target system. This approach needs a detailed knowledge about the building geometry, geographical location, physical characteristics, type of equipment and operating schedules, type of HVAC system, plant equipment, etc.

The forward methods develop a building energy simulation model and calibrate with the observed energy use of different physical inputs in order to match the simulation results. Once this is achieved, they perform more accurate predictions than the inverse statistical approaches. [18,19] Have tried to cast this approach into a formal scientific framework,
but this is still incomplete. Further research and standardization as well as integration in the existing BEMS are still needed. Furthermore, the inclusion of the user performance and HVAC control systems are still in very early development stages. A study was made [5,20] on a room using ESP-r to test using simulation for enhancing the control in the BEMS.

2.2.2 The Data-Driven (inverse) approach

The objective of Data-driven (inverse) approach is to determine a mathematical description of the system and to estimate system parameters [16]. This approach in contrast with the forward approach, the measured real data must be known for a certain period of time and the actual performance of the building is available. This approach is either used for evaluation or fault detection. The data-driven approach arises in many fields, such as physics, biology, engineering and economics. Although several resources are available in this area, the approach has not yet been widely adopted in energy-related curricula and by the building professional community. This approach is classified into two model approaches:

2.2.2.1 Empirical “Black-Box” Model

The Black box approach identifies a simple or multivariate regression model between measured energy use and the various influential parameters (e.g., climatic variables, building occupancy). They are non-physical models (statistical/ stochastic) without physically significant parameters. They reflect again the structure of the real behavior of the system using coefficients according to a regression analysis. At the end, a model is obtained that has the ability to have a sufficient accurate relationships between the input and output variables. Due to its limitation, it is mainly used for error detection not for optimization. This approach is appropriate to evaluate demand side management
programs, identify energy conservation measures in an existing building and to develop baseline models in energy conservation measurement and verification projects.

2.2.2.2 “Grey-Box” Model [combination of physical and non-physical models]

“Grey-Box” modeling gives a representation of the physical structure of the building developing a physical model and selects the most important parameters representing the aggregated physical model statistically. This approach has great potential for fault detection and support diagnosis. The grey method has been presented by Coffey [21] as a software framework what could be characterized as a “grey-box” approach to predictive control since it combines physically-based models with a generic (stochastic) algorithm. The results from a case study demonstrate that the framework can be used to minimize cooling demand through optimal demand response using zone temperature ramping in an office space [22]. This approach still needs some criticism, to see its effectiveness in solving complex problems like HVAC systems control.
Chapter 3

3 Methodology

To test the reliability, the advantage and disadvantage of the proposed control optimization framework a qualitative approach was followed in this research. The proposed framework will help the researcher and energy managers. Where it gives a guideline for detecting problems faced in office buildings operational cycle. On the other hand, it proposes an optimized control algorithm that works dynamically when connected to the BEMS. Nevertheless, it clarifies the procedure for model validation within the simulation environment by explaining the variables that should be considered during the process, thus an accurate model behaves almost as the real building could be created. Figure 3.1 demonstrates the communication structure for the simulation-Based control and the BMS.

Figure 3.1: Communication Structure for Simulations-Based Control and the BMS
The proposed framework consists of five layers shown in Figure 3.2: an investigation layer, Modeling and validation layer, the analysis and fault detection layer, the optimization layer and finally the communication layer.

The first layer revolves around doing investigations where at this stage all the relevant data to address the building behavior should be gathered. Therefore, sensors and energy metering were installed to cover the whole building. Secured connection to transfer directly the data from the BEMS and the model should be available. In our case, a secured connection between the BEMS and a data server in zafh.net institute\(^1\) using Virtual Private Network (VPN) was secured. For accurate results a real weather data should be provided to support the model simulation.

The second layer considered as representation for the building under consideration, thus it should be calibrated to reach the best fit between the model and real data measured. All the data is fed to the simulation model using appropriate software that has the ability to represent the building behavior accurately. For this purpose TRNSYS 17 was considered for modeling.

The third layer is analysis for the problems occurred in the building and its relation to the current heating control configuration. For this reason, a sampling method is conducted for two days to extract the current control configuration with the aid of graphical representation using carpet plots to help in diagnosis of the faults that occur in the heating system. This analysis is an indicator for the parameters that should be controlled and which will be used for the optimization process.

\(^1\) Center of sustainable energy technology; University of Applied Science Stuttgart, where this research took place.
Chapter 3 - Methodology

Figure 3.2: Research Methodology

Main objective
Test simulation-based control framework to reduce primary energy ($Q_P$) consumption

Investigation
Data collection: for building, HVAC system, occupants…etc.

Modeling
Modeling and calibration: create accurate model for the system

Problem Analysis
FDD and control parameters: Detect the faults in the current control configuration “cause & effect”

Optimization
Optimization in TRNSYS: using differential controls, and scheduling

Communication

First Layer

Second Layer

Third Layer

Fourth Layer

Fifth Layer

Optimization using LINPROG algorithm in MATLAB:

$$Z_{opt} = \arg \min_Z Q_p(Z), \text{ since } Z \text{ is the vector components of } Q_p. \text{ constraints are, } T_{min} \leq T_{room(i)} \leq T_{max}, \text{ } i = 1, ..., 288 \text{ and } Z \geq 0$$
The fourth layer is the optimization layer. At this stage, operational control alternative possibilities should be generated and evaluated. Two optimization alternatives will be tested in this research. The selection for the appropriate control method could be done either by using differential controllers, and schedules in TRNSYS or by doing constrained controls and setting boundaries using an optimization algorithm that have the ability to optimize dynamically the objective function in MATLAB. The choice of the algorithm depends on whether the objective function is linear or multi-objective function. However, it should be able to achieve all the constraints and boundaries assigned.

The fifth layer is the communication layer where, at the end of the optimization process, the control algorithm with the new control configuration should be assigned to the building management system BMS. That is why an online connection should be secured to transfer the data between the simulation model and the BEMS to obtain a dynamic control for the system. The following chapters will provide detailed descriptions for the whole process and the evaluation for this framework.
Chapter 4

4 Description of the case study

In this chapter a description of the building and the installed HVAC system will be presented with all the necessary information that is needed to understand the building components and the system interactions. Also it elaborates the organizational layer for the communication between the building management system (BMS) and the simulation tool. The complete data collected for the system is of October, November and December, so the control of the HVAC system is analyzed for only the heating period.

4.1 General Description

The building covered in this study is located in the Bosch real-estate at Schweiberdingen, Germany, see Figure 4.1. It has been refurbished in 2008 the glazing of the windows was exchanged. Additionally, heat insulation was applied on the outside of the external building walls and roof according to the national standard. It has a total useful floor area of 3300 m² with building height of 10m. Table 4.1 provides a description of the building envelope materials, and its properties.
Table 4.1: Building envelope characteristics

The office building consists of three floors, ground, first and second see Figure 4.2. The first and second floors are identical. They are used as opened work space with 16 divisions each is divided into four workstations. All workspaces are equipped with office appliances like computers, printers, faxes, etc. On the other hand, the ground floor is dedicated for workshops for workers equipped with welding machines, mill-drill machines and also a large space with 300 m² for HVAC system machines.

