University of Zurich[UZH]

MASTER THESIS

Improving on the Electricity Costs of Office Buildings by Optimal Smart Grid Integration

Author:

Sutharshini RASATHURAI

Student ID: 10-714-707

Supervisor:

Prof. Dr. Lorenz M. HILTY

Co-Supervisor:

Nikolaus A. BORNHÖFT

UNIVERSITY OF ZURICH

INFORMATICS AND SUSTAINABILITY RESEARCH

BINZMÜHLESTRASSE 14

8050 ZURICH

SWITZERLAND

August 24, 2012

Acknowledgements

I am extremely thankful to Eduard Kuhr for his kind, extensive and patient explanations, and for providing me the necessary data. I am specially grateful to my co-supervisor, Nikolaus A. Bornhöft, for his continuous guidance and feedback during the course of my work. I am also extremely indebted to my supervisor, Prof. Dr. Lorenz M. Hilty, for his invaluable support. I gratefully acknowledge Dieter Gantenbein from IBM Research for offering me this thesis topic.

I would like to express my deepest gratitude to my family and my fiancé for their constant support and encouragement during my studies.

Sutharshini Rasathurai

Zurich, Switzerland, August 2012

Abstract

The goal of this master thesis is to assess to which extent electricity costs caused by heating and cooling systems in office buildings can be reduced by applying dynamic prices. For this purpose, we analyze the heating and cooling system of the IBM business building in Zurich-Altstetten which is very efficient and thus certified by MINERGIE. The most salient components of this system are the three chillers which are used as the main source for cooling as well as heating energy. We model this system with its important properties as a simulation model in Desmo-J. We run the simulation experiments with data from a past winter month and a summer month so that we can compare the results between the different control strategies as well as the two seasons. The strategies include the current control strategies, new strategies under the current electricity pricing and new strategies under dynamic prices. With the help of the simulation results, we can estimate the electricity costs and saving potentials for the heating and cooling system of the IBM building. The results also help us to draw conclusions about the saving potentials for all office buildings.

Zusammenfassung

Das Ziel dieser Masterarbeit ist es, zu beurteilen, inwieweit die Stromkosten, die von den Heizungs-und Kühlanlagen in Geschäftsgebäuden verursacht werden, durch dynamische Strompreise reduziert werden können. Zu diesem Zweck analysieren wir das Heiz- und Kühlsystem vom IBM-Geschäftsgebäude in Zürich-Altstetten, das sehr effizient und somit von MINERGIE zertifiziert ist. Die wichtigsten Komponenten dieses Systems sind die drei Kältemaschinen, die als Hauptquelle für sowohl Kühlung als auch Heizenergie verwendet werden. Wir modellieren dieses System mit seinen wichtigen Eigenschaften als ein Simulationsmodell in Desmo-J. Wir führen die Simulationsexperimente mit Daten aus einem vergangenen Wintermonat und einem Sommermonat durch, so dass wir die Ergebnisse zwischen den verschiedenen Kontrollstrategien sowie den beiden Jahreszeiten vergleichen können. Die Strategien beinhalten die aktuellen Kontrollstrategien, neue Strategien unter den derzeitigen Strompreisen sowie neue Strategien unter dynamischen Preisen. Mit Hilfe der Simulationsergebnisse können wir die Stromkosten und Einsparpotenziale für das Heiz-und Kühlsystem des IBM-Geschäftsgebäudes schätzen. Diese Ergebnisse helfen uns auch Rückschlüsse für die Einsparpotenziale in allen Geschäftsgebäuden zu ziehen.

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Introduction

At business buildings, major part of electricity consumption is caused by huge cooling and heating systems. Although good storage capacities for cold and heat water are available, they are not efficiently used. We know that we can extract many useful advantages from optimal Smart Grid integration. There has already been some research in Switzerland about storing electricity in batteries to make the most of dynamic electricity tariffs [5]. But there are only few studies about saving electricity costs for cooling and heating systems.

The objective of our work is to estimate the potential to save electricity costs in office buildings using Smart Grid Demand Shaping. We have selected the IBM office building located in Zurich-Altstetten as an example for our analysis. Of special interest is the heating and cooling system of the building. To model this dynamic system and test it under different Smart Grid Demand Shaping criteria, discrete event simulation is selected as appropriate method. The main idea of Smart Grid Demand Shaping is to apply dynamic prices which reflect spot market prices. By knowing the electricity prices earlier, cold water production can be pushed up if the current electricity price is relatively cheap or postponed to a later time when electricity becomes cheaper.

2

Definitions

Before we explain the heating and cooling system of the IBM office building and our model, we need to understand some definitions which will be used throughout this thesis.

2.1 Power and Energy

Firstly, we have to understand what is meant by power and energy. Power is the rate at which energy is generated or used. Correctly said, power is the rate at which a device or equipment takes energy in one form and turns it into another form [1]. The kilowatt (kW) is a unit of power. kWh is a measure of energy, whilst kW is a measure of power. Energy is a measure of how much "fuel" is contained within something, or used by something over a specific period of time [1]. The kWh is a unit of energy which is defined as following [1]:

$$energy = power * time \tag{2.1}$$

$$kWh = kW * h \tag{2.2}$$

By rearranging the Equations 2.1 and 2.2, we can find out the value for power whose unit of measurement is kW:

$$power = \frac{energy}{time} \tag{2.3}$$

$$kW = \frac{kW}{h} \tag{2.4}$$

2.1.1 The Wording of Cooling Energy

Throughout this thesis, if we use the wording "cooling energy", we only mean the heat energy which is extracted from a substance like water in order to cool it. In thermodynamics, only the term heat energy exists. Because the thesis talks about the heating and cooling system where demands for heating as well as cooling occur, we need to somehow distinguish between the energy flows for cooling and the energy flows for heating. Furthermore, we need to find a wording to express how cold the water stored in the cold water storage is. This amount of coldness equals the heat energy removed from the water in order to keep it cold. Thus, to avoid complexity, we have decided to use the wording "cooling energy".

2.2 Specific Heat Capacity

The specific heat capacity "c" indicates how much heat energy must be transfered from a substance with 1 kg mass or absorbed by a substance with 1 kg mass so that its temperature changes by 1 °C equivalent to 1 K (Kelvin) [11]. The specific heat capacity of water is [11]

$$c = \frac{4.187\, kJ}{kg\ *\ K} \tag{2.5}$$

For instance, if we need to change the temperature of 10 liters water which is equivalent to a mass of 10 kg by 2 °C,

$$\frac{4.187\,kJ}{kg\,*\,K}\,*\,10\,kg\,*\,2\,K\;=\;83.74\,kJ$$

is needed. As

$$1\,kWh = 3600\,kJ$$

for the temperature change by 2 K, 0.0233 kWh heat energy must be transfered.

2.3 Coefficient of Performance

We know that the value of Coefficient of Performance (COP) of a refrigerating machine is equal to the quotient of output energy and input energy [9]:

$$COP = \frac{Q_c}{W} \tag{2.6}$$

Input energy (W) is the electrical energy you need for operating the refrigerating machines. Output energy of a refrigerating machine is actually the cold energy produced by them. But, because we decided to model only heat energy flows, we need to consider the waste heat as the output energy (Q_c) which equals the sum of the electrical energy (W)and the produced cold energyQ_t.

Thus,

$$Q_c = W + Q_t \tag{2.7}$$

From the technical specification of the refrigerating machines, we are able to gather the values for Q_c and W. Therefore, we need to know the exact type of these machines which is *Carrier* 30 *HXC* 260. By knowing the type, the values for nominal cooling capacity and nominal power input can be found. Three times nominal cooling capacity equals the cold energy produced by the three refrigerating machines which is Q_t. Three times nominal power input is equal to in the input energy of the three machines which is W.

$$Nominal\ cooling\ capacity \ = \ 902\ kW$$

$$Nominal\ power\ input \ = \ 203\ kW$$

Therefore,

$$Q_t \ = 902\ kW \ * \ 3 \ = \ 2706\ kW \tag{2.8}$$

$$W = 203\ kW \ * \ 3 \ = \ 609\ kW \tag{2.9}$$

$$Q_c \ = \ 609\ kW \ + \ 2706\ kW \ = \ 3315\ kW \tag{2.10}$$

$$COP \ = \ \frac{3315\ kW}{609\ kW} \ = \ 5.44 \tag{2.11}$$

If it is known that in a particular period of one hour, the three refrigerating machines together produce a cold energy of $hQ_t\ kWh$, then we can use the above calculated COP-value to determine the values for the electrical energy consumption (hW) as well the waste heat produced (hQ_c) in this particular hour.

We already know from Equation 2.11 that $COP \ = \ 5.44$.

$$5.44 \ = \frac{Q_c}{W} = \frac{hW \ + \ hQ_t}{hW} \tag{2.12}$$

$$hW = \frac{hQ_t}{4.44} \tag{2.13}$$

$$hQ_c = hW + hQ_t = \frac{hQ_t}{4.44} + hQ_t \tag{2.14}$$

$$hQ_t = hW * 4.44 \tag{2.15}$$

If for example, $hW = 50\ kWh$ has been consumed by the refrigerating machines, then you can calculate the amount of produced cold energy using the formula 2.15:

$$hQ_t = 50\,kWh * 4.44 = 222\,kWh$$

3

Situation Analysis and Problem Statement

The objective of this chapter is to describe the heating and cooling system of the IBM business building in Zurich-Altstetten and explain the current regulations and electricity pricing in use. After the situation analysis, the problem statement and goals of this work are presented.

3.1 Heating and Cooling System

IBM office building located in Zurich-Altstetten is certified by MINERGIE which consists of an efficient heating and cooling system. *MINERGIE is a sustainability brand for new and refurbished buildings and is supported by the Swiss Confederation, the Swiss Cantons along with Trade and Industry and is registered in Switzerland and around the world. Building to MINERGIE standards means providing high-grade, air-tight building envelopes and the continuous renewal of air in the building using an energy-efficient ventilation system.*

Specific energy consumption is used as the main indicator to quantify the required building quality [2]. Thus, the heating and cooling system of the IBM office building is very efficient. Office rooms in the upper floors are heated only with the internal heat generated by the computers, people and lighting. In summer, the window blinds are automatically closed in order to keep the office rooms cool so that they do not need to be cooled too much if the outside temperature is high.

The heating and cooling system is monitored using metrics logged with a building automation software by Comsys Bärtsch[1]. The main sources of cooling as well as heating energy are the three refrigerating machines in the underground of the office building. Furthermore, there are two cold water storages which currently store a part of the produced cold water with a temperature between 11 °C and 12 °C. The waste heat produced during the refrigeration process by the refrigerating machines is utilized as heating energy. Thus, the existing gas boilers are used only as additional heating energy source in case heating energy extracted from the waste heat is not sufficient for the heat consumption of the building. Main heat energy consumers of the IBM building are underfloor heating, air heaters and hot water supply whereas main cooling energy consumers are air coolers, no-frost refrigerators and cooling ceilings at each floor. The hot water supply also uses a storage for water heated by waste heat and if necessary additionally by gas boilers. Most data needed for our work are made available by the Comsys Bärtsch building automation software. With 15 000 physical and 40 000 virtual data points, the system offers a large amount of measured values. Some missing measurements can be derived from other available measured values.

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[1] Comsys Bärtsch AG: http://www.comsysbaertsch.ch

3.2 Components of the System

The heating and cooling system of the IBM building consists of three refrigerating machines, two cold water storages, two heat exchangers, two waste heat storages, three cooling towers, one hot water storage, one household hot water storage, two gas boilers and all the cooling and heating energy consumers.

3.2.1 Refrigerating Machines

The system has three refrigerating machines (i.e. chillers) which are the main electricity consumers of the building. Each of them contains three compressors. In total nine compressors are available for the refrigeration process. Each compressor is able to deliver a power of 300.67 KW. Thus, the three chillers can perform up to 300.67 KW * 9 = 2706.03 KW. There is a restriction that at least 50% of the compressor power must be utilized. The three chillers produce waste heat in the amount of the produced cooling energy and the input electricity.

