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Regulation of Individual Gas Consumers for Optimal Use of Limited Supply

Master Thesis

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Zurich, July 5 2009
Preface

I would like to thank the entire Power Systems Laboratory under Prof. Dr. Andersson for the possibility to write my master thesis with them. Stephan Koch deserves great thanks for his supervision and good ideas which helped greatly.

I am also very grateful to my project partner UjEP for the possibility to pursue this interesting topic, and learn many valuable lessons in the process.

This thesis concludes my Master’s Degree in electrical engineering at the ETH Zürich. It has been a most enjoyable, yet demanding, time. I am very glad to have chosen this field of study, and am much obliged to everyone who made this possible. My family has been very supportive during this time, and for this I would like to thank them. Further I would like to express my gratitude and appreciation to all the people which I have had the pleasure to meet during this time.

Zürich, July 5 2009

Emil Iggland
Abstract

The project partner supplies an industrial site with gas. The contract with the partner's supplier stipulates that only a certain amount of gas may be consumed during each hour. In cases where this amount is exceeded a penalty fee is due. This thesis attempts to provide a number of ways in which this overconsumption can be avoided.

A model of the site was developed in order to simulate the effect of the different schemes. To determine which method was most suitable for implementation a cost-benefit analysis was performed.

The result is a recommendation concerning which of the considered regulation methods could be implemented.

The methods used are general and can be used for other sites with a similar cost structure for gas purchase.
vi
Kurzfassung


Ein Modell des Geländes wurde erstellt um die Einflüsse der einzelnen Regulierungsmethoden zu simulieren. Um die am besten geeignete Methode zu bestimmen, wurde eine Kosten/Nutzen-Analyse durchgeführt.

Das Resultat ist eine Empfehlung bezüglich der Machbarkeit der einzelnen Methoden.

Die Methoden, die verwendet wurden, sind allgemein. Sie können auf andere Gelände mit einer ähnlichen Problemstellung angewendet werden.
# Contents

List of Figures xii

List of Tables xiv

1 Introduction 1
   1.1 Problem Formulation 1
   1.2 Site Description 2
   1.3 Gas Network 3

2 Current Gas Consumption 5
   2.1 Consumption Pattern 5
   2.2 Consumption Pattern for OFU 7
   2.3 Factors Affecting Consumption 9
      2.3.1 Dependence on Day of Week 10
      2.3.2 Dependence on Time of Day 13
      2.3.3 Dependence on Temperature 13
   2.4 Conclusion 16

3 The Cost of Consumption 19
   3.1 Fee Structure 19
   3.2 Cost of Overconsumption 20
   3.3 Improvements of the Subscription Amount 21
   3.4 Available Capital 22

4 Modeling 25
   4.1 House Model 25
   4.2 Heater Control 27
   4.3 Site Model 27
   4.4 Simulink Model 28
   4.5 Selection of Model Parameters 32
   4.6 Model Parameter Verification and Allocation 33
      4.6.1 Temperature Bandwidth 34
      4.6.2 Rate of Temperature Increase 34
      4.6.3 Rate of Temperature Decrease 35
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.5.1</td>
<td>Hard Limit</td>
<td>71</td>
</tr>
<tr>
<td>8.5.2</td>
<td>Soft Limit</td>
<td>71</td>
</tr>
<tr>
<td>8.6</td>
<td>Knowledge of Current Consumption</td>
<td>71</td>
</tr>
<tr>
<td>8.7</td>
<td>Weighting Factors</td>
<td>72</td>
</tr>
<tr>
<td>8.8</td>
<td>Simulated Case</td>
<td>72</td>
</tr>
<tr>
<td>8.9</td>
<td>Influence when Regulation is not Necessary</td>
<td>73</td>
</tr>
<tr>
<td>8.10</td>
<td>Comparison with Unregulated Site</td>
<td>73</td>
</tr>
<tr>
<td>8.11</td>
<td>Behavior with Unregulated Consumers</td>
<td>74</td>
</tr>
<tr>
<td>8.12</td>
<td>Use of Prediction</td>
<td>75</td>
</tr>
<tr>
<td>8.13</td>
<td>The Costs</td>
<td>76</td>
</tr>
</tbody>
</table>

9 Conclusion 79

A Site Map 81

Bibliography 85
List of Figures

1.1 Schematic description of the site .................................. 3
2.1 Year 2007 Hourly Gas Consumption .............................. 6
2.2 Temperature profile of OFU during a cycle ....................... 8
2.3 Detailed view of three OFU heating cycles ....................... 9
2.4 Comparison of average consumption per day of week between summer months and entire year ................. 11
2.5 Difference between mean consumption and temperature dependent consumption .............................. 12
2.6 Overconsumption occurrence frequency versus day of week .. 13
2.7 Deviation of actual mean hourly consumption and prediction based on mean temperature ......................... 14
2.8 Overconsumption occurrence frequency depending on hour of day ....................................................... 15
2.9 Plot of external temperature and gas consumption .......... 16
2.10 Linear relationship between consumption and temperature .. 17
3.1 Total cost and cost of overconsumption as a function of $Q_{\text{lim}}$ 22
4.1 Schematic description of an on-off heater control ............. 28
4.2 Simulink model of the site, without regulation ................ 30
4.3 Simulink model of the regulation infrastructure ............... 31
4.4 Measured temperature curves .................................... 34
4.5 Temperature and consumption curves for the unregulated site 36
5.1 Flow chart describing the storage algorithm .................... 38
5.2 Autocorrelation of consumption during year 2007 .......... 40
5.3 Comparison between measured and data predicted using linear regression ........................................... 42
5.4 Mean Error for linear regression with and without the current temperature as a regressor ......................... 43
5.5 Flow chart for predictive storage ................................ 44
5.6 Comparison of consumption with and without on-site storage capacity ............................................... 45
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7</td>
<td>Net present value versus the size of the storage vessel</td>
<td>48</td>
</tr>
<tr>
<td>5.8</td>
<td>NPV for linear variation in the consumption</td>
<td>50</td>
</tr>
<tr>
<td>5.9</td>
<td>Mean NPV for different band-widths of consumption</td>
<td>51</td>
</tr>
<tr>
<td>6.1</td>
<td>Schematic of regulation approach</td>
<td>55</td>
</tr>
<tr>
<td>7.1</td>
<td>Simulink model for the proportional allocation regulation approach</td>
<td>59</td>
</tr>
<tr>
<td>7.2</td>
<td>Consumption and temperature curves for heuristically controlled site, without minimal allocation constraint</td>
<td>60</td>
</tr>
<tr>
<td>7.3</td>
<td>Consumption and temperature curves for heuristically controlled site, with minimal allocation constraint</td>
<td>61</td>
</tr>
<tr>
<td>7.4</td>
<td>Comparison of consumption curves for unregulated and proportionally regulated sites</td>
<td>62</td>
</tr>
<tr>
<td>7.5</td>
<td>Comparison of heuristically regulated site with and without an active OFU</td>
<td>63</td>
</tr>
<tr>
<td>7.6</td>
<td>Estimated room temperature with consumption capped to 500 m$^3$</td>
<td>66</td>
</tr>
<tr>
<td>8.1</td>
<td>Temperature and consumption curves for system regulated with optimized allocation of consumption</td>
<td>73</td>
</tr>
<tr>
<td>8.2</td>
<td>Comparison between regulated and unregulated consumption when $Q_{lim} \to \infty$</td>
<td>74</td>
</tr>
<tr>
<td>8.3</td>
<td>Comparison between unregulated and optimally allocated consumption</td>
<td>75</td>
</tr>
<tr>
<td>8.4</td>
<td>Comparison between behavior with and without a single unmeasured consumer</td>
<td>76</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Percentile consumption ................................. 5
3.1 Cost components ........................................... 21
4.1 House parameters for selected buildings .............. 32
4.2 Temperature increase and decrease rates for selected buildings 35
LIST OF TABLES
Chapter 1

Introduction

UjEP Kft. manages the wholesale gas purchasing for an industrial site in Budapest, Hungary. The customers of UjEP are industrial and commercial buildings which use the gas for heating and for machining purposes. UjEP purchases gas from an upstream supplier and resells it to the on-site customers.

1.1 Problem Formulation

On-site customers are billed depending on the amount of gas they have consumed, however this does not reflect the cost of UjEP purchasing gas. The contract between UjEP, and it’s supplier, the Budapest Gas Works Co. \(^1\), dictates the structure of gas pricing as follows:

1. there is a fixed amount of gas which is subscribed to per period. This amount, called $Q_{\text{lim}}$, may not be exceeded. The upper limit, $Q_{\text{lim}}$, is chosen by the wholesale consumer. The period is currently one hour.

2. there is a price for consumed energy. This amount is measured at the end of each period.

3. if the consumption in a given period is greater than $Q_{\text{lim}}$ a penalty payment is due.

The upper limit on gas consumption cannot be freely moved on the short time, meaning that is is fixed for a longer period of time, typically a year.

The price paid by the wholesale customer to the supplier is dependent on the upper limit and the amount of energy consumed during a period. There is a fee for subscription to $Q_{\text{lim}}$ and another fee for the actual amount of gas consumed. In order to avoid overconsumption and the associated penalties

\[\text{\footnotesize \(^1\)Fővárosi Gázművek Zártkörűen Működő Részvénytársaság}\]
the solution has to date been to choose the upper limit on the gas consumption such that the $Q_{\text{lim}}$ is much larger than the maximum consumption, thus leaving a safety margin. This amount is based on historical values of gas consumption. The cost for this safety margin is substantial. The cost of subscription currently is $1000 \text{ HUF} \cdot \text{m}^{-3} \text{hr}^{-1}$. Using an exchange rate of $330 \text{ HUF/EUR}$ this translates to $3 \text{ EUR} \cdot \text{m}^{-3} \text{hr}^{-1}$. Assuming an energy density for natural gas that is $34 \text{ MJ m}^{-3}$, and with the current subscription amount of $Q_{\text{lim}}$ is $800 \text{ m}^3$, then this cost is $82'000 \text{ EUR}$ per year. A small correction in this amount would provide substantial savings.

The aim of the wholesale purchaser is to reduce the amount that is subscribed to. The ideal solution for UjEP would be a reduction below $500 \text{ m}^3$, which is the level for 'small' consumers. While a consumption of less than $500 \text{ m}^3$ does not offer a direct financial benefit, meaning a lower cost, there are implied benefits which include a greater security of supply. The upstream supplier is not allowed to shut off the supply of gas to the small consumers should upstream deliveries be canceled, or reduced, until all large consumer have been affected. This provides a clear benefit to UjEP’s customers.

The work presented in this document is aimed at finding a solution which enables UjEP to reduce the amount of gas which is subscribed to, ideally below the 'magical' amount of $500 \text{ m}^3$. It is aimed at finding a feasible solution to the problem, not at implementing such a solution. It compares several approaches to solving the problem and compares their influence on periodic gas consumption.

### 1.2 Site Description

The site for which UjEP performs wholesale gas purchase is located in Budapest, Hungary. The site is an industrial site, with mainly workshop buildings. The site also contains a number of buildings which are used for commercial purposes, mainly as offices. The site is approximately rectangular in size, and measures 400 by 200 meters.

The buildings at the site vary greatly in size and composition. The largest building is over 200 meters long and 60 meters wide, while the smallest buildings are 20 by 7 meters. Additionally to the large variability in size of the buildings there is also a large variation in the ages. The construction dates of the buildings range from 1870 to the present. The majority of the buildings were constructed in the 1950’s, 60’s and 70’s.

The buildings are generally low rise building, with one or two stories, but several buildings are higher. The height of the buildings ranges from 5 meters to almost 25 meters for the tallest buildings.

The buildings are constructed from a variety of materials including timber, reinforced concrete with brick exterior, as well as steel frame construc-
1.3. GAS NETWORK

The distribution of gas to the individual consumers is performed using a small on-site gas network. The gas network consists of a single central connection to the supply network, with piping delivering gas to the individual consumers. Gas is delivered to the site only via this main connection. This is also the place where the metering of the Budapest Gas Works takes place.

**Gas Meters** The customers are billed for their gas usage on a monthly basis. The billing is done on the basis of the energy consumed. For this purpose each building is equipped with a gas meter. These gas meters are
traditional, 'dumb', meters of a similar type as those generally installed in a residential or commercial buildings. In accordance with the large variability of the buildings on site, and their demand for gas, there is a similar variability in the meters. Several small meters are included on site, with maximum measurable gas flow ranging from $6 \text{ m}^3$ for the smallest buildings up to $400 \text{ m}^3$ for the largest consumers.

A schematic depiction of the site and the meters is presented in figure 1.1. The blue circles represent individual meters, while the black rectangles represent the consumers behind these meters. $M_0$ is the main site meter, and this one is monitored by the gas works.
Chapter 2

Current Gas Consumption

Any and all possible reduction in the maximum consumption must be placed in relationship to the current, unregulated consumption. As such it is necessary to understand the current consumption. Hourly consumption data for the year 2007 was made available by UjEP. This data describes the amount of gas consumed in the hour, as billed by the gas works. There is no information on the rate at which gas was consumed during each hour. A plot of this data is shown in figure 2.1. It is not sure that the consumption data for the year 2007 is representative of the general consumption, but as no other data was made available it will be assumed to be representative.

2.1 Consumption Pattern

The consumption is not a smooth curve with long periods of constant consumption, rather there is a large variability. This variability shows both on a short time scale, within the days, as well as over the entire year.

