Eindhoven University of Technology

MASTER

# Systematic energy performance assessment in operating office buildings

## identification and assessment of energy performance gaps in Dutch office buildings, using the Pareto analysis and LEAN Energy Analysis

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*Master of Science thesis*

*August 2016*

***University***

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| Faculty: | Department of the Built Environment |
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# Preface

This report is about my graduation project of the master Building Physics & Services, at the University of Technology in Eindhoven. It is performed in collaboration with the building services company ‘Kropman Installatietechniek B.V.’.

By B.J. (Ben) Lops, my supervisor from Kropman B.V., I got acquainted with the relevance of the topic of energy performance gaps in the existing building stock. During this study, I understood the complexity of the topic more and more, which sometimes made it hard to define the research scope and focus on the main objectives. Therefore, I sincerely thank Prof. ir. Wim Zeiler, Ir. Gert Boxem and Ir. Ben Lops for their assistance during this study! They all supported me with useful advices and positive critical views on my research and results.

Furthermore, I would thank the Kropman employees, because they were always available for helping in technical/practical questions. Especially Alet van den Brink and Hans van Driel, for their support and interesting discussions on technical issues!

Albert-Jan Huls

August, 2016

## Summary

Sustainability has become a very well-known phenomenon in many areas in the last years. While a lot of attention is paid to sustainability in the design of new buildings, studies show that a large part of the existing buildings stock does not meet the designed/calculated performances. Multiple studies are performed in this field about benchmarking of energy performances for existing buildings, to improve the ability to assess measured energy performances. About the identification of causes of these energy performance gaps between the 'reference frame' and the measurements, hardly any useful publications are available. There are some publications about reduction of these energy gaps, but they provide only very general tips or refer to 'technical experts' to interpret the identified energy gaps. A widely applicable, systematic analysis for the assessment of energy performance gaps is missing.

The Pareto analysis and the LEAN Energy Analysis seem to be promising in literature. The Pareto analysis is a widely applicable, stepwise approach, based on the principle that 80% of problems are caused by only a few major causes (20% of all involved causes). The LEAN Energy Analysis is focused on energy efficiency, analysing the correlations between the energy consumption and the primary goal(s) of this energy. In literature it is stated that causes for energy gaps can be derived from these correlations, by regression analysis and regression coefficients. Although these methods seem to be promising in this topic, the practical applicability of these methods, as systematic approaches of the energy performance gaps in the existing built environment, is unknown. Therefore, these methods are used in this study for identification, analysis and assessment of energy performance gaps in Dutch office buildings. In this way, the strengths and weaknesses of the methods are analyzed and it is investigated in which way these methods can contribute to a widely applicable, systematic approach for this topic.

Two representative office buildings are selected as case studies. The first case study is a traditional (1993) office building with traditional building systems and relatively simple system control. The second case study building is a newer, modern building (2004), contains a modern building system with complicated software control strategies and an ATES-system. Both buildings are simulated according to the original design situation. The used building simulation tool is 'Vabi Elements'. In both case studies, significant energy gaps were found by comparing annual simulated and measured heating and cooling consumption.

First the stepwise Pareto analysis is used to investigate whether 80% of energy gaps can actually be explained by only a few parameters/causes. Because a large quantity of parameters is involved, 15 parameters in building characteristics, internal heat gains, comfort demand, climate control settings and heat recovery are selected, based on the input of the building model. From these 15 parameters, the most important/critical ones are selected, based on a sensitivity analysis. The parameters do not have the same percentage impact on the energy consumption of both case studies, which means that no general conclusions can be drawn about the most important parameters from these two case studies. Therefore, additional case studies are needed to identify correlations between characteristics of building (systems) and the most critical parameters for the energy consumption.

With the selected critical parameters, it is analyzed if indeed 80% of the energy gap can be explained. For some analyzed energy functions, it was found that this is the case, but not for all of them. This finding can be explained by the fact that the selected parameters are within the boundaries of the simulation tool and aimed on the use of the building (system). Control and dynamic behavior of building systems is not included in these parameters, although they play a significant role in building energy consumption.

After that, the LEAN Energy Analysis is used, to investigate the practical applicability and contribution of this method. LEAN is targeted on the efficiency of correlations between energy consumption and their primary goal(s). In literature, outside air temperature is mentioned as a suitable indicator for the analysis of building heating and cooling efficiency. In this study, it turned out that this indicator is insufficient for an accurate energy assessment, due to several time-dependent parameters, playing a significant role in building energy consumption. Therefore, 'time' is considered as second, independent variable. By consideration of energy consumption within characteristic time blocks, influence of these time-dependent parameters is 'isolated', improving the ability to assess energy consumption.

Consideration of energy within these time blocks show ineffective energy consumption (energy gaps), which were not identified during the Pareto analysis, where energy consumption was considered over a year. The positive and negative energy gaps can cancel out each other, resulting in unnoticeable energy gaps over a longer period.

By trend analysis, the remaining energy gaps (which cannot be explained by the results of the Pareto analysis) are considered. In literature, regression analysis and regression coefficients are discussed as effective assessment methods. In this study, it turned out that application of regression analysis in energy profiles (which are separated for each identified time block), results in loss of useful information about energetic behavior of the building (systems). The regression coefficients (e.g. slope of the line) only provides very general information about efficiency of energy consumption. Because many parameters influence this efficiency (and slope of regression lines), no reliable conclusions can be drawn from regression coefficients about the causes of deviating energy efficiency. Therefore, the energy profiles within the specific time blocks are used for trend analysis. Although these profiles provides useful information about deviating energetic behavior of the building (system), they do not indicate specific root causes. Therefore, a trend analysis starts from global, overarching causes to specific causes, e.g. system components or settings.

By using both the Pareto analysis and the LEAN Energy Analysis, the strengths of both methods have become clear during this study. When these strengths are combined, this results in a useful, stepwise and widely applicable method. By identification and assessment of critical parameters, the most important causes in the use of building (system) can be identified. If these parameters provide insufficient information about the causes of the energy gap, it is concluded that the use of the building does not deviate that much from the assumed ('designed') use. In that case, the energy gap is caused by ineffective energy consumption within the building (system). To identify the causes of this ineffective energy consumption, trend analysis is useful, if required data is available. Because trend analysis does not indicate specific root causes, a trend analysis starts from global, overarching causes to specific causes, e.g. system components or settings.

# Content

# 1. Introduction

This study is about systematic assessment of energy performance gaps in existing buildings. In this chapter this widespread problem is introduced. Also earlier performed studies in this topic are discussed, which show that there is a lack of systematic and structured approaches to solve this problem. Besides that, two promising systematic methods of analysis are introduced in this chapter, which are further analysed and used in this study.

Furthermore, this chapter contains the defining of the research objectives research (sub) questions, used methodology and report structure.

## 1.1 Problem analysis & relevance of research

In recent years, sustainability has become a well-known phenomenon in many areas. In the built environment, a lot of attention is paid to sustainability in the design of new buildings, due to legal obligations and/or other motives. However, for the creation of a sustainable built environment, the existing building stock is at least as important.

First, in the existing building stock a lot of buildings are designed and built without or with low attention for sustainability. In these type of buildings there is an obvious large potential for a sustainable upgrade.

The other point for attention in the existing building stock is the fact that energy performances of existing buildings often do not even meet the designed/calculated performances. This conclusion is drawn in different optimization and monitoring studies in existing buildings, where percentages of unnecessary energy consumption of 5-50% were identified (Agentschap NL, 2011; BuildingEQ, 2009; CV-tuning, 2003; Elkhuizen, et al., 2006; Gommans (2008), Leijten, et al., 2012; Re-Co, 2014). Conclusions from Elkhuizen, et al. (2006) and ISSO (2010) that 70% of climate installations in Dutch office buildings do not provide the energy performances as designed, underline the statement that this topic is a widespread problem in the built environment. That results in an energy performance gap between the design-based expected and measured energy consumption. Section 1.1.1 contains an introducing analysis of this ‘performance gap’.

The studies referenced above, as well as studies like Agentschap NL (2012) and Havenaar (2011), show an important role of the use(rs) of buildings and building systems in this ‘energy performance gap’-topic. In section 1.1.2 the need for an effective, widely applicable and systematic approach in this topic is discussed, which is also the direct reason for this study.

### 1.1.1 Gap between designed and measured energy performances in existing building stock

The basic principle of the introduced problem of the ‘energy performance gap’ in the existing building stock, is shown in a simplified diagram in figure 1.1.1.

Performances of building and installations are influenced by the behavior of the users and the climate. The correlation between the building & installations and the use/users is often an interactive process, where user response is (often) based on comfort perception. The combination of use(rs), building (systems) and climate results in a certain energy consumption. During the building design process, assumptions are made for the use of the building (systems) and theoretical performances of building (systems) are defined. Based on these assumptions and performances an estimation/calculation of the energy consumption of the building can be made.

In the operational phase of the building there can be/arise deviations from the assumed use(rs) and performances in the design situation. This will result in an ‘energy gap’ between the designed and the real energy consumption.

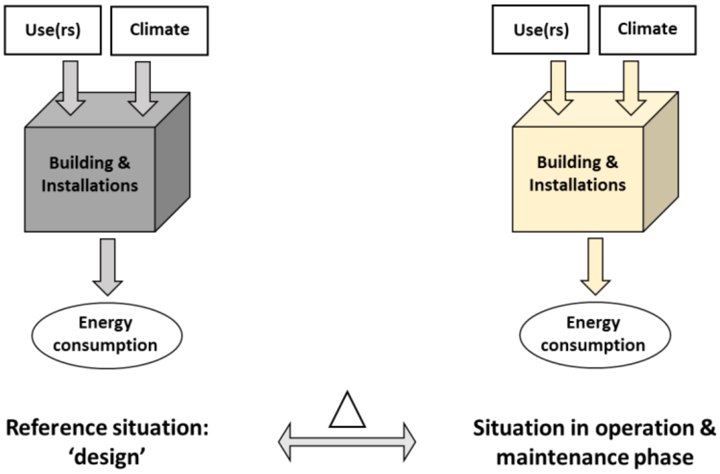


*Fig. 1.1.1: a schematic figure of the study topic/problem. When behavior of use(rs) and/or properties in building and building systems in an operating building deviate from the reference situation (e.g. design), it will result in an energy performance gap.*

## 1.1.2 Energy performance assessment in literature

The importance and scope of this 'energy performance gap-topic', is discussed in the sections above. To tackle this topic effectively over the wide variety of building types, a systematic, widely applicable approach is needed.

**Energy assessment methods in literature**

Studies are performed in the field of energy performance evaluation/assessment in existing buildings. In a literature review of Borgstein, et al. (2016), most common methods for benchmarking and evaluation of energy performances are discussed. In this review, 4 main methods (umbrella terms) for energy performance evaluation are categorized and discussed. The methods, as discussed in this review, are mentioned below:

- Engineering calculation. This method contains relatively simple calculation tools, which do not replicate dynamic processes of full simulation methodologies, which means that these calculations have are lower lever of accuracy. These calculations are suitable for quick energy scans and rough performance estimations.
- Dynamic building energy performance simulation. This method involves the use of computer models to simulate the performances of a building in determined conditions. This method can be very accurate for energy evaluation, but is highly dependent of the modeler knowledge/skills, model uncertainties and detailed model input (e.g. occupant behavior).
- Statistical methods. Different evaluation methods do exist for statistical evaluation of energy performance (gaps). In table 1.1.1, taken from Borgstein, et al. (2016), different statistical methods in building energy performance evaluation/assessment, are summarized. This review mentions that the principal limitation of statistical models would seem to be their lack of a relation to physical phenomena, meaning that it can be difficult to interpret the results and identify errors.
- Machine learning. Machine learning is in full development and consists mainly of algorithms, learning from patterns in big data sets. For example, by artificial neural networks or clustering techniques, patterns in large data sets can be identified or clustered. Although this techniques seem to be very promising, further development is needed. Currently, one of the main drawbacks of machine learning it is difficult to show real, physical interpretations for the used 'black-box' approach.

*Table 1.1.1: Summary of principal statistical methods applied to buildings. Modified from Borgstein, et al. (2016).*

| **Statistical methods** | **Applications** | **References** |
|---|---|---|
| Simple and multivariate linear regression | Simple models for building performance based on a few characteristics. | ASHRAE (2014), Sharp (1995) |
| Change-point regression | Model the non-linear effects of external conditions, e.g. below a certain external temperature, heating systems are switched on. | Zhang, et al. (2014), ASHRAE (2014) |
| Gaussian process and Gaussian Mixture regression | Prediction of dynamic performance, with an understanding of uncertainty. Flexible models, but more complex. | Zhang, et al. (2014) |
| Stochastic Frontier Analysis | Effective when there are a large number of efficient buildings and a few that inefficient. Outliers may make the method ineffectual, as residuals will be large. | Chung (2011), Buck, et al. (2007) |
| TOPSIS | Can be used to develop effective benchmarks, based on regressions. | Lin, et al. (2011), Wang (2015) |
| Data Envelopment Analysis | Evaluates the technical efficiency and improvement potential of buildings. Can only be applied to buildings within the original dataset. | Chung (2011), Lee, et al. (2011) |
| Correction factors | Relate building performance to physical parameters, useful for benchmarking. | Bloomfield, et al. (2010) |

**Missing aspects in published energy assessment methods**

There are obviously a lot of methods for evaluation and assessment of energy performances in existing buildings. The main focus of these studies is on the creation of benchmarks/reference frames, for comparison with measured data. Although this is the first main step, less studies are published on the second step, namely a structured method for the analysis of the causes of an identified energy gap.

Although there are a lot of studies performed on causes of energy gaps and ways to avoid these causes (e.g. Wilde (2014), Menezes, et al. (2012), Morant (2012), Carbon Trust (2011)), a structured analysis, which leads to the explanation of a specific energy gap is missing.

In optimization and system recommissioning studies (e.g. CV-tuning, 2003; Elkhuizen, et al., 2006; Re-Co, 2014; Oregon Department of Energy, 2014), there is used an individual approach to reduce energy performance gaps. High energy consumption is detected and followed by a quite labor-intensive check of the building systems. In these studies, a wide variety of errors/defects was found, varying from inefficient control strategies to leaking valves. As result, these found defects were solved/repaired and led to a certain energy reduction.

In these studies, a systematic approach is missing. For an effective approach, the basic and major causes of the high energy consumption should be identified, before starting repairs and recommissioning of building systems.

In other studies, e.g. BuildingEQ (2009) and Agentschap NL (2011), energy inefficiency is identified from energy profiles, based on trend analysis. Although in these publications to it is claimed to be a successful way to reduce energy consumption, it emphasizes the need for a systematic approach, because the assessment of these energy profiles requires much experience and technical knowledge. Without a systematic approach, it still results in an unstructured search for possible defects/errors.

Summarizing, studies are mainly focused on benchmarking methods for energy evaluation. But when an energy gap is identified with these benchmarks, this gap has to be assessed and the causes have to be found. For this second step, there is a lack of a systematic, widely applicable approach. In published studies, identification of energy gaps results in detailed, technical inspections and checks in the buildings, without a structured approach.

### 1.1.3 Pareto analysis and LEAN Energy Analysis as promising assessment methods in literature

Although there is a lack of a structured approach for an identified energy gap, there are some analytical methods described in literature which might be useful in this topic. Below, two different methods are discussed.

*Pareto Analysis*

The Pareto analysis, as discussed by Bartlett (2015), is a systematic, stepwise approach for the identification of major causes of problems. This approach is based on the principle that a large part of problems (e.g. 80%) is caused by only a small part (e.g. 20%) of all responsible causes (major causes), visualized in figure 1.1.2. The challenge in this topic is to identify this '20%', that is mainly responsible for an energy performance gap.

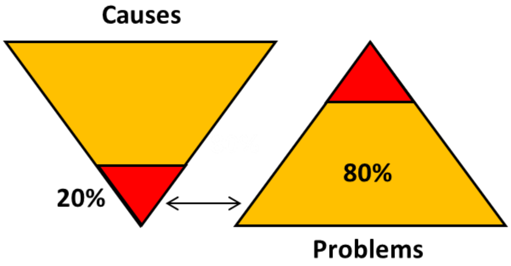


*Fig. 1.1.2: Methodology based on the Pareto analysis, acc. to Bartlett (2015): Major of problems can be identified by a few major causes (own figure).*

The hypothesis that this Pareto analysis might be useful as a systematic approach in this energy gap-topic, is based on a study of Schoenmakers (2015). In this study the Pareto analysis proved to be a clear, stepwise way to tackle energy waste in complex building systems in UMCs.

*LEAN Energy Analysis (L.E.A.)*

The LEAN Energy Analysis is discussed in several (scientific) studies and papers (e.g. Kissock, et al. (2003), Kissock, et al. (2004), (Sever, et al., 2011) and Donnelly, et al. (2013). In these publications, the L.E.A. is recommended as a useful method to recognize energy inefficiency and reduce energy waste. This L.E.A. is based on the general LEAN principle that all energy which is not used for the primary goal of the energy, is waste. That is why this method is aimed to identify the primary goals of all consumed energy flows in a building. The correlation between these primary goals and the energy consumption provides information about the efficiency of the energy consumption. An example is shown in figure 1.1.3.

An important promising aspect is the statement in Sever, et al. (2011) and Donnelly, et al. (2013) that the L.E.A. adds value to other regression/trend analysis methods by isolating regression coefficients and recognizing that they have physical meaning. In this way, causes can be derived from the physical meaning of the regression coefficients. The practical applicability of this L.E.A. in the built environment is only very limited shown/discussed. Therefore, the usefulness of these methods, as systematic analyzes of energy performance gaps in the existing built environment, has not been proven currently.

Summarizing, although the Pareto analysis and LEAN Energy Analysis seem quite promising in literature, the practical applicability of these methods, as systematic analyzes of the energy performance gaps in the existing built environment, is unknown.

## 1.2 Research objective & scope

The objective is the systematic identification of the major discrepancies between measured energy performances and the expected performances, which are based on a reference situation (e.g. design). To achieve this objective the Pareto analysis and the LEAN Energy Analysis are used.

The focus in this study is on office buildings in a Dutch climate. The first reason for this choice is that office building cover a significant part of the Dutch commercial building stock (figure 1.2.1). The second reason is the finding in Elkhuizen, et al. (2006) and ISSO (2010) that a large percentage (>70%) of office buildings is energetically underperforming.

The use of the Pareto analysis and the LEAN Energy analysis is based on the specific intentions of the methods. The Pareto analysis is a stepwise approach for the identification of major causes in an identified problem (Schoenmakers, 2015). The LEAN Energy Analysis is specifically aimed at identification and assessment of correlations between primary goals of energy consumption and the actual consumed energy. In this way information is provided about the efficiency of the energy consumption and the causes of discrepancies between expected and measured energy consumption.

This results in two, more concretely formulated, sub goals in this study:

- Systematic identification of critical parameters in the energy performances of office buildings, by use of the Pareto analysis (Bartlett, 2015; Schoenmakers, 2015).
- Systematic identification of (causes of) discrepancies between energy performances of operating office buildings and their reference situation, by using the LEAN Energy Analysis (Kissock, et al. 2011; Donnelly, et al. 2013).