3.2.2 Cold Water Storages

The cooling energy consumers receive the cooling energy for fulfilling their demands not only from the three chillers, but also from the two cold water storages. Each of these storages stores a water capacity of 13 000 liters. Currently, cold water with a temperature between 11 °C and 12 °C is stored in these two storages. If cold water produced is in excess of the demand, the remaining cold water is forwarded to the storages to be stored. If the cold water has warmed up to 12 °C, the storages are loaded with

Fig. 3.1: One of the three refrigerating machines in the underground

more cold water from the refrigerating machines to keep the water always in the same temperature range.

3.2.3 Heat Exchangers

There are two heat exchangers available for processing the waste heat produced by the chillers. They are responsible for forwarding the waste heat to the heating energy consumers and the waste heat storage, and the excess waste heat to the cooling towers to be destroyed. Each of them can perform a maximal power of 595 kW in winter and 315 kW in summer.

3.2.4 Waste Heat Storages

Two waste heat storages are available for storing the waste heat forwarded by the heat exchangers. Each of them has a capacity of 9000 liters. The

Fig. 3.2: Both cold water storages are located in the underground

temperature range of the stored hot water is between 39 °C and 41 °C.

3.2.5 Cooling Towers

The waste heat which is in excess of the capacity of the two waste heat storages and the current heating energy demand is forwarded to the three cooling towers to be destroyed. All of the cooling towers are hybrid cooling systems which use a combination of conventional water cooled and air cooled systems.

3.2.6 Hot Water Storage

There also exists a hot water storage which receives hot water from the waste heat storages in order to be later used as household hot water. This

Fig. 3.3: Waste heat storages in the underground

Fig. 3.4: One of the three cooling towers on the 13th floor

storage has a capacity of 3500 liters and stores hot water in a temperature range between 36 °C and 40 °C.

Fig. 3.5: Hot water storage

3.2.7 Household Hot Water Storage

The temperature of the water stored in the hot water storage is not sufficient for the water usage of the consumers. Thus, the water from the hot water storage is forwarded to the household hot water storage to be additionally heated by gas boilers. The temperature at which water is stored here after reheating with gas boilers ranges between 48 °C and 66 °C. The volume of this storage is 3500 liters.

Fig. 3.6: Household hot water storage with reheated water

3.2.8 Gas Boilers

Gas boilers are used in addition to the waste heat produced by the chillers. If the waste heat currently available through the heat exchangers and stored in the waste heat storages or household hot water storage is not sufficient to fulfill the heating demand of the consumers, additional heating energy is sourced from the existing gas boilers.

3.2.9 Heating and Cooling Energy Consumers

The main heating energy consumers are underfloor heating, air heaters and household hot water usage whereas the main cooling energy consumers of the building are air handlers, no-frost refrigerators and cooling ceilings.

3.3 Demand and Supply

The whole process of refrigeration begins with a demand for cooling energy. A demand for cooling energy can for instance be triggered by the weather. If the weather outside is hot and consequently the room temperature is high, the working area must be cooled in order to make it comfortable for the employees. The building control system automatically decides to start the cooling process. Thus, a demand for cooling energy has been created. The building control system has to decide how to fulfill this demand for cooling energy. This decision depends on the current fill level of the two cold water storages.

If there is sufficient cold water in the storages, the cooling energy demand can be satisfied using the stored cold water exclusively, otherwise if there is an insufficient amount of cold water stored in the storages, at least a part of the demand can be satisfied with the help of the stored cold water so that the chillers must produce cold water to satisfy only the remaining part of the demand. If there is no cooling energy demand at all or the stored cold water is sufficient to fulfill the current cooling energy demand, the chillers can be turned off in order to save electric energy. It is important to utilize the stored cold water as much as possible. In this way, it can be avoided that the chillers are turned on to no purpose and consume too much electric energy.

The amount of produced cooling energy and waste heat depends on the demand for cooling energy. In order not to waste cooling energy, only necessary amount of compressors are turned on by the refrigerating machines. If a compressor is turned on, at least 50% of its maximum power has to be utilized. Thus, it maybe that the chillers produce cold water in excess of the current cooling energy demand. If this happens, the part temporarily not used will be stored in the cold water storages to be utilized later as cooling energy. Each of the two cold water storages have a maximum fill level of 13 000 liters. If approximately 50% of the maximum fill level has been reached, a loading process will be initiated. This process runs even if there is no demand for cooling energy demand and lets the chillers produce cold water and load the cold water storage until approximately 75% of the maximum fill level has been reached. At which fill level the loading process exactly starts and stops is unclear or depends on many other parameters.

Refrigeration means that heating energy is eliminated from a resource such as water so that it becomes cold. The eliminated heating energy is transfered to another place as waste heat. This waste heat can be stored somewhere else to be later utilized as heating energy. For the storage of waste heat, there are two waste heat storages available each with a maximum capacity of 9000 liters.

3.4 Current Electricity Pricing

The electricity for the IBM business building in Zurich-Altstetten is supplied by Elektrizitätswerk der Stadt Zürich (ewz)[2] which offers different tariffs to select. IBM decided to use the ewz.naturpower tariff which consists of 100% renewable energy. The current pricing reflects time-of-use rates known as TOU [4] which distinguishes only the two tariff levels peak and off-peak and is same for all commercial customers. The time period from Monday to Saturday between 6 A.M. to 10 P.M. is considered as peak time and rest of the time as off-peak. In peak times, approximately the double of the off-peak price is charged per consumed kWh. As a penalty for peak demand, ewz additionally charges for the month's highest power demand over a 15-minute period which is measured in kW.

Figure 3.7 illustrates the main approach of time-of-use rates on which current pricing by ewz is based.

3.5 Spot Market Prices

Electricity prices are traded everyday by the electricity companies at EEX[3] based in Leipzig, Germany. EEX was founded in 2002 as the result of the

[2] http://www.stadt-zuerich.ch/content/ewz/de/index.html
[3] http://www.eex.com

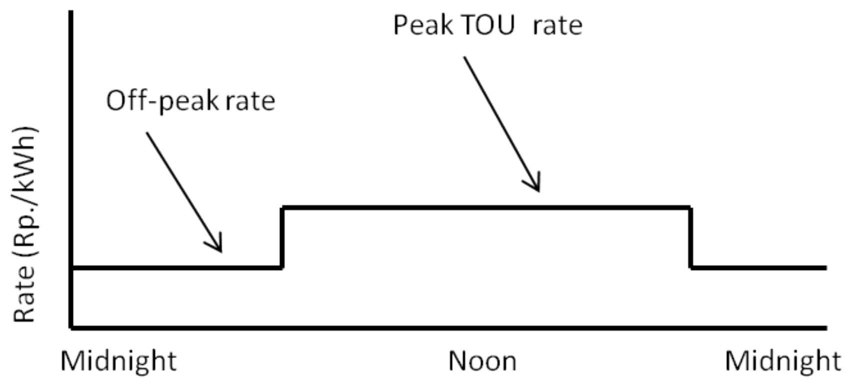

Fig. 3.7: Time-Of-Use Rates

merger of Leipzig Power Exchange (LPX) and European Power Exchange (EPX). Currently some 138 trading participants from 17 countries are trading at the EEX whereof about one half is non-German. The members range from top investment banks to small, regional producers from all over Europe. The EEX is a regulated market subject to the German Exchange Act and it is supervised by three different institutions: the Exchange Council, the Ministry of Economic Affairs of the Free State of Saxony and the German Financial Supervisory Authority [10].

The price at the exchange are the benchmark for the whole market including OTC, wholesale and retail business. EEX operates a spot and a derivatives market for electricity and also EU emission allowances under the EU Emissions Trading Scheme. The auction market allows market participants to place purchase and sales bids for single hours and block trades. The resulting equilibrium price is a market price, which is defined by way of bilateral auction by suppliers as well as consumers. The market for continuous block trading allows placing purchase and sales bids for base load blocks and peak load blocks. On the derivatives market, futures contracts and options are tradable [10].

In this way, the spot market prices are formed at which electricity companies buy and sell electrical energy. However, they are offering the electrical energy to the end consumers at time-of-use rates. If we want to estimate the saving potentials with dynamic electricity tariffs we cannot directly take the spot market prices as given. Electricity companies would want to make profits. Thus, they would add a profit margin for each kWh they sell to their end consumers. We need to estimate the profit margin which ewz would charge from the end consumers with the help of the spot market prices for the months December and June and the current time-of-use rates of ewz.

To do this, we have to firstly convert the spot market prices into Swiss Francs as they are given in Euro. For this conversion, we have taken the exchange rate of

$$EUR\ 1 = CHF\ 1.2$$

which was set as the minimum exchange rate in the summer of 2011 by the national bank of Switzerland. Furthermore, the prices are given per MWh which need to be converted into prices per kWh. To calculate the profit margin which ewz would charge, we calculate the average price of all the spot market prices from the months December 2011 and June 2012. The average price per kWh equals CHF 0.0588596. ewz normally charges CHF 0.0864 during off-peak period which lasts for eight hours per day and CHF 0.1620 during on-peak period which lasts 16 hours per day. Thus, on average ewz charges CHF 0.13008 per kWh. We can compute the profit margin ewz charges to the end consumers as follows:

$$\frac{0.13008}{0.0588596} = 2.21$$

Therefore, for each kWh we source from ewz, we can assume that we need to pay 2.21 times of the spot market price. Now, we have formed dynamic prices based on on real-time pricing (RTP) [4].

Figure 3.8 illustrates the main approach of real-time pricing on which the spot market prices are based.

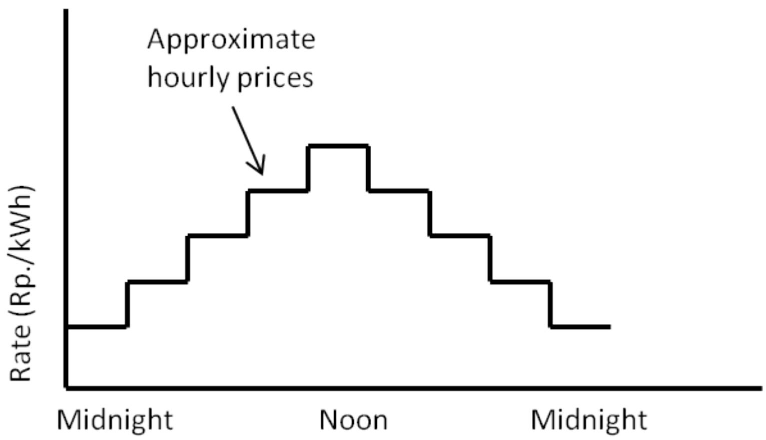

Fig. 3.8: Real-Time Pricing

3.6 Problem Statement

The main intention of this work is to find out the saving potentials in electricity costs for the heating and cooling system of office buildings. To facilitate our analysis, the IBM business building in Zurich-Altstetten has been selected as an example for modern office buildings and its data are used for our analysis. The first question to be answered is how we can change the current regulations of the system and save money under the current pricing model offered by ewz so that we can realize the difference between the current system and a system integrated with Smart Grid. The second question to be analyzed is if we can save more in electricity costs if dynamic prices related to spot market prices as computed in Section 3.5 are offered.

To answer these two questions, we need to do a comparison with the current regulations and costs. Therefore, we have to firstly model the system described in the previous sections with the current pricing and then adapt it in a way that we can predict the new costs and accordingly saving potentials under the new strategies and pricing.

4

Simulation as Modeling Method

4.1 What is Simulation?

Simulation is defined as *the modeling of dynamic processes in real systems, based on real data, and seeking predictions for a real system's behavior by tracing a system's changes of state over time starting form some initial state* [3]. It is reasonable to model real systems as computer-based simulation models if it is difficult or impossible to perform experiments with them. *In computer-based simulations, models are represented by (simulation) programs, and simulation experiments ("runs") are performed by a model's execution for a specified data set* [3]. Figure 4.1 shows the relations between system, model, and model user (observer) [3].