The yearly fluctuation follows an approximately sinusoidal curve, with its minimum during the summer months. The intra-day consumption does not show such clear tendencies.

The maximum gas consumption is 450% of the mean gas consumption during the year; 665 m$^3$ and 146 m$^3$ respectively. Table 2.1 shows the dis-

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<thead>
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<td>0</td>
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<tr>
<td>25</td>
<td>0</td>
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<tr>
<td>75</td>
<td>273</td>
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<tr>
<td>90</td>
<td>416</td>
</tr>
</tbody>
</table>

Table 2.1: Percentile consumption
CHAPTER 2. CURRENT GAS CONSUMPTION

Figure 2.1: Year 2007 Hourly Gas Consumption

The spread of the central 50% of the consumption is equal to the mean consumption. This indicates a large variability in the consumption. This large short-term variability, meaning that the actual maximum consumption is difficult to predict, was the primary reason that the subscribed amount was chosen to be so much higher than the maximum occurring consumption. Over 30% of the periods have zero consumption. 80% of these zero-consumption period occur during the summer. The remainder may be due to inaccurate measuring or communication errors between the meter and the data collector.

As stated in section 1.2 there are two main sources of gas consumption at the site: space and room heating and workshop related purposes. The heating demand is especially strong during the winter months. The consumption during such, typically colder, time is higher than the mean, while during the summer months the consumption decreases. During the summer months the consumption is mainly non-heating, and the peaks that occur during the summer months are attributed to the demand created by the workshops.
2.2 Consumption Pattern for OFU

The user with the highest consumption of gas for non-heating purposes is the so-called OFU-oven. The OFU is a large oven which is used for heat treating large metal constructions in order to relieve stresses in such constructions.

In order to de-stress the objects placed inside the OFU the oven cycles through a temperature profile. This profile consists of first heating the workpiece and then cooling it through a controlled process.

According to the operator of the OFU, the heating cycle of the OFU consists of the following parts:

1. Preheat the oven to 80 °C, and place the workpiece to be heated in the OFU.
2. Increase the temperature of the workpiece at a rate of 50 °C/hour until the temperature has reached 600 °C.
3. Maintain the workpiece temperature at 600 °C for 3-4 hours.
4. Reduce the temperature of the workpiece at a rate of 50 °C/hour until temperature has reached 450 °C. This is a controlled temperature decrease.
5. When the workpiece has reached a temperature of 450 °C, turn off the heating and allow for an uncontrolled cooling of the workpiece.

A schematic representation of such a cycle is shown in figure 2.2. This figure shows the temperature profile superimposed on the gas consumption curve.

The amount of gas consumed by the OFU is dependent on the workpiece to be destressed. Influences include the material that it is made of and the mass of the object. The maximum gas consumption of the OFU oven is 320 m³/hour. According to the operator of the OFU the average consumption of the OFU is 2000 m³ per de-stressing cycle, with such a cycle lasting on average 11 hours. The average power consumption at the separate stages was not known by the operator of the OFU.

Verification of OFU Consumption In order to verify the information delivered by the operator of the OFU an analysis of the consumption data was performed. For this analysis the consumption was split into two portions. These two portions, termed $C_{site}^{H}$ and $C_{site}^{nH}$, represent heating and non-heating consumption respectively. These portions are defined as in equation (2.1):

$$C_{site} = C_{site}^{H} + C_{site}^{nH}$$

From studies on heating systems it is known that the amount of energy consumed for heating purposes is dependent on the external temperature.
CHAPTER 2. CURRENT GAS CONSUMPTION

This relationship is the basis for the concept of heating degree days (HDDs), as discussed in [1] and [2]. The equation for a heating degree day is shown in equation (2.2).

\[ \text{HDD} = \max(18 - \text{temperature}, 0) \] (2.2)

The 18 °C used as the basis are taken from the referenced works. The more HDDs there are in a period the larger the amount of energy that is consumed. It is assumed that during the summer, taken to be the period represented by the meteorological summer from June to August, there will be zero HDDs, and that all consumption will be due to non-heating demand. Hence this is the ideal period to determine the correctness of the provided data.

The data set for the three summer months consists of 2208 values representing 24 values per day for 92 days, 30 for June, 31 each for July and August.

A visual inspection of the consumption data for this period shows that the consumption is almost zero most of the time, interrupted by period of high consumption. The consumption during the non-peak times is not strictly zero, rather there is a small consumption. Assuming that all consumption less than the 10th percentile of summer consumption is dependent

Figure 2.2: Temperature profile of OFU during a cycle
on either small heating demand, or stochastic consumption for workshop needs, such consumption will be disregarded for the comparison to the data presented by the OFU operator. Hour during which the aggregate consumption is less than 71 m$^3$ was thus excluded.

All hours during which consumption was greater than 71 m$^3$ are considered to be non-zero consumption period, and the remainder are considered to be zero consumption periods. Considering the information given by the operator, the periods during which the OFU is active should be non-zero consumption periods.

The mean duration of non-zero consumption periods is 11 hours, which while being slightly shorter than the cycle period as stated by the operator is close enough. The total consumption per non-zero consumption cycle is estimated to be 2350 m$^3$, which corresponds well with the information given by the operator.

### 2.3 Factors Affecting Consumption

During the remainder of the year, that is all times excluding the summer months, there is large variation in the consumption. This variation arises
from the variability in the temperature, and a number of stochastic influences.

At present the underlying cause of such consumption is expected to be space heating. It is thought that this demand varies, in addition to the variation with the external temperature, depending on other, external, factors as well.

Knowing the influence of these factors might allow for change in the way energy is consumed to be implemented, thereby avoiding the need to regulate. Such a method might be as simple as as preventing certain consumers from becoming active at specified times.

For the analysis of the gas consumption data it is assumed that there exists a set of factors which drive consumption. These factors reflect the underlying causes of the consumption. This chapter will attempt to identify these factors and to quantify their influence on consumption. A possible example of such a factor could be the day of the week, where a decreased passive heating, through computers, lighting and other consumer appliances, during weekends causes an increased heating demand at the beginning of the week. Further there may be buildings which are not heated during weekends, and workshop consumers which are not present during non-working times.

**Suspected Factors** Factors which are thought to affect consumption are the following:

- **Day of Week** - since some of the consumption is due to work being done in workshops it is expected that there will be a relationship between the hourly consumption and the day of the week. It is expected that consumption will be higher during working days, Monday through Friday, than on weekends. Further it is thought that some buildings will be heated less strongly during weekends.

- **Time Of Day** - as with the day of the week it is expected that consumption will be higher during working hours, approximately 0700 to 1800 than during the remaining hours of the day.

- **External Temperature** - the colder it is the higher the demand for heating. It is expected that, based on the relationship described in equation (2.2), a decrease in temperature will lead to an increased demand for heating energy.

Due to the nature of on-site consumers it is expected that the external temperature will be the largest driving force behind the consumption.

**2.3.1 Dependence on Day of Week**

The total heating energy input into a room is composed of several different factors. The main source is, in most cases, the radiator of the heating
system. Further sources include computers, people and lighting. If the heating system has been dimensioned to account for passive heat sources, such as people, then the temperature in the room will be lower after the weekend when there has been little, or no, activity. This suggests that there could be a larger need for heating on Mondays than on other days of the week. A similar effect might be expected when one considers the hours of the day, here the demand for heating should be higher in the early hours of the day. Additionally there are consumers which are not used for heating, due to the labor-dependent nature of these consumers, it is thought that they will not consume during non-working days.

![Comparison between whole year and summer consumption](image)

**Figure 2.4**: Comparison of average consumption per day of week between summer months and entire year

During the entire year there is a slightly lower consumption on weekends, days 1 and 7, with an increase towards the middle of the week. This trends is also seen during the summer months. During the summer months it should be noted that there is residual consumption on Sundays and Mondays, with most consumption taking place Wednesday through Friday.

While a linear prediction of consumption using only the temperature has a large error, this error is canceled in the mean; some values will be too large while other too small. As such the linear relationship can be used to detect differences between averages and a single day. The comparison between the
 CHAPTER 2. CURRENT GAS CONSUMPTION

mean daily consumption and the consumption predicted based on the mean daily temperature is shown in figure 2.5. Here it can be seen that during the weekend there is a significantly, between 12 and 17%, lower consumption than expected. Similarly there is an increase in consumption mid-week.

Days during which overconsumption occurs  As shown above the consumption during weekends, days 7 and 1, is lower than predicted by the linear relationship between the temperature and the consumption. Figure 2.6 shows the occurrence frequency of overconsumption depending on the day of the week. While the consumption was much higher than predicted on Wednesdays, the same is not the case for the overconsumption, here the rate of overconsumption is equally high on Thursdays.

The reduction in consumption during the weekends does not strongly impact the frequency with which overconsumption occurs. If it did, then the number of periods during which overconsumption occurs would be significantly higher on Mondays, which is not the case.

Figure 2.5: Difference between mean consumption and temperature dependent consumption
2.3. Factors Affecting Consumption

13

2.3.2 Dependence on Time of Day

Figure 2.7 shows the comparison between the consumption predicted based on the temperature, and the mean consumption during the different hours of the day. During the night the consumption is significantly lower than predicted, with deviations exceeding 20%. This is attributed, at least partially, to heaters being turned off during the night. There is also an increased consumption during the mid-day hours.

**Hours during which overconsumption occurs** Figure 2.8 shows the distribution of overconsumption depending on the hour of the day. It was shown above that the consumption during the night is lower than predicted, while the mid-day hours, from 10:00 to 15:00, have a consumption higher than predicted. The occurrence frequency of overconsumption is relatively stable for most hours of the day, there is however a large increase in the early morning hours, starting from 05:00.

2.3.3 Dependence on Temperature

The external temperature for the year 2007 is plotted along with the gas consumption in figure 2.9. The gas consumption measurements were taken...
once per hour, at the end of the hour. The time when the temperature measurements were taken is not known, but is assumed to be the mean temperature during the hour. It can be seen that the temperature curve has a similar shape to that of the consumption curve, subject to a reflection of the y-axis. When the temperature is low the gas consumption is high, and vice-versa. This is an indication that there is a strong relationship between gas consumption and the external temperature.

A plot of the external temperature versus the amount of gas consumed is presented in figure 2.10. It can be seen that a strong relationship is exhibited by the data. A straight-line linear least-squares fit to this data produces the fit-function described by equation (2.3). The error, calculated as the root mean square, is 104.8 m$^3$. The percentage error cannot be calculated as there are several times during which the consumption is zero.

$$\hat{y} = m \cdot x + c$$
$$\hat{y} = (-14.72) \cdot x + (342.20)$$

As described in equation (2.2) heating demand is expected to be zero when the temperature is above 18 °C. The straight-line linear least-squares fit on these consumption points is also shown in figure 2.10. This somewhat
2.3. FACTORS AFFECTING CONSUMPTION

Figure 2.8: Overconsumption occurrence frequency depending on hour of day

A steeper curve is a better fit for the low temperature consumption, giving a root mean square error of 99.6 m³. For the entire data set the prediction is significantly worse, giving a root mean square error of 271.5 m³. As demand cannot be smaller than zero, the predicted consumption during all times when the temperature is greater than 18 °C will be zero, this may be the reason behind the larger error. Since the mean error of the linear fit over the entire data set is smaller, this linear fit will be used for the remainder of the calculations.

As can be seen in figure 2.10 there is a large variability of the consumption at a given temperature. This large variability reduces the possibility of predicting the consumption accurately based solely on the temperature. While the temperature can be predicted relatively well using simple approaches, or by using data which can be purchased from an external supplier, such as a meteorological institute, the knowledge of temperature alone does not allow us to predict the gas consumption.

Considering an external temperature of 5 °C, the 10th percentile is 266 m³ and the 90th percentile is 466 m³. The spread between 10th and 90th percentile is more than half of the mean value. As the spread is so large there is little point of making predictions of the amount of gas consumed in
CHAPTER 2. CURRENT GAS CONSUMPTION

Figure 2.9: Plot of external temperature and gas consumption

a given hour based only on the temperature.

2.4 Conclusion

The analysis of the consumption data shows that the external temperature is the main driving factor behind consumption, and there is a strong relationship between the external temperature and the amount of energy consumed. The consumption during the weekends is lower than expected considering the influence of the temperature, the same is the case during the night.

The number of times that overconsumption occurs is strongly dependent on the time of the day. The most frequent occurrence of overconsumption is in the hours just after 05:00 in the morning. It is possible that a small decrease in the amount of overconsumption that can be achieved by changing the way in which the heaters are run. For example leaving the heaters on during the night would increase the morning temperature, thus possibly reducing the need for a large amount of heating during the early morning hours. The negative effect of this is increasing the total energy consumption. As consumers pay for energy but not for peak consumption this will probably not be implementable. It is not possible to test this using the available data, and as such this can only be taken as a recommendation. The over-
2.4. CONCLUSION

Figure 2.10: Linear relationship between consumption and temperature

consumption during the week is most frequent on Wednesday and Thursday. As the consumption during Thursdays closely resembles that predicted by the external temperature, this is attributed to a random grouping of cold days on Thursdays. On Wednesdays the consumption is much larger than predicted by the temperature. As the consumption is so much higher than predicted it is thought that much of the overconsumption is due to the OFU being run on Wednesdays. If the consumption was shifted to another day this would only lead to a shift in the location of the overconsumption, but not a reduction.