<table>
<thead>
<tr>
<th>Material Type</th>
<th>u-factor [w/m²K]</th>
<th>Density [kg/m³]</th>
<th>Capacity [kJ/kg K]</th>
<th>Conductivity [kJ/h m K]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exterior walls</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2.912</td>
<td>2240</td>
<td>0.75</td>
<td>6.23</td>
<td>300</td>
</tr>
<tr>
<td>Mineral wool 040</td>
<td>0.120</td>
<td>80</td>
<td>0.9</td>
<td>0.14</td>
<td>120</td>
</tr>
<tr>
<td>Aluminum Cladding</td>
<td>0.030</td>
<td>2700</td>
<td>0.86</td>
<td>720</td>
<td>30</td>
</tr>
<tr>
<td><strong>Adjacent ceiling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2.912</td>
<td>2240</td>
<td>0.75</td>
<td>6.23</td>
<td>200</td>
</tr>
<tr>
<td>Carpet</td>
<td>3.729</td>
<td>200</td>
<td>1.3</td>
<td>0.22</td>
<td>6</td>
</tr>
<tr>
<td><strong>Roof</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>2.912</td>
<td>2240</td>
<td>0.75</td>
<td>6.23</td>
<td>250</td>
</tr>
<tr>
<td>Mineral wool 040</td>
<td>0.120</td>
<td>80</td>
<td>0.9</td>
<td>0.14</td>
<td>130</td>
</tr>
<tr>
<td>PVC</td>
<td>5.556</td>
<td>1450</td>
<td>0.9</td>
<td>0.72</td>
<td>2</td>
</tr>
<tr>
<td>Gravel</td>
<td>5.128</td>
<td>1800</td>
<td>1</td>
<td>7.2</td>
<td>50</td>
</tr>
</tbody>
</table>
The building’s internal loads are confined to loads from occupants, lighting units and office appliances. Table 4.2 shows the calculated internal loads within one typical day for sizing the total internal gains. The total internal gains during a typical day are 300 kW. This gives an indication that the internal gains constitutes high amount of energy gain that could be used as a positive in winter times and as negative in summer time.

<table>
<thead>
<tr>
<th>Occupants</th>
<th>Lighting</th>
<th>Appliances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Gain in Watt</td>
<td>30000</td>
<td>62700</td>
</tr>
</tbody>
</table>

Table 4.2: Internal gains calculated on one day interval for the whole building

The fenestration percentage of the facades accounts for 25% northern façade, 38% southern façade, 36% western façade, and 21% eastern façade. Automated external shading system is provided for the windows which are controlled by the BMES. It starts when the total irradiation on the windows surfaces exceeds 270 W/m². Additionally, an internal shading is installed which is manually controlled according to user’s needs.

4.2 HVAC System Description and Components

The building is equipped with a typical HVAC system that follows the following process. The outdoor air flows into the air handling unit through a filter to dilute and remove air contaminants. However, the energy required to condition this outdoor air could be of a significant effect on the total consumed load. Following this process, the air is heated or cooled with respect to the difference between the ambient temperature and the required room temperature. The air passes through a primary heating coil in winter. The air is then blown by a fan powered by electricity to a secondary heater that heats up the air to reach a desired room temperature. Iteratively with this process, the air is returned back to a heat recovery that makes use of the (exhaust air) from the building.

The static heating system is powered by a pump with a maximum power of 93 kW that serves the three floors with a $\frac{T_{\text{supply,water}}}{T_{\text{return,water}}} = 60/40$. The scope of study is to find a compromise between both systems that can cover the heating demand with the minimum power consumption.
In the system here, the heating demand is covered by the HVAC system with the aid of a static heating system that is powered by a district heating for the whole Bosch real estate. Figure 4.3 gives a more detailed impression on how both systems work together, and identify the maximum power consumption for each component. The total heated area for the entire building is 2613 m² which is shown in Table 4.3; the heated area for each floor.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Ground Floor</th>
<th>First Floor</th>
<th>Second Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (m²)</td>
<td>578.77</td>
<td>1023.41</td>
<td>1011.46</td>
</tr>
</tbody>
</table>

*Table 4.3: Building heated areas*

The electrical power demand is calculated according to equation

\[
p_{nominal,\text{fan}} = \frac{\Delta p}{3600} \frac{V_{nominal} * 100}{\eta * 1000} \text{[kW]} \tag{4.1}
\]

where

- \( p_{nominal,\text{fan}} \) is Fan nominal power in [kW]
- \( \Delta p \) is Total pressure drop [Pa]
- \( V_{nominal} \) is Air volume flow rate [m³ h⁻¹]
- \( \eta \) is Total fan efficiency [%]

Table 4.4 shows the specifications of the installed ventilation system. As it is shown, the system contains two supply and two return fans with maximum air flow rate of 36500 and 27500 m³ h⁻¹ respectively for the entire building.

<table>
<thead>
<tr>
<th>Ventilators</th>
<th>Number of installed fans</th>
<th>Type</th>
<th>Air volume flow rate [m³ h⁻¹]</th>
<th>Total pressure drop [Pa]</th>
<th>Efficiency [%]</th>
<th>Electrical power demand [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply air ventilator</td>
<td>2</td>
<td>Siegle +Eppl ventilator T/NnsR 090</td>
<td>36500</td>
<td>2500</td>
<td>70</td>
<td>36.21</td>
</tr>
<tr>
<td>Return air ventilator</td>
<td>2</td>
<td>Siegle +Eppl ventilator G/D 090</td>
<td>27000</td>
<td>1130</td>
<td>70</td>
<td>12.11</td>
</tr>
</tbody>
</table>

*Table 4.4: Installed ventilation system specification*
Figure 4.3: HVAC system components [heating, ventilation only]
4.3 Building Energy Management System

The whole real estate is equipped with Siemens Building Management System (BMS) which is operated and maintained by the external company Distribution Management System (DMS). To demonstrate the feasibility of the simulation-based control approach in a multi-system context, sensors and actuators were deployed with more than 100 data points. The rooms are equipped with programmable room controllers, indoor environmental sensors mounted on ceiling that measures the temperature, luminance and humidity. Likewise, heat meters with data loggers for heating and cooling were installed and provided by separate electric meters for general power, see Figure 4.4 and Figure 4.5. Moreover, the local climatic conditions are monitored by a weather station which has been installed on top of the building.

![Figure 4.4: A plan showing the data points position within the working space](image-url)
4.3.1 Data Collection and Interfaces for Online Data Transfer of the Installed Siemens BMS

The communication structure of the installed Siemens BMS and its interfaces for data transfer are shown in Figure 4.6. For the implementation of online simulation tools, interfaces are required which enable an online data exchange of measured and simulated values between the BMS and the simulation tool. In the ideal case, the BMS system offers an OPC\(^2\) interface for online data exchange. In this case, an OPC client of the BMS writes the actual measured values or status information etc. to an own or third party OPC server. A second OPC client of the simulation tool connects to the server and reads the required values from the OPC server, performs the simulation and writes the results (outlet temperatures, energy consumption and error status etc. back to the OPC server. An OPC reader client of the BMS reads the simulation results from the OPC server and transfers them to virtual data points within the BMS. These virtual data

\(^2\) OPC is a software application that acts as an API (Application Programming Interface) or protocol converter.
points are stored in the database and can be displayed in trend graphs together with the measured values of the real system. If a TCP/IP connection e.g. over the local network exists, the simulation tool can run on a different PC than the BMS software does. Unfortunately, some of the OPC clients and servers are not clearly defined which means that they sometimes talk a kind of different ‘accent’. This may cause serious communication problems which are sometimes difficult to solve external data exchange. Historical data is stored in a large central SQL database[^3] which is located in the BOSCH computing center.