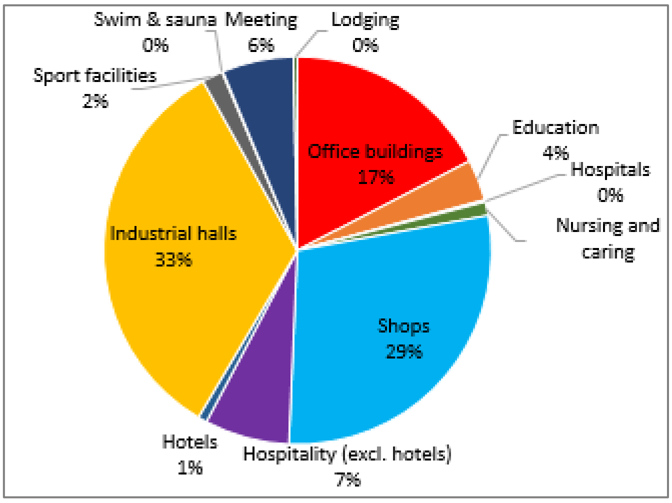


*Fig. 1.2.1: Percentage breakdown of commercial buildings in the Netherlands (2009). Modified from Prendergast, et al. (2010). The percentages are based on the number of commercial buildings in the Netherlands.*

## 1.3 Research question & sub questions

The main research question in this study is based on the discussed objective (§1.2):

*How much can the Pareto analysis and the LEAN Energy Analysis contribute to a widely applicable, systematic analysis of the identification and assessment of energy performance gaps in operating office buildings?*

The study is built on three sub questions, in line with the two defined sub goals (§1.2):

1. *What are the results when the Pareto analysis is used for identification of critical parameters in the energy performances of Dutch office buildings?*
2. *What are the results when the LEAN Energy Analysis is used for analysis of energy performance gaps in Dutch office buildings?*
3. *How much can individual strengths from both methods (Pareto and LEAN) reinforce each other in a combined method for the assessment of energy performance gaps?*

## 1.4 Methodology

- ***Background information of Pareto analysis and LEAN Energy Analysis and the application of them in this study -> §2.1-2.3***

The background of both introduced methods are further analyzed in §2.1 and §2.2. Based on this background, several steps are defined in §2.3 to apply the methods in this study.

- ***Selection of two case studies -> §2.4***

In the achievement of the study objective, the first step is the selection of case study buildings which are representative for the Dutch building stock. For these case study buildings, sufficient building (system) and energy data of the reference situation (design in this case) has to be available, as well as required data of the actual situation. In chapter 2 the selected case studies are discussed.

- ***Building simulation and climate data -> §3.1 (case study 1) and §4.1 (case study 2)***

For the defining of reference energy performances, the case study buildings are modeled in Vabi Elements, version 3.0 (Vabi, 2016), a building simulation, focused on the indoor climate comfort in a building and calculates the energy which is needed to achieve/maintain the required comfort level. The tool is not aimed at the energy losses within the supplying building systems (only thermal energy losses of the heat recovery wheel are included), so energy losses in the distribution and generation systems are not considered in this tool.

Two different climate files are used for both building simulation. To analyze ‘average’ energy consumption, the reference NEN 5060 climate data is used. For the assessment of the measured energy consumption, KNMI climate data of the nearest weather station is used in the simulations.

- ***Collect measurement data to analyze real energy performances***

For the analysis of the actual situation, measured data of the building systems is used for both case studies. This data is monitored with 8 minute-intervals. This accuracy is more than sufficient for the objectives of the analysis in this study.

- ***Results of Pareto analysis -> §3.1-3.4 (case study 1) and §4.1-4.4 (case study 2)***

The principle of the Pareto analysis is that the major part (80%) of most problems can be solved with only a minor part (20%) of all involved parameters/causes. In this study it is investigated whether this theory is applicable in energy performance gaps and energy performance gaps can be assessed/explained with only a few major parameters.

- ***Results of the LEAN Energy Analysis -> §3.5-3.7 (case study 1) and §4.5-4.7 (case study 2)***

It is investigated how much the LEAN Energy Analysis can contribute to identification and assessment of energy performance gaps.

- ***Method evaluation and recommendations for future energy assessment -> chapter 5***

The strengths and weaknesses of both the Pareto analysis and LEAN Energy Analysis are evaluated, based on the results of the case studies. Recommendations for future energy assessment are based on the strengths of both methods and the specific results of the study.

- ***Discussion -> §6.1***

The discussion contains limiting factors/assumptions in the performed study.

- ***Conclusions -> §6.2***

An answer on the research question is provided.

# 2. Background

In this chapter, the background information of the used Pareto analysis and LEAN Energy Analysis is discussed in sections 2.1 and 2.2.

Both methods are used in this study, to analyze the strengths, weaknesses and applicability in this topic. This way, an answer is also provided for the third sub question, namely if strengths of both methods can reinforce each other to a useful, combined method. The applied combination of both methods is discussed in section 2.3.

This study is based on case studies, which are representative for the Dutch office building stock. The characteristics of the office building stock in the Netherlands, as well as the selected case studies, are discussed in section 2.4.

## 2.1 Background information of Pareto analysis

As introduced in chapter 1, the Pareto analysis is used in this study. By this analysis, it is investigated if the theoretical ‘80/20’-rule is applicable in the assessment of energy performance gaps. In other words, it is investigated whether the major part of energy gaps can actually be explained with only a few parameters.

The hypothesis that this method might be useful in this topic, is the successful application of this method in Schoenmakers (2015). In that study, by use of the Pareto analysis, the major energy functions and energy waste is identified in a stepwise approach, resulting in specific, efficient recommendations for significant energy savings.

6 general basic steps of the Pareto analysis are used in Schoenmakers (2015):

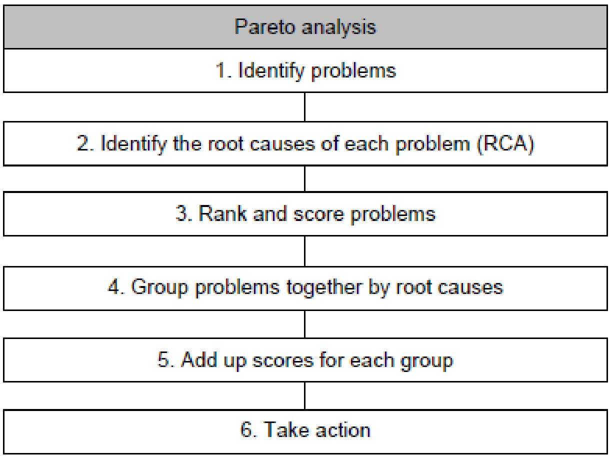


*Fig. 2.1.1: Basic steps of the Pareto analysis, used as guideline in this study. Taken from Schoenmakers (2015).*

These steps are also used as a guideline in this study. They are used more specifically in the following way:

> Step 1: Identify problems -> comparison between measured and design-based simulated energy consumption, to identify possible energy performance gaps.
>
> Step 2: Identify the root causes of each problem -> identify the involved causes in the energy consumption of the case studies and select a limited amount of ‘main parameters’, which are expected to be important in building energy performances.
>
> Step 3/4/5: Rank, score and group problems/causes -> these steps are combined for a more practical approach. The impact of these selected parameters on the annual energy consumption is assessed by a sensitivity analysis. The parameters with the largest impact are the most critical parameters, with a relatively high risk to cause energy performance gaps.

Step 6: Take action -> in this step it is investigated if 80% of the energy performance gaps in the case studies can indeed be explained by the few identified, most critical parameters.

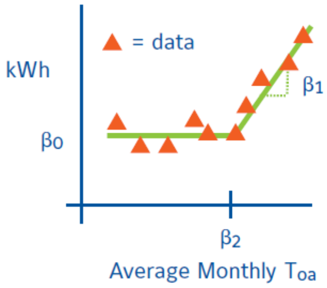
The applied steps are discussed more detailed in the corresponding sections in this report.

## 2.2 Background information of LEAN Energy Analysis

The LEAN Energy Analysis (LEA) is a systematic analysis that is specifically aimed at identification of energy saving potential based on energy trends and patterns. This LEA is derived from the general LEAN management/production philosophy, which is based on the principle that ‘any activity that does not add value to the product is waste’ (Kissock, et al. 2004). That means that the application of the LEA in the area of building energy consumption is about the identification of the energy that does not add value to production of goods/services, space conditioning and general facility support, such as lighting (Kissock, et al. 2004).

The LEA is an analysis method which can be performed on different detail levels. In this study the ‘statistical’ LEA is applied, according to Kissock, et al. (2004). This type of LEA analysis is also discussed in a conference presentation by Kissock (2015) and in an article of Donnelly, et al. (2013). The general idea in this analysis is to show the relation between the energy consumption of a certain function and its characteristic independent variable(s). In this way it can be detected if there is energy consumed that ‘does not add value to the product’. For example, Kissock, et al. (2003) identified that the energy consumption in most buildings can be adequately described by regression models that relate energy consumption to outside air temperature (Donnelly, et al., 2013). This is because building heating and cooling are large energy functions in buildings. The primary function of building heating and cooling is to bridge the gap between outdoor air temperature and the desired indoor temperature. Deviations in this correlation can be traced back (partly) to inefficient energy consumption by using these models.

An important aspect is the statement that the LEAN Energy Analysis adds value to other regression/trend analysis methods by isolating regression coefficients and recognizing that they have physical meaning (Sever, et al., 2011). In this way, causes can be derived from the physical meaning of the regression coefficients. For example, in the referenced studies, the use of multi-parameter regression models is discussed as an effective way of assessment of energy efficiency. An example of a 3-parameter model is shown in figure 2.2.1 (Donnelly, et al., 2013). This model exists of a regression line of electrical energy vs outside air temperature, composed by 3 typical parameters: baseload (independent of outside temp.), the regression coefficient of the cooling energy consumption (depends on outside temp.) and the intersection point between them.



$$\text{Energy} = \text{Baseload}\ (\beta_0) + \text{Cooling Sensitivity}\ (\beta_1)\ 2 \times \{\text{Outside Air Temperature}\ (T_{oa,1}) - \text{Cooling Break-even Temperature}\ (\beta_2)\}$$

*Fig. 2.2.1: Example of a 3-parameter regression model, discussed in literature (e.g. Kissock, 2015 and Donnelly, et al., 2013), as an effective way to assess energy efficiency. This model exists of a regression line of electrical energy vs outside air temperature, composed by 3 typical parameters (*β0, β1 *and* β2*).*

A stepwise approach in this LEAN Energy Analysis is discussed in Donnelly, et al. (2013). The main steps are shown in figure 2.2.2.

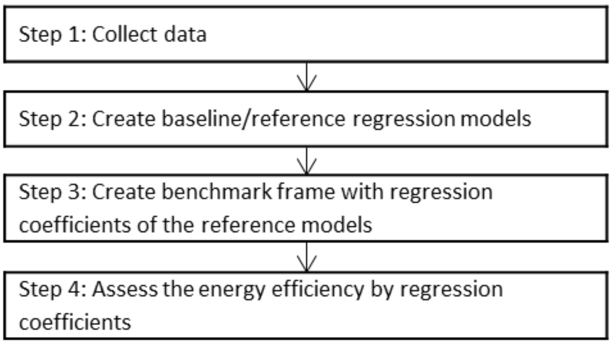


*Fig. 2.2.2: Stepwise approach of the LEAN Energy Analysis, modified from Donnelly, et al. (2013). These steps are used in this study as main guideline in the use of the LEAN Energy Analysis. In this way, the applicability, strengths and weaknesses of the method are analyzed.*

These steps are used in this study as main guideline in the use of the LEAN Energy Analysis. In this way, the applicability, strengths and weaknesses of the method are analyzed. The applied steps are discussed more detailed in the corresponding sections in this report.

## 2.3 Stepwise application of Pareto and LEAN Energy Analysis in this study

Both methods are used in this study, to analyze the strengths, weaknesses and applicability in this topic. This way, an answer is also provided for the third sub question, namely if strengths of both methods can reinforce each other to a useful, combined method.

The Pareto analysis is applied before the LEAN analysis, because it is expected that the Pareto analysis will systematically lead to required insight.

The application of the Pareto analysis and LEAN Energy analysis in used for each case study. The main structures of both methods are the same as shown in sections 2.1 and 2.2.

The combined, stepwise analysis in this study is shown below:

1. **Pareto analysis, step 1: Identification of problems**
   The case study building is modeled in Vabi Elements (according to the design of the building). With this model the ‘reference’ energy performance of the building is simulated. This simulated energy consumption is compared to the measured energy consumption, to identify the energy gap.

2. **Pareto analysis, step 2: Identify root causes of each problem**
   This step deals with the identification of the major parameters in the energy performance topic. There are a lot of settings, control strategies and properties in buildings and building systems, which all together determine the behavior of the energy consumption. All these factors are reduced to a small amount of (merged) ‘main parameters’. In the further steps (3-6), the impact of these parameters is analyzed, as well as the hypothesis if 80% of an energy performance gap can be explained by these parameters.

3. **Pareto analysis, step 3/4/5: Rank, score and group problems & causes**
   The impact of the parameters on the annual energy consumption is assessed by a sensitivity analysis. In this way it is determined which parameters are most important in the assessment of energy performance gaps.

4. **Pareto analysis, step 6**: **Assessment of energy gap by selected critical parameters**
   In this step, it is investigated if the energy performance gaps in the case studies can be assessed/explained by the selected parameters from the steps before.

5. **LEAN Energy Analysis, step 1: Collect weather & utility data**

Collect the required measurement data for a straight-line comparison with the simulated energy consumption.

6. **LEAN Energy Analysis, step 2: Create baseline/benchmark models**
   This step consists of identification of characteristic correlations in energy performances of the case study building and the creation of benchmark models, which can be used to assess measured energy efficiency. This step is based on the LEAN strategy, discussed in chapter 2.2, that consideration of characteristic, independent variables is an effective way to assess energy efficiency.

7. **LEAN Energy Analysis, step 3: Identify energy gaps with regression coefficients of benchmark regression models**
   This step consists of the identification of the energy gap, according to the LEAN method. This way consists of assessment with coefficients of multi-parameterized regression models, discussed in the background information of the LEAN Energy Analysis (§2.2).

8. **LEAN Energy Analysis, step 4: Assessment of remaining energy gaps (which cannot be explained by the results of the Pareto analysis)**
   In this step, the results of the LEAN Energy Analysis are used to assess the energy performance gaps, additionally to the earlier results of the Pareto Analysis.

## 2.4 Case studies

The case study buildings have to be representative for the Dutch office stock. Besides that, sufficient data have to be available about the buildings, for building modeling and analysis of the actual situation.

In section 2.4.1 the major characteristics of the Dutch office stock are discussed, as reference frame for the selection of representative case study buildings.

In section 2.4.2 and 2.4.3 the design situations of the selected case study buildings are analyzed (office buildings of Kropman Breda & Kropman Utrecht). These designs are considered as the ‘reference situations’ for these case studies, for the comparison with the measured energy data.

### 2.4.1 Characteristics of the Dutch office building stock

To select case studies which represent a significant part of the existing Dutch office buildings, first the statistics of the office building stock are investigated. Floor surface, energy functions, existing building systems and relevant developments in the office buildings are analyzed.

**Surface**

In figure 2.4.1, the Dutch office building stock is sorted by floor surface.

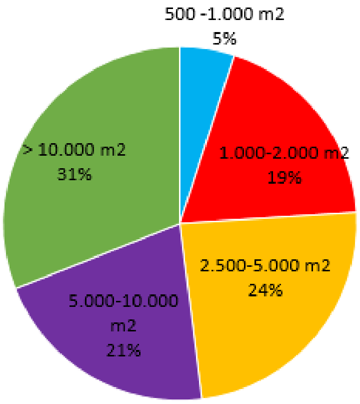


*Fig. 2.4.1: Dutch office building stock in 2014, sorted by floor surface. Modified from Bak (2015).*

### Current state of existing office building systems

The major part (>80%) of energy in Dutch office buildings is consumed by HVAC, lighting and office equipment (ICEDD, 2011). In table 2.4.1-2.4.4, some statistics are shown about the present building systems for these energy functions, in the current existing office buildings. The statistics for heating, cooling and ventilation systems are taken from market surveys in 2011, published in Stratus (2012). The statistics for lighting systems are taken from market surveys in 2008, published in Agentschap NL (2010).

*Table 2.4.1: Heating systems in existing Dutch office buildings in 2011. Statistics from market surveys, published in Stratus (2012)*

| **Building heating systems** | |
|---|---|
| Gas boiler | 86% |
| District heating | 5% |
| Combined Heat & Power | 1% |
| Aquifer Thermal Energy Storage | 4% |
| Combination of 2, 3, 4 and 5 | 0% |
| Other | 1% |

*Table 2.4.2: Cooling systems in existing Dutch office buildings in 2011. Statistics from market surveys, published in Stratus (2012)*

| **Building cooling systems** | **64% of offices contains an air-conditioning system** |
|---|---|
| Compression chiller | 27% |
| Absorption chiller | 3% |
| Heat pumps | 1% |
| Other | 14% |
| ‘don’t kow which system is used’ | 56% |

*Table 2.4.3: Ventilation systems in existing Dutch office buildings in 2011. Percentages of the survey results seem to be incomplete, because the total of percentages exceeds 100%. Therefore, in this table more global indications are shown, modified from the statistics of the market surveys, as published in Stratus (2012).*

| **Ventilation systems** | |
|---|---|
| Natural ventilation | 40-50% |
| Natural supply and mechanical exhaust | 20-30% |
| Mechanical supply and mechanical exhaust, without heat recovery | 20-30% |
| Mechanical supply and mechanical exhaust, with heat recovery | 10-15% |

*Table 2.4.4: Lighting systems in existing Dutch office buildings in 2008. Statistics from market surveys, published in Agentschap NL (2010).*

| **Lighting** | |
|---|---|
| Fluorescent lighting | 55% |
| Compact Fluorescent Lamp (CFL) (or: ‘energy-saving light’) | 15% |
| High frequency (HF) fluorescent lighting | 12% |
| Halogen light bulbs | 7% |
| HF+ lighting | 6% |
| Incandescent light bulbs | 5% |
| LED-lighting | 0-1% |

### Trends in Dutch office building stock.

Although the building systems of the current office building stock are shown above, it is also important to take into account developments/trends in Dutch office buildings. Therefore, the most significant developments in the use of renewable energy (heat and electricity) are shown in figure 2.4.2 and 2.4.3. The data is taken from CBS (Dutch institute for publication of statistics in multiple topics/fields).

In these figures a significant increase of consumed heat by geothermal and air-source heat pumps can be seen, as well a significant increase of consumed electricity from solar energy. These development are taken into account in the selection of case studies.