Due to continual energy flow and responses to demand changes, the whole heating and cooling system is very dynamic. There are many interacting processes between the system components as well as consumers which need to be modeled. Therefore, it is reasonable to design a simula-

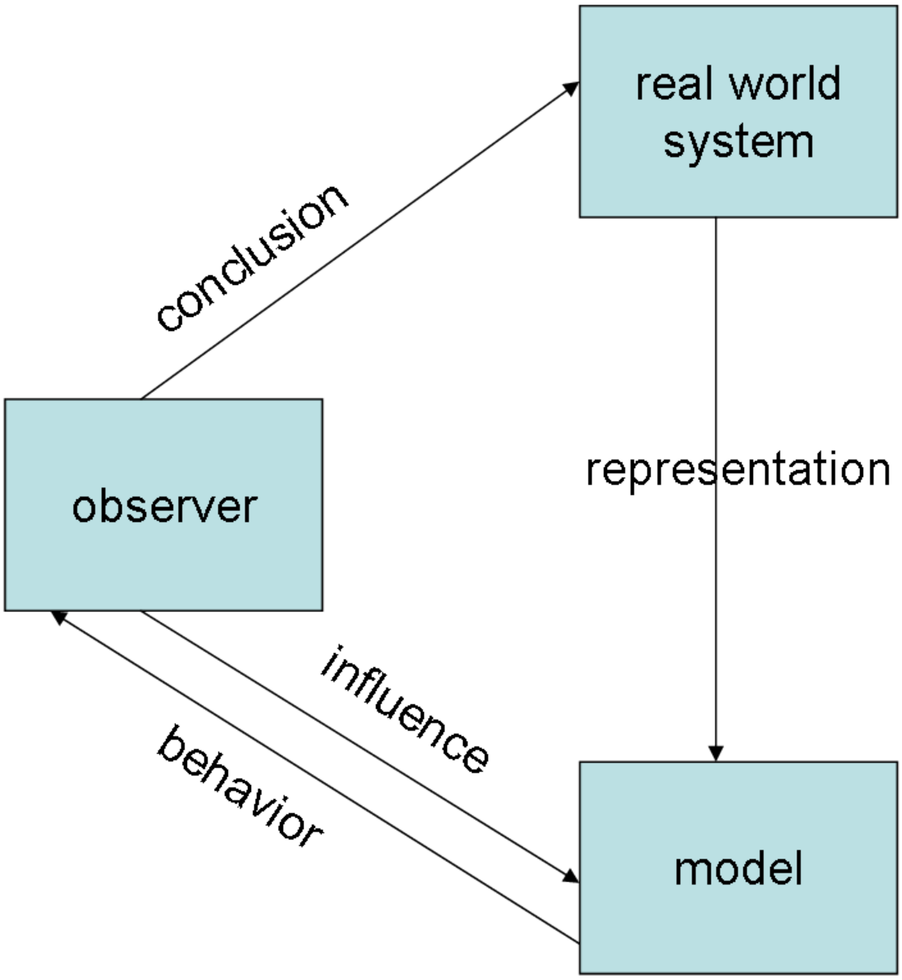

Fig. 4.1: System, model, and application

tion model of this system to facilitate experiments about the saving potentials and what-if analyses.

4.2 Discrete Event Simulation

Objective of the next chapter is to represent the heating and cooling system from Chapter 3 as a discrete event-driven simulation model *where all system state changes are mapped onto discrete events and assuming that nothing* *relevant happens between, i.e. that states remain constant and no computations are needed during such intervals* [3]. This type of simulation models are suitable for systems whose states do not fluctuate in a steady pattern and in which relevant changes of state happen suddenly and in irregular intervals [3].

Although the system consists of continuous flows of energy, we can model them as discrete flows as we already know when specific events, i.e. changes of states will occur in the system or we can calculate the points of time when they will occur.

Continuous simulation models are not suitable for our purpose as their *states change steadily over time, and models are framed in terms of differential equations with time as the free variable* [3]. Performing continuous simulations, which are often used to analyze engineering designs as well as complex physical or biological processes, would lead to solving complex mathematical equations.

4.3 Desmo-J as a Simulation Framework

As an appropriate simulation framework, DESMO-J (Discrete Event Simulation MOdeling in Java) is selected which is a framework for implementing discrete event simulation models developed at the University of Hamburg [8]. DESMO-J gives users the possibility to add complex functions and easily customize behaviors and properties of predefined model components [3].

5

Model Design

The objective of this chapter is to bring the system components into model components. Thus, we need to first explain the difference in the definitions of system and model. What we have seen in Chapter 3 is a system which as a whole represents the cooling and heating devices of the IBM building as well as the consumers and the interactions between them so closely as possible. This system has the same properties and behaviors as the real cooling and heating system of the IBM building. However, the purpose of a model is not to represent each and every property of its system. A model tries to describe only the most important and necessary properties of its original system. It may leave out some properties or make simplifications if these changes do not lead to a complete different behavior of the system. The system components and their interactions maybe illustrated in a different manner if it answers the purpose intended.

5.1 Available Data

Until November 2011, there was an old building automation software in use which has been replaced by a building automation software by Comsys Bärtsch. Due to this replacement taken place in November 2011, there are only data available logged from this date. Thus, it is not possible to model the system's behavior during a whole year. However, for a cooling and heating system, it is more important to assess the difference in its behavior during winter and summer. Therefore, we decided to retrieve data from the software only for the months December 2011 and June 2012. December should be representative for winter months and June for summer months because the demand for cooling and heating is similar in all winter months and summer months respectively. As demand for cooling and heating energy varies in these two seasons, we should be able to see a huge difference in the results, too.

In the data sets of December 2011, we have removed the measurements from the 1st of December in order to have the same weekday as the starting weekday in both months. This is necessary because the current electricity tariff is dependent on the weekday and if we have different starting weekdays in both months, we will need to work with two different files for storing prices. However, the removal of the 1st of December has led to the same number of days in both months which makes it easy to compare the results of both months.

The current building automation software logs a lot of measured values. Most of the data are logged in regular and short intervals, but some other are logged in irregular intervals because there are not so many changes happening. Measurements for gas energy usage happen in an irregular interval up to 1 hour because gas energy is not often used when enough waste heat is available. Measurements for cooling energy usage are logged every minute, because there is always a demand for cooling energy. However, we decided to fetch the data in 15-minutes intervals in order to avoid the complexity arising from too many data. This decision appears to be permissible as these measurements represent accumulated values which are given in kWh. To get the values for usage in a time period, we need to calculate the difference of the accumulated values at two consecutive points of time.

How much cooling energy the three refrigerating machines produce together, is nowhere logged in the system. But the system has measurements about the electricity consumption of three machines. With the help of these information and the coefficient of performance (COP) which is explained in 2.3, we are able to compute the amount of cooling energy the refrigerating machines produce during a specific time period. For the functioning of the model, we do not need the information about electricity consumption and cooling energy production, but they can serve to validate the model.

As we divide the consumers into the three groups cooling energy consumers, heating energy consumers and hot water consumers, we need to format the available data so that the model knows which demand occurs when. To estimate the demand for heating energy as well as for hot water, some calculations need to be done. The demand for hot water for instance equates to the sum of waste heat usage for hot water and gas energy usage for hot water. Thus, values from two different measurements need to be added. But, these two values are not always measured at the same time. It maybe that gas energy usage has been measured at 5:15 P.M., but the measurement for waste heat usage uses another interval and logs the value at 5:25 P.M. If we want to know the total demand for hot water at 5:15 P.M., we cannot directly sum up those two values, because they are measured at different points of time. As the value for waste heat usage at 5.15 P.M. is missing, we need to estimate it with the help of other values which have been measured at earlier and later points of time. This kind of estimation is called linear interpolation which will be explained in the next section in further details.

5.2 Linear Interpolation to Combine Data Sets

The reason why we need to do linear interpolation is that some points of time are missing in one data set which exist in the other data set. Thus, before we linearly interpolate the missing demand values, we need to add the missing points of time to both data sets so that both data sets contain the same points of time. This will facilitate the calculations with both data sets later. To add the missing points of time, both data sets need to be compared. Because we do not know, how many new points of time will be added to those data sets, it is reasonable to store them as linked lists. In this way, both data sets can be easily compared with each other and new records can be added to the end of linked lists without causing any problems due to length of the data sets. As time stamps can be difficult for calculations, it is reasonable to convert the time stamps to accumulated minutes before proceeding with the comparison.

```
public static void compareLists(LinkedList<double[]>
    data1, LinkedList<double[]> data2){
  int i = 0;
```

```
    while(i<data1.size()){
      if(data1.get(i)[0]!=data2.get(i)[0]){
        double[] d = {data1.get(i)[0],0.0};
        data2.add(d);
      }
      i++;
    }
    int k = 0;
    while(k<data2.size()){
      if(data2.get(k)[0]!=data1.get(k)[0]){
        double[] d = {data2.get(k)[0],0.0};
        data1.add(d);
      }
      k++;
    }
}
```

Listing 5.1: Compare two lists

The code in Listing 5.1 does the comparison of two data sets sorted by ascending amount of minutes. As both data sets can have different length, the comparison needs to be done in two steps. First, the Java method compares the first data set with the second one, and if there is a record which exists in the first data set, but not in the second one, it adds this missing amount of minutes along with a zero value for demand to the end of the second data set. The demand which has been now set to zero needs to be calculated later with the help of linear interpolation. In a second step, missing amounts of minutes in the first data set which exist in the second data set need to be added to the first data set along with a zero value for demand. It may still be that both data sets contain duplicate records which can be easily eliminated with the help of some EXCEL formulas. After eliminating the duplicates and sorting both data sets by ascending amount of minutes, they should have equal length and contain zeros for the missing demands. Now, it is easy to find the missing values with the help of linear interpolation.

Linear interpolation involves estimating a new value by connecting two adjacent known values with a straight line [6]. If the two known values are (x1, y1) and (x2, y2), then the y value for some point x is:

$$y = y1 + (x - x1)\frac{(y2 - y1)}{(x2 - x1)} \tag{5.1}$$

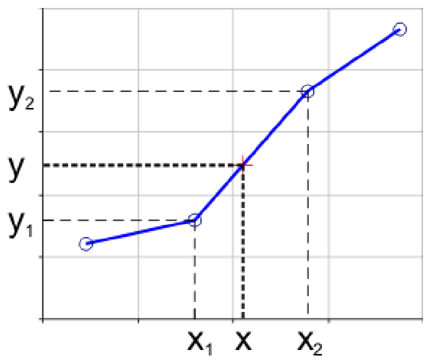

Fig. 5.1: Linear interpolation

The code in Listing 5.2 does the linear interpolation for a data set with missing values for demands:

```
public static void interpolate(LinkedList<double[]> data)
    {
  int i = 0;
  while(i<data.size()-2){
```

```
    if(data.get(i+1)[1]!=0.0)
      i++;
    if(data.get(i+1)[1]==0.0){
      double minStart = data.get(i)[0];
      double valueStart = data.get(i)[1];
      int index = i+1;
      while(data.get(i+1)[1]==0.0)
        i++;
      double minEnd = data.get(i+1)[0];
      double valueEnd = data.get(i+1)[1];
      int indexEnd = i;
      double diffEnergy = valueEnd-valueStart;
      double diffMins = minEnd-minStart;
      double energyPerMin = diffEnergy/diffMins;
      while(index<=indexEnd){
        double[] r = { data.get(index)[0], ((data.get(
            index)[0]-minStart)*energyPerMin)+valueStart};
        data.set(index,r);
        index++;
      }
      i++;
    }
  }
}
```

Listing 5.2: Linear interpolation

If for example x1 = 15 minutes, x = 18 minutes, and x2 = 21 minutes while y1 = 290765 kWh, y2 = 290900 kWh, and a value for y is missing which is given as a zero, the above method computes the missing value as follows

$$y1 + \frac{y2 - y1}{x2 - x1} * (x - x1) = y$$

$$290765\,kWh + \frac{290900\,kWh - 290765\,kWh}{21min - 15min} * (18min - 15min) = 290832.5\,kWh$$

5.3 Modeling the Energy Flows

The purpose of our model is to show the energy flows between the system components. Thus, it is important to use the same unit of measurement throughout our model. Measurements of demands such as cooling energy consumption, heating energy consumption and other energy flows are all given in kilowatt hours (kWh). But we do not have any information about the amount of cooling and heating energy stored in the storages. We only know the maximum capacity which is the volume of the storages and the temperature range at which cold or hot water is stored. To model the cold and hot water flows between the storages and other system components as energy flows, we need to take advantage of the known information about volumes and temperature ranges.