No peculiarities in the way gas is consumed could be detected. While there are recommendations that can be made, such as only using the OFU when the temperature is relatively mild, these recommendations are not sufficient to enable a reduction in consumption below the desired level.
Chapter 3

The Cost of Consumption

Gas is purchased by UjEP from the Budapest Gas Works and then resold to the on-site customers. The customers pay a consumption fee to UjEP. This fee is a linear function of the amount of energy consumed, and is calculated monthly. The structure of UjEP’s contract with the gas works is more complicated.

3.1 Fee Structure

The cost of gas consists of two portions: a fixed price and a variable price. The fixed portion is based on UjEP subscribing to a fixed amount of gas per calculation period. The calculation period is an hour. The variable portion is calculated depending on the amount that is consumed during a period. Additionally, if the hourly consumption exceeds the subscribed amount there is a penalty fee which is levied.

The total cost $C$ of fulfilling the gas demand for the site during a year is the fixed fee for subscription, $C_{\text{base}}$ plus the sum of the costs for the individual periods $c_k$, as described in equation (3.1).

$$C = C_{\text{base}} + \sum_{k=1}^{N} c_k \quad (3.1)$$

The cost during an individual period, $k$, is determined by four factors:

- $Q_{\text{lim}}$ - the capacity which is subscribed to, measured in m$^3$
- $Q_{\text{used}}$ - the amount of gas that is consumed, measured in m$^3$
- $Q_{\text{over}}$ - the amount of gas which is consumed in excess of the subscribed amount, measured in m$^3$
- $p_1, p_2, p_{3,1}, p_{3,2}$ - the prices for the subscribed amount, the amount consumed, and the overconsumption penalty
$p_1, p_2$ and $p_{3,2}$ are measured in HUF/m$^3$, $p_{3,1}$ is measured in HUF.

The cost make up is described in equation (3.2). During each period, $k$, from the first period of the year to the $N$-th period, 8760 for a non-leap year, there is a cost of consumption.

$$
C_{base} = p_1 \cdot Q_{lim}
$$

$$
c_k = p_2 \cdot Q_{used}^k + p_{3,1} \cdot \delta_{over}^k + p_{3,2} \cdot Q_{over}^k
$$

$$
Q_{over}^k = \max(0, Q_{used}^k - Q_{lim}^k)
$$

The cost for gas subscription is a linear function of the amount subscribed to, given by the term $C_{base}$. The variable cost of consumption is a linear function of the amount of gas consumed during a period, $k$, given by $p_2 \cdot Q_{used}^k$. The penalty fee levied when overconsumption takes place is determined by two factors. These two are explained in more detail in section 3.2, and are represented by the terms $p_{3,1} \cdot \delta_{over} + p_{3,2} \cdot Q_{over}$.

### 3.2 Cost of Overconsumption

The fine levied for overconsumption is determined by the subscribed amount and the amount consumed. The penalty is made up of two separate fines. The first is an hourly fine which is levied during each hour where overconsumption takes place, without taking into account the size of the overconsumption. The second is a fee-increase. In equation (3.2) the hourly fine is described by the term $p_{3,1} \cdot \delta_{over}$ where $\delta_{over}$ is defined as in equation (3.3).

$$
\delta_{over} = \begin{cases} 1 & Q > Q_{lim} \\ 0 & Q \leq Q_{lim} \end{cases}
$$

The hourly fine for overconsumption is based on the daily fee for capacity provisioning, that is 24 times the hourly fee for capacity. This is described in equation (3.4), where $p_1$ is the cost for provisioning, and 8760 is the number of hours in a year, assuming no leap days are present.

$$
p_{3,1} = \frac{24 \cdot p_1 \cdot Q_{lim}}{8760}
$$

The fee-increase is 20% of the variable price. Thus $p_{3,2} = 0.2 \cdot p_2$, as the original cost has already been taken into account.

Overconsumption is only possible if there is capacity available in the supply network. The supplier does not guarantee that there will be such capacity available. If there is no consumption available in the network supply exceeding the subscribed amount will be throttled.
3.3 Improvements of the Subscription Amount

The optimal level of $Q^{\text{lim}}$ is such that the total cost of gas consumption during the entire year is minimal. Subject to the constraints that $Q^{\text{lim}}$, $Q^{\text{used}}$ and $Q^{\text{over}}$ must all be $\geq 0$ for all times. This means that, as seen by the gas works, the site can only consume gas, and not deliver it to the network.

With an infinitely low cost for capacity, that is $p_1 \to 0$, the optimal level of $Q^{\text{lim}} \to \infty$ as this will guarantee that there will never be overconsumption. If the cost for overconsumption is low, $p_3 \to 0$, then $Q^{\text{lim}}$ should tend towards zero as the overconsumption will have zero cost. A compromise will have to be achieved between these two level depending on the relative costs. For very small levels of $Q^{\text{lim}}$ the total cost will be high as overconsumption occurs often, in the case of very high levels of $Q^{\text{lim}}$ the cost of provisioning the capacity is the driving factor behind the cost.

Two different pricing schemes are applied depending on the size of the gas consumer. This separation is made on the basis of the subscribed amount of gas consumption. When $Q^{\text{lim}} \leq 500 \text{ m}^3$ the site is considered to be a small consumer, while for $Q^{\text{lim}} > 500 \text{ m}^3$ the site is a large consumer. The prices paid by the different types of consumers is shown in table 3.1. Further rates for even smaller consumers are also available, but the limits are so low that they cannot fulfill the demand of the site.

<table>
<thead>
<tr>
<th>$Q^{\text{lim}}$</th>
<th>$p_1$ (HUF/ m$^3$/hr)</th>
<th>$p_2$ (HUF/ m$^3$)</th>
<th>$p_{3,1}$ (HUF/MJ/hr)</th>
<th>$p_{3,2}$ (HUF/ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 500$</td>
<td>34000</td>
<td>75.75</td>
<td>93.16</td>
<td>15.15</td>
</tr>
<tr>
<td>$&gt; 500$</td>
<td>34000</td>
<td>75.07</td>
<td>93.16</td>
<td>15.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Q^{\text{lim}}$</th>
<th>$p_1$ (EUR/ m$^3$/hr)</th>
<th>$p_2$ (EUR/ m$^3$)</th>
<th>$p_{3,1}$ (EUR/m$^3$/hr)</th>
<th>$p_{3,2}$ (EUR/ m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 500$</td>
<td>102</td>
<td>0.23</td>
<td>0.28</td>
<td>0.05</td>
</tr>
<tr>
<td>$&gt; 500$</td>
<td>102</td>
<td>0.23</td>
<td>0.28</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 3.1: Cost components

Using the measured gas data for the year 2007 the optimal gas subscription amount, without considering any regulation mechanisms, can be calculated. This calculation is performed by searching for the optimal value over the solution space, i.e. by varying $Q^{\text{lim}}$ and calculating the cost at the specified level. The result is shown in figure 3.1. The capacity subscription which causes the lowest total cost is 600 m$^3$. This is 250 m$^3$ less than the level that is currently subscribed to.
3.4 Capital Available for Investment in Regulatory Hardware

It is the aim of UjEP to reduce $Q^{\text{lim}}$ to under 500 m$^3$. At this level they will be categorized as a small consumer, which improves the security of supply. When gas supply to the upstream supplier is limited, large customers are the first ones to subjected to reductions. Any implementation of a regulatory algorithm will imply costs. In order to estimate the amount of money that could thus be made available, the cost of overconsumption using a limit of 500 m$^3$ was calculated using 2007 as a model year. The cost incurred due to overconsumption was 9.2 million HUF, or roughly 30’000 EUR. The cost of any regulation scheme will have to be paid for by the savings achieved by the regulation. In corporate finance the net present value (NPV) of a project is determined by the sum of cash outlay and inflows. The formula for calculating NPV is shown in equation (3.5). Here $A$ is the initial capital invested, $R_i$ is the cash inflow in year $i$, $r$ is the interest rate demanded and $n$ is the number of years for which the project will be active.

$$NPV = -A + \sum_{i=0}^{n} \frac{R_i}{(1+r)^i}$$

$$A \leq \sum_{i=0}^{n} \frac{R_i}{(1+r)^i} \quad (3.5)$$
3.4. AVAILABLE CAPITAL

Using an interest rate of 6% per annum, and assuming that the regulation scheme will have to be paid off within a ten year period, an upper limit for the amount that can be invested into the regulation scheme can be calculated. The net present value of any rational investment is at least zero, otherwise money will be lost, thus the initial investment amount must be less than the accumulated, time-discounted cash flow. This is represented by the second line in equation (3.5). With a virtual cash-flow of 30'000 EUR per year, the amount available for the investment in the regulation scheme 250'000 EUR. This assumes that the regulation is only used to reduce overconsumption and does not reduce the total energy consumption. It further assumes that all overconsumption will be accounted for, and disregards all savings that occur during years more than ten years in the future.

The reduction to under 500 m$^3$ does not imply minimum costs. Rather this is the aim, and in order to reduce the cost of overconsumption under this provision, regulation will be implemented. Using the money that would otherwise be paid for overconsumption, a relatively large amount of investment capital is thus available for investment into regulation schemes aimed at reducing the overconsumption of the site. Savings made under the implementation of the regulation schemes will have to be compared to the costs of implementing them. This will determine the individual economic feasibility of the approaches.
Chapter 4

Modeling

In order to be able to perform simulations on the different regulation methods a model of the site is required.

As the site consists of a collection of buildings the model of the site should reflect this structure: contain a number of individually controlled, diverse buildings and have a similar consumption characteristic to the real site.

4.1 House Model

In order to reduce the complexity of the model the house model should be kept as simple as possible. While the complexity of the real system is much larger there is no hope in capturing every influence; it is not feasible to create a perfect thermal model of the site as the time required would be excessive. For this reason it is seen as sufficient that there is a model which with reasonable accuracy reflects the behavior of a set of buildings. The model used is based on that used in [3], [4].

The house model kept as simple as possible. For this reasons the buildings are modeled as thin-walled cuboids containing a single radiator. For each building the walls are made of a homogenous material, and the interior consists of a single large room, filled with air. Thermal energy is supplied to the system by a water loop which is heated by a gas powered heater.

Equation (4.1) describes the energy balance of the heater. The burning of the gas provides energy to heat the water, this is reflected by the term $Q_{g,h}$. The rate, $\frac{dT_H}{dt}$, at which the water is heated depends on the thermal mass of the water, which is dependent on the volume, $V_H$, the specific heat capacity, $c_w$, and the density, $\rho_w$, of the water. The transfer of energy from the water to the room is assumed to be limited by the thermal conductivity, $K_{HR}$, of the heater and the surface area, $A_H$, of the radiator, as well as the room temperature, $T_R$. This approximation is also made in [4]. The temperature curves provided in [4] do not suggest that the approximation
leads to large deficiencies.

\[ c_w \rho_w V_H \frac{dT_H}{dt} = Q_{g,h} - K_{HR} A_H (T_H - T_R) \]  \hspace{1cm} (4.1)

Equation (4.2) describes the energy balance of the room. In the same way the water loop was heated by the energy fed into it by the gas powered heater, the air in the room is heated by the energy given off by the radiator. The thermal mass, \( c_{AP} V_R \), of the room has the analogous effect as the thermal mass of the water. Additionally to the energy brought into the system by the radiator there are other sources of heating energy. These sources are lumped into the term \( Q_{stoc} \). These uncontrollable sources include computers, sunlight and the heat given off by the inhabitants of the different buildings but also the influence of passive solar heating. Heat is given off from the room to the surroundings. The amount of energy that is given off depends, as was the case with the heater, on the area, \( A_{RO} \), of the building and the thermal conductivity, \( K_{RO} \), of the walls as well as the temperature, \( T_O \), of the surroundings.

\[ c_{AP} V_R \frac{dT_R}{dt} = K_{HR} A_H (T_H - TR) - K_{RO} A_{RO} (T_R - T_O) + Q_{stoc} \]  \hspace{1cm} (4.2)

Equations (4.3) and (4.4) are alternative formulations of equations (4.1) and (4.2), which are more suitable for formulating a state space solution.

\[ \frac{dT_H}{dt} = \frac{Q_{g,h}}{c_w \rho_w V_H} - \frac{K_{HR} A_H (T_H - TR)}{c_w \rho_w V_H} \]  \hspace{1cm} (4.3)

\[ \frac{dT_R}{dt} = \frac{K_{HR} A_H (T_H - TR)}{c_{AP} V_R} - \frac{K_{RO} A_{RO} (T_R - T_O)}{c_{AP} V_R} + \frac{Q_{stoc}}{c_{AP} V_R} \]  \hspace{1cm} (4.4)

In state-space representation, using \( \frac{d\vec{x}}{dt} = A \vec{x} + B \vec{u} \) and \( \vec{y} = C \vec{x} + D \vec{u} \), where \( \vec{x} \) is the state of the system, \( \vec{u} \) is the system input and \( \vec{y} \) is the system output, the system can be specified using the matrices \( A, B, C, D \).