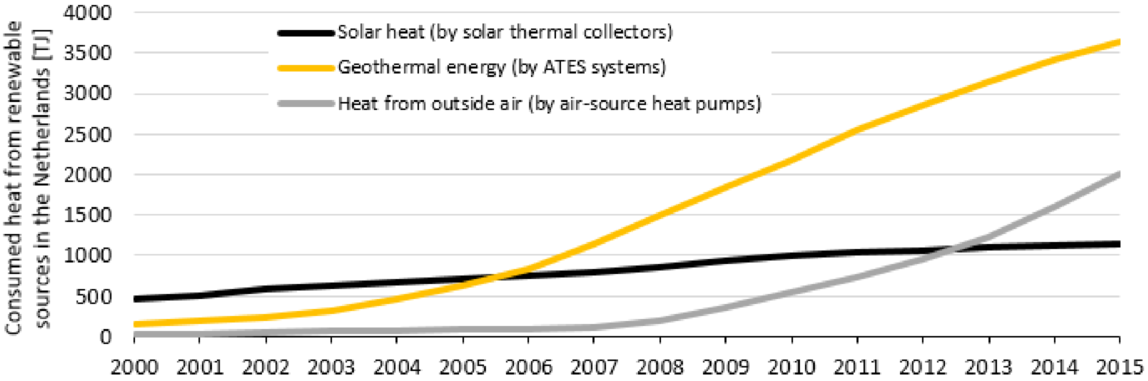


*Fig. 2.4.2: Consumed heat from renewable sources, in the Netherlands. The figure shows a significant increase of consumed heat by geothermal and air-source heat pumps during the past few years. These development are taken into account in the selection of case studies. (Source: CBS, 2016.)*

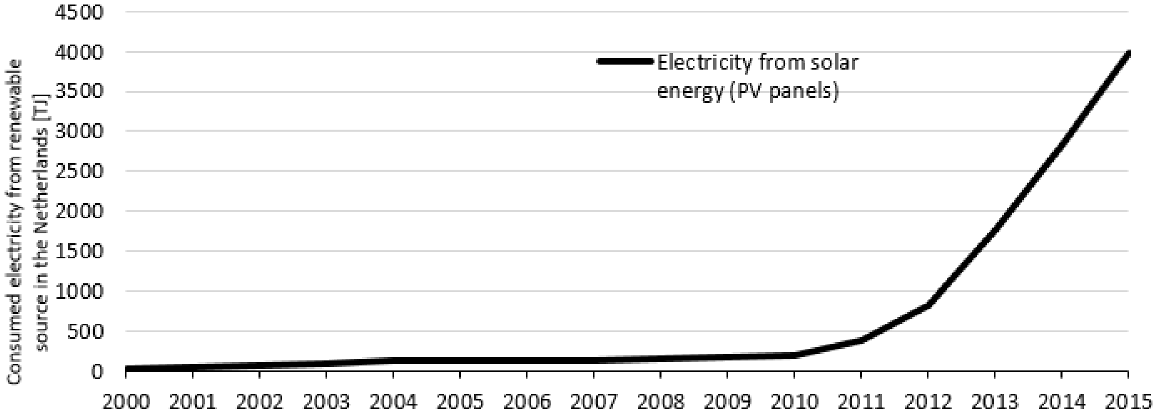


*Fig. 2.4.3: Consumed electricity from solar energy, in the Netherlands. (Source: CBS, 2016.)*

### 2.4.2 Reference situation of case study 1: design of office building Kropman Breda

This first case study building is a quite old (1993), traditional building. The present gas boiler, compression chiller, fluorescent lighting and balanced ventilation system make it a representative building for a large part of the Dutch office building stock (see section 2.4.1). Below the main properties and average comfort demand settings are shown below. More detailed properties are shown in Appendix I, as used input parameters in the building simulation model.

*Fig. 2.4.4: Impression of office building Kropman Breda. Left: N-W facades. Right: South façade. (Own figures)*

| **General** | | |
|---|---|---|
| *Gross floor area* | *1.650 m$^2$* | |
| *Year of construction* | *1993* | |
| *Floors* | *3* | |
| *Daily occupancy* | *Design (1993):<br>55-65 persons (estimated, based on available rooms)* | *2014:<br>40-50 persons* |
| *Office hours* | *7:00 – 17:00 h* | |
| *Orientation (longest side from X-X)* | *E-W* | |
| *Percentage of glass in facades* | *22%* | |
| *Lighting* | *Fluorescent lighting* | |

| **Building envelope** | |
|---|---|
| *R-value building envelope* | *2,5 m$^2$K/W* |
| *U-value glass* | *3,2 W/m$^2$K (double glazing)* |
| *U-value window frames* | *2,4 W/m$^2$K (wood)* |
| *Solar blinds* | *External (manual control)* |

| **Comfort demand & internal heat production** | | |
|---|---|---|
| *Average internal heat production over gross floor area* | *Design (estimated):<br>Occupants: 3-5 W/m$^2$<br>Appliances: 11-14 W/m$^2$<br>Lighting: -* | *2014:<br>Occupants: 3 W/m$^2$<br>Appliances: 10 W/m$^2$<br>Lighting: 9 W/m$^2$* |
| *Minimum room temp. (average over different room functions)* | *21,0 °C* | |
| *Maximum room temp. (average over different room functions)* | *24,0 °C* | |
| *Relative humidity* | *55%* | |

| **HVAC-system** | | | | |
|---|---|---|---|---|
| | ***Generation*** | ***Distribution*** | ***Release*** | ***Recovery*** |
| ***Heating*** | *High efficiency (HR) – gas boiler* | *Air & water* | *- Centrally controlled ventilation air (basic heating)*<br>*- Radiators (locally controlled additional heating)* | *Heat recovery wheel* |
| ***Cooling*** | *Compression chiller* | *Air* | *- Air handling unit (locally controlled air cooling (3 zones))*<br>*- Free night-time cooling during nights, by mechanical ventilation* | *Heat recovery wheel* |
| ***Air humidification*** | *Electric steam humidifier* | *Air* | *Air handling unit (centrally controlled air humidification)* | *Heat recovery wheel (hygroscopic)* |
| ***Ventilation*** | *Air handling unit* | *Air* | *Balanced ventilation (mechanical supply and mechanical exhaust) Centralized ventilation control (central air handling unit). Constant volume (15.000 m$^3$/h)* | *-* |

In figure 2.4.5 a schematic overview of the climate control system is shown. The building system is based on three different zones. Each room is basically heated by ventilation air on a set temperature (heating curve). Additional heating is supplied by radiators in each room, individually controlled. In case of cooling demand, the ventilation air is cooled and controlled on 'zone-level cooling demand'. Free cooling is used during nights, to cool down the building by mechanical ventilation, with outside air.

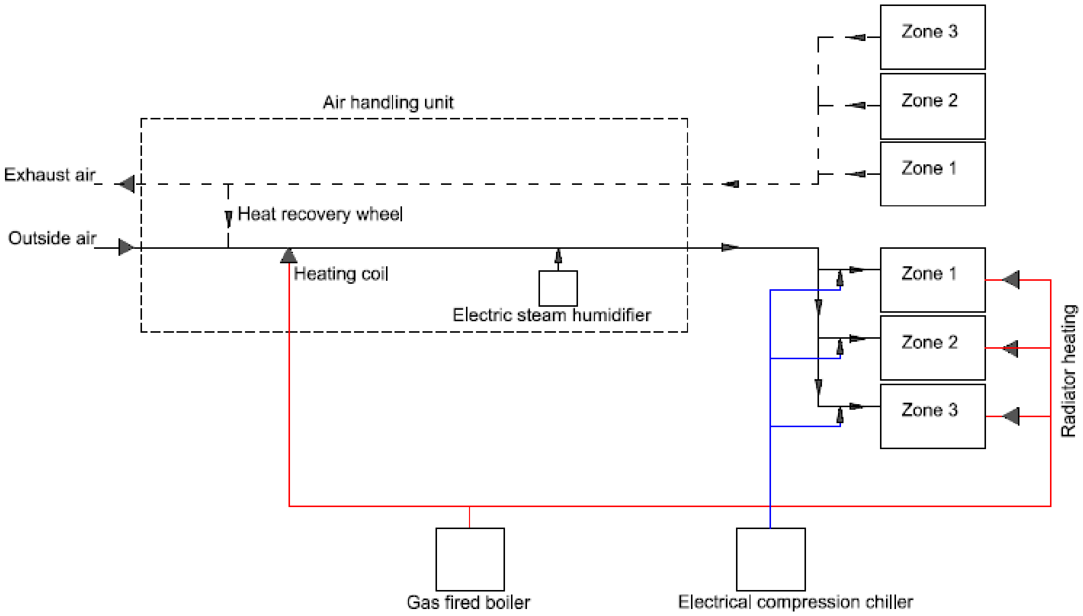


*Fig. 2.4.5: schematic overview of the climate control in Kropman Breda. Heating is supplied by heated ventilation air (heating curve) and radiators. Cooling is supplied on zone-level: ventilation air is cooled down in case of cooling demand.*

### 2.4.3 Reference situation of case study 2: design of office building Kropman Utrecht

The second case study is a newer (2004) and larger (5.500 m$^2$) office building. The building contains a more complex and modern HVAC system and more varied office hours, compared to the first case study. The building contains an aquifer thermal energy storage system, which makes it more representing for the newer office building stock, as shown in section 2.4.1. Furthermore, a balanced ventilation system is used (mechanical supply and exhaust) and commonly used fluorescent lighting is installed.

This case study is selected to create a broader representation of the Dutch office stock. The main properties and average comfort demand settings are shown in this section. Further detailed parameters are shown in Appendix II, used as input parameters for the building simulation model.

*Fig. 2.4.6: Impression of office building 'Kropman Utrecht'.* Upper left: *NW-façade (Google Streetview). Upper right: Atrium (Hoving, 2015).* Lower left: *NE-façade (Google Streetview).* Lower right: *office workplaces and restaurant (Hoving, 2015).*

| **General** | | |
|---|---|---|
| *Gross floor area (GFA)* | *5.500 m$^2$* | |
| *Year of construction* | *2004* | |
| *Floors* | *4* | |
| *Daily occupancy* | *Design (2004):*<br>*200-250 persons* | *2014:*<br>*130-150 persons* |
| *Office hours* | *6.00-21.00 h (different companies in the building with different office hours)* | |
| *Orientation (longest side from X-X)* | *E-W* | |
| *Percentage of glass in facades* | *45%* | |
| *Lighting* | *Fluorescent lighting* | |

| **Building envelope (double skin façade)** | |
|---|---|
| *R-value building envelope* | *2,7 m²K/W* |
| *U-value glass (incl. window frames)* | *1,8 W/m²K* |
| *Solar blinds* | *External (automatically controlled)* |

| **HVAC-system** | | | | |
|---|---|---|---|---|
| | ***Generation*** | ***Distribution*** | ***Release*** | ***Recovery*** |
| ***Heating*** | - *Aquifer thermal energy storage + heat pump*<br>- *District heating* | *Air & water* | *- Floor heating (locally controlled)*<br>*- chilled beam units (local reheating of centrally controlled ventilation air)* | *Heat recovery wheel* |
| ***Cooling*** | - *Aquifer thermal energy storage (+ heat pump)* | *Air & water* | *- Floor cooling (locally controlled)*<br>*- chilled beam units (local after-cooling of centrally controlled ventilation air)*<br>*- Free night-time cooling during nights, by mechanical ventilation* | *Heat recovery wheel* |
| ***Air humidification*** | *- no additional, active air humidification* | - | - | *Heat recovery wheel (hygroscopic)* |
| ***Ventilation*** | *Air handling unit* | *Air* | *Balanced ventilation (mechanical supply and mechanical exhaust)*<br>*Centralized ventilation control (central air handling unit).*<br>*Constant volume (21.500 m³/h)* | - |

| **Comfort demand & internal heat production** | | |
|---|---|---|
| *Average internal heat production over gross floor area* | *Design (2004):*<br>*Lighting: 10 W/m²*<br>*Occupants: 6-7 W/m²*<br>*Appliances: 9,5 W/m²* | *2014:*<br>*Lighting: 9 W/m²*<br>*Occupants: 4 W/m²*<br>*Appliances: 9 W/m²* |
| *Minimum room temperature (average over different room functions)* | *21,0 °C* | |
| *Maximum room temperature (average over different room functions)* | *24,0 °C* | |

### *Heating/cooling generation*

The heating in Kropman Utrecht is mainly supplied by a heat pump, taking a constant supply water temperature from the aquifer thermal energy storage system (ATES). For heating peak demands, also district heating is used.

For cooling, normally the ATES system is used. In cooling peak demands, the heat pump is used to increase the cooling capacity. Free cooling is used during nights, to cool down the building by mechanical ventilation, with outside air.

### *Heating/cooling distribution*

The air handling unit contains a heat recovery wheel and a central (change-over) heating/cooling coil. The ventilation air is centrally controlled, based on a heating curve. The ventilation air can be heated on floor-level, by duct heaters (duct heater for each office floor). On room level, the ventilation air is supplied to the room by ventilation vents and by chilled beam units. The surplus of air is transferred to the central atrium. Here, al the air from the offices is centrally exctracted by the air handling unit again and leaves the building, by passing the heat recovery wheel.

Furthermore, floor heating/cooling is installed in a part of the building (ground floor and the restaurant on the first floor).

### *Additional regeneration of ATES*

During the winter months, the air handling unit is also used for regeneration of the ATES, to provide additional cooling to the ATES. In that case, the intake fresh outside air is directly transferred to the return duct and exhaust fan. This cooling energy is used to cool down water, which is transferred to the aquifer. This 'regeneration state' is activated by outside air temperatures ≤ 4°C.

### *Presence detection*

Except for the floor heating/cooling system, the climate control is controlled on room level and based on presence detection of occupants.

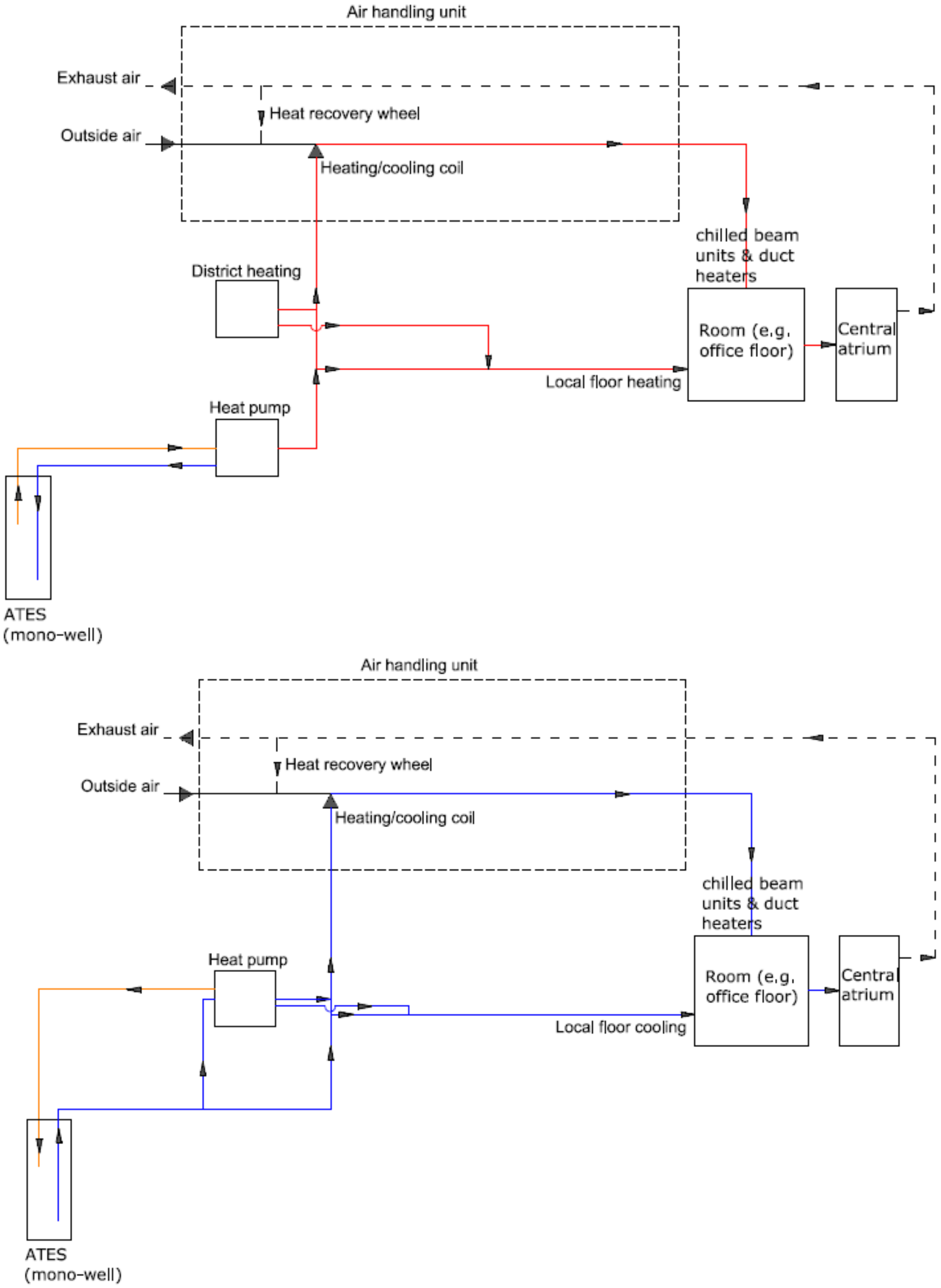


*Fig. 2.4.7: Simplified, schematic overview of the heating (above) and cooling (below) distribution in Kropman Utrecht. The figure only shows the main distribution lines and cannot be considered as complete system overview. The different system states and temperature ranges are shown in figures in appendix II.*

# 3. Systematic energy performance assessment in Kropman Breda

The sections in this chapter are sorted according to the defined research steps, discussed in section 2.3.

The first part of the chapter (§3.1 - §3.4) is about the identification of critical parameters in the energy performances of the case study buildings, by use of the Pareto analysis. The second part of the chapter (§3.5 & §3.7) consists of the identification and assessment of the energy performance gaps in the case study buildings, by use of the LEAN Energy Analysis. In section 3.8, the results of this case study are evaluated.

## 3.1 Pareto analysis, step 1: identification of problems

In this section the building simulation results are discussed and compared to the measured energy consumption.

### 3.1.1 Climate simulation

Two different climate files are used for the building simulations. For an indication of the 'average' energy consumption of the building, the reference climate file of NEN 5060 is used. This is an artificial aggregation of representative climate periods (e.g. January 2003, February 2004, March 1992, etc.).This reference climate file is used for the sensitivity analysis of the energy performances and the selection of critical parameters, because it shows a more representative, 'average' sensitivity over a year.

The second climate file contains measured climate data from the nearest official weather station of KNMI (Dutch climate institute) in Gilze-Rijen (± 10 km from Kropman Breda), for a fair comparison between simulated and measured energy consumption.

The climate data of 2014 is used for the building simulations. The reason for using this climate data is that 2014 was the year with the most complete measurement data for Kropman Breda, at the start of this study. In appendix I, a comparison is made with the energy data of 2013 (estimated, based on incomplete data sets) and 2015 (added later on, since this data set was not completed at the start of this study).

### 3.1.2 Model simplifications and assumptions

This section discusses the model simplification and assumptions, made in the calculations (within the Vabi Elements tool).

**Heating and cooling energy**

In section 1.4 (methodology) is already discussed that the used (version of) Vabi Elements does not include energy losses in generation and distribution system. However, in the available measured data of Kropman Breda, heating consumption can only be analyzed from the gas consumption of the boiler. That means that the generation efficiency, as well as distribution system efficiency, should be considered in the simulation results, for a straight-line comparison with the measured data. Therefore, an indication of the average, annual generation and distribution efficiency of the building systems in Kropman Breda is taken from a national standard (NEN 7120). These average efficiency numbers have been added manually to the simulation results. The used average efficiency numbers are:

- Heating generation efficiency (high efficiency gas boiler) – 95%
- Cooling generation efficiency (compression chiller) – 300% (COP =3)
- Heating distribution efficiency (central generation system, water & air distribution, thermal insulated ducts) – 88%
- Cooling distribution efficiency (central generation system, air distribution) – 94%

The most important comments for the building model of Kropman Breda are mentioned here:

- In the used Vabi model, only adiabatic air humidification can be simulated, while in Breda a steam humidifier is installed. Since adiabatic air humidification has consequences for the active cooling demand of a building, the air humidification is left out of the model in the calculations of the cooling load.