5.3.1 Refrigerating Machines

We know that each of the three refrigerating machines can deliver a cooling capacity of 902 kW and that each of them consists of three compressors. Thus, there are at total nine compressors available. The main restriction to these compressors is that if a compressor is turned on we must utilize at least 50% of its power which is equivalent to

$$0.5 * \frac{902\,kW}{3} = 150.33\,kW$$

As we can represent the power as a continuous value, we have decided to model the three refrigerating machines as one chiller component with nine compressors. Since the fix costs are negligible and do not need to be modeled, it does not matter how many chillers are turned on. The main aspect to know is the amount of total power the chillers can deliver. A power value under 150.33 kW is not allowed in our model. All values above 150.33 kW up to 2706 kW can be used. All values between 150.33 kW and 300.67 kW can be representative for one compressor. If it's a greater value than 300.67 kW and smaller than 601.33 kW, it can be representative for two compressors since we can divide this value into two summands so that each summand is equal to or greater than 150.33 kW. This method can be applied to all power values up to 2706 kW. Therefore, there is no necessity to model the refrigerating machines as three distinct components. It is permissible to model them as one single machine which can deliver a cooling capacity of 2703 kW.

5.3.2 Cold Water Storages

There are two equal cold water storages. Each of them has a volume of 13 000 liters and stores cold water in a temperature range between 11 °C and 12 °C. Thus, the storages will be always loaded with cold water if the temperature of the water inside the storages reaches the maximum of 12 °C. As the temperature always ranges between 11 °C and 12 °C, there is a maximum temperature difference of 1 °C which needs to be reached during the loading process. Loading with cold water or decreasing the temperature from 12 °C to 11 °C means that heat is extracted from the stored water and transfered as heating energy. Thus, it is a heating process with a temperature increase of 1 °C. We can use this knowledge as well as the definition for specific heat capacity from 2.2 to find out the amount of thermal energy which must be transfered from the storages so that cold water remains.

Each cold water storage has a water capacity of 13 000 liters which is equivalent to a mass of 13 000 kg. Thus, to decrease the temperature of the water stored in one cold water storage by 1 K,

$$4.187 \frac{kJ}{kg * K} * 13\,000\ kg * 1\ K = 54\,431\ kJ$$

is needed.
As

$$1kWh = 3600\ kJ$$

for the decrease of the temperature by 1 K, 15.117 kWh heat energy must be transfered. As there are two cold water storages with same properties, a maximum of 15.117 kWh * 2 = 30.234 kWh heat energy must be transfered to keep the whole water between 11 °C and 12 °C. Thus, we can conclude that in these two storages, a maximum of 30.234 kWh cooling energy can be "stored" as heat energy in the same amount is being transfered.

During our work, we have decided to model the two cold water storages as one entity where cold water can be steplessly stored as this does not make any difference for our purpose. In addition, we abstract from loss of energy because the storages are well insulated. Thus, we can say that the cold water storage in our model has a capacity for 30.234 kWh cooling energy.

When fulfilling cooling energy demand, cooling energy must be unloaded from the storage. It maybe, that the storage is being loaded with cold water. Thus, there are two important properties for the cold water storage which are load rate and unload rate. Both rates are set by the controller entity which will be explained in a later section.

5.3.3 Cooling Towers

The three cooling towers of the heating and cooling system are not modeled as they only serve for destroying the excess waste heat and do not play any significant role in the demand and supply side of the system.

5.3.4 Heat Exchangers

Each of the two heat exchangers can perform up to 595 kW in winter and 315 kW in summer. However, as we can see in the available data sets, their maximum power is never utilized which leads to a high loss of waste heat. In December 2011, both heat exchangers together delivered an average power of 50 kW only, and in June 2012, the average power was 145 kW. To reflect the as-is situation as close as possible, we take the same values in our model, too. This value is crucial for the maximal usage of the waste heat produced by the chiller. The higher this value the more waste heat can be utilized and the less gas energy is necessary for heating.

5.3.5 Waste Heat Storages

There are two equal waste heat storages which store waste heat produced by the refrigerating machines. Each of them has a volume of 9000 liters and stores hot water in a temperature range between 39 °C and 41 °C. Both storages will be loaded with hot water heated by waste heat if the water reaches the minimum of 39 °C. Thus, the maximum temperature difference which needs to reached during the loading process is 2 °C. If we apply the above explained method, we can use the given information about the temperature difference and volume to compute the maximum amount of heat energy that can be stored in the two waste heat storages.

Each waste heat storage has a water capacity of 9000 liters which is equivalent to a mass of 9000 kg. Thus, to increase the temperature of the water stored in one waste heat storage by 2 K,

$$4.187 \frac{kJ}{kg * K} * 9000\ kg * 2\ K = 75\,366\ kJ$$

is needed. As

$$1\ kWh = 3600\ kJ$$

for the increase of the temperature by 2 K, 20.935 kWh heat energy must be transfered.

As there are two waste heat storages with same properties, a maximum of

$$20.935\ kWh\ *\ 2 = 41.87\ kWh$$

heat energy must be transfered to keep the whole water between 39 °C and 41 °C. Thus, we can conclude that in these two storages, a maximum of 41.87 kWh heat energy can be "stored".

We make the same decision as for the cold water storages and model the two waste heat storages also as one entity with a capacity for 41.87 kWh heat energy.

5.3.6 Hot Water Storage

The hot water storage which receives hot water from the two waste heat storages has a volume of 3500 liters and stores the water in a temperature range between 36 °C and 40 °C. Thus, a maximum temperature difference of 4 °C must be achieved during the loading process. The water capacity of 3500 liters is equivalent to mass of 3000 kg. To increase the temperature of the hot water by 4 K,

$$4.187 \frac{kJ}{kg * K} * 3500\ kg * 4\ K = 58\,618\ kJ$$

is needed. As

$$1\ kWh = 3600\ kJ$$

for the increase of the temperature by 4 K, 16.28 kWh heat energy must be transfered. Therefore, we can draw the conclusion that in this hot water storage, a maximum of 16.28 kWh heat energy is "stored".

5.3.7 Household Hot Water Storage

The volume of the household hot water storage is same as the volume of the hot water storage. But the temperature ranges here between 48 °C and 66 °C. Thus, a maximum heat energy of 62.805 kWh could be stored in this storage. This amount of heat energy is generated with the help of additional gas energy. However, we decided not to model this storage in our work as we know that the hot water from the hot water storage is forwarded to this storage only for reheating when there is a demand for hot water. Thus, we can simplify this process by only modeling the energy flows from gas boilers and hot water storage to hot water consumers. By doing this simplification, we can save an additional entity to be modeled.

Figure 5.2 illustrates the energy flows we have modeled in our work. Objects colored blue signify the cooling side whereas the red color objects depict the heating side of the system. Grey objects represent the system components whose energy flows are only indirectly modeled as described in 5.3.3 and 5.3.7.

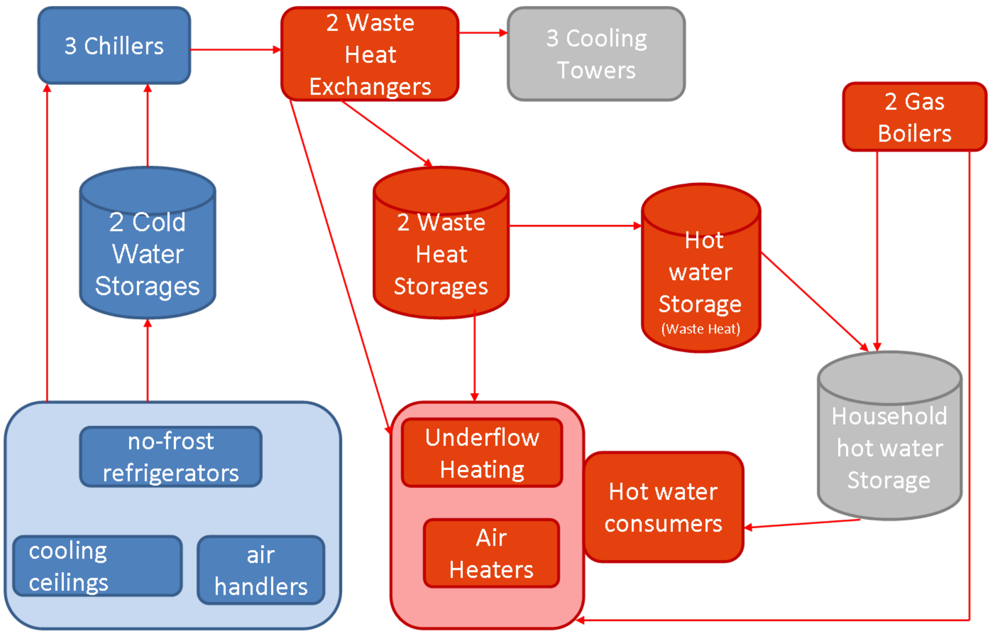

Fig. 5.2: Energy flows in the model

5.4 Controller

The building automation software which controls the demand and supply as well as logs all the important measurements is represented by a controller component in our model. This is the entity which makes decisions about the system's behavior depending on demand and supply of cooling and heating energy and plays therefore the most important role in our model. It decides at which rate the storage needs to be loaded or unloaded.

The controller component knows when to turn off the chiller or at which rate the chiller should produce cooling energy. It determines how to fulfill the cooling and heating energy demand of the consumers.

5.4.1 Demand and Supply

Cooling Energy Demand

For fulfilling cooling energy demand, the controller checks the energy level of the cold water storage and decides if it fulfills the demand only with the help of stored cold water or if it still needs the chiller. If there is enough cold water available in the cold water storage, first the stored water is utilized as much as possible. Only if the stored water is not sufficient to fulfill the cooling energy demand, the controller makes the chiller produce cold water. As there is a minimum amount of compressor power required, there can be more cold water produced than necessary for the current demand. Thus, the remaining cold water in excess of the current demand, is stored in the cold water storages.

Three different situations may occur which are explained in the following with some examples:

1. The cold water storage has enough cold water to fulfill the current cooling energy demand of the consumers:

   For example, there occurs a demand for cooling energy of 15 kWh for a duration of 15 minutes and the current fill level of cold water storage is amounting to 30 kWh. Thus, there is no necessity to use the chiller. The demand can be satisfied by only utilizing the stored cold water. The controller has to set a power value as the current unload rate of the cold water storage. The unload rate of the cold water storage is the rate at which cooling energy is being transfered from the storage to the consumers and can be calculated using the Equation 2.3:

$$\frac{15\,kWh}{\frac{15}{60}\,h} = 60\,kW. \tag{5.2}$$

The power value of the chiller is set to zero because there is no need to produce cooling energy. Since there is no cooling energy being "generated", no waste heat is being produced. After 15 minutes, the new energy level of the cold water storage will be

$$30\,kWh - 60\,kW * \frac{15}{60}\,h = 15\,kWh. \tag{5.3}$$

This value might change due to load rates set by the controller which increase the energy level of the cold water storage.

2. The cold water storage has got some cold water but it is not sufficient to fulfill the current cooling energy demand:

   For instance, there occurs a demand for cooling energy of 15 kWh for a duration of 15 minutes and the current fill level of cold water storage is amounting to 5 kWh. Thus, the stored cold water is not sufficient to fulfill the current demand. Therefore, the chiller needs to produce cooling energy. As the cold water storage already has 5 kWh cooling energy, it would be enough if the chiller produces 10 kWh cooling energy. To consume the 5 kWh cooling energy from the storage, the unload rate must be set which can be computed in the same way as in Equation 5.2:

$$\frac{5\,kWh}{\frac{15}{60}\,h} = 20\,kW. \tag{5.4}$$

The chiller also needs to know the necessary power value. For a chiller, power is the rate at which it transforms the input electricity into cooling energy and simultaneously heat energy. Now the controller has to compute the necessary power value depending on the energy demand which is equal to 10 kWh and inform the chiller about it. The power needed from the chiller for the current demand can be computed using the Equation 2.3:

$$\frac{10\ kWh}{\frac{15}{60}\ h} = 40\ kW \tag{5.5}$$

Thus, the controller is ready to set the power of the chiller to 40 kW. However, there is restriction that at least 50% of a compressors's power needs to be utilized. Thus, the controller needs to set the power of the chiller to 150.33 kW. If the above computed value of power was greater than 150.33, the controller does not need to worry about this restriction.