![Diagram showing data collection structure and communication interfaces of the Siemens BMS](image)

**Figure 4.6: Data collection structure and communication interfaces of the Siemens BMS**

### 4.3.2 Energy Management Tool

An energy management tool called ‘EM-Tool’ which has been developed at zafh.net within former projects and is used and further developed within the EnSim project[^4]. The

[^3]: SQL database is a programming language designed for managing data in relational database management systems
[^4]: This research is part of EnSim project
EM-Tool is designed as an add-on tool with communication interfaces to different BMS systems using OPC, SQL or FTP clients. Additionally, the tool is able to collect data from BMS independent data collection systems which operate as data loggers with communication interfaces either via TCP/IP (internet or local network) or modem connection. The architecture of the developed EM-Tool tool is shown in Figure 4.7. This tool is designed with a client server structure where the server is responsible for the data collection from the different sources and writes this data in a common database. EM-Tool clients are able to connect to the EM-Tool server by TCP/IP using the local network or an internet connection. Within the EM-Tool client, the user is able to select different data points which shall be displayed in a graph for a defined time period.

![Architecture and communication structure of the developed EM-Tool](image)

The selected data points and time periods are sent as request to the EM-Server which reads the requested data from the Database or directly from the data source and sends the whole package back to the EM-Client where the results are displayed in the selected graph. For comfortable fast fault detection, different types of graphs are available like simple line graphs, scatter plots and carpet plots. It is also possible to define a number...
of typical graphs for different HVAC system or building parts which for example plots the room temperature, heating energy, cooling energy, electricity consumption and the On/Off signal of the system in separate carpet plots. This allows quite fast and comfortable fault detections for a large number of systems. Within EnSim, the EM-Tool is coupled with the simulation environment INSEL. With this connection it will be possible to perform different predefined numerical and statistical analyses or even complete system simulations either on request or automatically.

4.4 Summary

This chapter has described the office space and ventilation system considered in the case study, along with the installed BMS, the communication structure for data transfer between the BMS and the simulation tools. After understanding the heating system installed, and the whole system interactions the next step is to model the system. This will be explained in the next chapter.
Chapter 5

Building Simulation and Validation

The first step in setting up a simulation based optimization control, is computing a dynamic model that almost performs as a real building. Therefore, dynamic simulation software is needed with the ability to compute the thermal behavior of the building, with a degree of flexibility and user-graphically interface. For this reason, TRNSYS v.17 [23] was used. This chapter will give a description of the modeling process while taking into consideration the assumption needed to simplify the modeling process. On the other hand, it will address all the relevant adjustments that are needed to achieve a calibrated model with a satisfying agreement between real building behavior and the modeled one.

5.1 Building Model using TRNSYS 17

TRNSYS is a dynamic simulation tool developed over 30 years ago, with flexibility in modeling systems of buildings [24]. The model is typically setup by connecting components graphically in the Simulation Studio. Each Type of component is described by a mathematical model in the TRNSYS simulation engine and has a set of matching Proforma's in the Simulation Studio. The proforma has a black-box description of a component: inputs, outputs, parameters, etc. TRNSYS components are often referred to as Types [25]. The type, which is considered in this research, is Type 56 multizone building. Due to the complexity of a multizone building, the parameters of TYPE 56 are not defined directly in the TRNSYS input file. Instead, a file so-called building file (*.BUI) is assigned containing the required information. This file is generated by TRNBuild (Building Visual Interface) which is a tool used to enter input data for multizone buildings. It allows specifying all the building structure details, as well as all relevant data that is needed to simulate the thermal behavior of the building, such as building material properties, heating and cooling schedules, etc. Figure 5.1 shows the interaction between the simulation environment and its interfaces.
For facilitating the process in version 17, a TRN3D (sketchup interface) is used to generate the building geometrical data via an IDF file which is then opened by the TRNBuild interface.

The Simulation Studio generates a text input file for the TRNSYS simulation engine. That input file is referred to as the deck file that contains all the data needed and the operations done in TRNSYS. The program creates output files by using plotters in the simulation environment that can create text file outputs which then can be opened in excel for analysis. The process of modeling this building by using TRNSYS and its interfaces will discussed later.
5.2 Building Model Process

As a first step, the building, colored with yellow, was modeled inside sketchup see Figure 5.2 where the geographical location was identified using Google-earth interface. This option is used to generate the shading files that will be feed into TRNSYS. Each floor was defined as a separated zone, with the actual areas for walls, floors, and windows. The surrounding buildings, colored with violet, were defined as shading objects in order to be taken into consideration for the shading calculations.

![Geometrical model in sketchup](image)

Figure 5.2: Geometrical model in sketchup

Some assumptions were made to simplify the model, such as the recesses in the building were ignored, the windows were modeled as a big glass surfaces and the internal wall divisions were not taken into consideration.

The next step is inserting the geometrical data into TRNBLD, as an IDF file. The data needed for this interface could be divided in three categories: parameters (either general, or airnode), inputs and outputs. The General parameters, see Figure 5.3, is needed for
defining the building envelope, the building materials, floors, walls, windows\(^5\), the internal gains, the schedules (for occupants, lighting and HVAC system), infiltration rate and ventilation. Some assumptions were made for the internal gains, as well as the infiltration and ventilation. Moreover, other parameters are needed to define separately each airnode, the volume of air within the airnode, thermal capacitance of airnode and any masses not considered as walls (e.g. furniture).

\(^5\) The windows were designed separately inside another program WINDOW 5, by LNBL. A software by Lawrence Berkeley National Laboratory. This program was used for calculating total window thermal performance indices (i.e. U-values, solar heat gain coefficients, shading coefficients, and visible transmittances).
The assumptions are made according to the following:

a) **Infiltration**

The infiltration rate is assumed because usually the accurate air change rate through infiltration depends on a lot of factors like the outside air velocity, the pressure distribution around the building, the tightness of the windows, etc. So, it cannot be precisely predicted. The assumption is based on a referred office building example in ASHRAE handbook 2009 [26]. This example assigned infiltration rate of 0.1 h\(^{-1}\) depending the building tightens and insulation. Likewise the example, the studied building has the same degree of tightens and it is well insulated. Thus, the infiltration rate is assigned as 0.1 h\(^{-1}\) in winter period. In summer the infiltration rate should be higher, due to the uncertainty of occupant’s behavior for opening the windows.

b) **Internal gains**

The heat gains from office appliances are assigned according to “ASHRAE Research Project 1482-RP [27]. It mentioned that flat panel monitors of 30 inches in size, has power consumption of 90W. And the printer’s power consumption during a printing cycle varies from 75 to 140 W depending on the model, print capacity, and speed. An average heat gain of 90 W was assumed for each monitor that is in total 85 monitors with total gains of 7650 W. Also, an average heat gain of 110 W was assumed for each printer which is in total 8 printers with total gains of 880 W.

c) **Ventilation rate**

The minimum required fresh air is calculated according to ASHRAE Standard 62-1999. One person needs, quantity of fresh air inside an office, 20 CFM which is equal to 35m\(^3\)/hr. Since the first floor zone is occupied by 85 employees, the minimum required fresh air is 3000 m\(^3\)/hr.
The second type of data that should be entered in TRNBLD is the inputs. The inputs here are defined as the linked inputs between the TRNBUILD parameters and the simulation environment in TRNSYS. For example, a schedule was defined for the lighting using Type 14-h, and this is linked as an input in TRNBUILD for the internal gains from lighting.

The third type of data is the outputs where they were identified according to their necessity for each airnode in the simulation. The needed outputs are:

- **NTYPE 1**  
  TAIR  
  air temperature of airnode  
  [°C]

- **NTYPE 2**  
  QSENS  
  sensible energy demand, heating (-), cooling (+)  
  [kJ/hr]

- **NTYPE 3**  
  QHEAT  
  sensible heating demand of airnode (positive values)  
  [kJ/hr]

Figure 5.4 shows the inputs and outputs variables of the airnode that affect the energy gain of an airnode.