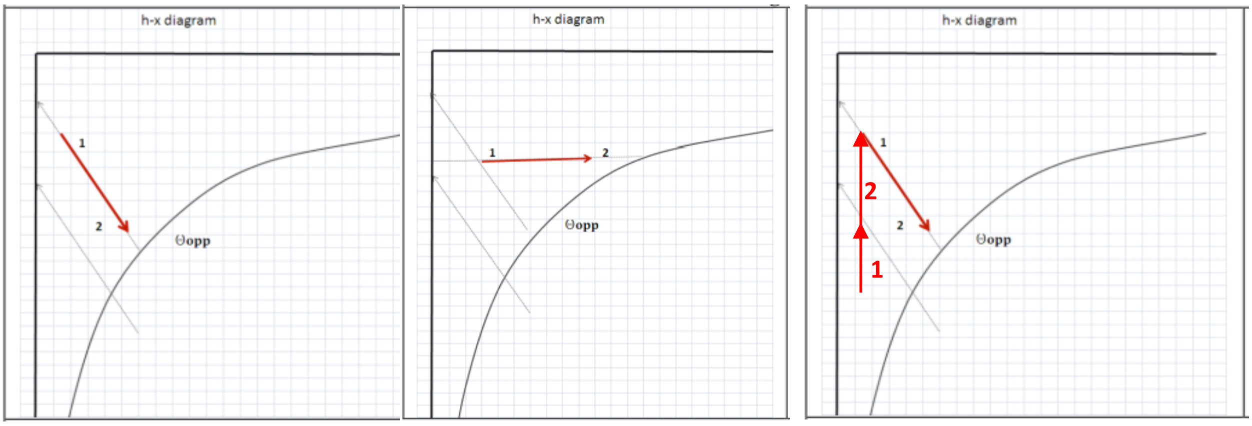
- Generation and release systems are considered with ‘unlimited’ capacity, because it was found that implementing the real capacities, acts as a barrier for the energy calculations. In reality, the building systems can easily handle the heating and cooling demand. That’s why the capacities are set as unlimited in the building model.
- The modeled internal heat production by occupants, appliances and lighting is based on an average measured level in the case study building, taken from Thomassen (2014).
- An indication of the infiltration level of the building envelope is based on rules of thumb from national standards (NEN 8088).

**Air humidification**

- In the used version of Vabi Elements, only adiabatic air humidification can be calculated. In the case study of Kropman Breda, an electric steam humidifier is used. Because this is basically another type of humidification, the consequences for the energy consumption are investigated. The principle of both humidification methods are shown in figure 3.1.1.

  In Vabi Elements, the heating consumption of the air handling unit is separated in ‘heating by heating coil’ and ‘heating by air humidification’ (figure 3.1.1). When the temperature of the supply air is higher than the set minimum temperature and the moisture content of the supply air is lower than the set minimum moisture level, the energy consumption of steam humidification will be larger than in case of adiabatic humidification. In general, the moisture content of air is relatively high at higher temperatures. Therefore, the consequences of this difference are only negligible in this case, the steam humidifier will additionally use 500-1.000 kWh/y.

- The used version of the Vabi Elements tool does not include moisture recovery, which means that this is not taken into account, while in the case study a hygroscopic heat recovery wheel (moisture recovery) is installed.
- As mentioned above for the simplifications in cooling simulation, the adiabatic air humidification has consequences for the active cooling demand of a building (as can be derived from figure 3.1.1). Therefore, the air humidification is left out of the model in the calculations of the cooling load.
- An efficiency of 93% for the steam humidifier has been added manually to the simulation results. This efficiency is based on experiences from Kropman employees.



*Afb. 3.1.1: Left: principle adiabatic air humidification (used in Vabi Elements). Middle: principle steam humidification (used in Kropman Breda). Right: heating demand for heating coil (1) and air humidifier (2), as separated in Vabi Elements.*

**Lighting**

- Installed lighting power is based on measurements. The related occupancy pattern is based on assumptions/estimations, which results in a certain simulated lighting consumption. Because the lighting system can be switched on per zone and no is not sensor based (e.g. presence-based, daylight-based, etc.), the lighting consumption is relatively easy to predict. The simulated lighting consumption can be seen as a relatively accurate indication over a year.

**Distribution energy (electricity of pumps, fans, etc.)**

- Distribution energy, as consumed by pumps and fans in the water and air distribution system, cannot be simulated in the used version of Vabi Elements, and is not taken into account (as discussed in section 1.4 in the limitations/boundaries of the used Vabi Elements tool. To get an indication of the significance of this energy consumption, the measured energy consumption is shown in section 3.1.3.

**Electrical appliances**

- The electricity consumption of multiple electrical appliances is measured in one ‘group’. This consists of different components as: ICT, elevator, kitchen & pantry, alarm and office appliances. The internal heating production of this appliances is roughly estimated for the building model. Further, these appliances are excluded from the simulations. A possible energy gap in this group can be caused only by the efficiency of the appliances, which is not the scope of this research.

### 3.1.3 Comparison between simulated and measured energy consumption

The simulation results are compared with the measured results, shown in table 3.1.1. The table shows the results for the artificial reference climate file ‘NEN 5060’ and KNMI climate data of Gilze-Rijen (nearest official weather station). As mentioned before, the analysis is based on 2014. In appendix I, a comparison is made with the energy data of 2013 (estimated, based on incomplete data sets) and 2015 (added later on, since this data set was not completed at the start of this study).

For the most accurate measured data of the heating consumption, the gas consumption of the boiler [m$^3$] is used for this analysis. To convert the gas consumption from m$^3$ to kWh, the higher heating value of Dutch gas is used (9,77 kWh/m$^3$), because the boiler uses also the heat of the flue gases to heat up the water in the building system.

*Table 3.1.1: Annual simulated and measured energy consumption of case study 1: Kropman Breda. In these annual consumptions, the mentioned ‘reference’ generation and distribution efficiencies are included, in order to make a straight-line comparison with the measured energy data.*

| | **Artificial ‘Reference climate’ NEN 5060** | **Gilze-Rijen, 2014** | **Measured (2014)** |
|---|---|---|---|
| **Building heating** (gas, converted to electrical energy) | 68.400 kWh$_e$/y | 50.700 kWh$_e$/y | 92.000 kWh$_e$/y |
| **Building cooling** (electricity) | 6.600 kWh$_e$/y | 8.100 kWh$_e$/y | 4.200 kWh$_e$/y |
| **Air humidification** (electricity) | 61.000 kWh$_e$/y | 49.000 kWh$_e$/y | 4.100 kWh$_e$/y |
| **Lighting** (electricity) | 33.500 kWh$_e$/y | 33.500 kWh$_e$/y | 30.000 kWh$_e$/y |
| **Distribution energy** (electricity consumption of pumps and fans) | - | - | 20.300 kWh$_e$/y |
| **Electrical appliances** (ICT, kitchen, elevator, office equipment, etc.) | - | - | 53.300 kWh$_e$/y |

Figure 3.1.2 also shows the comparison between simulated energy consumption (climate data Gilze-Rijen, 2014) and the measured consumption of 2014.

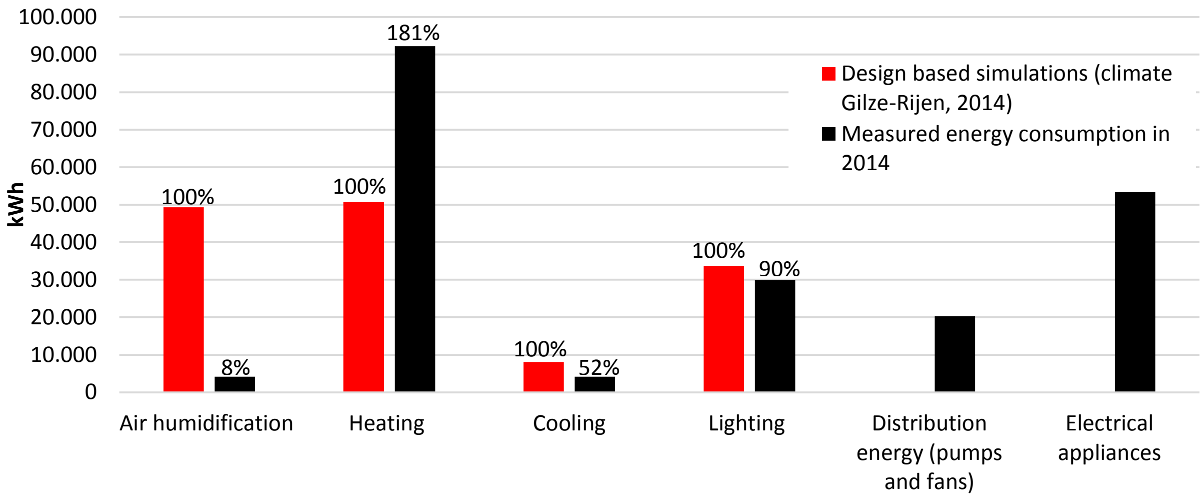


*Fig. 3.1.2: Annual energy consumption in Kropman Breda: simulated ('design situation') versus measured. The measured electricity of 'electrical appliances' and 'distribution energy' is only shown to provide an indication of the significance of this energy function. The simulated energy is considered as being '100%', to get an indication of the percentage energy gaps.*

The amount of cooling energy is relatively low, compared to the heating energy. From comparisons with data from 2013 and 2015 (Appendix I), it is concluded that this low cooling demand is caused by the installation of a new (more efficient) compression chiller in 2014. In 2013, the cooling electricity consumption was about 2x higher, compared to 2014. In 2015, the cooling consumption is even lower, compared to 2014.

## 3.2 Pareto analysis, step 2: identify root causes of the problem

The energy consumption of buildings depend on different, fluctuating and interdependent parameters. It all starts with a demand of the building users for electrical office equipment and a healthy and comfortable work environment (mainly light, temperature and relative humidity). All these parameters require energy if the outdoor climate does not meet the requirements. The amount of energy depends on the quality, use and properties of the building and the efficiency of the building systems. In figure 3.2.1 an indication of involved parameters is shown.

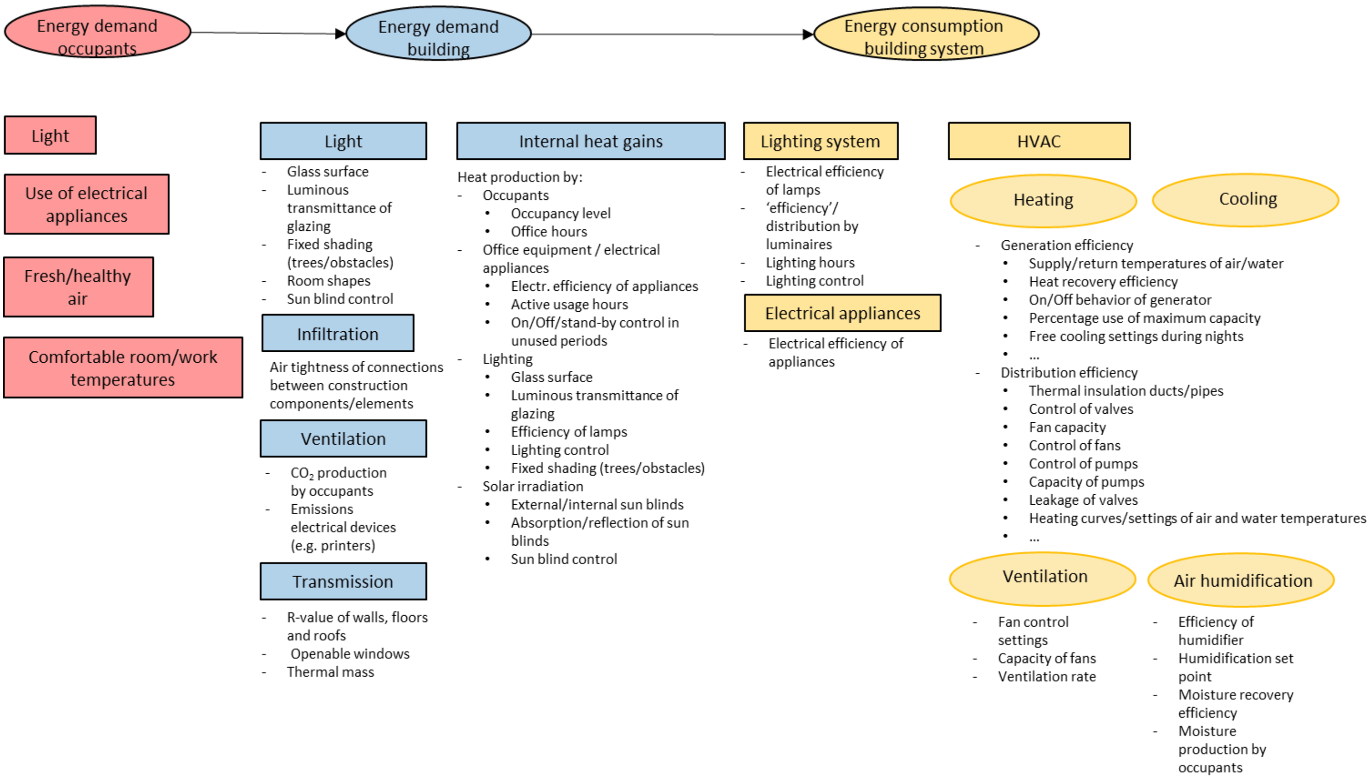


*Fig.3.2.1: Indication of involved parameters in building energy consumption. This list is created as a quite general overview, which is applicable on many office buildings. Several parameters are merged in this case and can be split up in multiple detailed parameters/settings.*

For a widely applicable method, it would be more useful to identify a few parameters for the assessment of the energy performances. Therefore, from this large quantity of parameters (indicated in figure 3.2.1), a relatively small selection of 15 (merged) 'main parameters' has been made, based on the input of the building model.

From these parameters, it is expected that they determine the major part of the energy demand. In the further analysis, the impact of these parameters on the annual energy consumption is analyzed, to select the most important ones. The goal in this part of the Pareto analysis is to investigate whether the energy performance gaps of the case studies can be assessed/explained with only a few 'root causes' (20% of all involved causes), in this case a few 'major parameters'. Although the selection of the parameters is based on this '80/20'-rule, the 15 parameters cannot be considered as a literal percentage of 20%, because the total number of involved parameters/settings is hard to define (as shown and explained in figure 3.2.1).

This analysis provides useful information for a widely applicable method, because energy performances can be monitored and analyzed more efficiently, if energy gaps can be assessed with only a few 'major parameters'.

**Analyzed energy functions**

In the further analyzes in this study, lighting, electrical appliances and auxiliary energy for the HVAC system (electricity by pumps and fans) are excluded, which means that the further Pareto analysis continues with heating, cooling and air humidification. The reason for the exclusion of lighting and distribution electricity are mentioned below:

- Lighting plays a significant role in the electricity consumption of the case study building. However, the electricity consumption of lighting is only dependent on the active hours of the lighting system. This means that an energy performance gap can be caused only by a difference between assumed lighting hours in the 'reference situation' and the real lighting hours. Outside office hours, lighting is always inactive for the case studies (checked). The only way to analyze possible energy waste in lighting during office hours is to compare lighting electricity consumption with the exact presence of occupants, which is not within the scope of this study.

- The distribution energy is measured centrally (the sum of the consumed electricity of all pumps and fans). Therefore, it is not possible to analyze the efficiency of the individual pumps and fans with the available data. Moreover, for a simulation of the distribution energy, an additional, detailed model is needed. Because it is not indispensable for the answering of the research question, the further analysis of the distribution energy is left out of consideration in this study.
- Electrical appliances. This group consists of different components as: ICT, elevator, kitchen & pantry, alarm and office appliances. A possible energy gap in the electricity consumption of this group can be caused only by the efficiency of the appliances, which is not the scope of this research.

**Selection of parameters in heating, cooling and air humidification, for further analysis**

The further analysis continues with heating, cooling and air humidification, as explained above. The selected parameters are based on the case study building, but most of them are general applicable. The parameter are further analyzed with the Vabi Elements building model, which means that the selection frame for the parameters have the same limitations as the building model. In chapter 1, the limitations of Vabi Elements have already been discussed.

The selected parameters are:

***Building***

1. R-value building envelope
2. U-value windows (glass incl. frames)
3. G-value windows
4. Infiltration

***Internal heat gains***

5. Internal heat production by occupants, appliances & lighting
6. Sun blind control

***Comfort demand/user requirements***

7a. Min. air temperature during office hours
7b. Max. air temperature during office hours
8. Min. air temperature outside office hours
9. Ventilation rate

***Climate control settings***

10a. Heating curve radiators (vertical shift)
10b. Heating curve radiators (horizontal shift)
11a. Heating curve AHU (vertical shift)
11b. Heating curve AHU (horizontal shift)
12. HVAC operation hours (time schedule office hours)
13. Night-time cooling
14. Min. absolute humidity in supply ventilation air

***Heat recovery***

15. Efficiency heat recovery wheel (sensible heat)

## 3.3 Pareto analysis, step 3/4/5: rank, score and group causes

The intention in this part of the Pareto analysis is to investigate whether the energy performance gaps of the case studies can be assessed/explained by only a few ‘major parameters’. Therefore, in this section the impact of the 15 selected parameters (from section 3.2) on the annual energy consumption is analyzed by a sensitivity analysis. Thereafter, the impact of the parameters is ranked, based on their impact on the annual energy consumption. In this way, it is becoming clear which parameters should be taken into account in the assessment of energy performance gaps.

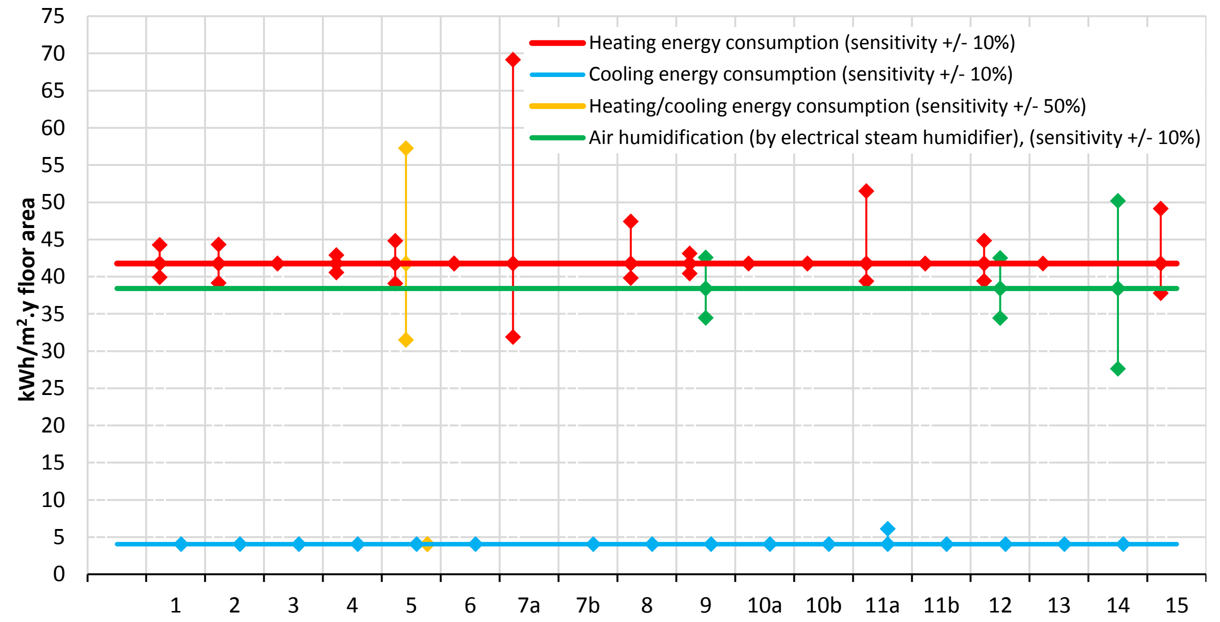
### 3.3.1 Sensitivity analysis

The sensitivity analysis is performed by varying the involved parameters individually with + and – 10% of the 'baseline' design settings. This method has been chosen because of the uniformity of the comparison and the fact that this method provides insight in the topic in a clear and practical way. The 10% change is considered as a uniform realistic variety for all parameters. Although this change is relatively small for some parameters (e.g. occupancy), a larger variety would be unrealistic because of other parameters (e.g. indoor temperature). In addition to this uniform sensitivity analysis, an additional larger variety is tested for the occupancy rate (+ and – 50%), to check a more realistic variation of this parameter.