With a rate of 150.33 kW, the chiller can produce

$$150.33\ kW * \frac{15}{60}\ h = 37.5825\ kWh \tag{5.6}$$

cooling energy in 15 minutes.

As there is only a demand of 15 kWh and the storage already had an energy level of 5 kWh, the controller takes only 10 kWh from the chiller to fulfill the cooling energy demand, and needs to store the rest of $37.5825\ kWh - 10\ kWh = 27.5825\ kWh$ in the cold water storage. Thus, the controller has to set the load rate of the cold water storage:

$$\frac{27.5825\ kWh}{\frac{15}{60}\ h} = 110.33\ kW \tag{5.7}$$

As we calculated in Equation 2.13, we know that the chiller needs $\frac{1}{4.44}$ kWh electrical energy to "generate" 1 kWh cooling energy. Thus, for producing above computed amount of 37.5825 kWh cooling energy, the chiller consumes

$$\frac{37.5825\ kWh}{4.44} = 8.465\ kWh \tag{5.8}$$

electrical energy.

We know from Equation 2.14 that the amount of produced waste heat during this refrigeration process is equal to the sum of input electrical energy and the produced cooling energy:

$$electrical\ energy\ +\ cooling\ energy\ =\ waste\ heat\ energy \tag{5.9}$$

$$8.465\ kWh\ +\ 37.5825\ kWh\ =\ 46.0475\ kWh \tag{5.10}$$

The controller forwards this amount of waste heat to the waste heat storage to be later utilized for fulling heating energy demand. Therefore, the load rate of this storage needs to be set to

$$150.33\ kW + \frac{150.33\ kW}{4.44} = 184.19\ kW \tag{5.11}$$

3. The cold water storage is empty. This situation occurs very rarely because if the cold water storage reaches a minimum fill level, a loading process will be started independently of the cooling energy demand:

   In this case, the chiller needs to produce the whole amount of cooling energy which is demanded by the consumers of the building. If for example a cooling energy demand of 160 kWh occurs for a duration of 15 minutes, and the cold water storage's cooling energy level is zero, the controller sets the chiller's power needed to fulfill this demand:

$$\frac{160\ kWh}{\frac{15}{60}\ h} = 640\ kW \tag{5.12}$$

To achieve this power, the controller must turn on three compressors (one compressor can deliver a maximum power 300.67 kW) although only

$$\frac{640\ kW}{300.67\ kW * 3} = 71\% \tag{5.13}$$

of their power is utilized. There is no remaining cooling energy which can be stored in the cold water storage because only necessary amount of cooling energy has been produced. As the storage is currently empty, it will be loaded separately as we will see in 5.4.2.

But during the cooling energy production, a large amount of waste heat must have been produced which can be stored in the waste heat storage. Again, we can compute the amount of necessary electrical energy as well as the produced waste heat:

$$\frac{160\ kWh}{4.44} = 36.036\ kWh \tag{5.14}$$

electrical energy is needed for the production of 160 kWh cooling energy. Thus,

$$36.036\ kWh\ +\ 160\ kWh\ =\ 196.036\ kWh \tag{5.15}$$

waste heat is produced during the refrigeration process. The controller needs to set the load rate of the waste heat storage to

$$640\ kW + \frac{640\ kW}{4.44} = 784.144\ kW \tag{5.16}$$

By loading the cold water storage and waste heat storage, there is always a capacity restriction. As we have seen in 5.3.2 and 5.3.5, the cold water storage can store a maximum of 30.234 kWh cooling energy and the waste heat storage has a maximum capacity for 41.87 kWh waste heat. Thus, we assume that excess cooling energy and waste heat are destroyed if the maximum energy level of the storages has been reached.

Heating Energy Demand

For fulling heating energy demand, the controller needs to check the energy level of the waste heat storage and decide to what extent the gas boilers must be utilized. The controller always tries to utilize the waste heat as much as possible to save costs for gas energy.

As for the cooling energy demand, three different situations may occur which are explained in the following with some examples:

1. The waste heat storage has enough hot water to fulfill the current heating energy demand of the consumers:

   If for example, there occurs a heating energy demand of 25 kWh for a duration of 30 minutes and the waste heat storage has an energy level of 40 kWh. Thus, the demand can be fulfilled without the use of gas energy. The controller needs to set the unload rate of the waste heat storage. The unload rate of the waste heat storage is the rate at which heating energy is being transfered from the waste heat storage to the consumers and can be calculated using the Equation 2.3:

$$\frac{25\ kWh}{\frac{30}{60}\ h} = 50\ kW. \tag{5.17}$$

   The power value of the gas boiler is set to zero because there is no need for gas energy. After 30 minutes, the new energy level of the waste heat storage will be

$$40\ kWh - 50\ kW * \frac{30}{60}\ h = 15\ kWh. \tag{5.18}$$

This value might change if additional waste heat is produced by the chiller and a load rate is set by the controller which increases the energy level of the waste heat storage or if the hot water storage is loaded with waste heat from the waste heat storage and an additional unload rate is set by the controller which decreases the energy level of the waste heat storage.

2. The waste heat storage has got some hot water but it is not sufficient to fulfill the current heating energy demand:

   For instance, there occurs a demand for heating energy of 60 kWh for a duration of 30 minutes and the current energy level of waste heat storage is amounting to 40 kWh. Thus, the stored hot water is not sufficient to fulfill the current demand. Therefore, the gas boiler needs to deliver some heating energy. As the waste heat storage already has 40 kWh heating energy, it would be enough if the gas boiler delivers 20 kWh heating energy. To consume the 40 kWh heating energy from the waste heat storage, again the unload rate must be set to

$$\frac{40\ kWh}{\frac{30}{60}\ h} = 80\ kW. \tag{5.19}$$

   After 30 minutes, the energy level of the waste heat storage will be 0 kWh, but it may change due to additional waste heat produced by the chiller.

To consume the remaining 20 kWh heating energy from gas energy, the power of the gas boiler needs to set to

$$\frac{20\ kWh}{\frac{30}{60}\ h} = 40\ kW. \tag{5.20}$$

3. The waste heat storage is empty. This situation can occur because waste heat is produced only if cooling energy is generated. Thus, if there is no or low demand for cooling energy, it may be that there is no waste heat stored in the storage:

   In this case, the gas boiler needs to deliver the whole amount of heating energy which is demanded by the consumers of the building. If for example a heating energy demand of 200 kWh occurs for a duration of 30 minutes, and the waste heat storage's heating energy level is zero, the controller sets the gas boiler's power needed to fulfill this demand:

$$\frac{200\ kWh}{\frac{30}{60}\ h} = 400\ kW \tag{5.21}$$

Hot Water Demand

Fulfilling hot water demand works in most cases same as fulfilling heating energy demand. However, there is a difference between the waste heat storage and the hot water storage. The waste heat storage is directly loaded with the waste heat from the chiller, but the hot water storage is loaded only with waste heat from the waste heat storage. Thus, there is a dependency between the energy level of the waste heat storage and the energy level of the hot water storage. This loading process will be explained in detail in 5.4.2. While for a heating energy demand the controller tries to utilize the waste heat from the waste heat storage as much as possible, for a hot water demand, it tries to maximally utilize the hot water stored in the hot water storage before accessing the gas energy.

5.4.2 Loading the Storages

Waste Heat Storage

The waste heat storage is loaded only if the chiller produces waste heat. There is no additional loading process executed by the controller. An additional loading of the waste heat storage would mean that the chiller produces cooling energy and consumes electrical energy without a demand for cooling energy only for the purpose of waste heat production.

Hot Water Storage

As long as there is a cooling energy demand, waste heat is being produced and the waste heat storage being loaded. This means that there is always enough waste heat stored in the waste heat storage so that it can serve the hot water storage. Therefore, it is reasonable to load the hot water storage whenever it is not full. In our model, we have defined that the hot water storage is being loaded from the waste heat storage once the energy drops to 95% of the maximum energy level.

For the loading process, the controller has to set a load rate for the hot water storage and the unload rate for the waste heat storage. But there are no information available about these rates. Thus, we have to make some assumptions for our model. The only available information is that the hot water storage is always kept with the highest energy level possible. To make an assumption about the load and unload rates, we can make use of this information and available measured values about hot water demand.

Therefore, we have analyzed the two data sets of December as well as June and found out the maximum power value demanded by hot water consumers to be 60.75 kW. We have decided to take this value as the load rate for the hot water storage so that we can fill the storage as fast as possible and be ready to maximally utilize the stored hot water to fulfill the hot water demand of the consumers. This also helps to reduce the amount of unused heat energy destroyed by the cooling towers.

Whenever a loading process is initiated, the load rate of the hot water storage is set to 60.75 kW by the controller. As the waste heat storage can already have an unload rate set by the controller due to heating energy demand which must be fulfilled with the help of the waste heat storage, the controller must add 60.75 kW to the already existing unload rate so that the waste heat storage can serve the hot water storage as well as the other heating energy consumers.

As soon as the hot water storage has reached more than 99% of the maximum energy level, the loading process is stopped by the controller. This means that the load rate of the hot water storage is set to zero and the unload rate of the waste heat storage is set to the current unload rate subtracted by 60.75 kW. By doing this, the controller enables the waste heat storage to continue to serve the other heating energy consumers except the hot water storage which has already enough heating energy.

Cold Water Storage

The cold water storage is loaded with cold water whenever the chiller produces more cooling energy than the current demand. Besides this, the cold water storage is loaded separately if its energy level reaches a specific value which is not clearly defined in the system and may depend on many other parameters. We know that this value always approximates 75%. However, for our model to work, we need to define a fix value which we set to 75%.

To load the cold water storage, the chiller needs to deliver more power than necessary for fulfilling the current cooling demand. But only as less additional power as necessary should be utilized for loading the cold water storage. Thus, we find a compressor power equivalent to 451 kW is reasonable to use as the extra power used when loading the storage and set it as the maximal additional load rate. Furthermore, the storage is currently not loaded up to the maximal energy level. Also this value is not clearly defined in the system, thus we assume for our model that this value will be at 90% of the maximal energy level of 30.234 kWh. If the storage's energy level reaches 90% of the maximum energy level, the controller stops the loading process and substracts 451 kW from the current load rate of the cold water storage.

5.5 Smart Grid Demand Shaping

We have only described the as-is situation and which abstractions have been made to the model. However, we need to analyze which improvements can be achieved using Smart Grid Demand Shaping. Thus, new control strategies must be developed.

5.5.1 Smart Grid Ideas in General

Smart Grid means *combining time-based prices with the technologies that can be set by users to automatically control their use and self-production, lowering their power costs and offering other benefits such as increased reliability to the system as a whole* [4].

To be able to extract advantages from the Smart Grid ideas, i.e. dynamic prices, we need to know the important components of a Smart Grid. The storage component plays a major role in a Smart Grid. Due to the disjoint between peak availability and peak consumption, it is important to find ways to store the generated energy for later use [7]. Especially electricity storages such as batteries are used for balancing the electricity grids without turning power plants on and off constantly [4, 5].

In the heating and cooling system of the IBM office building, this strategy of balancing is already partially in use. Heating and cooling energy are kept in storages for later use if they are currently not needed. Following sections discuss the possibilities to achieve improvements with these storages. Another important component of a Smart Grid is the monitoring and control technology which is already represented by the building automation software in the system and by the controller component in the model. It is responsible for important decisions within the system using the control strategies. Current control strategies include for example the temperature of the cold water storages to range between 11 °C and 12 °C. Changing control strategies can for example mean that we change the temperature range of the cold water storages and thus store more cooling energy for a longer period. Furthermore, a new pricing will be applied to the system, i.e. the next day's spot market prices from EEX will be made available. This pricing reflects real-time pricing known as RTP[4]. Depending on the prices and demands, the system will be able to make decisions. The system can for instance decide to postpone cold water productions when electricity is expensive and continue the process when electricity becomes cheaper. With new strategies described in the following sections, the functions of the controller can be extended.