The state variables in the model are the temperature of the heating water and the temperature of the room \( \vec{x} = [T_H \ T_R]^T \). The input variables for the model are the amount of energy added to the system by the heater, the amount of energy added by stochastic sources as well as the external temperature \( \vec{u} = [Q_{g,h} \ Q_{stoc} \ T_O]^T \), the output variable of the model is the temperature of the room, \( \vec{y} = [T_R] \)

\[ A = \begin{bmatrix} \frac{K_{HR} A_H (T_H - TR)}{c_{AP} V_R} & \frac{K_{HR} A_H (T_H - TR)}{c_{AP} V_R} \\ \frac{K_{HR} A_H (T_H - TR)}{c_{AP} V_R} & \frac{K_{HR} A_H (T_H - TR)}{c_{AP} V_R} \\ \frac{c_w \rho_w V_H}{K_{HR} A_H (T_H - TR)} & \frac{c_w \rho_w V_H}{K_{HR} A_H (T_H - TR)} \\ \frac{c_w \rho_w V_H}{K_{HR} A_H (T_H - TR)} & \frac{c_w \rho_w V_H}{K_{HR} A_H (T_H - TR)} \\ \end{bmatrix} \]  \hspace{1cm} (4.5)

\[ B = \begin{bmatrix} \frac{1}{c_{AP} V_R} & 0 & 0 & \frac{1}{c_{AP} V_R} \\ 0 & \frac{1}{c_{AP} V_R} & 0 & \frac{1}{c_{AP} V_R} \\ \end{bmatrix} \]  \hspace{1cm} (4.6)
In order to simplify the matrices the following variables can be defined:

\[ \theta_1 = \frac{1}{C_p \rho_w V_H} \]
\[ \theta_2 = K_{HR} \cdot A_H \]
\[ \theta_3 = \frac{1}{C_p A R_T} \]
\[ \theta_4 = K_{RO} \cdot A_{RO} \]

using the \( \theta \) variables the system matrices can be simplified, as shown in equation (4.9) through (4.12).

\[ A = \begin{bmatrix} -\theta_1 \theta_2 & \theta_1 \theta_2 \\ \theta_2 \theta_3 & -\theta_3 (\theta_2 + \theta_4) \end{bmatrix} \]

(4.9)
\[ B = \begin{bmatrix} \theta_1 & 0 & 0 \\ 0 & \theta_3 & \theta_3 \theta_4 \end{bmatrix} \]

(4.10)
\[ C = \begin{bmatrix} 0 & 1 \end{bmatrix} \]

(4.11)
\[ D = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix} \]

(4.12)

4.2 Heater Control

As with the rest of the site the model for the control of the heater was made as simple as possible. Each heater is controlled by an individual and autonomous controller. The controllers are all of ‘on-off’, or ‘bang-bang’, type, which is the typical behavior of a simple thermostat controlled device. The heater is turned on when the temperature drops below a lower bound, and is turned off when the temperature rises above the upper bound. This causes the temperature to vary in a band around the temperature set-point. An exemplary temperature and power curve is shown in figure 4.1.

4.3 Site Model

As the real site consists of a large number of individual consumers with no interaction this structure is reflected in the site model. Each buildings is modeled as described in section 4.1. The site model is created by concatenating the models of the individual buildings, and filling the remaining places with zeros. This reduces the computational intensity as compared to
CHAPTER 4. MODELING

Figure 4.1: Schematic description of an on-off heater control having separate entities for each building. Equation (4.13) shows how this concatenation is done, where $L$ is a placeholder for the $A,B,C,D$ matrixes.

$$L_{\text{site}} = \begin{bmatrix} L_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & L_n \end{bmatrix} \tag{4.13}$$

The site state vector is a simple concatenation of the individual building state vectors: $x_{\text{site}} = [x_1 x_2 \cdots x_n]$.

4.4 Simulink Model

In order to be able to study the effect of different variables on the site a model was created in Simulink. Figure 4.2 shows the layout of the model. The block labeled $\text{PowerDemand}$ contains the controllers for the heaters. The output is a vector containing the power flowing to each heater. The $\text{powerToEnergy}$ block integrates the power flow into an energy consumption, with a periodic reset to reflect the hourly billing periods. The house models are present in the state-space block. The regulation is implemented in the $\text{PowerDemand}$ block. An example of a regulated system is shown in figure 4.3. Common to all regulation schemes is that, in addition to the autonomous control of the heaters, signified by a the relay and gain elements, there is an auxiliary control signal. This control signal represents the allocation of power, for
example by the valve setting. The calculation of this signal is performed in the \textit{variable Allocation} block.
CHAPTER 4. MODELING

PowerToEnergy (periodic)

Power (W)

Energy (J)

Energy _lastPeriod

To Workspace 6

CumConsumption

To Workspace 3

To Workspace 1

PowerOut

Sum of Elements

\[ x' = Ax + Bu \]

\[ y = Cx + Du \]

Product 2

Matrix Multiply

PowerDemand

\[ \text{Constant 2} \]

\[ \text{Constant 1} \]

F

Figure 4.2: Simulink model of the site, without regulation
4.4. SIMULINK MODEL

Figure 4.3: Simulink model of the regulation infrastructure
4.5 Selection of Model Parameters

In order to have a good model performance the model parameters must be chosen so that they reflect the behavior of the actual site.

The buildings were all approximated as cuboids, with four walls and a flat roof. The size of the buildings was constructed from the site-map, presented in Appendix A. In order to simplify the model, only the largest buildings were considered. A total of 19 model-buildings were created to resemble the site. Several of the large buildings on-site are made up of multiple parts; these buildings were coupled together into single buildings. Table 4.1 shows the size parameters for some selected buildings.

The thermal transfer coefficient of the radiators was calculated assuming they were made of stainless steel with a thermal conductivity of around 15 W/m·K, and a thickness of 10 cm. While this is a greater thickness than would normally be the case, it is thought that due to several influences, including interior contamination, dust and old age, the thermal conductivity of the radiators will not be optimal. The size of the radiators was chosen so that it was between 1 and 5% of the external area of the building.

As brick is the prevalent construction material on site, the initial selection of the thermal transfer coefficients of the building walls was made assuming that the walls of the building were made of brick. Brick has, according to the Austrian brick association (www.ziegel.at), a thermal conductivity of 0.40 to 0.50 W/m·K. The walls were assumed to have a thickness of 0.3 m. The typical thermal transfer thus comes to around 1.6 W/m²·K, which is roughly a hundred times lower than the thermal transfer through the radiators. While the walls are significantly less insulated than is expected of modern buildings, with the Austrian brick association suggesting a transfer coefficient of around 0.5 W/m²·K, the buildings on-site are often old, and consequently not very well insulated.

In order to calculate the necessary size of the heaters the thermal loss at a norm temperature is used. The norm temperature was chosen as the lowest temperature that was expected during the year. This temperature was

<table>
<thead>
<tr>
<th>House Number</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Outer Area (m²)</th>
<th>Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27.78</td>
<td>44.44</td>
<td>5.00</td>
<td>1956.74</td>
<td>6172.72</td>
</tr>
<tr>
<td>3</td>
<td>26.67</td>
<td>23.33</td>
<td>10.58</td>
<td>1680.21</td>
<td>6582.99</td>
</tr>
<tr>
<td>4</td>
<td>16.67</td>
<td>55.56</td>
<td>24.50</td>
<td>4465.46</td>
<td>22691.54</td>
</tr>
<tr>
<td>5</td>
<td>13.33</td>
<td>22.22</td>
<td>14.89</td>
<td>1354.87</td>
<td>4410.31</td>
</tr>
<tr>
<td>7</td>
<td>41.11</td>
<td>73.33</td>
<td>12.00</td>
<td>5761.16</td>
<td>36175.16</td>
</tr>
<tr>
<td>8</td>
<td>7.78</td>
<td>30.00</td>
<td>10.00</td>
<td>989.00</td>
<td>2334.00</td>
</tr>
</tbody>
</table>

Table 4.1: House parameters for selected buildings
chosen to be -6°C. Further it was assumed that the temperature loss is given by equation (4.14), where $A$ is the total wall area, $\Delta T$ is the temperature difference, $\lambda$ the thermal transfer coefficient of the wall.

$$Q = \lambda \cdot A \cdot \Delta T$$

$$\Delta T = T_{\text{room}} - T_{\text{outdoor}}$$  (4.14)

It was assumed that the room temperature would be 22°C. The temperature difference thus amounts to 28°C. The heater size was then chosen so that there was a variation between the buildings, while the fraction of time during which the heaters must be active is between 0.04 and 0.7 for all the buildings. This ensures that the heaters can supply the necessary energy even at external temperatures below -6°C.

The selection of the amount of water in the heating system was chosen so that the cycle time of the system seemed reasonable. Clearly a heater will not have a cycle time ranging in the minutes, but rather closer to an hour.

The final selection of the parameters was performed by adjusting the parameters, determined as above, so that that all the important parameters remained with reasonable bounds. For example there were buildings where the heating water temperature was almost equal to the room temperature, in which case the thermal transfer coefficient of the radiator was reduced.

### 4.6 Model Parameter Verification and Allocation

The performance of the model is strongly dependent on the parameters which are used to describe the different thermal transfers which take place.

In order to be able to estimate if the input parameters assigned to the buildings are reasonable some form of verification is necessary. This verification shall not serve the purpose of finally describing a single building to perfection, but rather to find an interval in which the model buildings are found.

The parameter which can be measured most easily is the temperature of the buildings. The room temperature is also the parameter which best describes the performance of the heating system, as it is the only parameter which directly affects the inhabitants.

The building which was chosen to house the measuring equipment should be an average building, it should not be either the largest of the smallest building. Preferably it should also contain an (almost) vacant space in which the measuring equipment can be placed, so as to minimize the effect of external heat sources. The chosen room was a vacated office in building 27, which is a mainly commercial building. The measurements took place over a period of 50 days, with a temperature reading taken every 5 minutes. The resulting temperature curves are shown in figure 4.4.
4.6.1 Temperature Bandwidth

The temperature of the measured building varies in bands roughly 1°C wide, this is only half as much as used in the model. However, in the measured building the temperature does not fluctuate around a steady value, but rather changes with time. The reason for this fluctuation is not known, but could be due to the input of heating energy being constant as the control input is not the temperature of the room, but rather of the water leaving the heater. In the model system this effect is not present. It is assumed that during colder times, when the heating demand is generally large, the temperature will fluctuate less. This effect is hinted at during the first week of the measurement when the outdoor temperature was cold, and the indoor temperature fluctuated relatively little.

4.6.2 Rate of Temperature Increase

The measured date has a mean temperature increase of 0.8°C per 8 hours. This gives an average rate of increase of 0.1°C per hour.
4.7. THE UNREGULATED SYSTEM

<table>
<thead>
<tr>
<th>Building</th>
<th>Rate of Increase</th>
<th>Rate of Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.67</td>
<td>0.43</td>
</tr>
<tr>
<td>2</td>
<td>0.52</td>
<td>1.48</td>
</tr>
<tr>
<td>5</td>
<td>1.89</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 4.2: Temperature increase and decrease rates for selected buildings

4.6.3 Rate of Temperature Decrease

The measured data has a mean temperature decrease of 0.3 °C per 12 hours. This gives an average rate of decrease of 0.025 °C per hour.

4.6.4 Rates of Simulated Buildings

Table 4.2 shows the rates of temperature increase and decrease for selected buildings. The rates of both decrease and increase are higher than those measured. The measured building is an office building, and as such has relatively good insulation, and also contains a relatively large amount of stochastic heating, such as computers and people. The increased rates of temperature change make the simulated system faster. If the temperature in the buildings drops only slowly, then there will be fewer times during which the heaters will have to run. The performance of the real system will thus be less critical than the performance of the system that was modeled. As such any control actions taken on the model system should also be applicable to the real system which is slower.

4.7 The Unregulated System

In order to have a base case to compare regulation schemes against a base scenario was created. This scenario depicts the performance of the site as it is currently found.

The resulting temperature and consumption curves are shown in figure 4.5. It can be seen that the temperature does not drop below the designated temperature band although the external temperature changes. The consumption pattern is erratic and fluctuates greatly, as is also the case of the real system.

Based on the desire to limit real consumption to 500 m$^3$, the limit chosen for the simulation is 500 m$^3$, a value which is exceeded a few times during the simulation duration. Due to limitations in memory handling the simulation could only be performed for 94 hours. The first 10 hours have been discarded as they show transient behavior arising from the starting values.
Figure 4.5: Temperature and consumption curves for the unregulated site
Chapter 5

Storage

Gaseous fuels have a long history of being stored. In large cross-continental supply networks much of natural gas storage is performed underground, for example in depleted gas fields. The reasons for storing gas are similar to those for storing electrical energy, and include leveling generation fluctuations, speculation and protecting against malfunction of upstream systems. Above ground storage has been performed since the middle of the 19th century. Traditionally storage was performed at close to atmospheric pressure. While this means that a large storage volume was necessary, the buildings were kept relatively simple. As the system pressure was close atmospheric pressure, the filling and emptying of gas was simple. In order to decrease the space necessary to store a given amount of gas the pressure can be increased. As natural gas can be stored in the form in which it will later be consumed, its storage is not associated with any real losses of energy. As such natural gas is much more suitable to be stored than electrical energy.

5.1 Requirements

In order to be able to store gas a storage vessel is required. Further an inlet and outlet to this vessel are required. The outlet can be realized by a valve which can be opened when gas is to be taken out of storage. In order to reduce the volume necessary to store the desired amount of gas, it is pressurized. Filling the storage is therefore more complicated and requires a pumping device, usually a compressor. Furthermore an online measurement of the current consumption of the site, as well as the withdrawal from the supply network and the amount of gas stored is necessary.