The used method of the sensitivity analysis includes the interdependence between different parameters. The modification of one parameter can influence the impact of other parameters, which means that the cause for the resultant impact on the energy consumption cannot be traced 100% to the modified parameter. The reason that this method has been chosen is the fact that this is a quite practical approach, because these interdependence/connections are also present in real buildings. If each parameter is analyzed completely independent from the other ones, it will result in an endless (unusable) amount of parameter combinations, because most parameters change several times during a year.

The sensitivity analysis has been performed for the NEN 5060 reference climate, because this is an artificial created 'average' climate and leads to an 'average' impact on the annual energy consumption.

The results of the sensitivity test are shown in a diagram, in figure 3.3.1. As mentioned above, the internal heat gain is additionally tested with a variety of + and – 50%. These results are also shown in figure 3.3.1.



***Building***
1. *R-value building envelope*
2. *U-value windows (glass incl. frames)*
3. *G-value windows*
4. *Infiltration*

***Internal heat gains***
5. *Internal heat production by occupants, appliances & lighting*
6. *Sun blind control*

***Comfort demand/user requirements***
- *7a. Min. air temperature during office hours*
- *7b. Max. air temperature during office hours*
- *8. Min. air temperature outside office hours*
- *9. Ventilation rate*

***Climate control settings***
- *10a. Heating curve radiators (vertical shift)*
- *10b. Heating curve radiators (horizontal shift)*
- *11a. Heating curve AHU (vertical shift)*
- *11b. Heating curve AHU (horizontal shift)*
- *12. HVAC operation hours (time schedule office hours)*
- *13. Night-time cooling*
- *14. Min. absolute humidity in supply ventilation air*

***Heat recovery***
- *15. Efficiency heat recovery wheel (sensible heat)*

*Fig. 3.3.1: Results of sensitivity test of the annual energy consumption in Kropman Breda. The used values for the tested parameters are shown in table 3.2.1.*

*Table 3.3.1: Tested parameters in Kropman Breda, changed by ± 10% of 'design' settings/assumptions to provide insight in the sensitivity of the annual heating and cooling consumption.*

| ***Building*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 1 | R-value building envelope | 2,5 $m^2K/W$ | 2,25 $m^2K/W$ | 2,75 $m^2K/W$ | - no data available |
| 2 | U-value windows (glass incl. frames) | 2,9 $W/m^2K$ | 2,6 $W/m^2K$ | 3,2 $W/m^2K$ | - no data available |
| 3 | G-value windows | 0,7 | 0,63 | 0,77 | - no data available |
| 4 | Infiltration | 0,1-0,3 1/h | 0,09-0,27 1/h | 0,11-0,33 1/h | - no data available |

| ***Internal heat gains*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 5 | Internal heat production by occupants, appliances & lighting | 34 kW *(4+ 15+15)* | 30 kW (-10%)<br>17 kW (-50%) | 37 kW (+10%)<br>51 kW (+50%) | 34 kW *(model was based on measured data for this parameter* |
| 6 | Sun blind control | 300 $W/m^2$ | 270 $W/m^2$ | 330 $W/m^2$ | - no data available |

| ***Comfort demand / user requirements*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 7a | Min. air temperature during office hours | 21,2 °C | 19,1 °C | 23,3 °C | Different per zone:<br>20 - 22 °C |
| 7b | Max. air temperature during office hours | 24,0 °C | 21,6 °C | 26,4 °C | Different per zone:<br>24 - 25 °C |
| 8 | Min. air temperature outside office hours | 18,0 °C | 16,2 °C | 19,8 °C | 18,0 °C |
| 9 | Ventilation rate | 14.900 $m^3/h$ | 13.400 $m^3/h$ | 16.500 $m^3/h$ | 14.900 $m^3/h$ *(model was based on measured data for this parameter* |

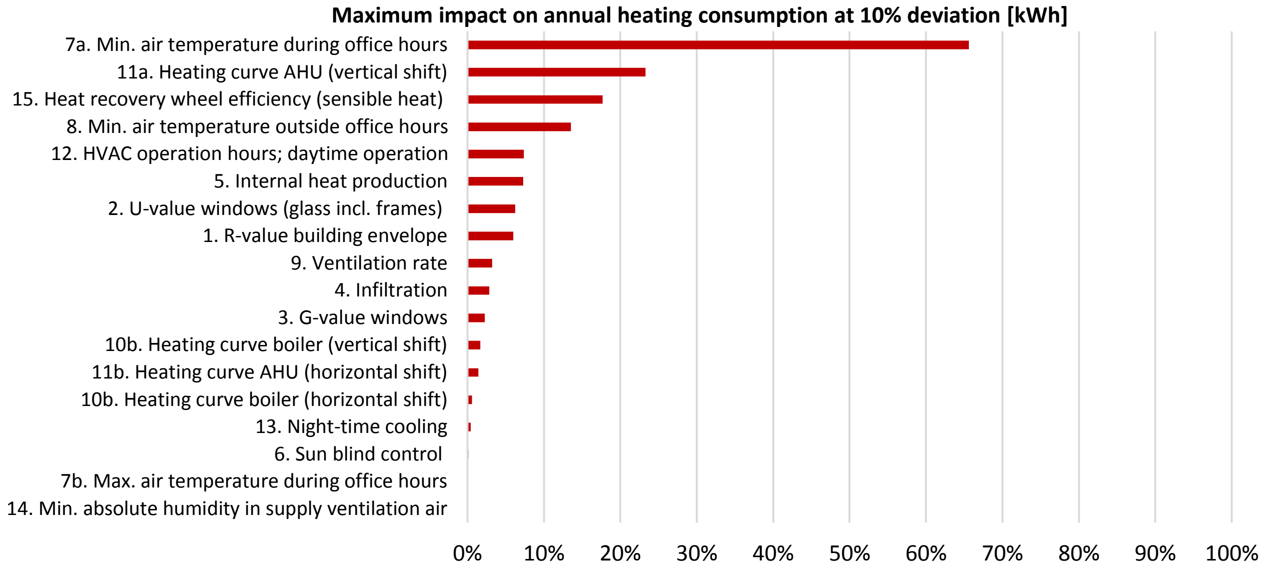
| ***Climate control settings*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 10a | Heating curve radiators ($T_{outside}/T_{water}$) (vertical shift) | -10/90 °C & 20/20 °C | -10/81 °C & 20/11 °C | -10/99 °C & 20/29 °C | -5/90 °C & 20/20 °C |
| 10b | Heating curve radiators ($T_{outside}/T_{water}$) (horizontal shift) | -10/90 °C & 20/20 °C | -8/90 °C & 18/20 °C | -12/90 °C & 22/20 °C | -5/90 °C & 20/20 °C |
| 11a | Heating curve AHU ($T_{outside}/T_{supply\ air}$) (vertical shift) | 16/20 & 21/18 °C | 16/18 & 21/16 °C | 16/22 & 21/20 °C | 20/22 & 25/25 °C |
| 11b | Heating curve AHU ($T_{outside}/T_{supply\ air}$) (horizontal shift) | 16/20 & 21/18 °C | 14/20 & 19/18 °C | 18/20 & 23/18 °C | 20/22 & 25/25 °C |
| 12 | HVAC operation hours (time schedule office hours) | Mon: 13 h (5:00-18:00 h)<br>Tue-Fri: 11 h (7:00-18:00 h) | Mon: 12 h (6:00-18:00 h)<br>Tue-Fri: 10 h (8:00-18:00 h) | Mon: 14 h (4:00-18:00 h)<br>Tue-Fri: 12 h (6:00-18:00 h) | Mon: 11 h (6:00-17:00 h);<br>Tue/Wed: 12 (5:00-17:00 h)<br>Thu/Fri: 10 (7:00-17:00 h) |
| 13 | Night-time cooling | activated | deactivated | | Activated |
| 14 | Min. absolute humidity setting in supply ventilation air | 8,2 g/kg | 7,4 g/kg | 9 g/kg | 8,0 g/kg |

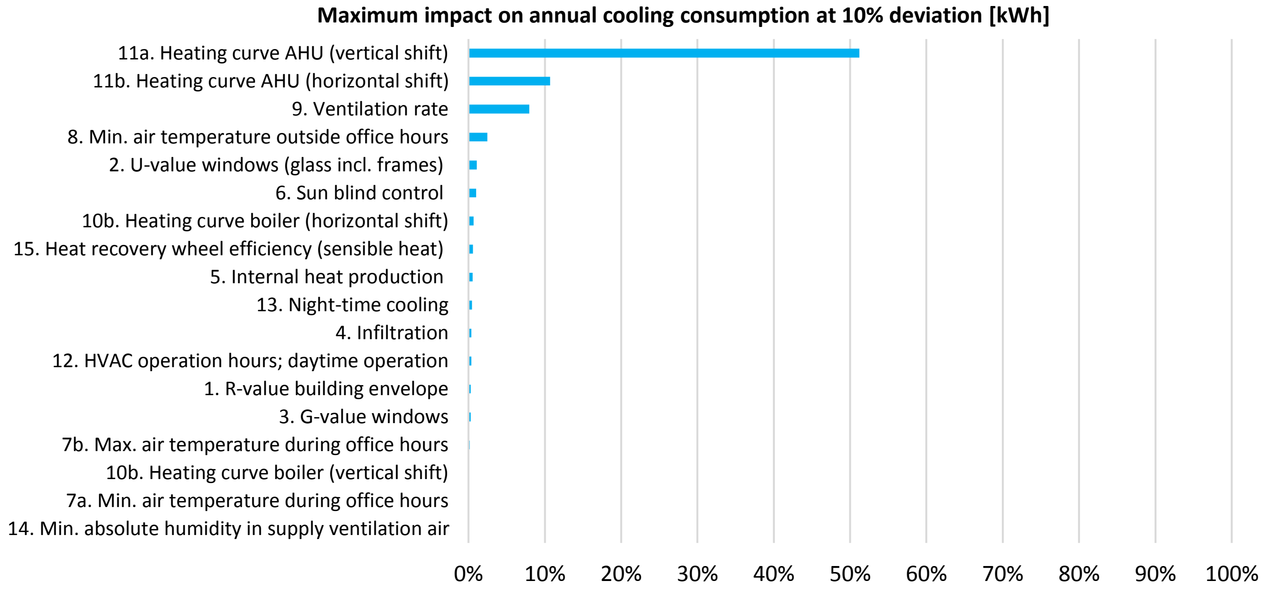
| ***Heat recovery*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 15 | Heat recovery wheel efficiency (sensible heat) | 70% | 63% | 77% | - no data available |

### 3.3.2 Ranking and scoring of parameters

In figure 3.3.2 the results of the sensitivity analysis are ranked by the impact on annual energy consumption, for heating, cooling and air humidification.

The maximum value on the X-axis in each figure (100%) is the simulated annual energy consumption (in the reference NEN 5060 climate, because the sensitivity analysis is performed for this 'average' climate). In this way, it can easily be derived which parameters are important and should be taken into account in the assessment of the identified energy performance gaps.





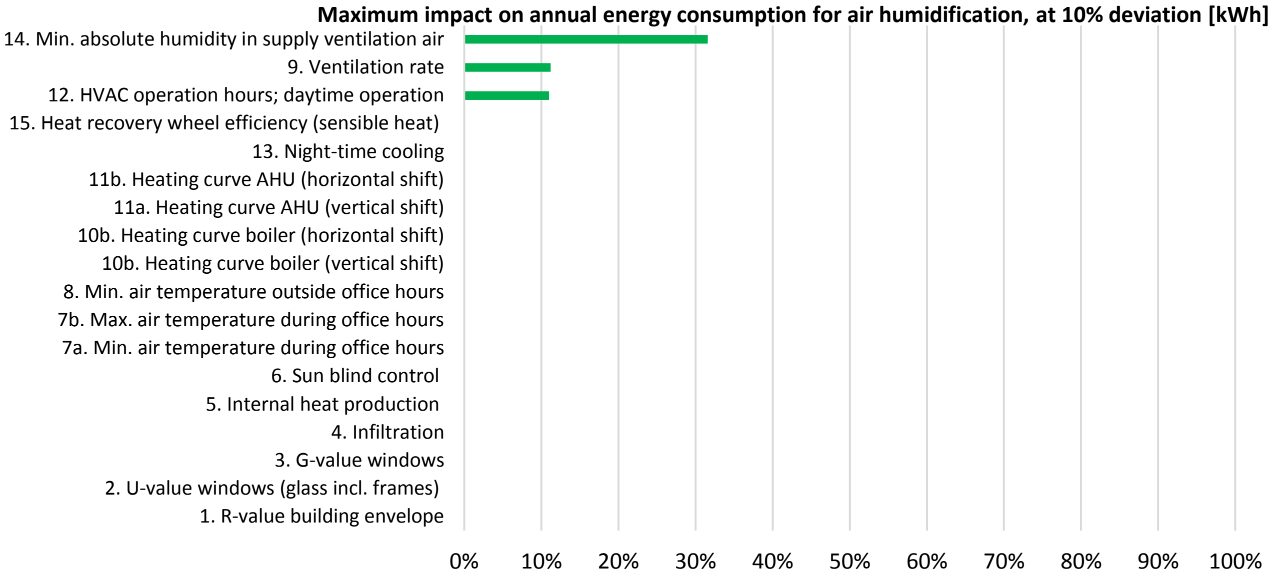


*Fig. 3.3.2: Tested parameters, sorted by impact on annual energy consumption (above: heating; middle: cooling; below: air humidification). The maximum value on the X-axis (100%) in each figure is the simulated annual energy consumption (reference NEN 5060 climate data). In this way, the relative impact on the annual energy consumption can be seen.*

From figure 3.3.2 it can be derived that there are several parameters with a large percentage impact on the annual energy consumption, at a deviation of 10%. These parameters are different for each energy function. The reason for the (unexpected) robustness of the cooling system is unknown, can be caused by the fact that the cooling energy is limited to the constant ventilation air and the set heating curve, or by model limitations.

The most important parameters, which can make a real difference in energy performances are selected below from figure 3.3.2. These parameters should surely be taken into account in assessment of energy performance gaps.

In the sensitivity analysis (section 3.3.1), the internal heat production has additionally been analyzed with a sensitivity of +/- 50%. In that case, this parameter would have a large impact on the energy consumption. However, over a year, the assumed internal heat production has been estimated quite carefully and does not deviate for 50% over a year. But it is concluded from this result that this parameter can play a significant role in energy consumption when shorter time periods are considered. For example, over a day, the internal heat production can easily deviate 50% from the assumed daily internal heat production.

**Heating**

- Min./max. air temperature during office hours
- Heating curve AHU
- Efficiency heat recovery wheel (sensible heat)
- Min. air temperature outside office hours
- HVAC time schedule; daytime operation
- Internal heat production by occupants, appliances & lighting (only for energy assessment of relative short time periods)

**Cooling**

- Heating curve AHU

**Air humidification**

- Min. absolute humidity in supply ventilation air
- Ventilation rate
- Time schedule AHU

## 3.4 Pareto analysis, step 6: Assessment of energy gap by selected critical parameters

In this section, the real share of the selected 'critical parameters' (§3.3) in the identified energy gaps, is assessed. In this way, it is investigated if the theoretical '80/20-ratio', according to basic principle of the Pareto analysis, is true for the energy gaps in this case study.

Cooling energy is not considered in this section, because there was no significant energy gap and cooling energy is only a small part of the annual energy consumption. Therefore, this step of the Pareto analysis is focused on air humidification and heating consumption.

### 3.4.1 Air humidification

In air humidification, a straight-line comparison between simulated and measured energy cannot be made, because of the fact that there was a technical breakdown during a long period in the humidifier and the fact that no moisture recovery was taken into account in the simulations (discussed in section 3.1.2). Therefore, only the impact of the most critical parameters, selected in the section before, on the annual simulated energy consumption, are assessed.

The selected critical parameters, with the design and real values, are shown in table 3.4.1.

The real values of the critical parameters are implemented in the building model to see the impact on the annual energy consumption. The results are shown in figure 3.4.1: the critical parameters decrease the annual energy consumption for air humidification by about 10.000 kWh for 2014.

*Table 3.4.1: most critical parameters for air humidification, selected in section 3.3. The real values do not significant deviate from the design values. The impact on the annual energy consumption is shown in figure 3.4.1.*

| **Parameter** | **Design value** | **'Real' value** |
|---|---|---|
| Ventilation rate | 14.900 m$^3$/h | 14.900 m$^3$/h *(design model was based on measured data for this parameter* |
| HVAC operation hours (time schedule office hours) | Mon: 13 h (5:00-18:00 h)<br>Tue-Fri: 11 h (7:00-18:00 h) | Mon: 11 h (6:00-17:00 h);<br>Tue/Wed: 12 (5:00-17:00 h)<br>Thu/Fri: 10 (7:00-17:00 h) |
| Min. absolute humidity setting in supply ventilation air | 8,2 g/kg | 8,0 g/kg |

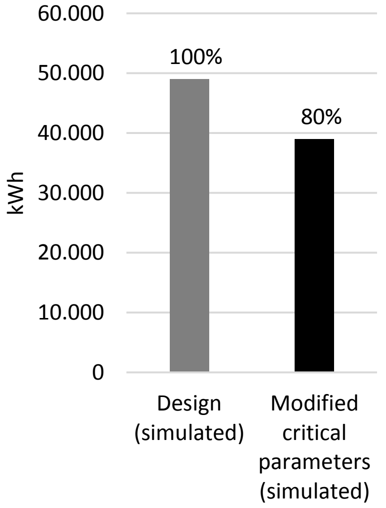


*Fig. 3.4.1: The effect of the selected most critical parameters on the annual energy consumption of the air humidification energy in Kropman Breda. A straight-line comparison with the measured data is not possible, due to technical break-downs of the humidifier and the fact that no moisture recovery is taken into account in the simulation model (discussed in §3.1.2.).*

Although the real set point for the minimal moisture level in the ventilation supply air does not really deviate from the design value, it was concluded that this value is relatively high. Therefore, this setting is lowered, for future energy savings.

### 3.4.2 Heating energy

Also for heating energy, the selected most critical parameters are assessed and the impact on the simulated energy consumption is investigated. Besides the selected critical parameters, the efficiency of the gas boiler is analyzed here, because this efficiency is involved in the measured data, but is not taken into account in the sensitivity analysis (because of the limitations/boundaries of the used (version of) the Vabi Elements tool).