5.5.2 Off-Peak Loading

Currently there is a pricing system which distinguishes only the two tariff levels peak and off-peak. We can take advantage of this pricing system as we know the time periods for the two tariff levels always in advance as explained in 3.4. The additional loading of the cold water storage is currently triggered only by the energy level. If the stored cold water's energy level warms up to 75% of the maximal energy level, a separate loading process is started. The loading process will be stopped as soon as the energy level drops to 90% of the maximal energy level. In the following subsections, two different strategies for loading the cold water storage are presented. First stragegy refers to the current pricing model which reflects the time-of-use rates while the second strategy makes use of the real-time pricing based on the spot market prices. Both of them represent alternative control stratgies for the controller.

5.5.2.1 Time-of-Use Rates

We should add the information about the pricing as an criterion to decide if the cold water storage should be additionally loaded with cooling energy. As the additional loading process is independent of the current demand for cooling energy, it should not be started if it is known that the current electricity price is high. This strategy will help reduce the electricity costs for refrigerating machines. Thus, even if the energy level has reached a specific energy level at which the loading process should be started, the controller will not start the additional loading process if it is not off-peak period. But this shifting should be limited to six hours in the summer and twelve hours in the winter. In summer months, there is always a demand for cooling energy and it is not reasonable to shift the loading process to many hours. In winter we can think of shifting the loading process to more hours so that the loading process can wait until the electricity price becomes really cheap because demand for cooling energy is low. As soon as peak period starts, the loading process will be stopped by the controller. This happens only if the loading process has not been shifted for more than six hours in summer and more than twelve hours in winter.

5.5.2.2 Spot Market Prices

Dynamic electricity prices related to the spot market prices as explained in 3.5 are not predefined as time-of-use rates and are different for each hour. Thus, we have to compare the current hour's price with the following hour in order to find out if it is currently "off-peak", i.e. the electricity price is relatively cheap. Only if the current price is cheaper than the next hour's price, a loading process can be started. Otherwise, it is shifted to the next hour. Like with the time-of-use rates, the shifting should be limited to twelve hours in the summer and 24 hours in the winter. Spot market prices are published up to 34 hours earlier. Thus, this information can be used to make decisions about loading processes. However, in the summer, it is not reasonable to shift a loading process to far future as there is always a demand for cooling energy. If it is known that in the next hour the price becomes cheaper, the loading is stopped and shifted to the next hour. This happens only if the loading process has not been shifted for more than twelve hours in summer and more than 24 hours in winter.

5.5.3 Increasing Storage Capacity

5.5.3.1 Cold Water Storage

The maximal energy level of a storage depends on the temperature range at which the cold or hot water is stored in the storage. As we have seen in Section 5.3.2, the cold water storage can store a maximal energy of 30.234 kWh in a temperature range between 11 °C and 12 °C. This amount of energy is dependent on the temperature difference which must be reached for cooling the stored water. Thus, if we increase the temperature difference from 1 K to a greater value, we can expect that the maximal energy which can be stored in the cold water storage will also increase. However, we need to consider the restrictions given in the technical specifications of the cold water storage. Hence, we can store the water in the cold water storage at a minimal temperature level of 5 °C. Thus, a maximal temperature difference of 7 K must be achieved during the refrigerating process. This increase in temperature difference leads to a higher amount of energy that can be stored:

$$4.187 \frac{kJ}{kg * K} * 26\,000\, kg \ * \ 7\, K = 762\,034\, kJ = \ 211.68\, kWh$$

Now, about seven times of the previous storage capacity is available. This capacity can be optimally used in combination with off-peak loading. The storage is loaded during off-peak period so that the stored cold water can be used as cooling energy during peak periods when electricity is expensive. Because the amount of cooling energy stored in the cold water storage is very high compared to the current system, you can now utilize the cooling energy from the storage for a longer period instead of always turning on the refrigerating machines and wasting electricity. Only if there is insufficient amount of cooling energy stored, refrigerating machines will be turned on. Furthermore, a separate loading process will be started only if it is off-peak period and stopped if it is on-peak period.

5.5.3.2 Hot Water Storage

The same idea from cold water storage can be applied to the hot water storage in order to save costs for gas energy. Currently, hot water in a temperature range between 36 °C and 40 °C is stored. The upper temperature level can be increased only up to 41 °C as the waste heat storage, which serves the hot water storage with heat, stores hot water in a temperature range between 39 °C and 41 °C. Thus, the maximal temperature of the hot water storage can be only 41 °C whereas the minimal temperature can remain 36 °C. Hence, the maximal temperature difference of the hot water storage can be only 5 K. Therefore, the energy level increases to

$$4.187 \frac{kJ}{kg * K} * 3500\,kg \;*\; 5\,K \;= 73\,272.5\,kJ \;=\; 20.35\,kWh$$

However, there is no huge improvement in the energy level of the hot water storage because we have to consider the given restrictions. As the main objective focuses on reducing electricity costs, we do not further analyze improvement opportunities for hot water storage.

5.5.4 Maximal Utilization of Storage Capacity

In order to take further advantages of the known on- and off-peak periods, we can increase the limit at which the controller starts to load the cold water storage to a high value such as 95%. By doing this, we can have the storage as full as possible. Whenever it is off-peak period and the energy level is only little less than the maximal energy level, the controller loads the storage and keep it as full as possible. The loading process is stopped only if the energy level has reached the maximum energy level which is equal to 100%.

Besides the limit for starting and stopping the loading process, we need to change the load rates of the cold water storage. As we have seen in Section 5.5.3.1, the maximal energy level of the cold water storage has now changed from 30.234 kWh to 211.68 kWh. To fill this large capacity as fast as possible when it is off-peak period, the storage needs a higher load rate. Thus, it is necessary to increase the maximum number of compressors available for the separate loading process. In winter, the demand for cooling energy is less than in summer. Therefore, in winter there should be a maximum of five compressors available for the additional loading of the cold water storage while in summer this number should be six. Thus, maximum load rate in winter equals to 1503.35 kW and in summer 1804.02 kW.

5.5.5 Maximal Utilization of Heat Exchangers

Currently, heat exchangers which forward the waste heat to the heating energy consumers and the waste heat storages are not optimally utilized. They can both together deliver up to 1190 kW in winter months and 630 kW in summer months. But, if we analyze measurements of the heat exchangers, we can realize that this power is not maximally utilized. In December 2011, the maximum power delivered by the heat exchangers was 875.3 kW and in June 2012, it was 644.7 kW although enough waste was heat produced by the chillers which could be processed with a higher power in order to make it available as heating energy for the consumers. Therefore, the heat exchangers must be optimized so that they can perform their maximal power whenever enough waste heat is available. Thus, we need to change the maximum power rate of the heat exchangers to 1190 kW for winter and 630 kW for summer.

6 Implementation

Objective of this chapter is to implement the simulation model of the heating and cooling system of the IBM office building with its current control strategies and pricing in Desmo-J.

6.1 HeatColdModel and Controller

The class `HeatColdModel` extends the class `Model` and represents the whole model of the heating and cooling system. In its `init`-method it creates all other `SimProcess` objects and activates the `Controller` object in its `doInitialSchedules`-method. `Controller` object is responsible for activating the other `SimProcess` objects which are `ColdConsumer`, `ColdWaterStorage`, `Chiller`, `ElecPriceChanger`, `HeatConsumer`, `WasteHeatStorage`, `GasSupplier`, `HotWaterStorage`, `HotWaterConsumer` and `WasteHeatExchanger`.

```
public void init() {
    control = new Controller(this, "Controller", true);
```

```
    coldConsumer = new ColdConsumer(this, "cold consumer
       ", true);
    coldStorage = new ColdWaterStorage(this,"cold Storage
       ", true);
    chiller = new Chiller(this,"chiller",true);
    if(this.getCurrentStrategy()!=3)
      priceChanger = new ElecPriceChanger(this, "price
          changer", true, DataUtil.getNormalPrices("mydata
          /normal prices.csv")) ;
    else{
      if(month==6)
        priceChanger = new ElecPriceChanger(this, "price
            changer", true,
          DataUtil.getSpotMarketPrices("mydata/spot
              market prices matrix juni.csv"));
      if(month==12)
        priceChanger = new ElecPriceChanger(this, "price
            changer", true,
            DataUtil.getSpotMarketPrices("mydata/spot
                market prices matrix dezember.csv"));
    }
    heatConsumer = new HeatConsumer(this, "heat consumer
       ", true);
    hotWaterConsumer = new HotWaterConsumer(this, "hot
       water consumer", true);
    wasteHeatStorage = new WasteHeatStorage(this,"waste
       heat storage",true);
    gasSupplier = new GasSupplier(this, "gas supplier",
       true);
```

```
    hotStorage = new HotWaterStorage(this,"hot Storage",
       true);
    wasteHeatExchanger = new WasteHeatExchanger(this, "
       exchanger", true);
}
```

Listing 6.1: init() method of HeatColdModel class

```
public void doInitialSchedules() {
    control.activate();
}
```

Listing 6.2: doInitialSchedules() method of HeatColdModel class

The constructor of `HeatColdModel` looks like the following:

```
  public HeatColdModel(Model arg0, String arg1, boolean
     arg2, boolean arg3, int strategy, int month) {
    super(arg0, arg1, arg2, arg3);
    this.currentStrategy = strategy;
    this.month = month;
  }
```

Listing 6.3: Constructor of HeatColdModel class

The parameter `strategy` stands for the strategy selected when executing a simulation experiment. If it equals a `1`, that means that the simulation experiment must be started with as-is properties of the model, i.e. no Smart Grid strategies should be applied. If the value of this parameter equals `2`, the simulation experiment must be performed with Smart Grid strategies, but still with the current pricing system consisting of two tariffs. A value of 3 means that the simulation must be executed with Smart Grid strategies under Spot Market Pricing.

The parameter `month` is used to differentiate between input data from winter and summer. A value of 12 stands for the December month of 2011, while a value of 6 signifies the June month of 2012.

`Controller` is not only responsible for activating the simulation processes, but also for controlling all of them and making important decisions while the system is running. The main functions of controller are:

- fulfilling cooling energy demand
- fulfilling heating energy demand
- fulfilling hot water demand
- starting and stopping of cold water storage loading
- starting and stopping of hot water storage loading

Actions of the `Controller` as well as all other SimProcesses are triggered by objects of `ExternalEvent`. Such an event can be `ColdDemandChangedEvent` or `PriceChangedEvent` among others. In `eventRoutine`-method of an `ExternalEvent` object, the actions to be taken if that particular event occurs are defined. All `SimProcess` subclasses consist of a `lifeCycle`-method where its behavior over system run time is defined. It may contain information about when an `ExternalEvent` is triggered. In some `SimProcess` subclasses such as `ColdWaterStorage`, `lifeCycle`-method might be empty if a `SimProcess` for example does not do anything at the system start but becomes active only if some other methods are called such as `setLoadRate(double loadRate)` of `ColdWaterStorage`.

6.2 Demand and Supply

Everything starts with an `ColdDemandChangedEvent` which occurs in an interval of 13, 14 or 15 minutes. If such an event happens, its `eventRoutine`-method is executed.

```
public void eventRoutine() {
  myModel.control.updateEverything();
  myModel.control.fulFillColdDemand(demand);
}
```

Listing 6.4: eventRoutine() method of ColdDemandChangedEvent class

All other work is delegated to `control` which is an object of `Controller`. Its `updateEverything`-method is responsible for updating values such as cold water storage's fill level and energy demands:

```
public void updateEverything() {
  myModel.chiller.updateProducedEnergy();
  myModel.wasteHeatStorage.updateWasteHeatAmount();
  myModel.coldStorage.updateFillLevel();
  myModel.chiller.updateEnergyDemand();
  myModel.wasteHeatStorage.updateEnergyDemand();
  myModel.coldStorage.updateEnergyDemand();
  myModel.hotStorage.updateEnergyDemand();
}
```

Listing 6.5: updateEverything() method of Controller class

In fulFillColdDemand-method, the Controller mainly checks the fill level of ColdWaterStorage and decides how to fulfill the current cold demand and sets the necessary power rates to Chiller and ColdWaterStorage as descrribed in 5.4.1. By using setUnloadRate-method, cooling energy is taken from the cold water storage and forwarded to the consumer. setLoadRate helps the Controller forward cooling energy to the cold water storage and store it there. With the help of setCompressorsFromDemand-method of the Chiller, compressor power rates are assigned and amount of produced waste heat is computed. Load rate of the waste heat storage is assigned in order to store a part of the produced waste heat in the waste heat storage.