![Figure 5.4: the inputs and outputs for the airnode](image-url)
5.3 Model Types and Connections in the TRNSYS Environment

Figure 5.5 shows the entire model structure done inside the TRNSYS environment where it is defined by 17 modules (Types). (Type 9a) data reader was installed to read the real weather data which was created as a.txt file. This data consists of the ambient temperature, irradiation and the relative humidity that was gathered from the weather station installed on the top of the building. For modeling the HVAC system, two auxiliary heaters (Type 6) were used as the primary and secondary heaters. And two controllers (Type 2b), on/off differential controller, were used for controlling the supply air temperature of the heaters. For the HVAC and the static radiator system (type14-h) scheduling, forcing functions were used to define the schedule of the weekdays and weekends.

![Figure 5.5: The simulation done in TRNSYS environment](image)

Figure 5.5: The simulation done in TRNSYS environment
Figure 5.6 illustrates the internal connections between modules in the TRNSYS model. As it can be observed, the inputs and outputs data exchange within the HVAC and the building model. Some equations were also used for identifying the current controllers to define when the ventilation system should work; supplying fresh air or heating the air before going into the rooms.

5.4 Model Calibration and Validation

The model described before and discussed in this chapter should be validated against measured performance data to assure a precise model for analyzing and optimizing the existent control strategies. The validation method which follows is a “realistic
validation”, since the model is compared to the monitoring data. The real measured room temperature was assigned as an indicator for the validation process. Figure 5.7 shows an initial simulation output that compares the simulated zone temperature to the real one with the influence of the internal gains.

By analyzing the model, it is noticed that there is a shifting down in the modeled zone temperature by 5°C from the actual zone temperature. On the other hand, this temperature behavior of the building does not exist during the weekends. These findings indicate that some parameters should be checked and see how it correlates with the modeled temperature. Some researchers [28,29] have discussed some parameters (e.g. Occupancy behavior) that could influence the accuracy of the model. But, until now, no clear guidelines for how to indicate these parameters have been provided.
In this model the behavior of occupants had a great influence on the model accuracy since it affects the heating, cooling demands, the amount of lights needed and some additional loads from computers, appliances, etc. Nevertheless, the researcher found that it was not only this parameter that needed to be checked. After several trials, the researcher found some other influencing parameters like the building thermal capacitance (air and furniture), the infiltration rate, and air exchange rate.

For achieving model validation, an iterative process of calibrating the model took place; comparing the model to actual system behavior. This process was repeated until sufficient model accuracy was reached. The calibration process is performed manually by making small changes to the values of the parameters and re-running the simulation to see the results. Figure 5.8 illustrates the calibration methodology with the parameters that were checked iteratively. After 40 simulation trials, satisfying results were obtained for the model. The simulation was done from October till December for a 5 minutes time interval and each trial took 2 minutes running.
Figure 5.9 presents a TRNSYS plot output where the purple line represents the internal gains, the blue line represents the modeled temperature and the brown line represents the real temperature. The model shows that the modeled room temperature has high accuracy compared to the real room temperature. The temperature difference between the real and the simulated result is within the range of $\pm 0.5^\circ C$ which is considered as a high degree of accuracy. The assigned values of the chosen parameters for the validated model are as follows:

- The room’s thermal capacitance = 8000 kJ/K
- Infiltration rate = 0.1 h$^{-1}$
- Air supply flow rate = 6 h$^{-1}$
- Number of occupants for the first floor = 85
- Internal heat gains from lighting = 40 W/m²
- Internal heat gains from Monitors = 90 W

To be sure that the model is validated, the correlation between the real temperature data and the modeled one was tested. As a result, a regression model analysis was used. This analysis identifies linearly the relation between the independent variable (x), and the dependent (y). It is expressed by a correlation coefficient, R² (R-squared). The closer R² is to 1.00, the better the fit. In this case, (x) and (y) presents the real room temperature and the modeled room temperature respectively. Figure 5.10 shows the correlation of the data which a value of [R²=0.9105] had been achieved. This correlation coefficient shows that the TRNSYS model is a reliable identification for the real building. Thus, this model can be adopted as a base structure to build on the control strategies.

Figure 5.9: A plot comparing the actual room temperature to the modeled room temperature, after validation
Moreover, this model could be used for online predictions of the BOSCH building in future.

From the calibration methodology used in this case, it could be identify that the manual calibration is one of the approaches that relies on user knowledge, past experience, engineering judgment, and an abundance of trial and error [18]. It gives not only accurate results, but also a time consuming process. Another approach for the validation is to treat it as a minimization error problem and identify it as a mathematical equation with variables by using an optimization algorithm that has the ability to find out the most appropriate values and assign it for the parameters. This approach was used by [28,18]. It is a promising technique with less time consuming but is still needs to be tested for complicated systems with many parameters that contains a high degree of uncertainty metrics. Finally, either the manual calibration or the automated one was
applied, they must achieve at the end the main objective of reaching a high accurate model behaving as the real building.

5.5 Summary

This chapter presented an overview for the modeling steps in TRNSYS, and also the methodology for the validation and calibration process. A validated model with 91% accuracy was obtained. This model is then will be used in analysis, and could be of a trustful base to test new control configuration
Chapter 6

6 FDD & Control Problem Analysis

This chapter aims at analyzing the control problem existing in the heating system of Bosch building. This analysis goes through the following procedure. First, investigation using graphical representation by carpet plots will be presented to indicate the problems occur during the operational process. This analysis is used as a first intuition about the different control problems that could be faced. Second, a more details investigation for the current control configuration will be done. This analysis will help in building a knowledge base that supports the evaluation for new control configuration strategies. Third, a sensitivity analysis will take place to identify the parameters that should be controlled to reduce the primary energy consumption.

6.1 Fault Detection and Diagnosis using Carpet plots

Figure 6.1 demonstrates a carpet plot for the heating system, the supply temperature, compared to the room temperature, and the ventilation system status for the first floor in Bosch building for December. The ventilation system is operated with maximum power in morning and constant power during the day. As clearly visible from the carpet plot that in some holidays during December the system was working without no clear reason, on the other hand the room temperature reaches more than 23.6 °C which is high, and it hasn’t an identified reasons. The inefficient behavior was caused by an error in the control of the heating coils; this error could only be identified using graphical performance observations. By correcting this error it could reduce the energy consumption. On the other hand, an initial idea on how the heating system perform could be figured out, and From this graphical analysis it is found out that improving the graphical presentation method for the data could help in fault detection and diagnosis, also it has high potentials to save energy.
Figure 6.1: Carpet plot diagrams to detect the faults in the ventilation system using DIAdem program
6.2 Control Problem Analysis

As it is illustrated in Figure 6.2 the ambient temperature is relatively low especially in December where it reaches (–10°C), this requires more heat energy to heat the ambient temperature to reach a satisfy supply air temperature. For example at the 3rd of December the ambient temperature is (–9°C), the supply air temperature is (26°C), the energy required to heat from (–9°C) to (26°C) is 209 kWh.