The assessed critical parameters, including the efficiency of the boiler, are shown in table 3.4.3:

*Table 3.4.2: most critical parameters for heating, selected in section 3.3. The real values do not significant deviate from the design values. The impact on the annual energy consumption is shown in figure 3.4.1.*

| **Parameter** | **Design value** | **'Real' value** | **Difference caused by:** |
|---|---|---|---|
| Min./max. air temperature during office hours | 21,2 °C - 24,0 °C | Different per zone:<br>Min. 20 - 22 °C Max. 24 - 25 °C | No significant differences. The temperature can be controlled individually for each room, by radiator valves. |
| Heating curve AHU | Break-points heating curve Toutside/Tsupply:<br>16/20 &<br>21/18 °C | Break-points heating curve Toutside/Tsupply:<br>20/22 &<br>25/25 °C | Heating curve modified in building management system |
| Efficiency heat recovery wheel (sensible heat) | 70% | No data available | No data available. This can be measured if energy gaps cannot be explained by available data. |
| Min. air temperature outside office hours | 18,0 °C | 18,0 °C | No significant differences. |
| HVAC operation hours (time schedule office hours) | Mon: 13 h (5:00-18:00 h)<br>Tue-Fri: 11 h (7:00-18:00 h) | Mon: 11 h (6:00-17:00 h);<br>Tue/Wed: 12 (5:00-17:00 h)<br>Thu/Fri: 10 (7:00-17:00 h) | Time schedule modified in building management system |
| Generation efficiency of gas-fired boiler | 95% | 90% | High return temperatures of the boiler. A more detailed analysis is shown in Appendix III. |

The real values of the critical parameters are implemented in the building model to see the impact on the annual energy consumption. The real annual average efficiency of the gas boiler (90%, see table 3.4.2), has been added manually to the simulation results. The impact of the parameters is shown in figure 3.4.2. It can be seen that the critical parameters over a year have only a relatively small impact on the energy consumption and only a small part of the energy gap can be explained by the selected parameters. In the LEAN Energy Analysis, the remaining energy gap is further analyzed.

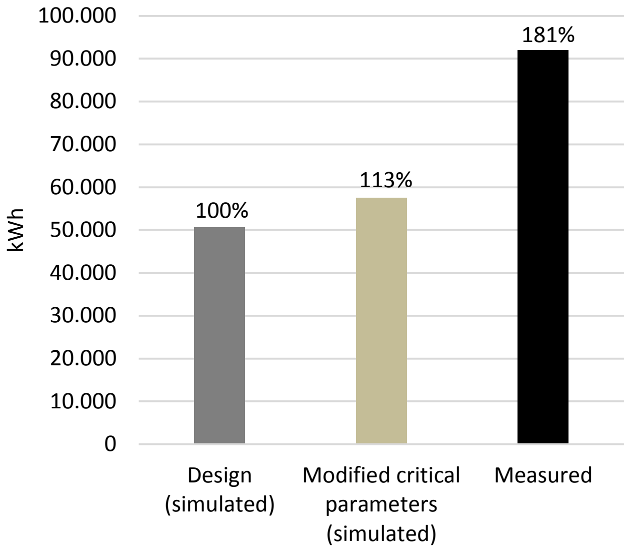


*Fig. 3.4.2: The effect of the selected most critical parameters on the annual heating consumption in Kropman Breda. It can be seen that the critical parameters over a year have only a relatively small impact on the energy consumption and only a small part of the energy gap can be explained by the selected parameters.*

## 3.5 LEAN Energy Analysis, step 1 & 2: collecting data & create baseline/benchmark models

Step 1 (collecting utility and weather data) is a continuous step in the analyzing process and is not specifically described in this report. Therefore, this section deals with step 2: creation of benchmark models, which can be used to assess measured energy consumption.

According to the LEAN principle, the way to create a benchmark model is to consider the used energy consumption as a function of the primary goal of this energy, already discussed in section 2.2. Therefore, in this section characteristic, independent variables are identified for the analyzed energy functions.

The primary function of room heating and cooling is to bridge the gap between the outdoor temperature and the desired indoor temperature. Kissock, et al. (2003) state that building energy consumption can be adequately described by models that relate energy consumption to outside air temperature. Therefore, in section 3.5.1 the correlation between the energy and the outdoor temperature has been analyzed.

It was found that the correlation between the analyzed energy consumption and the outdoor temperature is weak, because of the several involved time-dependent parameters (as solar irradiance, internal heat production, stored heat in the building mass, different temperature settings between day and night), which ‘disturb’ this correlation. With these models/profiles, measured energy cannot be assessed.

Therefore, additional correlations have been identified, within characteristic time blocks. These correlations are shown in section 3.5.2.

In the Pareto analysis, heating and air humidification is assessed. In the LEAN Energy analysis, only heating is considered for Kropman Breda. Air humidification is excluded here for several reasons:

- For a major part, the air humidification is dependent on the efficiency of the moisture recovery. As explained before, no moisture recovery can be simulated with the used version of the Vabi Elements tool, which means that an additional, detailed model of moisture recovery is needed, which would be very time consuming.
- Besides moisture recovery, the electricity consumption for air humidification is only dependent on the efficiency of the electric steam humidifier. This efficiency is more or less constant over time (between 90-95%) and can be hardly influenced in practice (this statement is based on experiences from Kropman employees).

- Because the need for an additional, detailed model of the moisture recovery (by the heat recovery wheel), the fact that the efficiency of the humidifier can be hardly influenced and the fact that this is not indispensable for the achievement of the research goals, it is decided to leave air humidification out of consideration in this study.

### 3.5.1 Building heating as function of outdoor temperature

This section shows an analysis of the major energy functions as function of the outdoor temperature (as the primary function of the energy consumption, as explained in the introduction above).

Here, the results from the simulations with the climate data of KNMI weather station ‘Gilze-Rijen’ (2014) are used. This has already been discussed in step 1 of the Pareto analysis.

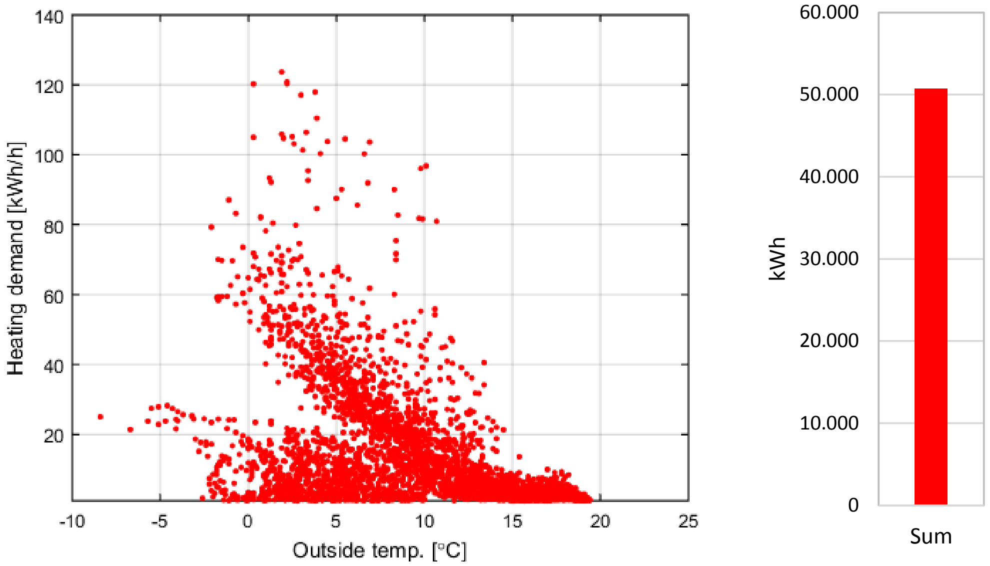


*Fig. 3.5.1:* Left: *simulated annual heating consumption as function of outdoor air temperature. Each data point represent an hourly energy consumption.* Right: *sum of all data points.*

In figure 3.5.1 the simulated annual heating consumption is shown as function of outdoor air temperature. There is a correlation between the heating consumption and the outdoor temperature, but there are obviously other factors which ‘disturb’ this correlation.

The large bandwidth of the profile shows that the correlation is too weak to asses measured energy consumption. Roughly, two different profile can be distinguished in this figure. But only when the measured energy consumption of the building would have a completely different profile, non-specific conclusions can be drawn about an energy gap. In all other cases, the profile would provide too less information. That is why other correlations are analysed in section 3.5.2.

### 3.5.2 Building heating as function of outdoor temperature & time

Because of the weak correlation between the heating/cooling energy consumption and the outdoor temperature, time is involved as second independent variable in the analysis of the energy consumption. This section identifies typical time blocks for both case study buildings and combines them with the earlier analyzed variable of outdoor temperature.

Solar irradiation is the first significant factor which changes in time and has large influence on the heating demand of the building. Since the solar has a generally characteristic curve over a year, the heating demand is divided into three ‘seasons’:

1. Winter: January, February & November, December
2. Spring/Autumn: March, April & September, October
3. Summer: May, June, July, August

Besides this solar influence, the heating demand fluctuates a lot over a day, due to different parameters which change over time, as:

- Internal heat production by occupants, lighting and appliances
- Day and night temperature settings
- Amount of stored heat in the thermal building mass

Because of these time-dependent parameters, different time blocks are identified in the heating demand over a day. In figure 3.5.2, a typical daily profile of the simulated heating demand (January) is divided into different time blocks. The figure shows two curves (Monday and Friday), since the heating system starts earlier on Mondays (5:00 h instead of 7:00 h).

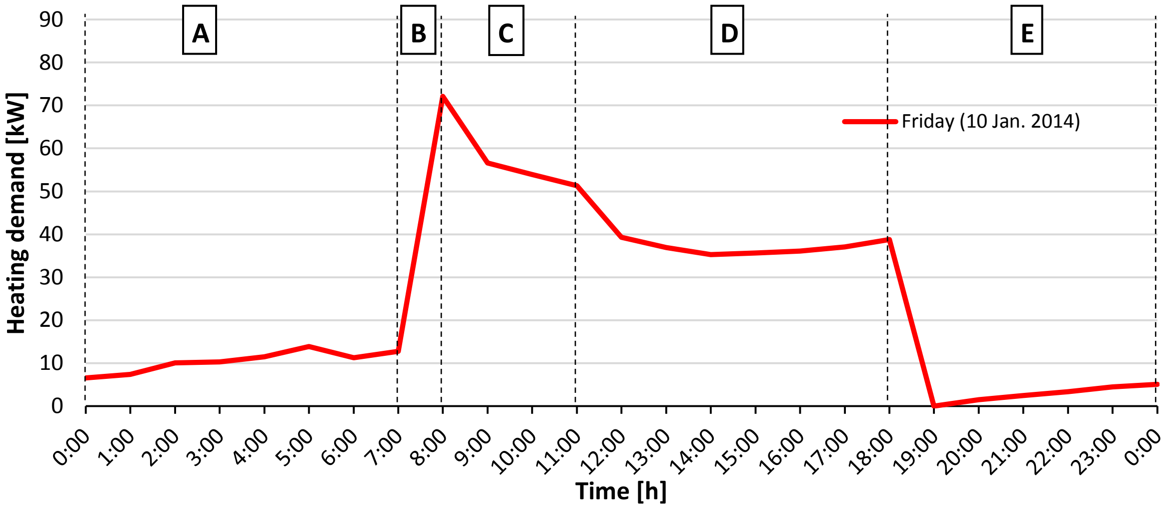


*Fig. 3.5.2: Typical profile of the simulated daily heating demand. The daily heating load is divided into different, characteristic time blocks (A-E in the daily heating load and block F (weekend)).*

A. 0:00- 7:00 h (Tuesday- Friday):
   *The thermal mass of the building releases the stored heat and the indoor temperature is controlled at a set minimum temperature.*
B. 5:00-8:00 h (Mondays) and 7:00-8:00 h (Tuesday-Friday):
   *The heat up period. In this block, the heating systems has to heat up the building to the set minimum temperature. In this block also the internal heating by employees, appliances and lighting is starting. The climate control systems starts earlier on Mondays and needs more heating capacity to heat up the building to the desired level after a weekend.*
C. 8:00-11:00 h:
   *The internal heat production is relatively constant and reduces the heating demand, but solar irradiation does not play a significant role in this block. In this period the building mass is heated up to a constant temperature.*
D. 11:00-18:00 h:
   *In this block the heating demand is quite constant and relatively low, due to the solar irradiance and the fact that the building mass has reached a constant temperature and helps to reduce fluctuating heating demand.*
E. 18:00-24:00 h:
   *Office is closed, building mass releases the stored heat to the indoor air.*
F. Weekend (Saturday 0:00 h. – Monday 5:00 h)
   *Office is closed, the indoor temperature is controlled at a set minimum temperature.*

The correlations between the heating demand and the outdoor air temperature are considered again within these defined time blocks. The results are shown in the figures below.

During the study, it was found that energy profiles with hourly data do not well represent the dynamic behaviour of the building systems. Therefore, the heating demand is summed over a day within each time block. This means that each time block has 365 data points over a year, instead of 8760. In this way, the dynamic behavior of the building system is better included within the time blocks.

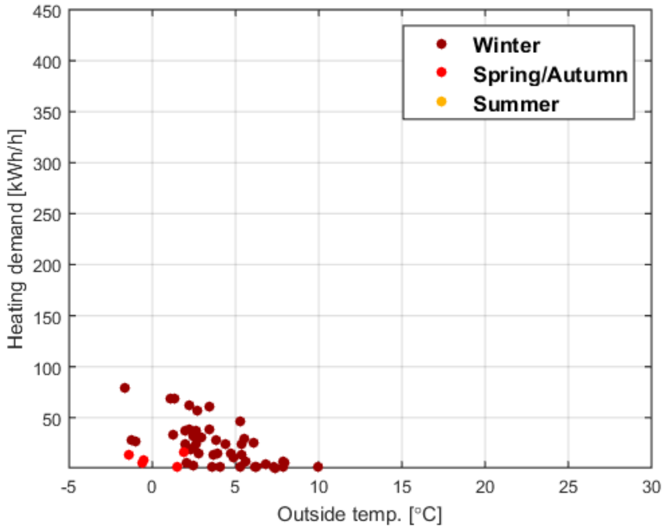


*Fig. 3.5.3. Simulated annual heating demand in time block A (0:00-7:00 h (Tuesday – Friday).*

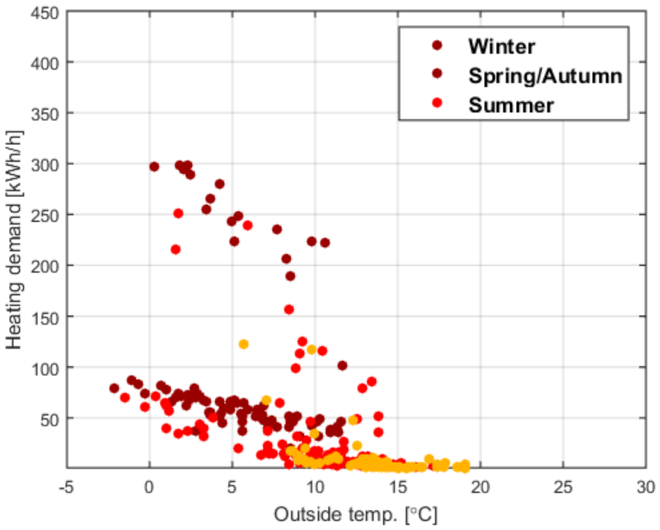


*Fig. 3.5.4. Simulated annual heating demand in time block B 5:00-8:00 h (Mondays) and 7:00-8:00 h (Tuesday-Friday). The heat up period on Mondays ('upper part of the profile') has a significant different profile, compared to the profile of Tuesday-Friday (lower part of the profile).*

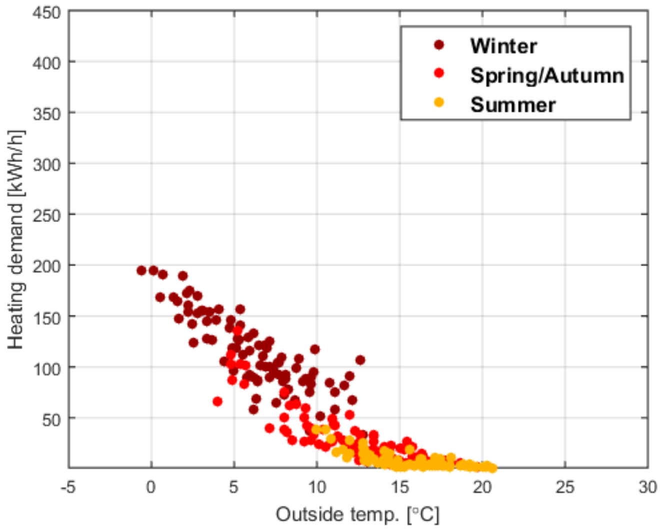


*Fig. 3.5.5. Simulated annual heating demand in time block C (8:00-11:00 h).*

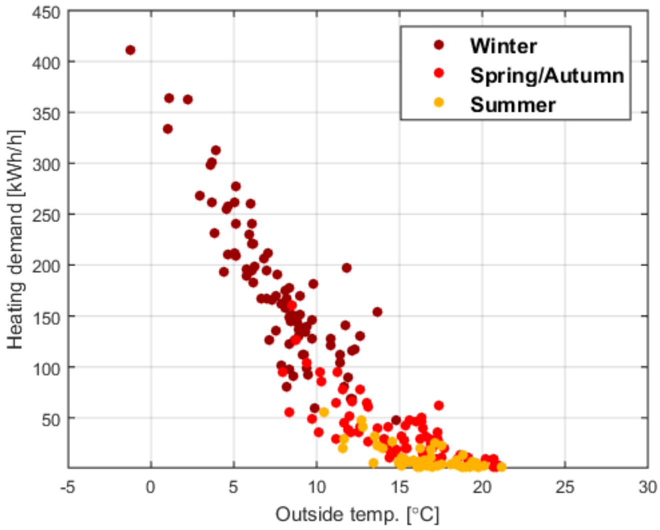


*Fig. 3.5.6. Simulated annual heating demand in time block D (11:00-18:00 h).*

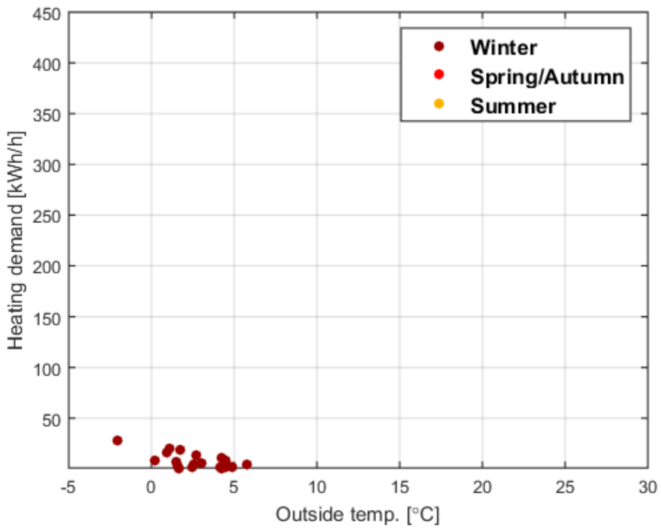


*Fig. 3.5.7. Simulated annual heating demand in time block E (18:00-0:00 h).*

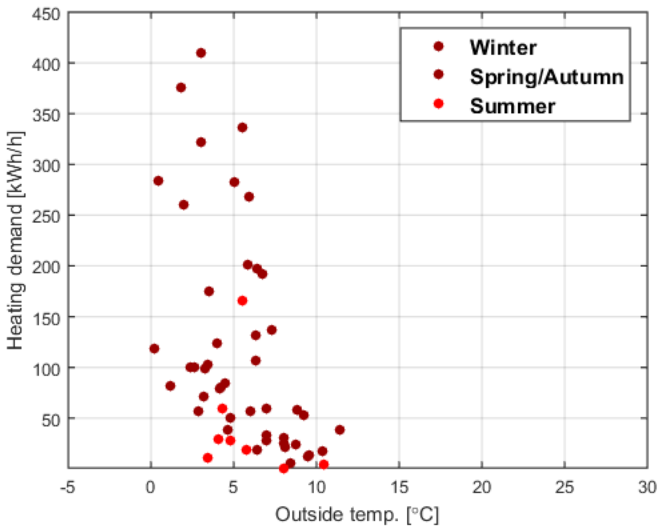


*Fig. 3.5.8. Simulated annual heating demand in time block F (weekend; Saturday 0:00 h – Monday 5:00 h).*

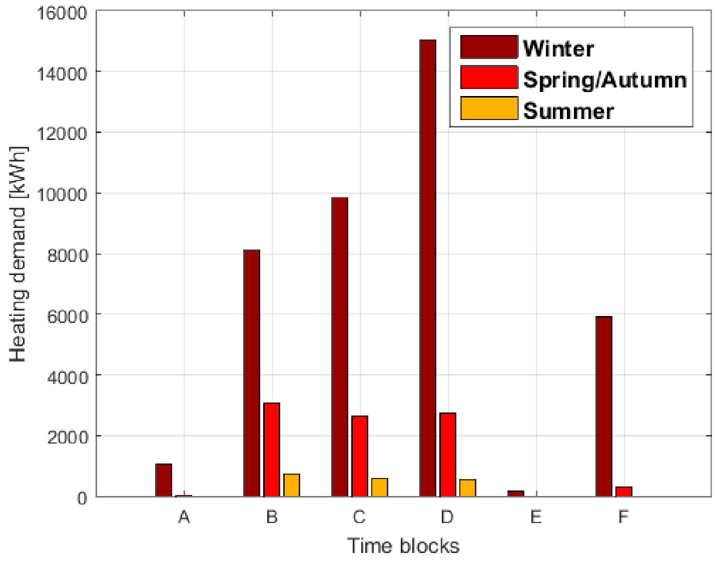


*Fig. 3.5.9. Sum of simulated annual heating demand, divided in time blocks.*

From the figures above, it is concluded that the correlation between the heating demand and the outdoor air temperature is much better within these time blocks, which makes it much easier to assess measured energy performances. This is caused by parameters which change over time, as stored heat in thermal mass of the building, different temperature settings during day and night and internal heat production. Also the seasonal shift of the heating load can be derived. The results show that time can be considered as a sufficient, second independent variable in the assessment of energy performance (gaps).