In setLoadRate and setUnloadRate of the ColdWaterStorage, other help methods such as calculateStorageFullDuration and calculateStorageEmptyDuration are invoked to calculate how many minutes the cold water storage would need to become full or empty with the current load and unload rates. By knowing the number of minutes, LoadColdStorageEvent and StopLoadingColdStorageEvent for starting and stopping loading processes can be triggered. eventRoutine-methods of these events again check the conditions for the cold water storage to be full or empty and take the necessary steps to start a loading process or stop the ongoing loading process. For starting a loading process loadColdStorage-method of the Controller and for stopping an ongoing loading process stopColdLoading-method are invoked.

The sequence diagram in Figure 6.1 illustrates the interactions between different SimProcess objects after an ColdDemandChangedEvent has occured, i.e. its eventRoutine-method has been invoked. The detailed steps involved in the invocation of fulFillColdDemand-method would lead to a complex sequence diagram and are thus not included here.

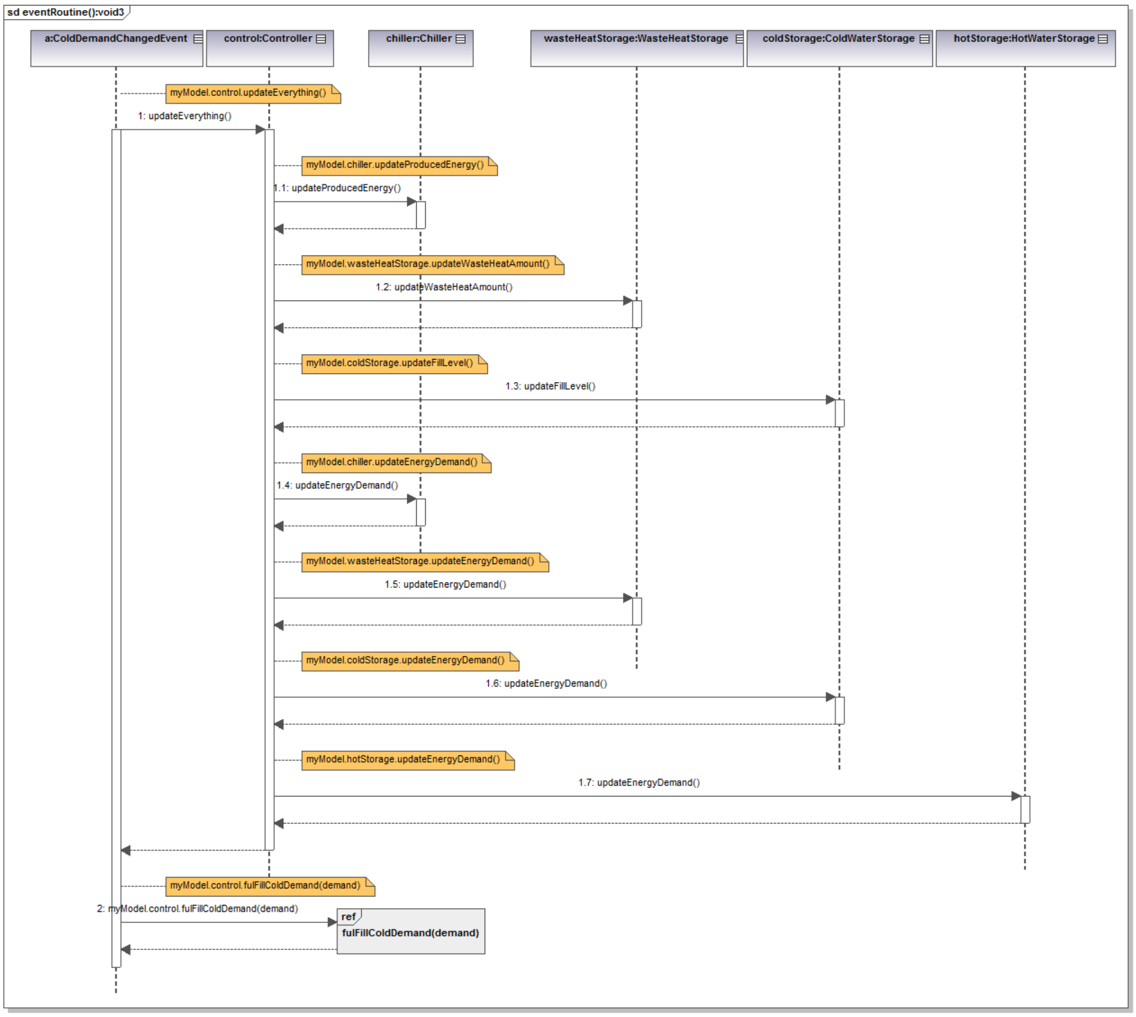

Fig. 6.1: Sequence Diagram for eventRoutine() method of ColdDemandChangedEvent

Meanwhile, a demand for heating energy or hot water can occur which lead to a `HeatingDemandChangedEvent` or `HotWaterDemandChangedEvent`. A similar procedure as for the `ColdDemandChangedEvent` is invoked. The `Controller` checks the fill level of the `WasteHeatStorage` and assigns the unload rate of the `WasteHeatStorage` and if necessary also the unload rate of the `GasSupplier`.

In an interval of two minutes, a `LoadHotWaterStorageEvent` is triggered. In the `eventRoutine`-method of the `LoadHotWaterStorageEvent`, the fill level of the `HotWaterStorage` is checked, and if 95% of the maximum fill level is reached, `loadHotWaterStorage`-method of the `Controller` is invoked which is responsbile for setting the load rate to the `HotWaterStorage` and the unload rate to the `WasteHeatStorage` in order to unload heating energy from the waste heat storage and load it to the hot water storage.

6.3 Highest Power Demand

For calculating the occurred costs during a specific period, in addition to the consumed amount of kWh, we need to find out the highest power value in a 15-minute interval during peak time as mentioned in 3.4. This computation happens always when the power value of the `Chiller`, i.e. number of compressors, is set. The `Chiller` needs to track the currently highest power value and replace it when a higher power value has been performed by itself. It is not sufficient if the new power value is just higher than the previous value but it also needs to last for a minimum period of 15 minutes.

```
double pow = this.getHighestPower1();
      if((this.getPower()/4.44) > getHighestPower1()
           && !myModel.priceChanger.offPeak()){
        setHighestPower1(this.getPower()/4.44);
        double duration = (TimeOperations.diff(
           highestPowerStartTime1,myModel.presentTime()))
```

```
            .getTimeAsDouble()/60.0;
        if(duration >= 15){
          setHighestPower15MinInterval(pow);
        }
        setHighestPowerStartTime1(myModel.presentTime());
}
```

Listing 6.6: Calculate the highest power demand

When measuring the highest electricity power value, the whole electricity consumption of the building must be considered in order to pay the penalty s to ewz. Thus, in reality the highest value might be a little more higher than the value calculated by the above method. However, we perform the simulation only for the heating and cooling system of the building. As the heating and cooling system is the major electricity consumer of the building which regularly causes high electricity power consumption, we can calculate the highest power value only for its electricity consumption as if it was the only electricity consumer.

The above described calculation of highest power value is not needed if the selected strategy is `3` as peak demands are already incorporated in the spot market prices.

6.4 Control Strategies

Spot market prices as well as current prices with two tariff levels are given in an interval of one hour. Thus the `ElecPriceChanger` checks for the new price at the beginning of each hour and triggers a `PriceChangedEvent` in order to pass the new price to the `Controller`. Before triggering the PriceChangedEvent, the ElecPriceChanger sets a variable called expensiveNow by deciding if the new electricity price which it has just got to know is currently expensive. When the current simulation is started with a strategy value of 1 or 2, the value of expensiveNow becomes true, only if the new price equals the peak price which is valid in the peak periods mentioned in 3.4. If the currently selected strategy value equals 3, the ElecPriceChanger compares the new price for the current hour with the price for the next coming hour and sets the value of expensiveNow to true if the current hour's price is more expensive than the price of the next hour.

Therefore, when the offPeak-method is executed, especially before starting and stopping an additional loading process of the cold water storage, an answer to the question if it is currently off-peak period is given. This information helps by deciding about loading processes. In strategies 2 and 3, only if the offPeak-method delivers a true, a loading process is started and it is stopped as soon as the offPeak-method delivers a false. The code of the offPeak-method looks as simple as following:

```
public boolean offPeak() {
    return !this.expensiveNow;
}
```

Listing 6.7: offPeak() method says if the current price is expensive

6.5 UML Class Diagram

Figure 6.2 illustrates all involved Java classes with their relationships and associations. It also shows the importance of the HeatColdModel-class which is a subclass of `Model` and has connections to all other classes except `DataUtil` and `RunExperimentIBMCoolingHeating`.

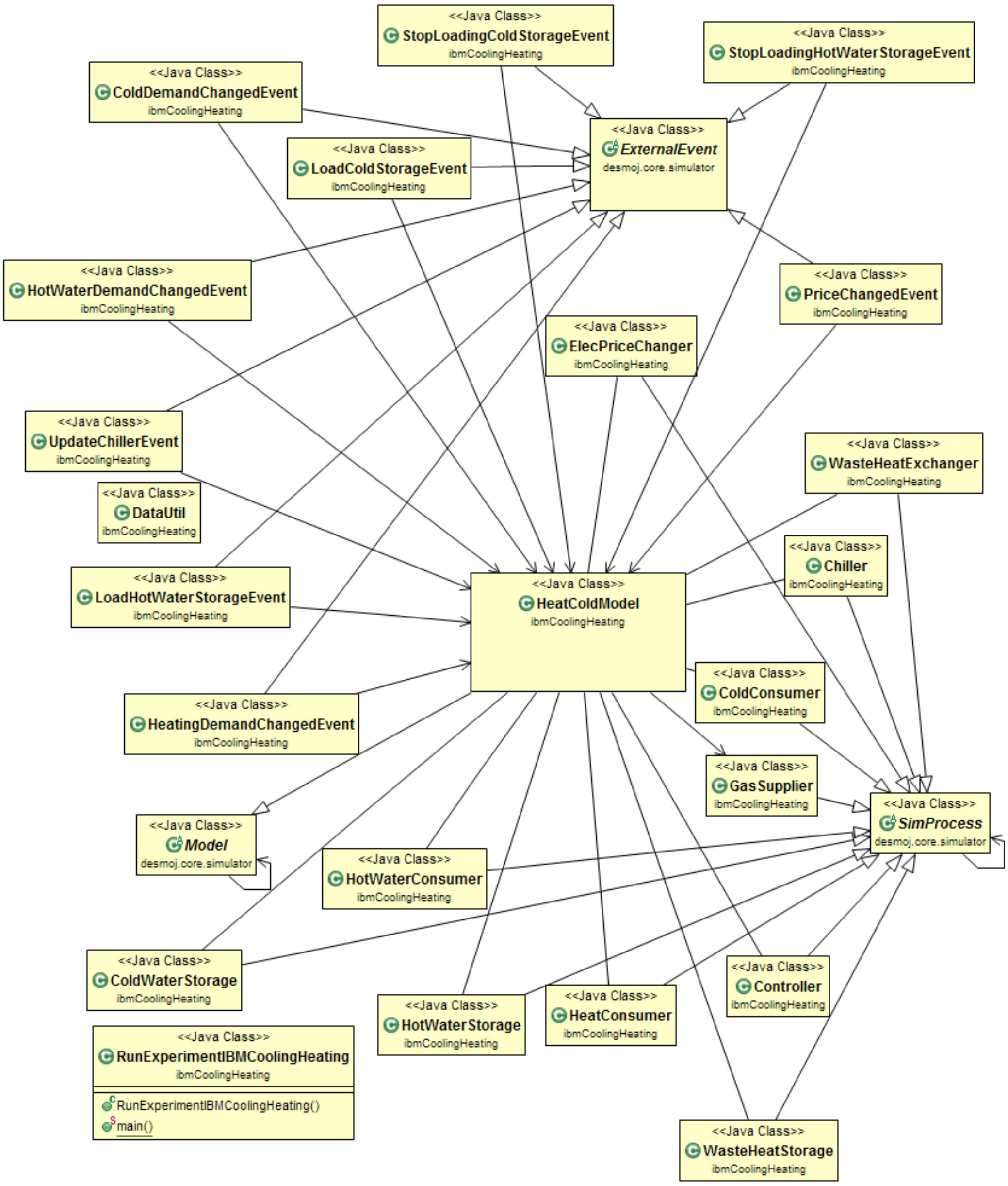

Fig. 6.2: UML Class Diagram

7

Simulation Results

Data from the past have been given to the simulation model so that we can validate the results of the as-is situation and then calculate what we would have saved using Smart Grid Demand Shaping. We know from our data, that from December 2, 2011 to December 31, 2011, there was a total cooling energy demand of 137 612 kWh. The total demand for heating energy including hot water was amounting to 174 918 kWh. From June 1, 2012 to June 30, 2012, there was a total demand for 306 411 kWh cooling energy. Demand for heating energy including hot water was amounting to 44 319 kWh. The input data show us the difference in the demands in summer and winter months. We performed several simulation experiments with measurements about cooling and heating energy demands as input data and received the results described in the following sections.