![Figure 6.2: Diagram showing the relation between the primary heater energy consumption, the supply temperature, and the ambient temperature](image)

We can clearly visualize from Figure 6.2 that the room temperature reaches more than 23°C during working hours, and in range of 20°C-19°C during night and weekends. For the secondary heater, the supply air temperature needed to reach the room temperature reaches more than 31°C, and the energy required for heating the room at the specified temperature reaches 70 kWh at some days. For the static radiator system it appears that during the cold days it works the whole days, also in weekends. During working hours, it reaches in the morning 31 kWh. For the 3rd of December the supply
air temperature is (28 °C), the energy required from the secondary heater (65 kWh), for
the radiator system it reached 31 kWh in the morning this was required to reach a room
temperature of (22 °C)

![Figure 6.3: Diagram showing the relation between the secondary heater required energy, the supply
temperature, the static radiator energy consumption and the zone temperature](image)

**Figure 6.3** shows the relation between the power consumption and the air volume flow rate. We can see that the air volume flow rate at the working hours reaches 18000 m³/hr in the morning, and during the day it reaches 12000 m³/hr. On the 3rd of December the air volume flow rate at the morning was 18500 m³/hr, and the power consumption from fan supply equal (1.6 kW =1600 watts).
Figure 6.4: Diagram showing the relation between the power consumption and the air volume flow rate

From the above observations, for the relations between different parameters on the room temperature, and the energy consumption we can obviously see that the supply air temperature for both heaters is high, the room temperature is considered high in winter times, nevertheless, the volume flow rate is relatively high they reach 6 or more air rate change per hour, which influence the power consumption from fans, however, this parameters will be analyzed in details and tested in simulation to see the suitable control settings to reduce the energy consumption, while achieve comfort degree for the occupants.

6.2.1 Sate of Art for the Control Configuration in Bosch Building

To implement the proposed model-based control strategy, the actual control configuration code should be either taken directly from the BEMS (it was difficult to get this data from Siemens), or driven out by visualizing the monitored data and analyzing
it. Furthermore, this analysis can provide feedback to improve the proposed control code. For this reason, two samples from two different days were analyzed from the first floor. One day was chosen during the week in December whereas the second one was chosen at the beginning of the working week (Monday) to give a better overview on the behavior of the heating system; its schedules, the room set temperature, the relation to the ambient air temperature, how long it is needed to heat up the room to a certain point after a period with reduced room temperature set point (nighttime and weekend), etc.

6.2.1.1 Sample no. 1: the 1st of December

It is clearly visible in Figure 6.5, in the first sample, the static radiation system starts at 5:25 am to heat up the rooms with full power till the room temperature reaches the \( T_{\text{set,day}} \), and then decreases the power during the day. It stops at 18:00 pm, and then when the room temperature goes below \( T_{\text{set,night}} \), it works again with lower power so the room temperature doesn’t go below 20°C during the night. On the other hand, the ventilation system operates at 5:45 am with full power prior to the occupancy arrival period to maintain a comfort room temperature \( T_{\text{set}} \). This process needs at least an hour to heat up the room. The HVAC system is scheduled to stop at 18:00 pm by the end of the occupancy working hours.
Figure 6.5: Control scheme for December 1st
From these observations we can write the control code as following:

**Control Code #1** At \( T_{amb} \leq 20 \, ^\circ C \)

For static radiator:

\[
\begin{align*}
T_{set,\text{day}} & = 22.6 \, ^\circ C \\
T_{set,\text{night}} & = 20 \, ^\circ C
\end{align*}
\]

- Start static radiator with full power at \( (t) = 5:25 \, \text{am} \), when \( T_{room} \geq T_{set} \), then lower the power of the pump, and keep \( T_{room} = T_{set} \)
- Stop at 18:00 pm
- when \( T_{room} \leq T_{set,\text{day}} \), start the static radiator with low power and keep \( T_{set,\text{night}} \)

For ventilation system:

\[
\begin{align*}
T_{set,\text{day}} & = 22.6 \, ^\circ C \\
\text{Upper bound} & = 1 \, ^\circ C \equiv (23.6 \, ^\circ C) \\
\text{Lower bound} & = 1 \, ^\circ C \equiv (21.6 \, ^\circ C) \\
T_{\text{supply,vent, max}} & = 28 \, ^\circ C \\
\dot{V}_{\text{air, max}} & = 18000 \, m^3 \, h^{-1} \equiv 6 \text{ air change per hour}
\end{align*}
\]

Ventilation system turned OFF during night time

- Start heating coil at \( (t) = 5:45 \, \text{am} \), and \( T_{\text{supply, fan}} = \text{max} \), \( \dot{V}_{\text{air}} = \text{max} \). when \( T_{room} \geq T_{set} \), then cut off.
- When \( T_{room} \leq T_{set} \), start the heating coil with suitable \( T_{\text{supply,vent.}} \) and \( \dot{V}_{\text{air}} \).
- Stop at 18:00 pm.

**6.2.1.2 Sample no.2: the 13th of December**

In Figure 6.6, it is shown that the control code for the static radiator and the HVAC system didn’t change. Nevertheless, the starting time for ventilation system is shifted up 20 minutes and for the static radiator 10 minutes. This is due to the cold temperature in the rooms at the weekend prior to the working day.
Figure 6.6: Control scheme for December 13th
Control Code #2
Please change accordingly!

For static radiator:
\[
\begin{aligned}
\text{At} & \quad T_{\text{amb}} \leq 20 \, ^\circ C \\
T_{\text{set,day}} &= 22.6 \, ^\circ C \\
T_{\text{set,night}} &= 20 \, ^\circ C \\
\end{aligned}
\]
- Start static radiator with full power at \( (t) = 5:15 \, \text{am} \) when \( T_{\text{room}} \geq T_{\text{set}} \), and then lower the power of the pump and keep \( T_{\text{room}} = T_{\text{set}} \).
- Stop at 18:00 pm.
- when \( T_{\text{room}} \leq T_{\text{set,day}} \), start the static radiator with low power and keep \( T_{\text{set,night}} \).

For HVAC system:
\[
\begin{aligned}
T_{\text{set,day}} &= 22.6 \, ^\circ C \\
\text{Upper bound} &= 1 \, ^\circ C \equiv (23.6 \, ^\circ C) \\
\text{Lower bound} &= 1 \, ^\circ C \equiv (21.6 \, ^\circ C) \\
T_{\text{supply,fan}} &= 28 \, ^\circ C \\
\dot V_{\text{air}} &= 18000 \, \text{m}^3 \, \text{h}^{-1} \equiv 6 \, \text{air change per hour} \\
\end{aligned}
\]
- Start the heating coil at \( (t) = 5:15 \, \text{am} \) and \( T_{\text{supply,fan}} = \text{max} \), \( \dot V_{\text{air}} = \text{max} \). when \( T_{\text{room}} \geq T_{\text{set}} \), then cut off.
- When \( T_{\text{room}} \leq T_{\text{set}} \), start the heating coil with suitable \( T_{\text{supply,fan}} \) and \( \dot V_{\text{air}} \).
- Stop at 18:00 pm.

From the control configuration analysis we can conclude that the ventilation system is working with the maximum volume flow rate it can afford at the morning hours, and it less during the day. This is constrained with the day working hours. While the static radiator system works the whole day. From this, the parameters that need to be taken into consideration during the new control configuration process are the air volume flow rate, the supply temperature, and the energy required for the static radiator system. From this conclusion, the influence of these parameters on the primary energy consumption.
will be then studied. In the next paragraphs, the relation between the primary energy consumption and control parameters will be identified using the simulation model.