## 3.6 LEAN Energy Analysis, step 3: Identify energy performance gaps

This section deals with the comparison between the simulated and the measured energy consumption.

### 3.6.1 Regression (coefficients) analysis in energy assessment

In literature studies of the LEAN Energy Analysis, the assessment of energy consumption is based on regression coefficients of linear regression models, as discussed in the background information of the LEAN method. In this study it is tried to apply this way of analysis. However, it turned out that linear regression lines do not represent the physical shapes of the identified energy profiles. In figure 3.6.1 some examples are shown. Most common outdoor temperatures do have much more data points, having a large impact on the regression line. This results in regression lines which do not represent the energy data at less common outdoor temperatures, which means that information about the energy ‘behavior’ is lost when the energy data is reduced to a regression line.

Although multi-linear regression analysis can be applied for a better representation of the physical meaning of the data profiles, it is found that the assessment with characteristic coefficients of regression lines (or other ‘best fit’ curves) does not improve the ability to assess the energy consumption. The regression coefficients (e.g. slope of the regression line), do contain only general information about efficiency of the system. Since in regression lines physical information about the behavior of the building (system) is lost, compared to the energy data profiles, physical parameters cannot be derived from the regression coefficients. Involved parameters do not have that specific impact on regression lines. The combination of all parameters determine the regression coefficients, resulting in the fact that no reliable conclusions can be drawn from a difference between coefficients in the ‘design’ regression lines and the ‘measured’ regression lines.

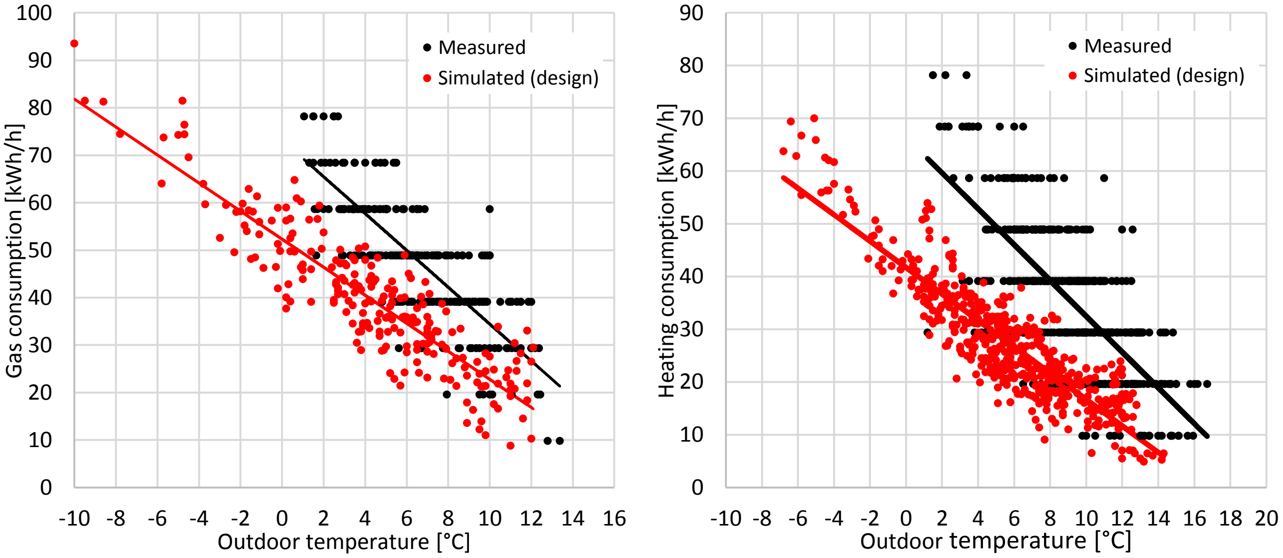


*Figure 3.6.1: Linear regression (least squares method), does not represent the physical shapes of energy profiles. Multi-linear regression would improve the fit/representativeness of the regression lines, but it is found that regression analysis and/or coefficients do not improve the ability to assess energy consumption. On the contrary, useful information is lost by reducing the energy profiles to regression lines.*

### 3.6.2 Cumulative energy in characteristic time blocks

Based on section 3.6.1, it is decided to assess the cumulative energy consumption of the case study in each identified, characteristic time blocks. This way provides more insight in the relevance of the energy gap in each time block.

The simulated heating consumption has been compared to the measured energy consumption in tables 3.6.1 - 3.6.3, for each defined time block. The tables are sorted by the defined ‘seasons’:

- Table 3.6.1: Winter (January, February, November & December)
- Table 3.6.2: Spring/Autumn (March, April, September & October)
- Table 3.6.3: Summer (May – August)

Because a part of the energy gap has already been explained by the results of the Pareto analysis (the selected most critical parameters), the results of the modified building model (with the implemented real values of the critical parameters) are also shown. With this comparison, it can be seen in which time blocks the critical parameters have the largest impact and which part of the energy gap is not explained by the results of the Pareto analysis. Based on these findings, the further analysis can be continued more specific and effective.

*Table 3.6.1: Comparison of measured and simulated heating consumption in winter period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 7:00 h (Tuesdays - Fridays)** | 1.100 | 14.300 | 7.100 |
| **B** | **5:00-8:00 h (Mondays) and 7:00-8:00 h (Tuesday-Friday):** | 8.100 | 6.900 | 7.500 |
| **C** | **8:00-11:00 h** | 9.800 | 11.800 | 11.700 |
| **D** | **11:00-18:00 h** | 15.000 | 18.000 | 15.700 |
| **E** | **18:00-24:00 h** | 200 | 350 | 50 |
| **F** | **Weekend (Saturday 0:00 h. – Monday 5:00 h)** | 5.900 | 13.200 | 4.100 |

*Table 3.6.2: Comparison of measured and simulated heating consumption in spring/autumn period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 7:00 h (Tuesdays - Fridays)** | 50 | 7.200 | 2.800 |
| **B** | **5:00-8:00 h (Mondays) and 7:00-8:00 h (Tuesday-Friday):** | 3.100 | 3.400 | 2.500 |
| **C** | **8:00-11:00 h** | 2.700 | 3.800 | 2.600 |
| **D** | **11:00-18:00 h** | 2.700 | 3.500 | 1.900 |
| **E** | **18:00-24:00 h** | 0 | 0 | 0 |
| **F** | **Weekend (Saturday 0:00 h. – Monday 5:00 h)** | 300 | 2.400 | 100 |

*Table 3.6.3: Comparison of measured and simulated heating consumption in summer period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 7:00 h (Tuesdays - Fridays)** | 0 | 2.800 | 500 |
| **B** | **5:00-8:00 h (Mondays) and 7:00-8:00 h (Tuesday-Friday):** | 750 | 1.300 | 500 |
| **C** | **8:00-11:00 h** | 600 | 1.100 | 300 |
| **D** | **11:00-18:00 h** | 600 | 1.100 | 200 |
| **E** | **18:00-24:00 h** | 0 | 0 | 0 |
| **F** | **Weekend (Saturday 0:00 h. – Monday 5:00 h)** | 0 | 800 | 0 |

The most relevant seasons are shown in figure 3.6.2 (winter) and figure 3.6.3 (spring/autumn).

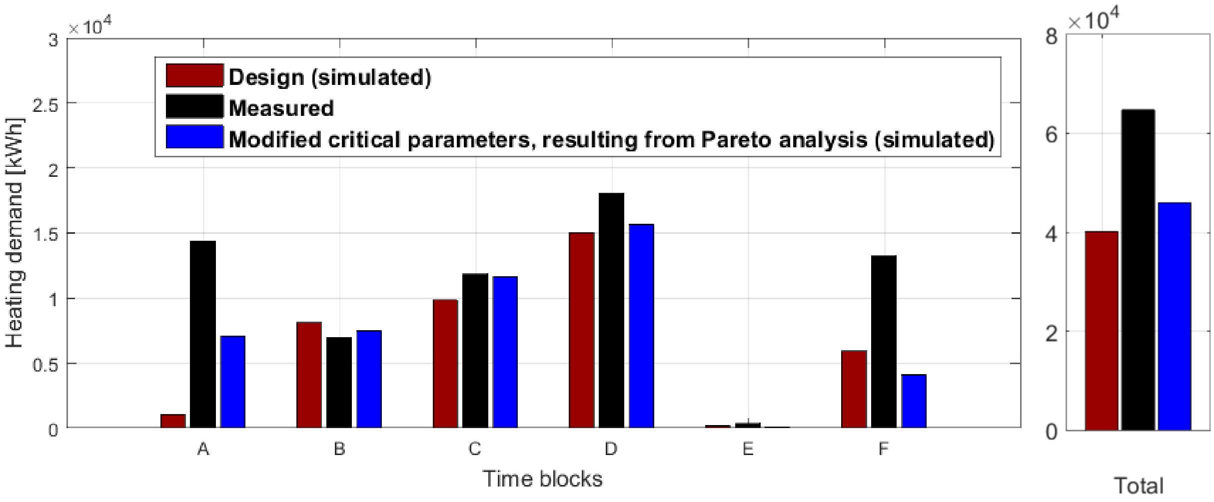


*Fig. 3.6.2: Winter season (January, February, November & December): comparison of the simulated and the measured heating consumption in the defined time blocks of Kropman Breda.*

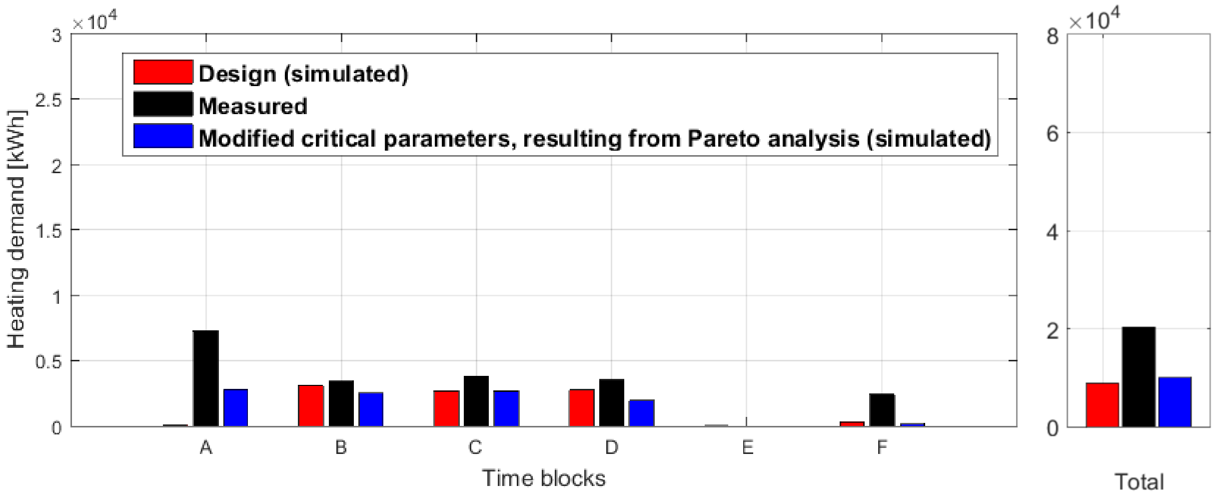


*Fig. 3.6.3: Spring/Autumn season (March, April, September & October): comparison of the simulated and the measured heating consumption in the defined time blocks of Kropman Breda.*

As can be seen from this figures, the major energy gaps are outside the office hours, in time block A & F (0:00-7:00 h on Tuesday-Friday and during weekends (Saturday 0:00 h- Monday 5:00 h)). In section 3.7, the energy gaps are further analyzed, to identify the cause of this relatively large difference.

## 3.7 Assessment of remaining energy gaps (which cannot be explained by the results of the Pareto analysis)

This section deals with the last step of the LEAN Energy Analysis (assessment and opportunities). This last step is to identify the causes of the remaining energy gaps (which cannot be explained by the results of the Pareto analysis) in a specific and effective way. This is possible due to the results of the steps before, in which the energy gaps are identified within specific time blocks.

It was concluded that the remaining energy gaps in heating consumption mainly occur in time block A and F, which are both outside office hours. Therefore, the simulated and measured heating profiles of these time blocks are considered and shown in figure 3.7.1. Because the energy gaps occur in all seasons, all seasons are shown in the same profiles.

For the simulated heating profiles, the 'modified' building model is used, with the implemented real values of the critical parameters, resulting from the Pareto analysis. In this way a more straight-line comparison is made.

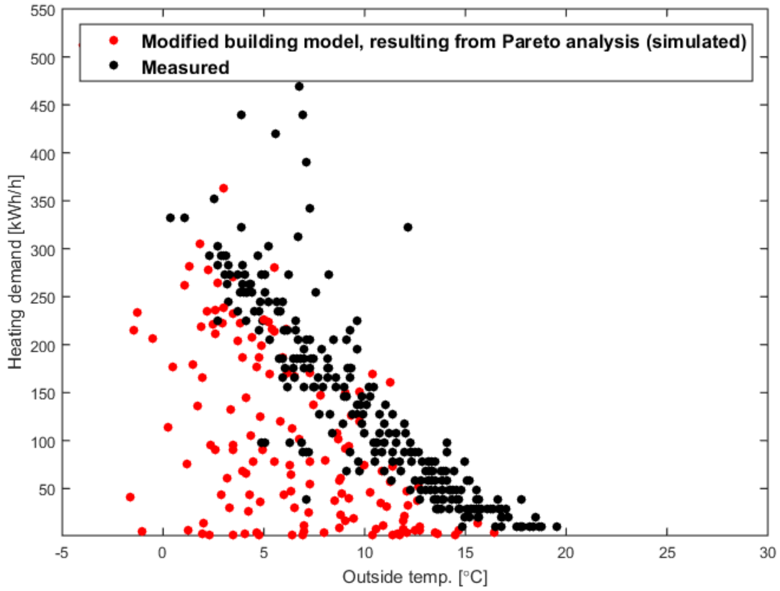


*Fig. 3.7.1: simulated versus measured heating profile op Kropman Breda. The tight correlation between outside temperature and the measured heating demand seems to indicate a heating demand from the building. Because heating is supplied by only one boiler, with only a few control 'rules', a more detailed analysis is started with this control of the boiler.*

In figure 3.7.1, the tight correlation between outside temperature and the measured heating demand seems to indicate a heating demand from the building. Because heating is supplied by only one boiler, with only a few control 'rules', a more detailed analysis is started with this control of the boiler. In figure 3.7.2, the supplied heat of the boiler is analyzed over time, during a week. The red line indicates the supplied heat by the boiler, the black line indicates the energy consumed by auxiliary energy (pumps and fans). From this black line, the 'daytime' time schedule can be derived. It can be seen that the boiler supplies heat before the 'daytime' time schedule is started.

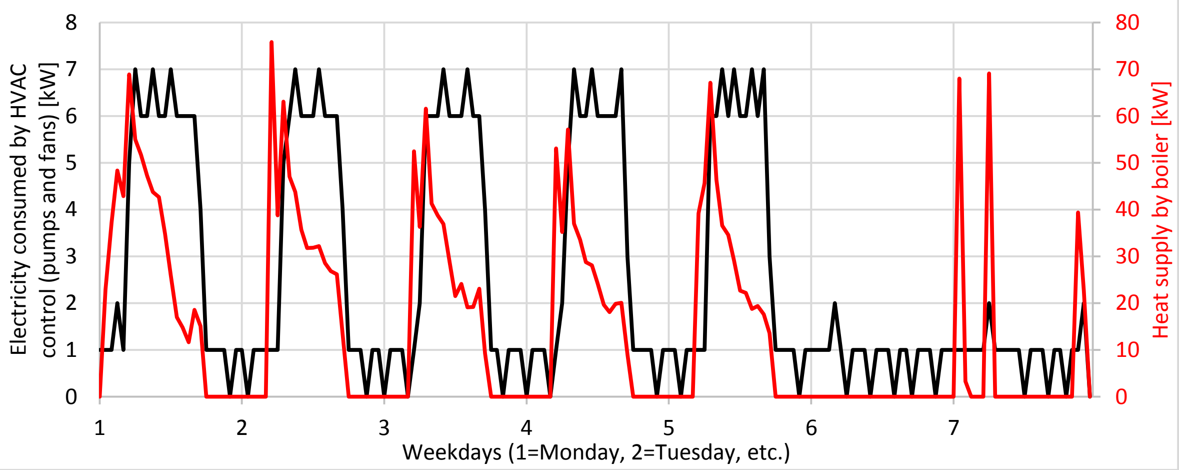


*Fig. 3.7.2: Supplied heat of the boiler, during a week. The red line indicates the supplied heat by the boiler, the black line indicates the energy consumed by auxiliary energy (pumps and fans). From this latter, the 'daytime' time schedule can be derived. It can be seen that the boiler supplies heat before the 'daytime' time schedule is started.*

In a more detailed analysis, based on figure 3.7.2, it was found that the control of the boiler is based on (amongst others) this rule: "If the outside temperature is lower than 17°C, the boiler determines a starting point (based on the room temperature), to guarantee the desired room temperature at the start of the 'daytime' time schedule. Desired room temperature is 21,2°C." (Quoted and translated from the functional description of the boiler).

This rule explains the heating profile during nights and weekends. Namely, in this figure it can be seen that the measured heating consumption in this block is only in the mentioned temperature range (< ±17°C). When the heating supply of the boiler is shown as function of time, it can be seen that in cold winter periods the boiler already starts up between 2:00-3:00 h, in order to guarantee the minimum temperature during the set time schedule of the office hours. Also in weekends, the boiler starts up suddenly during cold hours. Because the air handling unit (daytime operation schedule) is not active during these moments, the heat is only transferred to the building by radiators.