7.1 Current Strategies

7.1.1 Winter Season

During the time period from December 2, 2011 to December 31, 2011, the chillers produced 203 306 kWh cooling energy and thus 249 095 kWh waste heat. This has led to an electricity consumption amounting to 45 789 kWh. From the 249 095 kWh of produced waste heat, only 35 142 kWh could be used as heating energy. The remaining part of the heating energy demand has been fulfilled with the help of gas energy amounting to 139 776 kWh.

The highest power, the chillers needed to perform in a 15-minutes interval during peak period was 887 kW which led to an electricity power of $\frac{887kW}{4.44} = 199kW$. According to the current pricing system, for the electricity consumption of 45 789 kWh IBM needs to pay CHF 22341 to ewz. Additionally for the highest power of the month which equals 199 kW, IBM has to pay 199 $kW * CHF\ 11/kW = CHF$ 2189. Therefore, total costs of approximately CHF 24 530 have occurred for the period from December 2, 2011 to December 31, 2011.

Now we can compare these values resulting from the simulation experiment with the real data:

According to the measurements, in December 2011, there has been an electricity consumption of 43 397.6 kWh which is approximately close to the simulation result of45 789 kWh. Gas energy consumption and waste heat consumption in that month amount to 144 289.2 kWh and 30 603.8 kWh respectively. These values are also close to the simulation results. However, the small differences might be due to the power value of the heat exchanger which is only an average value as explained in 5.3.4.

7.1.2 Summer Season

During the whole of month of June 2012, the chillers produced 450 597 kWh cooling energy and thus 552 083 kWh waste heat. This has led to an electricity consumption amounting to 101 485 kWh. From the 552 083 kWh of produced waste heat, 30 638 kWh could be used as heating energy. The remaining part of the heating energy demand has been fulfilled with the help of gas energy amounting to 13 680 kWh.

The highest power, the chiller needed to perform in a 15-minutes interval during peak period was 1496 kW which led to an electricity power of $\frac{1496kW}{4.44} = 337kW$. According to the current pricing system, for the electricity consumption of 101 485 kWh IBM needs to pay CHF 49665 to ewz. Additionally for the highest power of the month which equals 199 kW, IBM has to pay 337 $kW * CHF\ 11/kW = CHF$ 3707. Therefore, total costs of approximately CHF 53 372 have occurred for the period from June 1, 2012 to June 30, 2012.

Now we can compare these values resulting from the simulation experiment with the real data:

According to the measurements, in June 2012, there has been an electricity consumption of 92 216.9 kWh which is approximately close to the simulation result of101 485 kWh. Gas energy consumption and waste heat consumption in that month amount to 12 939 kWh and 31 371 kWh respectively. These values are also close to the simulation results. However, the small differences might be due to the power value of the heat exchanger which is only an average value.

7.2 New Control Strategies

This section summarizes the results from the simulation experiments with new control strategies for heating and cooling system of the IBM business building. The demands for cooling and heating energy, i.e. the input data, are the same as in the as-is simulation experiments.

7.2.1 Winter Season

First of all, we can see a huge difference in the amount of produced cooling energy. In contrast to the as-is situation, only 164 521 kWh cooling energy would have been produced which would have led to less waste of cooling energy and thus less electricity consumption. Consequently, only 37 054 kWh electricity would have been consumed by the chillers which is about 8735 kWh less than the result for December 2011 in the as-is simulation experiment. Waste heat would have been produced in the amount of 201 576 kWh large part of which would have been used as heating energy due to the maximal utilization of heat exchanger's power. Amount of waste heat used as heating energy would have been about 140 686 kWh. Following that, only 34 231 kWh gas energy would have been needed as heating energy source. This also would have led to a reduction in costs for gas energy.

Moreover, due to the increased cold water storage capacity, cooling energy could be saved for a longer time. This is also in consequence of the control strategy to load the cold water storage only if it is off-peak period and stop the loading process if it is on-peak period. However, the highest power demand of the month has increased due to higher load rate of the cold water storage. But it helped to load the storage as fast possible when it was off-peak period.

ewz would have charged only CHF 17 865 for electricity consumption of 37 054 kWh and additionally a penalty charge of CHF 4191 for the highest power of the month. Thus, total costs of approximately CHF 22 056 would have occurred which would have led to a saving of approximately 10% of the costs occurred in December 2011.

7.2.2 Summer Season

Also in the simulation experiment with input data from June 2012, similar improvements like in the experiment with data from December 2011 have been realized. Compared to the as-is simulation experiment of the summer month, the chillers would have produced only 341 788 kWh cooling energy. Thus, less cooling energy would have been wasted and less electricity would have been consumed by the chillers. 418 768 kWh waste heat has been produced and 41 555 kWh could be utilized as heating energy. Only 2763 kWh gas energy was needed as additional heating energy.

Electricity consumption is amounting to 76 979 kWh which is 24 506 kWh less than in the as-is simulation experiment of the summer month. However, the highest power demanded by the chillers has gone from 1496 kW to 2419.8 kW. Thus, the highest electricity power would have been 545 kW instead of 337 kW as in the as-is simulation experiment. This increase is due to the higher load rate of the cold water storage and helped to load it very fast when it was off-peak period. Although the highest power demand is now larger than in the as-is simulation, the total costs have declined. ewz would have charged only CHF 44 147 electricity costs including CHF 5995 for the highest power demand of the month. Electricity costs were amounting to CHF 53 372 in the as-is simulation experiment. Thus, we could have achieved a saving of approximately 17.6%.

7.3 Dynamic Electricity Pricing

This section shows the results from simulation experiments with the same properties as in the simulation experiments from previous section except that dynamic prices based on spot market prices are used instead of the current two tariff prices. As mentioned in 5.5.2.2, to find out if electricity is currently cheap, the current price is compared with next hour's price.

7.3.1 Winter Season

The results of these simulation experiments show us that cooling energy has been produced only little more than the actual demand. Thus, less cooling energy has been wasted than in the previous two scenarios. The amount of produced cooling energy totals to 141 058 kWh while the demand for cooling energy was 137 612 kWh. This has led to waste heat production amounting to 172 829 kWh. 138 949 kWh of the produced waste heat could be used as heating energy. Only 35 969 kWh heating energy was sourced from the gas boilers.

In total, the chillers have consumed 31 770 kWh of electricity. As the peak demands are already incorporated in the spot market prices, there is no need to calculate the highest power demand of the month. Thus, we would have only paid for the electricity consumption of 31 770 kWh and the total costs would have been CHF 21 937. Compared to the as-is situation, we would have saved about 10.6% which is actually not an improvement from the simulation experiment without spot market prices. This situation may improve when another profit margin is selected. As we have already explained in 3.5, the selected profit margin is an average value and might in reality be lower.

7.3.2 Summer Season

A huge improvement can be realized for the summer season. Only 338 053 kWh cooling energy and simultaneously 414 191 kWh waste heat have been produced by the chillers. 42 039 kWh waste heat could be used as heating energy while 2279 kWh heating energy was sourced from the gas boilers. In total, only 76 138 kWh electricity has been consumed by the chillers which is 25 347 kWh less than the as-is simulation result. With the new control strategies as well as the spot market prices, total costs of only CHF 36 786 would have occurred during the period from December 2, 2011 to December 31, 2011. This would have led to a saving of approximately 31.3% compared to the as-is situation.

7.4 Summary

Table 7.1 summarizes the simulation results for the different control strategies by showing the costs and saving potentials for the two seasons.

	Winter	Summer
Current strategies	Costs: CHF 24 530	Costs: CHF 53 372
New control strategies	Costs: CHF 22 056 Saving: 10.0%	Costs: CHF 44 147 Saving: 17.6%
Dynamic electricity pricing	Costs: CHF 21 937 Saving: 10.6%	Costs: CHF 36 786 Saving: 31.3%

Tab. 7.1: Comparison between strategies

8

Conclusions

We have seen that the simulation framework Desmo-J is an appropriate tool for modeling a dynamic system with different scenarios and with the help of the simulation experiments we are able obtain results which help us draw conclusions about the real system.

We have also seen that under the given conditions, significant savings in electricity costs can be achieved using Smart Grid Demand Shaping. The simulation results from Chapter 7 reveal the difference in saving potentials between summer and winter season. The Smart Grid Demand Shaping ideas work better with the high cooling energy consumption in the summer months than with the low cooling energy consumption in the winter months. In contrast to the current control strategies in use, the new control strategies with or without dynamic prices achieve huge improvements in summer. Because there is a high demand for cooling energy in the summer months, it is possible to extract all the advantages from Smart Grid Demand Shaping. Especially, the extended storage capacities can be utilized more efficiently in the summer months, when demand for cooling energy is high, than in the winter months, when demand for cooling energy is low. In summer, the cold water in the storage is often utilized and thus, the storage needs to be loaded very often. That is why, the controller can benefit from the increased capacity of the cold water storage as well as cheap electricity prices. As soon as the electricity price is relatively cheap and the storage's energy level is little under the maximum energy level, the controller starts the loading process and saves electricity costs. Due to the high demand in the summer, this happens more often than in the winter. In the winter months, due to the low demand for cooling energy, the cold water storage does not need to be loaded very often, and thus the opportunities for saving electricity costs by loading the storage when electricity is cheap are less.

There are differences between the strategies under time-of-use rates and dynamic pricing. With time-of-rates which are currently in use less savings than with dynamic pricing can be achieved although the control strategies and storage capacities are the same. It maybe that we can obtain even better results with dynamic pricing if another profit margin has been selected. Although the profit margin of 2.21 as calculated in Section 3.5 seems to be high and the real profit margin may be a smaller value, a smaller value would only improve our results and bring more savings because we have currently modeled the worst case. The difference between the two pricing systems are more apparent in the results of the summer season. In the summer, with the new control strategies under the current pricing, only 17.6% savings compared to the results with the current strategies have been achieved whereas with the new strategies under dynamic pricing, about 31.1% savings compared to the results with the current strategies have been obtained. Although, the new strategies lead to less electricitiy costs, peak power demands may not decrease. This is because the cold water storages are loaded only if it is off-peak period. Thus, if the cold water storages have not been loaded for many hours because the prices have been very expensive, the chillers need to produce the necessary amount of cooling energy in order to fulfull the current cooling demand.

We can conclude that dynamic pricing related to spot market prices will help office building operators reduce the electricity costs for their heating and cooling systems. The savings might depend on their storage capacities and at which extent the storage capacities can be increased. As the results of our simulation experiments will be similar for other office buildings with similar heating and cooling systems, we can use them for drawing conclusions about saving potentials in other office buildings. Especially the differences in demands for cooling energy between summer and winter will be the same for all office buildings. Thus, by optimal Smart Grid Integration, electricity costs can be saved especially in the summer months in all office buildings.

However, in order to make use of Smart Grid Integration, smart interfaces that interact with the systems of the electricity companies must be available. This also requires a secure and reliable network for the transmission of important information about prices and demands. Advanced metering technologies must be available for measuring the energy levels of the storages and the demands for cooling and heating energy. They can help the control component with accurate calculations and quick decisions for the system.

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Listings

Bibliography

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