5.2 How Storage is Performed

The simplest regulation method would be to pump gas into and out of the storage vessel so that the net flow rate from the supply network does not
Chapter 5. Storage

Figure 5.1: Flow chart describing the storage algorithm

exceed $R_M$, with $R_M$ defined as in equation (5.1), where $Q_{\text{lim}}$ is the amount of gas subscribed to, and $T$ is the period length. $R_M$ is thus the maximum sustainable rate of gas consumption.

$$R_M = \frac{Q_{\text{lim}}}{T} \quad (5.1)$$

Using the small consumer upper limit of 500 m$^3$ we arrive at $R_M = 0.13$ m$^3$/s, or 4.7 MW. When the site consumption is lower than this the storage vessel is filled at the maximum rate possible, limited either by the rate at which the storage vessel can be filled, by the difference between site consumption and the maximum flow rate or by the free capacity of the storage vessel. When the site consumption exceeds $R_M$ gas is taken from the storage vessel and fed to the consumers. This algorithm is shown in the flow chart in figure 5.1. $R_{\text{site}}$ is the amount of gas that the site is currently consuming, and $R$ is the gas storage rate.

Equation (5.2) describes this relationship. $R_{\text{store}}$ is the amount of gas that is taken out of, or put into, storage at a given time. Positive values imply feeding gas into storage. The net withdrawal from the supply network is given by the sum of these two values. As shown in equation (5.3).

$$R_{\text{store}} = R_M - R_{\text{site}} \quad (5.2)$$

$$R_{\text{net}} = R_{\text{store}} + R_{\text{site}} \quad (5.3)$$
5.3 Storage without Prediction

When the decision to feed gas into the storage vessel is made using on-line measurements, the amount that is taken out of, or put into storage is dependent only on the current consumption.

The total consumption, as seen by the upstream provider, during the period is given by the integral of the flow rate. The flow rate is the net consumption relative to the supplier, \( f = R_{\text{site}} - R_{\text{store}} \). The total consumption during the period is thus given as in equation (5.4).

\[
Q_{\text{period}} = \int_{0}^{T} f \, dt \quad (5.4)
\]

In this case the storage will be used during the earliest possible time. As soon as the momentary site consumption is higher than the average rate, as defined in equation (5.1), stored gas is used as to level short term consumption. As the rate at which gas is fed into the storage vessel is chosen so that the momentary net withdrawal from the supply network is always equal to or less than the average rate, the possibility of causing an overconsumption by storing gas is avoided. When gas is taken out of storage it is only taken out at the rate necessary to bring the net withdrawal from the supply network below the average rate. Thus when the storage is being emptied it will reduce the overconsumption as much as possible, but only as much as necessary, thereby preserving stored gas for later periods.

5.4 Storage with Prediction

There are some cases, typically when the storage vessel is almost empty, during which the early emptying of the vessel is detrimental to the total cost of consumption. Such a case would occur when the amount of gas available in storage is smaller than the overconsumption during the current period, but larger than the overconsumption in the next period. This means that by completely emptying the storage vessel in the current period an overconsumption cannot be avoided, only reduced in size. Likewise the overconsumption in the next period cannot be avoided. If it were possible to predict the consumption during the next period, the usage pattern of the storage vessel could be improved. In the case discussed above this would mean that the overconsumption during the current period were allowed to take place, and the stored volume is used to remove overconsumption during the next period.

5.4.1 Prediction of Consumption

In order to be able to improve the usage of the storage vessel relative to the simple scheme considered prior, it is necessary to be able to make a good
prediction of the consumption in the next periods. As was seen in chapter 2.3 the influence of the temperature is strong, but variability is too large to allow for prediction to be made using only the temperature as a parameter.

Auto-correlation is a measure of how similar a curve is to a time-shifted copy of itself. If a signal exhibits a strong auto-correlation then the signal itself can be used to make predictions of future values. If such similarity does not exist other factors must be considered.

Figure 5.2 shows the autocorrelation of the consumption during the year 2007. The correlation drops relatively quickly, and can be seen to have periodic peaks every 24-hour period.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{autocorrelation.png}
\caption{Autocorrelation of consumption during year 2007}
\end{figure}

It is presumed that the main reason for the auto-correlation present in the consumption data is the strong dependence on the temperature, which in turn has strong auto-correlation.

**Linear Regression** Linear regression is a method that is used to find linear relationships between input and output variables. Using linear regression to predict electrical load during the day is discussed in [5]. The methods used there have been adopted to fit the problem at hand.

Equation (5.5) describes the creation of a least squares regression on the observed values. \( h \) represents the regressor parameters, and \( y \) is the
measured consumption used for determining the regression matrix \( X \), \( \hat{h} \) the input parameters used to predict the consumption \( \hat{y} \).

\[
y = Xh + \epsilon \\
\hat{h} = (X^T X)^{-1} X^T y \\
\hat{y} = X\hat{h}
\]  

(5.5)

As the consumption possesses a periodic peaking in autocorrelation for lags up of \( 24 \cdot n \) hours, it is expected that the best regressors that can be fitted will be the consumption during the proceeding 24-hour period. For the consumption during period \( t \) the prediction is thus based on the consumption during periods \( t - 1 \) to \( t - 25 \).

The maximum prediction horizon depends on which is the last period to be used for the prediction. A minimal lag of 1 period means that only the consumption during the current period can be predicted, while a minimum lag of 2 period allows the consumption during the next periods to be predicted as well.

Several different lag lengths were considered in order to determine how this factor influences the prediction.

Adding current temperature as input factor  
As the temperature has such a large influence on the consumption it is assumed that including the temperature as an additional regressor would improve the prediction. Not using the temperature as a linear factor provides relatively good prediction values. Two versions were considered. The first is using only the current temperature. The second was to use both the current temperature and the temperature during the preceding day.

Error comparison  
While a visual inspection can provide a rough estimate of which prediction method is better, it can not quantify how good this prediction is. In order to have a metric for the ‘goodness’ of the prediction the mean error was used. The mean error is defined in equation (5.6), where \( Y \) is the measured signal, and \( Y_p \) is the predicted signal,

\[
ME = mean \left( \sqrt{(Y - Y_p)^2} \right)
\]  

(5.6)

For all calculations the the consumption curves for the first month of the year 2007 were used to calculate the regression matrix \( H \). Independent of the lag 24 regression was performed over 24 values of the gas consumption. For a lag of 1 hour, the resulting prediction can be seen in figure 5.3. The lags which were considered were 1 hour, 2 hours and 5 hours. These lags are termed lag set 1 2 and 3 respectively.

The results of the linear regression prediction are potentially relatively good. The short term prediction using only the past consumption as a re-
CHAPTER 5. STORAGE

Figure 5.3: Comparison between measured and data predicted using linear regression

A regressor has a mean error of about 10 m$^3$, while the two period prediction has a mean error of 20 m$^3$. Compared to the yearly mean consumption this is an error of 7 and 14 % respectively. Percentage errors relative to the current consumption cannot be properly calculated as the consumption is frequently zero. Increasing the prediction length quickly causes the prediction to worsen. The same is the case when adding regressors. This can be seen in figure 5.4. The worsening of the prediction when adding more regressors may be due to the multi-collinearity of the regressors. Collinearity occurs when two regression variables are correlated to each other. Multi-collinearity occurs when multiple regression variables are strongly correlated, as is the case with the temperature and the gas consumption. A consequence of such multi-collinearity is to a deterioration of the prediction.

5.4.2 Storage Algorithm with Prediction

A prediction horizon of 2 hours was shown to be reasonably reliable. A prediction horizon of two hours means that the consumption during the current and the next period can be predicted. Using such a prediction horizon, the formulation of an algorithm for improved storage can be as follows:
5.4. STORAGE WITH PREDICTION

Figure 5.4: Mean Error for linear regression with and without the current temperature as a regressor

- IF the predicted consumption for next period is greater than the limit
- AND the predicted consumption for the current period is greater than the limit
- AND the predicted overconsumption, during the current period is greater than the amount present in storage
- AND the predicted overconsumption during the next period is smaller than the amount present in storage
- THEN the storage should be used during the next period

This algorithm only regulates the discharge time of the storage. Filling the storage is still performed at the earliest time possible. During times when the store is being emptied, emptying the storage is performed at the same rate as in the non-predictive algorithm. The algorithm is shown in figure 5.5, where $C^p_i$ is the predicted consumption during period $i$ and $A^s$ is the amount of gas available in the storage vessel.
Figure 5.5: Flow chart for predictive storage
5.5 Simulation of Storage on Real Data

As the storage algorithm is a relatively simple system, its effect on the measured data from the site can be simulated.

In order to perform the simulation the measured consumption for the year 2007 and the proposed storage size are taken as input. The output of the simulation is a modified consumption curve. Figure 5.6 shows the comparison between the original consumption curve, and the consumption curve when storage is implemented. During much of the times the curves are the same, the storage has no influence on the consumption. This is due to the fact that the storage vessel is filled relatively quickly, and emptied during only a few periods. However, the effect of the storage can be seen clearly when there is overconsumption.

![Performance of Storage Scheme](image)

Figure 5.6: Comparison of consumption with and without on-site storage capacity

Using a 2-period ahead linear prediction of the consumption, and the algorithm explained above, a total cost for overconsumption using predictive storage, using a storage vessel containing 500 m$^3$ at system pressure, is 1.67 MHUF (5010 EUR), while the total cost for overconsumption using non-predictive storage is 1.86 MHUF (5400 EUR). The absolute savings are relatively small. Due to the small savings caused by the predictive storage, it will not be considered differently from the non-predictive method for
calculating the storage cost.

5.6 The Cost of Storage

The cost of storage is primarily dependent on the amount of gas that is to be stored. As there is no time-dependent price fluctuation associated with the cost of purchasing gas, the cost which is incurred when gas is pumped into the storage vessel can be recovered when the gas is taken out of storage again.

5.6.1 The Cost of the Storage Vessel

The cost of the storage vessel is mainly dependent on the amount of steel which has to be used to make it. The amount of steel required to make the vessel is dependant on the thickness of the vessel walls and the inner radius of the hollow sphere. An estimate for the mass of a spherical pressure vessel is given by equation (5.7), according to Wikipedia. In this equation $P$ is the pressure under which the gas is stored, $V$ the volume of gas that is to be stored, $\rho$ is the density of the steel and $\sigma$ is the maximum stress which can be applied to the material before its deformation is no longer reversible.

$$M = \frac{3}{2} PV \rho \sigma$$  \hspace{1cm} (5.7)

As this approximation could not be verified from other sources, the approximation was compared to exact values. For the verification of the estimated formula the equation for shell thickness, as described in [6], [7] and [8], shown in equation (5.8) was used. Here $P$ is the gauge pressure, $r$ the inner radius, and $X$ the thickness of a hollow sphere. For the considered storage sizes the maximum deviation between this estimated mass and the actual mass is 0.2%. As such the approximation is thought to be sufficiently good.

$$X = \frac{Pr}{2\sigma}$$  \hspace{1cm} (5.8)

The calculations for the cost of the storage vessel were performed using a steel density of 8000 kg/m$^3$, a yield strength of 250 MPa, a gas pressure of 10 bar, 10$\cdot$10$^5$ Pa, and a steel cost of 2.2 EUR/kg. The value of 2.2 EUR/kg for the cost of steel was taken from discussions with manufacturers of pressure vessels. The prices for raw steel are significantly lower, however this higher price reflects the cost of transporting, taxes and other costs incurred during construction.

The savings available due to storage are calculated as the difference between the cost incurred by overconsumption in the system without storage minus the cost of overconsumption in the system with storage implemented.
5.6. THE COST OF STORAGE

5.6.2 The Cost of the Compressor

The cost of the compressor is made up of two portions. The first is the cost of purchasing the compressor, the second the cost of operating the compressor.

The cost of purchasing the compressor

The cost of purchasing the compressor is dependent on the flow rate, that is the amount of gas that can be compressed during a given time. A second factor is the pressure to which the gas is to be compressed.

The maximum flow rate with which the storage vessel can be filled is given by the subscription amount. As $Q_{\text{lim}}$ has been set to 500 m$^3$ the maximum flow rate is 8.3 m$^3$/min. During times when overconsumption is likely, that is during the winter months, there will be a negligible amount of periods during which the entire 500 m$^3$ can be used to fill the storage. The mean consumption in the periods where the external temperature was lower than 5 $^\circ$C was 388 m$^3$. It will be assumed that the maximum fill rate that can realistically be achieved during a majority of the hours during a year will be 100 m$^3$/hr or 1.6 m$^3$/min. The pressure that was selected for the sizing of the vessel was 10 bar, and will be the pressure that the compressor must be able to compress to. A range of compressors can be found on the Internet. Many of these do not fulfill all the demands posed above, but are used in order to estimate a price for a suitable compressor. An example of such a compressor is the Birkenstock K30/90/400, which can compress 0.6 m$^3$/min to a pressure of 10 bar. The rated power of such a compressor is 4 kW and the cost is roughly 1'500 EUR. A Compair C20, which can compress 2 m$^3$/min to a pressure of 8 bar has a rated power of 16.3 kW and a cost of approximately 5000 EUR. The compressor with ratings matching the demands most closely was a Atmos E.140, capable of compressing 1.5 m$^3$/min to a pressure of 13 bar, and with at rated power of 15 kW. The cost for this compressor is 8'500 EUR. The price for all three compressors is in the range between 1’000 and 10’000 EUR. For further calculations it will be assumed that the cost of purchasing the compressor be 10’000 EUR and the power rating 15 kW.