### 6.3 Primary Energy Sensitivity Analysis

The total primary energy was calculated form equation (6.1). It is equal to the total energy required to cover the heat demand from (coils, pumps, and fans) multiply the primary energy factor for each. The primary energy factor according to GEMIS for electricity is 2.5, and for gas is 1.1 in Germany. The total primary energy consumption from the ventilation system and the static radiator system is 63.8 MWh for the whole building. The consumption from the heating system excluding the primary heater accounts for 33.2 MWh. For the optimization process, we will exclude the primary heater from our calculations. The optimization will be influenced by the secondary heater, the fans from the ventilation system, and the static radiator system.

\[ Q_{p, total} = \sum Q_{elect} * P_{f, elect} + \sum Q_{heat} * P_{f, gas} \]  \hspace{1cm} (6.1)

To investigate the influence of the air volume flow rate and the supply air temperature on the primary energy consumption, simulations were performed with different volume flow rates, and at different supply air temperature. For this analysis a fixed room temperature of 22 Cº, 60 RH was assumed. The primary energy presented here is considered for the secondary heater only. Figure 6.7, Figure 6.8 demonstrate the resulting primary energy consumption. It is clearly shown that the primary energy consumption increases by the increase of the supply temperature. On the other hand, the power consumption increases exponentially with the volume flow rate, which influence directly the primary energy consumption. These relations are defined mathematically as following:

\[ Q_{heat} = \rho V C_{p,air} [T_{supply} - T_{room}] \]  \hspace{1cm} (6.2)
The energy required to heat coils is calculated from equation (6.2); therefore the primary energy consumed is result of multiplying equation (6.2) with the primary energy factor of gas as in equation (6.3).

\[ Q_{p,\text{heat}} = Q_{\text{heat}} = \rho V C_{\text{p,air}} \left[ T_{\text{supply}} - T_{\text{room}} \right] * P_{f,\text{gas}} \]  

(6.3)

The energy required from the electric fan to supply air to the zones is calculated from equation (6.4), and to calculate the primary energy consumed it is multiplied by primary energy factor for electricity as in equation (6.5)

\[ P_{\text{fan}} = P_n \left( \frac{n_{\text{fan}}}{n_n} \right)^3 = P_n \left( \frac{\dot{V}_{\text{fan}}}{V_n} \right)^3 \]  

(6.4)

\[ Q_{p,\text{elect}} = = P_n \left( \frac{\dot{V}_{\text{fan}}}{V_n} \right)^3 * P_{f,\text{elect}} \]  

(6.5)

Figure 6.7: Heat energy calculated in dependence of supply air temperature and air volume flow rate.
Figure 6.8: Power consumption calculated in dependence only on air volume flow rate.

From the above analysis we can identify that the supply temperature have high influence on the primary energy consumption. For example to cover a demand of 25 kW, the supply temperature could be adjusted at 28 °C, and the air volume flow rate till 12000 m³/hr, we could cover the energy demand sufficiently. As it is obvious from this analysis, the supply air temperature, and air the volume flow of a great influence on the primary energy consumption, where it was proved mathematically, and also by doing simulation, nevertheless, the energy required to heat the water in the radiator system. This parameters should be taken into consideration in setting the new control strategies.

6.4 Summary

From the previous analysis it is obvious that using graphical representation is of a good help to observe the faults which could exist in the system. By enhancing this method energy savings could be achieved. On the otherhand, the current control configuration is analysed and the main control parameters have been addressed. In the next chapter will new control optimization strategies will be introduced, and test it’s influence on the primary energy consumption.
Chapter 7

7 Simulation-Based Control optimization

Optimization attempts to find the optimal values of selected design parameters for a defined design problem in building and its systems (e.g. HVAC system) by minimizing or maximizing a selected objective function. In this case, it is used to optimize the primary energy consumption by setting new control strategies for the heating system. Based on the findings of the sensitivity analyses of the control parameters and according to the existing problems in the current control configuration, an attempt for primary energy control optimization for the heating system is adopted. The optimization strategies herein, will take into consideration the secondary heating system and the static radiator system, an assumption was made for primary heater, that the temperature outlet is 20°C. Two optimization approaches will be conducted: (I) Control optimization using TRNSYS (forward model) and (II) Optimization using MATLAB Algorithms (data-driven model). Both approaches will be described and discussed in the following paragraphs.

7.1 Optimization using TRNSYS

Recalling the parameters that will be controlled in this case are: the air supply temperature for the primary, the secondary heater, the air volume flow rate and the power consumption for the pump. For this reasons, the controllers of type 2b were used for controlling the supply air and room temperatures. On the other hand, the volume flow rate and the power consumption by pump control were done by defining new schedules and assigning certain values for them.

Before describing the scenarios that was adopted for this case study, some observations from the simulation trials will be denoted. One of the problems that are faced in setting the right control configuration is the rapid switching which causes a lot of fluctuations in the temperature profile. As it is illustrated in Figure 7.1, the supply temperature was
suffering from sharp cut-off during the day which caused by the rapid switching on and off as the temperature drifts around the set point. This indicates that filter signals (hysteresis) are needed so that the controller reacts slowly by taking recent history into account, this would be achieved by tuning the upper and lower bounds of the controller. For the upper and lower bounds they were adjusted to 1.5 and -1.5 where the rapid switches has lessened and the controller reacts slower.

After taking into consideration the hysteresis, the proposed control scenarios will be shown next to overcome the building control problems. The control values used in these proposed controls were identified after 16 simulation trials.
7.1.1 Scenario (1): using the ventilation system for covering the heating demand

In this scenario, the ventilation system was used to cover the heating demand, by setting new control regulation. As it is shown in Figure 7.2, for the secondary heater that serves the first floor, it was controlled by scheduling its start at 5:30 am and stop at 18:00 pm during working days and during weekends, it is shut down. The supply temperature was adjusted at (26 °C), the room temperature controller was set to (21 °C), the upper bound was set to (1.5) and the lower bound was set to (-1.5). For controlling the supplied volume flow rate from the fan see Figure 7.3, it was scheduled its start at 5:30 am with volume flow rate of 18000 m³/hr equivalent to (6 h⁻¹). After one hour and 20 minutes, the volume flow rate drops till it reaches a constant value of 9000 m³/hr equivalent to (3 h⁻¹) and then stops at 18:00 pm during working days. While in the weekends, it is turned off.

Figure 7.2: Diagram showing the proposed control (1) for the supply temperature of the secondary heater, the energy required, and their effect on the zone temperature
Figure 7.3: Diagram showing the relation between the power consumption and the air volume flow rate in control (1)

The used codes are as following:

**Control Code #1** At \( T_{amb} \leq 20 \degree C \)

For HVAC system:

\[
\begin{align*}
T_{set, day} &= 21 \degree C \\
Upper \ bound &= 1.5 \\
Lower \ bound &= -1.5 \\
T_{supply, fan} &= 26 \degree C
\end{align*}
\]

Start the heating coil at \((t) = 5:30 \ am\), and \( T_{supply, fan} = 26 \degree C \),
\( \dot{V}_{air} = 18000 \ m^3/\text{hr} \) and at \((t) = 6:50 \ am \ \dot{V}_{air} = 9000 \ m^3/\text{hr} \), then,
when \( T_{room} \geq T_{upper \ bound} \), cut off.

In this scenario, the heating energy demand was covered by the ventilation system which succeeded in covering the whole load without integrating the static radiator. The
maximum room temperature was set at 22.5 °C by a difference of one degree lower than the current temperature set in the BEMS. The ventilation system needed 1:20 hour to heat up the room in the morning which is more than the current control by 20 minutes. The fluctuations of the temperature control was minimized by adjusting suitable lower and upper bounds which helped in increasing the hysteresis to avoid sharp on and off in the controller.

7.1.2 Scenario (2): trade-off between the ventilation system and the static radiator system.

In this scenario, tradeoff between the ventilation system and the static radiator system is applied. The control in this case depends on scheduling for both systems and using on/off controllers. For the actual control configuration used in the building, the static radiator is used during the night to heat up the rooms and to less the power consumed in the morning. In the proposed scenario as shown in Figure 7.4, the radiator system will be shut down during the night and turns on at 5:00 am with 31 kW, which is the maximum power needed for rising water to the first floor and after one hour the power drops to 10kW, then it stops at 18:00 pm.