The cost of running the compressor

The cost of running the compressor is assumed to be dependent on the cost of electricity to power the compressor. Using the simulation performed on the real data there are 160 hours during the year in which the compressor must run in order to feed gas into the storage. Assuming that 15 kW compressor is used, and an electricity cost of 25 EUR/MWh, the electricity cost for running the compressor is 60 EUR. If the compressor were allowed to run for the entire year, that is all 8760 hours, then the cost would be 3'300 EUR. For further calculations it will be assumed that there is no cost associated with the running of the compressor. Thus it is free to pump gas into and out of the storage vessel.
5.6.3 NPV

In order to have a single number which can be used to compare the value of the different storage sizes, the Net Present Value, or NPV, of each storage structure is calculated. The NPV is the sum of time discounted cash flows for each storage size. Equation (3.5) describes how the NPV is calculated, where \( A \) is the initial investment amount, \( R_i \) is the cash flow in each period, and \( r \) is the interest rate. The initial investment here was taken to be the cost of constructing the storage vessel, without a compressor and control equipment. In order to get to the results of figure 5.7 the initial investment was taken as the cost of the storage vessel, the yearly cash flow was taken as the amount that could be saved by using a storage vessel, the time to write off was 10 years and the interest rate was 6\%. Scrap value was not taken into account as it is not assumed that the storage vessel will be torn down after ten years.

The maximum NPV is achieved at a storage size of 2250 m\(^3\).

This calculation does not include the cost of the compressor. As far as can be determined, without a thorough specification of the compressor with corresponding charge rate and pressures, it is thought that this cost can range from 5'000 to 10'000 EUR. This is significantly lower than both the maximum NPV, around 180'000 EUR, and the minimum NPV, around
80'000 EUR, of the storage vessel. As there is a negligible cost of operating
the compressor adding the cost of the compressor will perform a linear shift
of the NPV curve. The same optimal size of the storage vessel will be
achieved.

5.7 Sensitivity Analysis of Storage Vessel Size

The effectiveness of the storage is greatly dependent on the size of the storage
vessel. The optimal size of the storage vessel depends on the consumption
during a year. In order to determine the long-term optimal sizing it is
necessary to know the long-term development of the consumption curve. Due
to the lack of available data, it is not possible to determine any development
pattern for the consumption.

Due to this limitation sensitivity analysis was performed. Sensitivity
analysis is a method for determining the variability of the output based on
variations on the input parameters. In the studied case the input parameter
is the consumption curve. The output is the optimal size for the storage
vessel. Optimal in this context meaning the largest NPV.

Two types of variation in the consumption curve can be expected. The
first is a general increase in the size of consumption, as could be expected
either by a much colder year, or by additional consumers being added to the
site. The second is a fluctuation in the consumption pattern, as would be
expected when the site is subjected to a temperature profile with a similar
distribution as that during 2007.

5.7.1 Proportional Increase in Consumption

The first variation is based on a linear increase in the consumption. Using the
linear regression of consumption versus external temperature, as described
in chapter 2.3 it is known that there is a 30 m$^3$ increase in consumption
for a 2 °C fall in temperature. A three degree decrease in temperature
is equal to a 15% increase in the mean consumption during times when
the temperature is lower than 10 °C. The same range of temperatures is
considered for increasing temperatures.

It is assumed that the increase, or decrease, in temperature causes a
linear increase in the consumption over the entire year. This relationship is
shown in equation (5.9).

$$C' = \beta \cdot C$$

$$\beta \in \{0.85, 0.90, 0.95, 1.00, 1.05, 1.10, 1.15\}$$

(5.9)

The linear increase in consumption will cause additional times of over-
consumption and increase the size of the already occurring overconsumption,
as well as reducing the amount of consumption which is available for refilling
the storage. This generally stresses the storage more. Figure 5.8 shows
the NPV for the different levels of consumption. A relatively small increase in consumption, 5%, causes a large increase in the optimal storage volume, 600 m$^3$ from 2250 to 2850 m$^3$. While a corresponding decrease in the consumption causes an almost equal large decrease in the size of the storage vessel.

![Graph showing NPV for linear variation in consumption](image)

**Figure 5.8: NPV for linear variation in the consumption**

Assuming that each of these changes in consumption amounting to 0.5 and 10% in each direction are equally likely the optimal storage volume is 2900 m$^3$, calculated as the volume at which the mean NPV is maximum. At this level the NPV only becomes negative if the consumption decreases by 15%.

### 5.7.2 Random Variation of Consumption with Constant Mean

The second scenario considers a mean temperature which does not change, but with a variation in the size of the consumption pattern.

For this scenario, the change in consumption, $C_\beta$, is distributed randomly, and equally, in a band on each side of the original consumption curve. The width of the band is the parameter which reflects the variability. In an approach based on Monte-Carlo simulation, 1000 different consumption curves were calculated based on equation (5.10). For each of these curves the NPV was calculated for the considered storage levels.
5.7. SENSITIVITY ANALYSIS OF STORAGE VESSEL SIZE

\[ C' = C + C_\beta \]
\[ C_\beta = C_{\text{offset}} + C_{\text{var}} \]
\[ C_{\text{var}} \in [\beta_{\text{min}}, \beta_{\text{max}}] \] (5.10)

Figure 5.9: Mean NPV for different band-widths of consumption

For each level of variability the average NPV for the 1000 iterations curves was calculated and is shown in figure 5.9. It can be seen that for variations in the consumption of up to 50 m$^3$, the optimal size of consumption storage does not change significantly. The optimal storage size remains around 2250 m$^3$. The same is the case for larger variations as well.

The consideration of variability shows that the effectiveness of the storage vessel does not depend on the momentary fluctuation of the consumption, but primarily on the mean consumption.

Allowing for a mean increase in consumption by 25 m$^3$, with a variability of ±50 m$^3$, causes an increase in the optimal storage size to 2950 m$^3$, which is comparable to the optimal storage size for a linear increase of 5%. As 25 m$^3$ is equal to 5% of the subscribed to amount this is not surprising.

The optimal storage is not affected by variability in the supply. While the NPV increases with increasing variability the optimum storage size remains constant.
5.8 Conclusion

Flattening the consumption curve with a storage vessel is a relatively simple yet successful method for reducing overconsumption. The amount by which overconsumption can be reduced is limited by the frequency with which overconsumption occurs. In the considered case overconsumption does not occur frequently, and do not last excessively long. As such storage can be implemented at the site. The net value of a storage would be positive considering a ten year payback time.
Chapter 6

Regulation of Consumers

The following chapter discusses the aspects involved in regulating a single consumer. Two sorts of regulation are considered: the decrease, and the increase of consumption.

6.1 Gas Consumption

The energy content of a block of gas is determined by the volume gas, the density of the gas, and the combustion energy of the gas. The volume and density of the gas determines the mass of the gas.

The power flow into a consumer is thus determined by the product of the mass-flow of gas into this consumer, and the energy content of the gas. The mass of gas present in a volume can be calculated using the ideal gas equation, as shown in equation (6.1). The mass of the block of gas is dependent on the number of molecules, $n$, present. Provided that neither the temperature, $T$, nor the gas constant, $R$, change, the mass of gas present in a volume is dependent only on the volume of the gas and the pressure it is under.

$$pV = nRT$$ (6.1)

The power flowing to a consumer is given by equation (6.2), where $e$ is the energy content of the gas, $p(t)$ is the, time-dependent, pressure of the gas, and $V(t)$ the, also time-dependent, volume of gas flowing into the consumer.

$$P(t) = e \cdot p(t) \cdot V(t)$$ (6.2)

The energy content of the gas is assumed to be constant. While this is not strictly true, there is a slight variation due to changes in the make-up of the gas, there is no simple way in which the energy content can be
influenced. Further the variation is small, so it shall be assumed that the energy content of the gas is constant.

\[ E = \int_{t_0}^{t} e \cdot p(t) \cdot V(t) dt \quad (6.3) \]

The energy consumed is given by the integral of the power, as described by equation (6.3). Taking this formulation there are three factors which influence the amount of energy delivered to a customer:

1. Gas pressure
2. Gas volume
3. Delivery time

### 6.2 Reducing Gas Consumption

Using the three factors described it can be seen that consumption reduction can be achieved in three ways.

The first way is to reduce the delivery time. This is essentially a forced change in the behavior of the heater-controller. It is not clear that all consumers will react well to such an intrusion. For this reason this method is seen as the worst possible method of reducing gas consumption.

Reducing the pressure of the gas requires an regulator valve. Most such regulator valves available on the market are targeted at maintaining a constant output pressure given a varying input pressure. For a pressure regulator to be an applicable solution they would need to be easily controllable. While patents for controllable solutions exists, such as [9], there is a lack of available products on the market.

Reducing the volume of gas flowing into the consumer can be done using a throttling valve. A throttling valve limits the area through which gas can flow, thereby limiting the volume. A large selection of throttling valves are available on the market. These are easily controllable through electrical means. A schematic description of this is shown in figure 6.2.

The throttling valve can reduce the consumption from 0 to 100% of the nominal consumption. The control signal for the valve can accept values from the range \([0, 1]\) where 1 means allowing nominal consumption, and 0 meaning completely inhibiting consumption. This method allows a linear regulation of consumption over the range \([0, P_{\text{nominal}}]\).

Placing a throttling valve at each consumer allows us to individually control the allocation of gas flow to each consumer.

\[ P_i(t) = x_i(t) \cdot P_{i,\text{nominal}} \]
\[ x_i \in [0, 1] \quad (6.4) \]
6.3 Increasing Gas Consumption

Ideally one would be able to increase the consumption of gas during certain periods. This would enable an increase in the building temperature in anticipation of a pending cold period. This would increase the amount of ‘wiggle-room’ available.

Unfortunately it is not possible to, with individually controlled heaters, to force them to consume. As is the current state of affairs each consumer autonomously decides on whether they want to consume. There is no manner in which they can be forced to start consuming.

If the consumer is consuming, then it would be possible to increase their consumption by increasing the pressure of the incoming gas stream. As was the case with the limitation, there is a limit to how much gas consumption can be increased. This limit is due to security considerations as the boiler will not have been designed for such operation.

When both a decrease and an increase in the consumption is possible, the power flow into a consumer can be written as in equation (6.5)

\[
P_i(t) = x_i(t) \cdot P_{t,\text{nominal}} \\
x_t \in [0, X_{\text{max}}]
\] (6.5)

Increasing the consumption of a consumer does not given any beneficial effect to the total energy consumption. During a given period the consumption will not be reduced by increasing the allocation to a consumer, as such it will not be considered any further.
6.4 Consumers which cannot be Regulated

Some consumers on site have demand characteristics which prevent them from being regulated. Such a consumer is the OFU. As the OFU must be heated at a specific rate it’s energy demand is given. Reducing the allocation to the OFU can prevent it from running, or cause it to malfunction.
Chapter 7
Heuristic Regulation

A heuristic solution is a solution based on previous experience and rule-of-thumb approaches. In many cases these solutions are good enough and provide satisfactory performance. For the considered site, several different schemes were considered, many of which were not successful. These include a forced shutting off of heaters where the temperature was over the set point, and reducing the allocation depending on the temperature of the building. None of these solutions were able to consistently reduce overconsumption under the determined level, and did thus not provide any real improvement.

The chosen heuristic was based on proportional allocation, this is a concept known from the allocation of funds during a bankruptcy proceeding, and is explained in detail in such works as [10]. The bankruptcy problem considers the division of a fixed amount of goods to a number of stakeholders. The amount available is lower than the total desired amount, thus the total demand cannot be fulfilled. The simplest rule for distributing a limited amount to a diverse set of stakeholders is the proportional method. This gives each stake-holder the proportion of his claim, relative to the ratio between the total amount to be allocated and the total amount available. This is described in equation (7.1), where $A$ is the total amount available, $D$ it the total demand, $C$ is the total claim held by the stake-holder and $G$ is the amount finally allocated to the stake-holder.

\[
\lambda = \frac{A}{D}
\]
\[
G = \lambda \cdot C
\]

(7.1)

7.1 What is Required

While heuristic solutions can be arbitrarily complex, the proportional allocation of consumption requires little additional measuring and control structure. As the supply of the site is performed through a single source, and as all consumers will be given proportional allocation, a single regulation
point is sufficient. What must be measured is the following: the consumption to date in order to determine how much consumption remains and the time remaining during the period. Further the rated demand, $P_{\text{rate}}$ of all consumers on site must be known.

### 7.2 How is the Regulation Performed

The proportional rule is a simple method for allocating the consumption between the different consumers. In order to do this the amount to be distributed has to be calculated. The amount that is to be distributed is the remaining energy, and it is to be distributed across all consumers and the remaining time. At each regulation instance during the period the remaining gas volume is calculated by comparing the already consumed, and measured, volume to the subscription level. This remaining amount is then divided by the remaining time in order to get a rate of consumption which could be maintained for the remainder of the period without exceeding the subscription amount. This consumption rate is termed the target rate, and denoted $R_T$. This is described in equation (7.2).

$$R_T = \frac{E_{\text{rem}}}{T_{\text{rem}}} \quad (7.2)$$

In order to ensure that there is no possibility that the total consumption of the site does not exceed the target rate, the allocated amount is calculated based on the total rated power of the site. The calculation of the allocation $\alpha$ is shown in equation (7.3).

$$R_T = \alpha \cdot P_{\text{rate}} \quad \alpha = \frac{R_T}{P_{\text{rate}}} \quad (7.3)$$

While this reduces the allocation below the level necessary if only the consumers that were active at a given time were considered in order to determine the allocation, the measurement need is much smaller. In order to accurately be able to determine the state of the heater, the consumption would have to be measured. This would require a meter placed at each heater, thus greatly increasing the complexity of the solution.

### 7.3 Accounting for Under-Dimensioned Heaters

With the proportional allocation all consumers are given the same allocation. In the case where this allocation does not allow the heater to provide sufficient heating input to the building the temperature will begin to drop.

In order to account for this a minimum allocation can be calculated at each instance. For this the energy need of all the buildings is estimated and placed in relation to the rated power of the heaters.
The minimal power demand of the building is given by the power lost from the building. This is dependent on the thermal transfer coefficient of the buildings, and the temperature difference between the building and the environment, as shown in equation (7.4). Here \( h \) is the heat transfer coefficient of the building, \( A^{\text{ext}} \) is the external surface area of the building and \( \Delta t \) is the temperature difference between the interior and the surroundings.

\[
P^{\text{loss}} = h \cdot A^{\text{ext}} \cdot \Delta t
\]  

(7.4)

As the difference between the upper and lower boundaries of the band within the building should be maintained is small compared to the difference between the interior temperature and the external temperature, the interior temperature need not be measured, but can be assumed to be constant. This means that the individual building temperatures need not be measured. The minimum allocation which is in all cases able to maintain the temperature of all buildings is given by the building with the highest relationship between power lost and rated heater power, as shown in equation (7.5), where \( \alpha \) is the allocation and \( P^{\text{rate}} \) is the rated power of the buildings.

\[
\alpha_{\text{min}} = \max\left( \frac{P^{\text{loss}}}{P^{\text{rate}}} \right)
\]

(7.5)

During times when this minimum allocation is higher than the allocation \( \alpha \) overconsumption may not be avoided. However it will assure that all buildings are able to maintain their temperature.

The performance of the allocation with and without determining the minimum allocation will be compared.

### 7.4 Simulation on Modeled System

![Simulink model for the proportional allocation regulation approach](image)

Figure 7.1: Simulink model for the proportional allocation regulation approach

As the effect of this regulation method cannot be calculated on the measured data, the modeled system will be used to determine the effect which it
has on the consumption. Figure 7.1 shows the Simulink model that is used to perform the calculation.

Using the benchmark case for the site, as described in section 4.7, as comparison the performance of this regulation scheme is simulated. The regulation is successful in reducing the consumption below the subscription amount, this is the case for all times, there are no periods during which the regulated amount exceeds the limit.

![Performance of Proportional Allocation without minimum](image)

**Figure 7.2:** Consumption and temperature curves for heuristically controlled site, without minimal allocation constraint

Figures 7.2 and 7.3 show the temperature and consumption curves for the site when the proportional allocation method is considered. Figure 7.2 concerns the case when there is no minimal allocation, in which case the consumption is successfully reduced under the limit, but there is a building which is not able to maintain an acceptable temperature. Figure 7.3 shows the case when a minimal allocation is determined. Here all the buildings are able to maintain their temperature, but the site consumes too much energy during certain hours.
Influence on the Site when No Regulation is Necessary  As the regulation algorithm should not influence the consumption of gas during periods when it is not needed the upper limit is increase to a level greater than the largest possible consumption. When the site is simulated with this level of consumption all buildings are able to maintain their temperature as desired, and the consumption is not greatly different from the non-regulated site. This is the case for the proportional allocation.

7.5 Comparison to Unregulated Site

In order to determine how good the different regulation schemes are they are compared to the unregulated site. This comparison is shown in figure 7.4.

The proportional allocation without minimum is able to maintain the consumption below the limit at all times. This is not the case for the proportional allocation without minimum. In the unregulated case there are
26 hours during which the consumption is in excess of the limit, for the proportional allocation with minimum this number is reduced to 25. This is not through to be a significant reduction, but is rather attributed to 'luck'.

Only the proportional regulation without a minimum consumption is able to maintain consumption at a level lower than the limit. As the proportional allocation with minimum allocation cannot limit the site consumption it will not be considered for the remainder of the discussion.
7.6 Behavior with Unregulated Consumers

As there are some consumers on site which cannot be regulated they will have to be excluded. As such they will cause a problem when consumption is high. Ideally the regulation routine would be able to prevent all overconsumption even in this case, however this is not expected.

![Comparison between site with and without OFU consumption](image)

Figure 7.5: Comparison of heuristically regulated site with and without an active OFU

Figure 7.5 shows the consumption curves of the site with and without an active OFU oven. While the regulation does not succeed in preventing the overconsumption it greatly reduces the size of it. In the worst case the consumption of the OFU would be added on top of the regulated consumption, giving a maximum consumption of over 650 m³, however the maximum realized consumption is only 510 m³.

7.7 The Costs

The monetary cost of the proportional allocation regulation scheme is low. The only material that is needed is a gas meter that is able to output the consumption to date and a regulating valve which can change the amount of gas that is fed into the system. Further a small control system is needed to
control the valve. Even using costs at the upper end of the reasonable price range, 25'000 EUR for the valves 5'000 EUR for the meters and another 10'000 EUR for the control devices and the necessary wiring the time to repayment is less than 3 years, assuming that the algorithm is constantly capable of reducing the consumption below the subscription amount, and that the consumption pattern for the year 2007 is representative.

The large potential cost with this method of regulation is the decreased comfort in the buildings. Unfortunately this comfort loss is very difficult to quantify. Most research into the thermal comfort of buildings is concerned only with a relative well being, measured on descriptive scales such as the ASHRAE and Bedford scales. The Bedford scale ranges from 'Much too hot’ to 'Much too cool’. Apart from the lack of monetary value introduced by such descriptive scales, there is also a large variability in the perceived comfort level. Research in [11] shows that there is a very large variability in the perceived comfort. Using the ‘proportion of subject comfortable’ as a measure a range of 10 °C was comfortable. This is much more than subjectively expected, and is possibly due to the number reflecting expected temperature shifts in Pakistan. In [12] the percentage of people dissatisfied (PPD) is expected to be 20% for a one degree change in temperature. Accounting for the 5% of people that are dissatisfied at the set temperature the expected amount of people dissatisfied is reduced slightly. Thermal comfort is dependent strongly on the type of building, the activity and the dress of the building inhabitants. As many of the buildings are workshop buildings subjected to significant draughts due to large open doors, lost of movement but with inhabitants generally dressed sufficiently warmly and performing physical labor their discomfort is expected to be lower than that of office inhabitants.

In order to be able to have an estimate of the cost for lost thermal comfort the following assumptions were made:

- For every 1 °C degree temperature drop below the lower bound of the temperature scale an additional 10% of people experience discomfort. For temperatures above 18 °C no one experiences discomfort.

- At temperatures below 15 °C all inhabitants experience thermal discomfort

- GDP per capita in Hungary is around 20’000 USD, around 15’000 EUR, according to [13]

- Thermal discomfort leads to complete loss of productivity. That is someone who is not comfortable does not do any work.

Assuming that the average worker has a work week of five days, eight hours per day, and works 47 weeks per year, the total number of hours worked during a year is 1880. Thus the average value of an hours work is
7.7. THE COSTS

around 8 EUR. It is assumed that much of the work performed on site is of higher value than the average, and thus an hourly value of 15 EUR will be assumed. Using 2000 workers on site, the total site productivity is estimated at 30'000 EUR/hour.

We assume that the site has a total volume of 100'000 m$^3$, this corresponds to an average height of 4 m over the roughly 25'000 m$^2$ of floor space available on site. Further air is assumed to have a specific heat capacity of 1.3 kJ m$^{-3}$ K$^{-1}$. This means that the air on-site has a specific heat capacity of 130 MJ K$^{-1}$. However the air is not the main store of thermal energy, but rather the walls are. Assuming that the buildings are made of a half-and-half mixture of brick and concrete, with specific heat capacity of 0.84 and 0.88 kJ · kg$^{-1}$ K$^{-1}$ respectively, the mean specific heat capacity of the walls is 0.86 kJ · kg$^{-1}$ K$^{-1}$. The mean density of the walls, calculated following the same scheme as above, is 1920 kg · m$^{-3}$. For a building 10 meters wide, 10 meters long, and 10 meters high the heat capacity is in the range of 100 · 10$^6$ J · K$^{-1}$. Most of the buildings on-site are larger than this, with a correspondingly larger heat capacity. The largest buildings on-site have a heat capacity in excess of 1 · 10$^9$ J K$^{-1}$. The actual heat capacity is much higher as the interior walls are not considered here.

The heuristic regulation scheme is able to cap consumption at 500 m$^3$ during all times. This means that the temperature loss will be dictated by the amount that consumption is reduced by. The maximum hourly consumption during the year 2007 was 665 m$^3$. Using an energy content of 34 MJ · m$^3$ this amounts to 5.6 · 10$^9$ J. As a calculation a total site heat capacity of 30 GJ · K$^{-1}$ was used. The estimated site temperature decrease by less than 0.2 K/hr. The longest consecutive time during which consumption was in excess of 500 m$^3$ lasted 24 hours. Thus the maximum temperature decrease is only expected to be about 5°C.

In order to have a metric to compare the costs due to lost productivity to the savings due to reduced overconsumption the room temperature was estimated for the entire year. The room temperature was calculated as described in equation (7.6), where $C$ is the site heat capacity, roomTemp$_i$ is the room temperature during period $i$, and $A_i^{\text{missing}}$ is the amount of gas that is missing due to the capping of consumption. In cases where the actual consumption was less than 500 m$^3$ the room is heated using the consumption between the actually measured consumption and 500 m$^3$.

$$\text{roomTemp}_i = \min(20, \text{roomTemp}_{i-1} - C \cdot A_i^{\text{missing}}) \quad (7.6)$$

The estimated room temperature is shown in figure 7.6. During 35 hours of the year the temperature drops below 18°C, while it never drops below 17°C. The loss of productivity thus caused amounts to around 105'000 EUR. However this estimate is high, as several hours during which the temperature dropped below comfort level will have occurred during nights and weekend.
Figure 7.6: Estimated room temperature with consumption capped to 500 m$^3$

Assuming that 25% of the week (42 hours of 168) are used for productive work the lost productivity is around 26'000 EUR. Which is approximately equal to the costs incurred due to overconsumption.

The calculation of the value of the proportional allocation scheme is rather simple. In the worst case all savings are offset by the cost for lost productivity, and then the NPV is negative. This is the case when the site-operator UjEP has to pay for costs. However, if the cost is borne by the consumer the NPV is large, above 200’000 EUR.
Chapter 8

Regulation with On-Line Optimization

In order to properly and fairly distribute the energy provided by the gas to the consumers there are several possibilities. As seen in the previous chapter heuristic approaches do not always guarantee satisfactory results. The allocation based on heuristics can cause a single building to perform badly. In order to counter this an approach based on optimally allocating consumption to the consumers was sought.

8.1 Introduction to Optimization Theory

The mathematical discipline of optimization is concerned with finding the best solution to a problem. Generally the solution is not a global optimum, but a local one. The solution space is bounded by physical limitations on the system to be optimized. The general formulation of an optimization problem is stated in equation (8.1). The objective function $f(u)$ is the metric that is to be optimized. The functions $g(u)$ and $h(u)$ place bounds on the possible solution space.

$$
\begin{align*}
\min & \quad f(u) \\
\text{subject to} & \quad g(u) \leq 0 \\
& \quad h(u) = 0
\end{align*}
$$

(8.1)

This framework is only the general formulation of the problem, and does not provide any solution to it.

8.2 On-line Optimization

The basis for the on-line optimization is the notion that there is a amount of energy left which can be consumed during the remainder of the period.
The aim of the optimization is to consume as much as necessary, but that the amount consumed should not exceed the amount of energy remaining.

As the optimization concerns the allocation of consumption capacity to consumers the amount of energy remaining cannot be directly used in the optimization problem. The first step is to perform an estimation on the desired rate of consumption, henceforth called the target rate.

\[
E_{\text{rem}}^{\text{target}} = Q_{\text{lim}} - \int_{kT}^{t} p(t) \, dt
\]

\[
R_{T} = E_{\text{rem}}^{\text{target}} \cdot \frac{(k + 1) \cdot T - t}{(k+1) \cdot T - t}
\]  

This target rate is based on a Taylor expansion of the consumption around the current time. Instead of using the derivative of the function to determine what the total consumption at the end of the period will be, the maximum allowable derivative, that is the rate of consumption, is set so that the consumption at the end of the period equals \(Q_{\text{lim}}\).

\[
f(y) = f(y_0) + f'(y_0) \cdot (y - y_0)
\]

\[
F((k + 1)T) = F(t) + R_{T} \cdot [(k + 1) \cdot T - t]
\]

**8.2.1 The Objective Function**

The fundamental objective of the optimization is to fairly distribute heating energy to the consumers. Fairness in this case shall imply that the consumers are given the amount which most closely reflects their portion of the total momentary demand. In the considered case the building temperature is the driving factor behind demand. In order to be able to compare the different buildings their temperature is normalized. In order to do this the relative thermal energy content, as described in [14], is used. This number includes all the information necessary to describe the thermal state of the object relative to the limits of expected performance. The numerator describes the deviation of the temperature from the temperature set-point, while the denominator adjusts for the influence of the width of the acceptable temperature band.

\[
E_{\text{th}} = \frac{T - T_{\text{set}}}{T_{\text{hi}} - T_{\text{lo}}}
\]

Energy should be allocated to consumers so that those with the lowest temperature are given preferential access. A low temperature is reflected by a low thermal energy content.