For the secondary heater that serves the first floor, it is controlled by scheduling its start at 5:45 am and stop at 18:00 during working days and during the weekends, it is shut down. The supply temperature was adjusted at (26 °C), the room temperature controller was set to (21 °C) the upper bound was set to (1.5) and the lower bound was set to (-1.5). For the control of the volume flow rate (see Figure 7.5), it was controlled as a schedule which starts at 5:30 am with volume flow rate of 12000 m³/hr equivalent to (4 h⁻¹). After 45 minutes, the volume flow rate drops till it reaches a constant of 6000 m³/hr equivalent to (2 h⁻¹) and then stops at 18:00 pm during working days. While in the weekends, it is turned off.
Figure 7.4: Diagram showing the proposed control (2) for the supply temperature of the secondary heater, the energy required, the energy required from static radiator and their effect on the zone temperature

**Control Code #2** At \( T_{amb} \leq 20^\circ C \)

For static radiator:

\[
\begin{align*}
T_{set, day} & = 21.0^\circ C \\
T_{set, night} & = -
\end{align*}
\]

Start the static radiator with full power of 31 kW at \( t = 5:00 \) am, when \( T_{room} \geq T_{set} \) then lower the power of the pump to 10 kW and keep \( T_{room} = T_{set} \)

Stop at 18:00 pm

when \( T_{room} \leq T_{set, day} \), then start the static radiator with low power and keep \( T_{set, night} \)
For HVAC system:
\[
\begin{align*}
    T_{\text{set,day}} &= 21 \degree C \\
    \text{Upper bound} &= 1.5 \\
    \text{Lower bound} &= -1.5 \\
    T_{\text{supply, fan}} &= 26 \degree C
\end{align*}
\]

Start the heating coil at \((t) = 5:30\) am and \(T_{\text{supply, fan}} = 26 \degree C\), \(\dot{V}_{\text{air}} = 18000 \, m^3/hr\), and at \((t) = 6:15\) am \(\dot{V}_{\text{air}} = 9000 \, m^3/hr\), then, when \(T_{\text{room}} \geq T_{\text{upper bound}}\), cut off.

Stop at 18:00 pm

![Diagram showing the relation between the power consumption and the air volume flow rate in control (2)](image)

In this scenario, the heating energy demand was covered by tradeoff between both the ventilation system and the static radiator. The temperature of the room was adjusted at maximum 22.5 °C. The radiator system needed 20 minutes more than the current setup to heat the room while the ventilation system needed 45 minutes to heat up the room in
the morning which is more than the current control by 20 minutes. However, the volume flow rate was decreased in the morning from 18000 to 12000 m³/hr and during the day, it was decreased from 12000 to 6000 m³/hr which is about half the volume flow rate used in the first scenario.

7.2 Optimization using MATLAB

MATLAB is a program which designed to simplify the implementation of numerical linear algebra routines. It is used to implement numerical algorithms for a wide range of applications. These algorithms solve constrained and unconstrained continuous and discrete problems. It consists of optimization algorithms that can solve a variety of functions for linear programming, quadratic programming, nonlinear optimization and multi-objective optimization. Using optimization algorithm could help in having a dynamic algorithm that is connected to the BEMS and can find the optimum control parameters dynamically. MATLAB was chosen for the optimization of the primary energy by using a Linprog algorithm. In the next lines the algorithm description and evaluation will be denoted.

7.2.1 Identification of the optimization problem in MATLAB

The success of the optimization is strongly affected by the properties of the formulation of the objective function and by the selection of an appropriate optimization algorithm [30]. In this case, the objective function is to minimize the vector component \( Z \) which is the argument for minimizing the primary energy consumption.

\[
Z_{opt} = \arg \min_Z Q_p(Z)
\]

The vector component \( Z \) of the targeted control parameters is defined as:

\[
Z = \begin{bmatrix}
T_{Supply,\, air} \\
Q_{Pump} \\
V_{air}
\end{bmatrix}
\]

Since the MATLAB is a black-box program, the optimization problem should be identified numerically in terms of matrices and vectors. As a first step, a model
representing the relation between the control parameters and the room temperature, also
the primary energy should be created, where this model will be used first for fitting
process (validation). The zone temperature will be the reference to represent a real
fitting; the same process for validation which was used before in chapter 5 will be
applied here numerically. Regression coefficients were calculated for this reason. The
relation was calculated from equation (7.1). The considered time index for the
optimization process is 57 days. The weekends were neglected due to bad conditioned
matrices in the fitting process. Data was calculated for 5 minutes interval per day giving
a total of $57 \times 288 = 16416$ samples overall. The size of the coefficient matrix is 16416
rows and 4 columns.

$$T_{room} = \alpha_1 + \alpha_2 T_{\text{supply},air} + \alpha_3 Q_{\text{pump}} + \alpha_4 \dot{V}_{\text{air},fan}$$  \hspace{1cm} (7.1)

The coefficient vector ($Q_p$) is defined as follows:

$$Q_p = \beta_1 + \beta_2 T_{\text{supply},air} + \beta_3 Q_{\text{pump}} + \beta_4 \dot{V}_{\text{air},fan}$$  \hspace{1cm} (7.2)

Figure 7.6 shows a comparison between the modeled zone temperature and the real zone
temperature for fitting purpose. As it is clearly shown, the fitting is interrupted and it is
not accurate enough to build on the optimization process.
As a result, a regression analysis will be used by means of a linear fit approach to calculate the coefficients for the validation process. Therefore, a *pseudoinverse* will be used since this algorithm is used to compute a 'best fit' (least squares) solution to a system of linear equations that lacks a unique solution. The regression coefficients are calculated for both $T_{\text{zone}}$ and $Q_p$.

These coefficients identify the inequality constraints for the optimization function. Now a model that represents the actual relation is created. The next step is identifying the parameters that will be optimized in terms of the primary energy consumption. The optimization is generated on daily basis and the sum of the parameters is calculated for a 5 minutes time interval ($12 \times 24 = 288$). The primary energy could be calculated from equation (7.1).

![Figure 7.6: Modeled temperature in MATLAB compared to the real room temperature for one day](image)
By substitution of equations (5.2), (5.4), into equation (7.1) the formula could be written as equation (7.2):

\[
Q_P(z) = \sum_{i=1}^{i=288} Q_{f,elect}(i) P_{f,elect} + \sum_{i=1}^{i=288} Q_{coil}(i) P_{f,thermal} + \sum_{i=1}^{i=288} Q_{pump}(i) P_{f,thermal}
\]

(7.3)

By defining the primary energy in terms of the desired control parameter, an algorithm should be chosen that have the ability to solve this optimization problem.

### 7.2.2 Scenario (3): Optimization using Linprog Algorithm- for linear Problems

The relation between the parameters and the primary energy consumption is a linear function. As a result, the optimization algorithm should be able to solve a linear objective function. Linprog optimization algorithm is used since it uses a linear programming algorithm for minimizing the objective function while additionally satisfying the equality constraints. The objective function formula is as following:

By defining the primary energy in terms of the desired control parameter, an algorithm should be chosen that have the ability to solve this optimization problem.
x = linprog (f,A,b,Aeq,beq,lb,ub)

\[
\min_{x} \quad f^T x \quad \text{such that} \quad \begin{cases} 
A \cdot x \leq b, \\
A_{eq} \cdot x = b_{eq}, \\
lb \leq x \leq ub.
\end{cases}
\]

Since x is the optimum value for the objective function. The formula used for this case here is written as:

Qpopt = linprog (fvec,Amat,Bvec[,][,],Zminvec,Zmaxvec)

Input arguments:

- fvec Linear objective function vector
- Amat Matrix of inequality constrains
- Bvec Matrix of quality constrains
- Zminvec Zminvec \leq Z_{opt} : lower bounds for Zopt
- Zmaxvec Z_{opt} \leq Zmaxvec : upper bounds for Zopt

Output arguments:

- Qpopt Optimal value of the objective function

The objective function based on the following assumptions:

It arises from fitting measurements of the primary energy \( Q_p \) taken from a building in a linear model as a function of the vectors \( T_{supply}, Q_{pump} \) and \( V_{dot} \) based on using a \textit{pseudoinverse} approach on a daily basis.