In the formulation of the relative thermal energy content given in equation (8.5) the lower boundary of the thermal band is given by \(E_{\text{th}} = -0.5\). Assigning gas to consumers which must be heated is done by formulating an alternative objective, \(H\). This ensures that consumers may be allocated
8.3 Boundary Formulation

Limitations on the solution space  The solution space consists of a set of actuator variables. The actuator can be completely open, partially open, or completely closed. For each actuator this means that the allocation to the consumer can be in the range from 0 to 1, in units of nominal consumption, as shown in equation (8.8)

\[ x_i \in [0, 1] \quad (8.8) \]

There may be situations in which the valve may not be completely shut off, as this could potentially damage the heaters. For this reason the lower bound on the allocation is increased to \( x_{LB} \), so the acceptable range for \( x \) is \([x_{LB}, 1]\).

While it is also possible to perform a binary selection on the allocation of consumption to the consumers, \( x_i \in \{0, 1\} \), this solution cannot be better than the continuous solution. The selection of binary variables will mean that the marginal consumer will have no consumption allocated to them. This is the classical problem associated with the knapsack problem. The last object that can be placed into the knapsack will, in almost all cases, not fill the capacity, thereby leaving spare and unused capacity.

8.4 Limit on Consumption

The optimization should guarantee that the consumption does not exceed the amount amount available. However, there may be a certain amount of leeway granted. In words this difference can be expressed as 'should' versus 'must'. In the 'must' case a hard limit is formulated which may under no circumstances be exceeded, and in the 'should' case any exceeding of the limit incurs a cost penalty.
The total consumption of the group is given by the sum of the individual consumptions, and the individual consumption is given by the product of nominal consumption and allocation.

### 8.4.1 Hard Limit

The hard upper limit can be formulated as in equation (8.9). This does not require any change in the objective function, as is thus the easiest formulation.

$$\sum_{i=1}^{N} P_i \cdot x_i \leq R_T \quad (8.9)$$

### 8.4.2 Soft Limit

If a soft upper limit is included the upper limit on consumption can be reformulated as in equation (8.10). The addition of $\varepsilon$ requires that this variable is included in the objective function.

$$\sum_{i=1}^{N} P_i \cdot x_i + \Upsilon \leq R_T \quad (8.10)$$

$$\Upsilon \leq 0$$

$\Upsilon$ is zero for all those time when there is no overshoot.

In order to be able to compare it with the temperature the overshoot on consumption must be normalized, so that the order of magnitude is similar, and the units are the same. The normalization is described in equation (8.11).

$$\varepsilon = \frac{\Upsilon}{R_T} \quad (8.11)$$

The objective function, equation (8.7), must be rewritten in order to account for the cost of overconsumption, as can be seen in equation (8.12). The variables $\alpha_1$ and $\alpha_2$ are weighting variables which enable giving different relative weights to the two factors.

$$f(x) = \alpha_1 \sum_{i=1}^{N} H_i \cdot x_i - \alpha_2 \cdot \varepsilon \quad (8.12)$$

### 8.5 Formulation of the Optimization Problem

The objective function that is chosen depends on the desired formulation of the upper limit on consumption.
8.5.1 Hard Limit
- Objective function - Equation (8.7)
- Solution Space - $x \in [x_{LB}, 1]$
- Upper Limit - Equation (8.9)

8.5.2 Soft Limit
- Objective Function - Equation (8.12)
- Solution Space - $x \in [x_{LB}, 1]$
- Upper Limit - Equation (8.10)

8.6 Knowledge of Current Consumption

Two different formulations can be made pertaining to the amount of knowledge of the current consumption of the consumers. The first case is that it is not known which consumers are currently active, but that their maximum consumption is known. Without the knowledge of which buildings are currently heating, the allocation to each consumer is too low. The group among whose members the consumption is allocated is spread over the entire site. Buildings which are not actively heating, and are thus not contributing to the possible overconsumption are treated in the same manner as those which are causing a problem. This means that the total calculated consumption is greater than the actual one, and therefore leads to a lower allocation. Thus is clearly not an ideal situation.

The second case is that knowledge about the current consumption of the heaters is known. This reduces the size of the allocation group to those consumers that are active. With this reduction in the number of consumers the allocation can be spread more fairly. This additional knowledge comes at the cost of increased measurement, but without this knowledge the allocation is incorrect.

There are two different manners in which this knowledge can be derived. Either through the measurement of the current gas consumption, or by an approximative approach which considers the temperature. Buildings in which the temperature is increasing are probably being heated, while buildings in which the temperature is decreasing are not being heated. A metered solution is the better solution as there is less room for error; there are several other influences apart from heating which can cause the building temperature to rise or to fall thus giving an erroneous estimate. Buildings which are thought to be off are not regulated, they are allocated their norm consumption. Hence, if the estimate is wrong, that is a consumer is thought
to be off when they are on, will lead to the actually consumed amount being greater than the consumption expected based on the allocated amounts, thus giving site consumption which potentially exceeds the set limits.

When the state of the consumers is known the consumption problems can be reformulated. The limit on consumption, as formulated in equation (8.9), can now be extended as shown in equation (8.13), where $\delta_{i}^{on}$ is an indicator variable describing the state of heater $i$, as stated in equation (8.14).

\[ P_i = \delta_{i}^{on} \cdot P_{i}^{0} \quad (8.13) \]
\[ \delta_{i}^{on} = \begin{cases} 1 & \text{if } P_i \neq 0 \\ 0 & \text{if } P_i = 0 \end{cases} \quad (8.14) \]

8.7 Weighting Factors

As was the case with the proportional allocation, there may be some consumers which are not allocated sufficient energy to maintain their temperature. This is an effect of the optimization. As the objective function can be minimized by allocating consumption to a large number of consumers, certain large consumers will be negatively impacted. In order to remedy this, the objective function can be weighted with the rated power of the heater in relationship to the total rated power. This is formulated in equation (8.15), where $P_{tot}$ is the total power of the site, with $P_{on}$ as defined in equation (8.16).

\[ \text{obj} = H \cdot W \cdot x \]
\[ W = \text{diag}(P_{on}/P_{tot}) \quad (8.15) \]
\[ P_{on}^i = \begin{cases} P_{i}^{rate} & \text{if heater } i \text{ on} \\ 0 & \text{if heater } i \text{ off} \end{cases} \quad (8.16) \]

The actual weighting could be further adjusted to account for different needs of buildings. Whereas an office building may need to maintain its temperature, this need not be the case for a storage. For the further calculation it was assumed that all buildings had equal need to maintain their temperature.

8.8 Simulated Case

The simulated case consists of the same parameters that was used in the unregulated simulation.

The objective function that was used is given by equations (8.12), with a relative weighting of 1:100 between temperature and overconsumption, thus according the overconsumption a much larger penalty. The lower limit of
8.9 Influence when Regulation is not Necessary

As was the case with the proportional allocation of consumption the regulation scheme with optimized allocation does not influence the system when the consumption is low. This is shown in figure 8.2. The difference between the unregulated site consumption and the regulated site consumption is small, less than 3 m$^3$, during all times.

8.10 Comparison with Unregulated Site

Figure 8.3 the consumption curves for the unregulated and optimally regulated sites are shown. Further the consumption curve for the site regulated
with proportional allocation without a minimum is included. As was the case with the proportional allocation without minimum the optimization is able to reduce the consumption below the limit, however due to the soft limit of the consumption it does not do this all the time. There are 8 hours during which the consumption exceeds the limit. However, as the overconsumption is small the same effect could be achieved by lowering the limit used in the calculation slightly below the actual subscription amount. The benefit of the optimal allocation is that there are no buildings which are not able to maintain their temperature.

Further it can be seen that there are more periods during which consumption is at the limit than is the case with the proportional allocation. The optimized allocation consumes the subscription amount during many hours, while the proportional allocation does not, as such the limit is better used with the optimal allocation.

8.11 Behavior with Unregulated Consumers

When all consumers are regulated their aggregate behavior is as predicted. It is known how much each consumer uses. As there are on-site consumer
which can not be regulated this scenario must also be considered. At the site studied such a consumer is the OFU-oven.

Figure 8.4 shows the resulting demand curves for the case when all consumers are regulated and the case when not all consumers are regulated. The regulation is not able to prevent overconsumption with a non-controlled consumer, it is however able to reduce the effect of this unmeasured consumption. The first cycle of the OFU runs between hours 24 and 36 of the simulation. In the worst case scenario the OFU would add its entire consumption on top of the regulated consumption, causing overconsumption which is correspondingly large. The simulated overconsumption is in the range of 10% of the OFU consumption. The increase in overconsumption is much smaller than could have been expected. This shows that the regulation works well even in cases when not all consumers are considered.

8.12 Use of Prediction

Predicting the short term consumption of the buildings does not offer any real improvement on behalf of the regulation scheme. Buildings which are currently off and are expected to be turned on during the current period
would cause a reduction in the currently allocatable amount, thereby reducing the temperature of all buildings currently heating. Buildings which are on and are expected to be turned off will increase the amount available when they are turned off. As this amount will be allocated as soon as the heater shuts off, no gain is achieved. As such there is not incentive to predict the short term behavior of the buildings in order to improve the regulation.

### 8.13 The Costs

In order to implement the optimal regulation method a relatively large amount of measurement and control hardware has to be purchased.

Currently there are 43 meters available on the site. Each of these meters would require a regulation valve, a meter which can measure the current flow rate and also transmit it to the control device, a measurement device will be needed which determines the temperature of the building. Additionally a central control unit to allocate consumption is necessary.

Milwaukee Valve has butterfly valves rated up to 80 PSI for a cost of 1025 USD, about 800 EUR per unit. Assuming that the cost of a valve is slightly higher, taken to be 1'000 EUR, the total cost for control valves
would be 43'000 EUR. As the current consumption must be known for each consumer all the meters need to be replaced. Assuming that the cost for a new meter is the same as the cost for the regulation valves, the running total is 86'000 EUR. The temperature measurement and transmission is assumed to cost 200 EUR per building. The total cost of the regulation arrives at around 100'000 EUR. In contrast to the proportional allocation there is little risk that a building will drop below the desired temperature level. As such the cost due to lost productivity is zero. Due to the the large cost of necessary control equipment this scheme is most closely related to the storage scheme. As for the storage the NPV for the regulation with optimal allocation was calculated, using equation (3.5). The initial investment for the optimal regulation scheme is assumed to be 100'000 EUR. It is assumed that the regulation scheme can remove all overconsumption. The savings are therefore 27'000 EUR per year. The NPV of the regulation with optimal allocation is 98'000 EUR.
Chapter 9

Conclusion

It could be shown that the amount currently subscribed to is not optimal, and could be reduced to 600 m$^3$ in order to minimize the cost of consumption even without implementing any regulation schemes.

Three methods for regulating the site consumption were considered. All of them are capable of performing the necessary site regulation. The first method is based on storage of gas. This requires a storage vessel which can take gas from low consumption times, and store it for later consumption. This method is strongly dependent of the size of the storage vessel, the rate at which the storage vessel can be filled and the rate at which it can be emptied. By properly selecting the size of the storage vessel the savings can be substantial. Problems arise when the storage vessel is empty, during such times there is no further capacity to reduce and avoid overconsumption. The biggest benefit of the storage method is that all consumers on site can be regulated.

The proportional allocation method is the simplest method to implement, requiring only a small amount of investment. While this method is able to properly regulate the consumption it may not be able to allocate sufficient energy to certain buildings, causing them to cool off. The loss of comfort arising from the cooling is the main source of cost for this method. This cost could be reduced by improving the thermal characteristics of the buildings, for example by improving insulation.

The optimized allocation of consumption requires extensive measurement and control hardware. It is able to maintain both the consumption and the temperature in the desired bands.

Both the proportional and the optimized allocation schemes cannot be applied to all consumers, such as the OFU which must be heated at a constant rate, thus requiring a certain temperature input. In such cases where such consumers are active both methods are able to reduce the overconsumption, but not able to avoid it completely.

When the site operator has to pay for lost productivity, the most prof-
itable method is the storage method, followed by the optimized allocation method. If the possible loss of productivity is paid for by the consumer, then the proportional allocation method is by far the most profitable.

When the choice has to be made which method to actually implement the question of the complexity of the system is paramount. The optimal allocation method is the most complicated, the simplest is the proportional allocation.

The recommendation on which scheme to implement is dependent on the cost of lost productivity. As the simplest schemes are also the most profitable they should be chosen. In the case when the site operator has to pay for lost productivity the storage method is recommended, if they do not have to pay then the proportional allocation method is recommended.

Further improvement on the consumption patterns of the site could be made by giving preferential treatment to specific consumers during colder days. This would mean that non-essential consumers, such as the OFU oven, would not be allowed to be active. However such a measure would have to be implemented through contracts with the customers and manual intervention. This is a possible field for further study.
Appendix A

Site Map
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