The room temperature \( T_{Zone} \) is subject to constraints. Namely \( T_{Zone} \) has to be less than \( T_{max} \) and larger than \( T_{min} \) during office hours on working days. The vector \( T_{min} \) is to be chosen according to the specification of the building conditions.

First calculate coefficients for building the constraints, where it consists of matrices defining the relation coefficients between the control parameters and the primary energy, with respect to the room temperature.
The room temperature control is

$$19 \, ^\circ\text{C} \leq (\alpha_1 + \alpha_2 T_{\text{supply,air}} + \alpha_3 Q_{\text{pump}} + \alpha_4 V_{\text{air, fan}}) \leq 22.5 \, ^\circ\text{C}$$

Second define the lower and upper bounds for the Z vector since it consists of the lower and upper bounds.

$$Z \text{ vector} = \begin{cases} 0 \leq T_{\text{supply}} \leq 30 \, ^\circ\text{C} \\ 0 \leq V_{\text{air}} \leq 18000 \, m^3/hr \\ 0 \leq Q_{\text{pump}} \leq 31 \, kW \end{cases}$$

As illustrated in Figure 7.7, the constrains for the zone temperature control was achieved; the temperature ranges between 22.5 and 19 C°
In this scenario, the heating energy demand was covered by tradeoff between both the ventilation system and the static radiator as in scenario 2. The constrained zone temperature was adjusted at maximum 22.5 °C. The algorithm, as shown, iterates several times till it achieve the identified constraints for the zone temperature while minimizing the identified parameters.

The three scenarios have succeeded to control the defined parameters either by applying controllers in the TRNSYS environment or using a dynamic algorithm defined by constraints and lower and upper bounds which acts also as controllers. To clarify the effect of the applied control scenarios on the primary energy consumption, it was calculated for each scenario and in the next paragraphs each control scenario will be compared in terms of primary energy.
7.3 Comparison between the 3 optimization Scenarios in terms of primary energy consumption

Figure 7.9 demonstrates a comparison between each scenario in terms of primary energy and the actual consumed primary energy. The findings illustrates that for the ventilation scenario (1), the primary energy required to heat the secondary heater coil =19.5 MWh while the primary energy consumed by electricity from the fan = 9.19 MWh with a total of 28.67 MWh. When compared to the actual primary energy consumption, 13.7% savings was achieved by controlling the air flow rate and setting new schedules for the heating as it was referred in scenario (1).

For the tradeoff scenario (2), the primary energy required to heat the secondary heater coil =8.0 MWh while the primary energy consumed by electricity from the fan = 2.3 MWh and the energy consumed for the radiator system=14.76 MWh with a total of 25.18 MWh. When compared to the actual primary energy consumption, 24.2% savings was achieved by distributing the heating load on both systems, integrating controls and setting new schedules as it was referred in scenario (2).

For the optimized scenario (3) using linprog algorithm, the primary energy required to heat the secondary heater coil =12.1 MWh while the primary energy consumed by electricity from the fan = 3.72 MWh and the energy consumed for the radiator system=9.58 MWh with a total of 25.41 MWh. When compared to the actual primary energy consumption, 23.5% savings was achieved.
Analyzing the results helped in observing that for the first scenario, the power consumption from fans and the energy required to heat the secondary coils was relatively higher than the actual case. This was a result of using the maximum flow rate of 18000 m³/hr for 1.20 hours more than the actual case by 20 minutes to heat up the zone to satisfy the set temperature. However, by neglecting the radiator system and decreasing the supply temperature from 31°C, in actual case, to 26°C and by using less flow rate during the day (9000 m³/hr) the savings reached 13%. For the second scenario, the radiator system consumed more energy than the actual case, since it was scheduled to work at 5:00 am earlier than the actual case by 20 minutes. While the power consumption from the fan decreased, since it started later 15 minutes than the actual case with less flow rate. Not only the scheduling have affect the consumption from the ventilation system, but also the supply air temperature was lessen to 26°C which influenced the consumption from heating the secondary coil. This scenario was successful to reach savings of 24%. The optimized scenario does not have much difference in terms of savings when compared to the second scenario. Thus, it was successful in finding the optimum values for the control parameters.
Chapter 8  

8 Discussion and Conclusion

By analyzing both methods, these methods have succeeded in achieving optimization control. The physical model had high potentials for providing an accurate model compared to the real one taking into consideration all the physical effects. Moreover, it succeeded in implementing and testing new optimized control configurations. But for implementing the new control set up in the BMS, it lacks the ability to do this optimization dynamically for the system since it tests only values that could act better with the system according to a known condition. On the other hand, by using a black-box approach, a dynamic optimization could be achieved using a certain algorithm but it still needs to be more accurate in finding the right relations between the control variables. This requires defining the physical conditions and all the interacting variables in mathematical formulas, which on one hand has high ability to produce an accurate model, but on the other hand it is a very complex process. Finally, both optimization approaches could be adopted to solve the control problem. But for having an accurate model that represents the physical properties of a building, and can be connected to the BMS to do optimization dynamically, a coupling between both programs could achieve this aim. Figure 8.1 illustrate the proposed connection between the software and the BMS.
8.1 Further Optimization Development

The proposed control for the heating system could be implemented in the BEMS in Bosch building, as a development for the possibilities to optimize the energy consumed from the heating system, an attempt to reduce the consumption from the primary heater will be introduced. For this optimization, a simulation was done for controlling the supply temperature from the primary heater. As it is shown in Figure 8.2, the actual case, the supply air temperature needed to supply appropriate temperature to heat coils that deliver heat for the secondary heater is relatively high, it reaches 26°C, and the heating energy required to cover this temperature reaches a maximum of 209 kWh. So the supply temperature will be controlled, and with the aid of the secondary heater the heating demand could be covered. The control configuration for the secondary heater, and the static radiator was set as in Scenario (2), and for the Primary heater the supply temperature was set to (20°C), the upper bound was zero, the lower bound is (-0.5), as it is shown in Figure 8.3. The actual primary energy consumption from the
whole heating system accounts for 63.8 MWh, the share of the primary heater represents 30.56 MWh. By applying this developed control for the primary heater the primary energy required represents 31.02 MWh, with about 7% savings could be achieved from only controlling the primary heater supply air temperature.

Figure 8.2: Diagram showing the relation between the primary heater energy consumption, the supply temperature, and the ambient temperature for the current configuration
Figure 8.3: Diagram showing the new control configuration for the primary heater supply temperature, in relation to the energy consumed from heating coils and the ambient temperature.
8.2 Conclusion

In this research a framework for implementing of simulation based optimization control has been introduced to reduce the primary energy consumption from a heating system in a Bosch office building in Schwieberdingen close to Stuttgart, Germany. This reduction was achieved by controlling some parameters that influence the energy consumption from the heating system. Within this framework, simulation based optimization control methods were compared, and developed to find the best control configuration. The development of these methods arises from using analytical methods, by implementing graphical observation for fault detection, and testing these methods within a simulation environment. These optimization approaches have high potentials to guarantee efficient control configurations. This framework could be implemented to solve similar operational problems; moreover, it could also be adopted for reducing the load for cooling demand, while taking into consideration the parameters that could affect the consumption. Furthermore, the simulation based optimization control, offers high potential in energy savings, as it was shown in our results, more that 25% savings could be achieved by choosing the appropriate algorithms. The developed new control code can be directly implemented into the programming of the Siemens BEMS control unit.
References