From this analysis it is concluded that the real building needs much more heat to reach the set minimum temperature at the start of the daytime schedule, compared to the simulation model. Also during weekends, much more heat is used, which means that the real building loses more heat, compared to the simulation model. This fact seems to indicate heat loss by/in the building envelope, but additional, specific measurements are needed to prove this hypothesis. These measurements (e.g. on the heat radiation from the building) are not within the scope of this study, but are recommended for future investigation. This analysis ends with the hypothesis that the cause is in heat losses through the building envelope and the recommendation for specific measurements on the heat radiation from the building.

## 3.8 Findings from case study 1

### Findings from the Pareto analysis

By simulating the annual energy consumption (with/using climate data from Gilze-Rijen 2014) and comparing it with the measured energy consumption in 2014, there appeared to be a significant energy performance gap in the heating consumption of this building (§3.1). Although air humidification also seems to be a major energy function from the simulation results, a straight-line comparison with the measured electricity from the electric steam humidifier cannot be made, because of model limitations and technical breakdowns of the humidifier.

The intention of using the Pareto analysis here, was to investigate whether 80% of the energy gaps could actually be explained by 20% of the involved causes. It was found that it is hard to define '100%' of the involved parameters, because of the quantity of the interdependent parameters and settings. Therefore, 15 parameters are selected, based on the building model input, to investigate their impact on the annual energy consumption.

To investigate the sensitivity and impact of parameters, a simple, common applicable method is preferred. Because it is very building specific how much a parameter can deviate and it would take a lot of time to investigate what the average deviations would be, a relatively simple and straight-lined sensitivity analysis has been chosen to use. Every parameter setting, as it should be according to the design, is varied with + and – 10%. The parameters that had the biggest impact in this sensitivity analysis, are considered to be the most critical parameters. These give the highest risk on an energy performance gap, from the investigated parameters (§3.3). These parameters are different for heating, cooling and air humidification. Cooling energy seems to be very robust, compared to heating energy. The exact reason is not sure: it can be caused by the fact that the cooling energy is limited to the combination of a constant ventilation rate and a set heating curve, or by model limitations. More detailed research is needed to explain this finding. Furthermore, it turned out that a fluctuation of 50% of internal heat production has a large impact on energy consumption. Although the average internal heat production over a year will not deviate that much, when energy is considered over short time periods, it is a decisive parameter.

The actual effect of these parameters on the energy performances from Kropman Breda (with heating and air humidification as the biggest energy functions) has been investigated by checking the real values of the selected critical parameters in the building (§3.4). It turned out that the settings in the building model must be compared with the measured energy data, because they cannot be compared straight-lined with the settings in the actual building installation. For example, a minimum temperature set point in the model is easy to define, but in practice, there is a bandwidth that prevents an installation from turning on and off. Although the air humidification energy consumption is not straight-lined compared to measured data (explained above), it was found in this analysis that the current setting for the minimum air humidification percentage in the ventilation air was set very high (8g/kg). Based on this finding, this setting is lowered, which will save energy in future. For heating it was found that only a small part (17%) of the energy gap can be explained by the found 'critical parameters'.

### Findings from the LEAN Energy analysis

In the LEAN Energy Analysis, the (energy gap in) heating energy consumption is analyzed. Based on literature, energy was considered as function of outside air temperature. The resulting energy profile shows only a weak correlation, because of influencing time-dependent parameters (as solar irradiation, internal heat production, stored heat in thermal building mass, etc.). Therefore, characteristic time blocks are defined, based on these time-dependent parameters. It turned out that the correlation between the heating consumption and the outside air temperature becomes clarifies when the heating consumption is considered within these time blocks individually. This improves the ability to assess measured energy consumption data.

In the discussed literature and background information of the LEAN Energy Analysis, heating energy is benchmarked and assessed by linear regression analysis and regression coefficients. In this case study it was found that energy data profiles for different time blocks, are more appropriate for measured energy assessment, compared to regression analysis. Reducing these energy profiles to linear (or multiple) regression lines results in loss of useful information about the 'behavior' of the heating consumption. Regression coefficients only provide very general information about the efficiency of the system (e.g. the slope of a regression line), but too many parameters are involved to draw reliable conclusions about specific causes for deviating regression coefficients; physical causes of energy gaps do not have that specific impact on regression lines.

Comparison between the simulated and the measured energy consumption within the defined characteristic time blocks, provides a clear view on the energy performance gap. In this case study, the energy gap mainly occurs outside office hours (nights and weekends). This finding made it possible to start a targeted analysis on the real cause of the energy gap. Following the LEAN method, trend analysis with the corresponding energy profiles was used to identify the cause of the remaining energy gap (which cannot be explained by the results of the Pareto analysis). In this analysis a clear heating demand was identified (strong correlation between heating consumption and outside air temperature), while the simulated energy demand shows only a weak correlation in these time blocks (because only a minimum indoor temperature should be maintained during nights and weekends). Because heating is only supplied by a gas boiler in this building, the analysis leads to the control of the boiler. There, it was found that the boiler is programmed to define its own starting point (based on the room temperature), to guarantee the desired room temperature (21,2°C) at the start of the 'daytime' time schedule. Although the set 'daytime' time schedule is similar to the building model, the real building needs significantly more heat to reach the set minimum temperature at the start of the daytime schedule, compared to the simulation model. Also during weekends, more heat is used, which means that the real building loses more heat, compared to the simulation model. This fact seems to indicate heat loss by/in the building envelope, but specific measurements are needed to prove this hypothesis. These measurements (e.g. on the heat radiation from the building) are not within the scope of this study, but are recommended for future investigation.

It is hard to define the percentage of the explained part of the energy gap, because no sufficient data is available to check the specific effect of an identified cause.

# 4. Systematic energy performance assessment in Kropman Utrecht

This chapter deals with the systematic energy performance analysis and assessment of the second case study. The sections in this chapter are sorted similar to chapter 3 and according to the defined research steps, discussed in section 2.3.

The first part of the chapter (§4.1 - §4.4) is about the identification of critical parameters in the energy performances of the case study buildings, by use of the Pareto analysis. The second part of the chapter (§4.5 - §4.7) consists of the identification and assessment of the energy performance gaps in the case study buildings, by use of the LEAN Energy Analysis. In section 4.8, the results for this case study are evaluated.

## 4.1 Pareto analysis, step 1: identification of problems

In this section the building simulation results are discussed and compared to the measured energy consumption.

### 4.1.1 Climate simulation

As for case study 1, the energy consumption is simulated again for 2 different climate files.

The reference climate file of NEN 5060, discussed in §3.1.1, indicates an 'average' energy consumption of the case study building. This reference climate file is used for the sensitivity analysis of the energy performances (Pareto, step 2) and the selection of critical parameters (Pareto, step 3), because it shows a more representative, 'average' sensitivity over a year.

The second climate file is again measured climate data from the nearest official weather stations of KNMI (Dutch climate institute), for a fair comparison between simulated and measured energy consumption. Therefore climate data of weather station 'de Bilt' is used (± 8 km from Kropman Utrecht).

Because for Kropman Breda, the energy consumption is analyzed for 2014 (because of the completeness of the available data), this year is also analyzed for the second case study. In this way there can be made a comparison between the simulation results of the two case studies.

### 4.1.2 Analyzed energy functions

Also in this case study, the simulation results are focused on the heating and cooling energy consumption of the building, because data is only available for these two energy functions. Lighting and distribution energy (pumps, fans, etc.) is only measured in one centralized electricity meter, which means that no information can be derived for the individual energy functions.

### 4.1.3 Model simplifications and assumptions

Additional implementing of generation efficiency, as done for Kropman Breda, is not necessary for Kropman Utrecht. That is because there are enough measurement points to analyze the 'supplied' heating and cooling consumption, instead of the 'produced' energy consumption. Only distribution efficiency of the building systems is assumed, additionally to the 'net' energy simulation results. Indications of the 'reference' distribution efficiencies in Kropman Utrecht are based on the national standard NEN 7120:

- Heating distribution efficiency (floor heating and air distribution) – 95%
- Cooling distribution efficiency (floor cooling and air distribution) – 98%

The most important comments for the building simulation model of Kropman Utrecht:

- In reality, the climate system is controlled by presence detection. In the used Vabi Elements simulation tool, climate systems are controlled by weekly profiles. For the open office rooms (±80% of the building), climate systems are constantly activated within office hours (starts in the morning when the first employee is present and is deactivated when the last employee has left), which is easy to model. For the meeting rooms and other small office rooms (±20% of the building), the climate systems are partly deactivated within office hours, when the rooms are unoccupied. For this part of the building, it is assumed in the building model that the climate control is activated for 50% of the office hours (spread throughout each working day).

- Internal heat production by employees are based on estimates from Kropman employees which were working in the building in 2014.
- Internal heat production by lighting and appliances are estimated, based on the occupancy pattern and the installed electrical power.
- Adjacent, similar rooms in the building are grouped to simplify the building model.
- An indication of the infiltration level of the building envelope is based on rules of thumb from national standards (NEN 8088).
- In the building system, a strategy had been designed for redistribution of heat within the building (heated, returned water from the local cooling system is used to heat supply air in the air handling unit). However, due to errors in software implementation, this strategy was not activated in 2014. Because this strategy would make the building model far more complex in the used Vabi Elements tool, this 'free cooling' strategy is not included in the building simulation.
- In Kropman Utrecht, the surplus of ventilation air is transferred to the central atrium. In this atrium, the air of all rooms is 'collected'. At the top of the atrium, the air is extracted by the atrium. Furthermore, the roof of this atrium has a large glass area. This results in high return air temperatures in the air handling unit, which cannot be simulated in Vabi Elements.

### 4.1.4 Comparison between simulated and measured energy consumption

The simulation results are shown in table 4.1.1. In figure 4.1.1, the results are compared with the measured heating and cooling consumption.

*Table 4.1.1: Annual simulated and measured thermal energy consumption of case study 2: Kropman Utrecht. Results are shown for the artificial reference climate file 'NEN 5060' and KNMI climate data of de Bilt (nearest weather station).*

| | **Artificial 'Reference climate' NEN 5060** | **De Bilt, 2014** | **Measured (2014)** |
|---|---|---|---|
| **Heating consumption** | 240.000 $kWh_{th}$/y | 192.000 $kWh_{th}$/y | 177.000 $kWh_{th}$/y |
| **Cooling consumption** | 105.000 $kWh_{th}$/y | 119.000 $kWh_{th}$/y | 268.000 $kWh_{th}$/y |

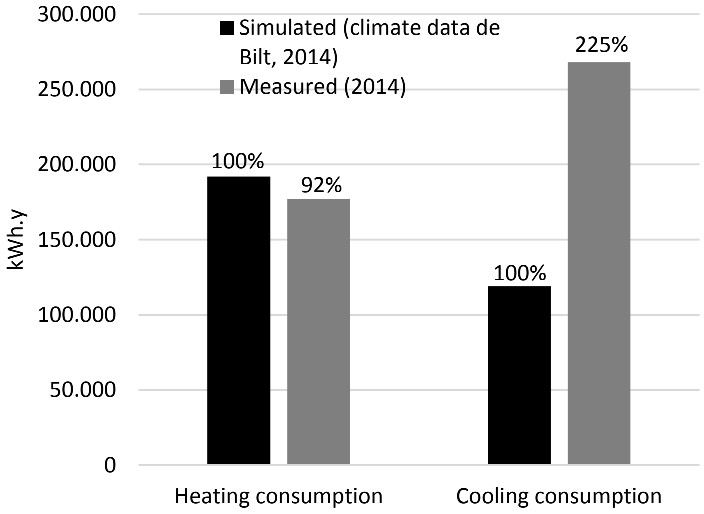


*Fig. 4.1.1: Heating and cooling consumption in Kropman Utrecht: simulated ('design situation') versus measured. The mentioned percentages indicate the percentage energy gaps. A large energy gap is identified in cooling consumption.*

## 4.2 Pareto analysis, step 2: identify possible causes of the problem

In section 3.2, the large quantity of involved parameters in the energy performances of a building (system) has been discussed. Therefore, for the first case study, 15 (merged) parameters are selected, based on the impact of the building model. From these parameters, it is expected that they determine the major part of the energy demand. In the further analysis, the impact of these parameters on the annual energy consumption is analyzed. In this way, the objective is to identify a few 'major parameters' with a high risk to cause an energy performance gap.

Although the selection of the parameters is based on the '80/20'-rule (Pareto principle), the 15 parameters cannot be considered as a literal percentage of 20%, because the total number of involved parameters/settings is hard to define (as shown and explained in figure 3.2.1).

For this case study, the same method is used. First 15 parameters are identified from the design of the building. In the next steps of the Pareto analysis, these parameters are further analyzed.

Most of the parameters are general applicable; therefore most parameters are the same for both case studies. As already mentioned for the first case study, the parameters are further analyzed with the Vabi Elements building model, which means that the selection frame for the parameters have the same boundaries as the building model. In chapter 1, the boundaries of Vabi Elements are discussed already.

The selected parameters are:

**Building**

1. R-value building envelope
2a. U-value windows (facades, glass incl. frames)
2b. U-value windows atrium
3. G-value windows
4. Infiltration

**Internal heat gains**

5. Internal heat production by occupants, appliances & lighting
6. Sun blind control

**Comfort demand/user requirements**

7a. Min. air temperature during office hours
7b. Min. air temperature during office hours
8. Min. air temperature outside office hours
9. Ventilation rate

**Climate control settings**

10. Distribution temperatures to chilled beam units (heating/cooling)
11a. Heating curve AHU (vertical shift)
11b. Heating curve AHU (horizontal shift)
12. HVAC operation hours (time schedule office hours)
13. Night-time cooling
14. Min. absolute humidity in supply ventilation air

**Heat recovery**

15. Efficiency heat recovery wheel (sensible heat)

## 4.3 Pareto analysis, step 3/4/5: rank, score and group problems & causes

The goal in this part of the Pareto analysis is to investigate whether the energy performance gaps of the case studies can be assessed/explained by only a few 'major parameters'. Therefore, in this section the impact of the 15 selected parameters (from section 4.2) on the annual energy consumption is analyzed by a sensitivity analysis. Thereafter, the impact of the parameters is ranked, based on their impact on the annual energy consumption. In this way, it is becoming clear which parameters should be taken into account in the assessment of energy performance gaps.

### 4.3.1 Sensitivity analysis

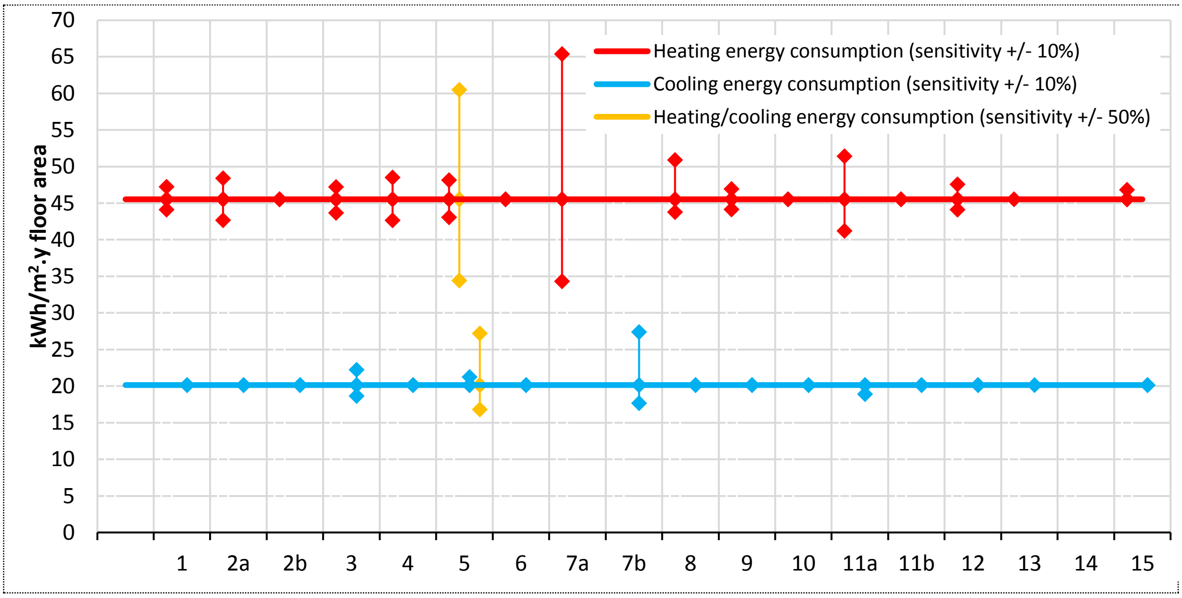
The sensitivity analysis is performed by varying the involved parameters individually with + and – 10% of the 'baseline' design settings. This method has been chosen because of the uniformity of the comparison and the fact that this method provides insight in the topic in a clear and practical way. The 10% change is considered as a uniform realistic variety for all parameters. Although this change is relatively small for some parameters (e.g. occupancy), a larger variety would be unrealistic because of other parameters (e.g. indoor temperature). In addition to this uniform sensitivity analysis, for the occupancy rate an additional larger variety is tested (namely + and – 50%), to check a more realistic variation of this parameter.

The used method of the sensitivity analysis includes the interdependence between different parameters. The modification of one parameter can influence the impact of other parameters, which means that the responsibility for the resultant impact on the energy consumption cannot be traced 100% to the modified parameter, theoretically. This method had been chosen because of the fact that this is a quite practical approach, since these interdependences are also present in real buildings. If each parameter is analyzed completely independent from the other ones, it will result in an endless (unusable) amount of parameter combinations, because most parameters change several times during a year.

The sensitivity analysis is performed for the artificial NEN 5060 reference climate, because this is an artificial created 'averaged' climate and leads to an 'average' impact on the annual energy consumption.

The results of the sensitivity test are shown in a diagram, in figure 4.3.1. As mentioned above, the internal heat gain is additionally tested with a variety of + and – 50%. These results are also shown in figure 4.3.1.

The used values in the sensitivity analysis are shown below for each involved parameter.



***Building***

*1. R-value building envelope*
*2a. U-value façade windows (glass incl. frames)*
*2b. U-value windows atrium*
*3. G-value windows*
*4. Infiltration*

***Internal heat gains***

*5. Internal heat production by occupants, appliances & lighting*
*6. Sun blind control*

***Comfort demand/user requirements***

*7a. Min. air temperature during office hours*
*7b. Max. air temperature during office hours*
*8. Min. air temperature outside office hours*
*9. Ventilation rate*

***Climate control settings***

*10. Distribution temperatures to chilled beam units (heating/cooling)*
*11a. Heating curve AHU (vertical shift)*
*11b. Heating curve AHU (horizontal shift)*
*12. HVAC operation hours (time schedule office hours)*
*13. Night-time cooling*
*14. Min. absolute humidity in supply ventilation air*

***Heat recovery***

*15. Efficiency heat recovery wheel (sensible heat)*

*Fig. 4.3.1: Results of sensitivity test of the annual energy consumption in Kropman Utrecht. The used values for the tested parameters are shown in table 4.3.1.*

The used values in the sensitivity analysis are shown below for each involved parameter.

*Table 4.3.1: Parameters in Kropman Utrecht, changed by ± 10% of 'design' settings/assumptions to provide insight in the sensitivity of the annual heating and cooling consumption.*

| ***Building*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 1 | R-value building envelope | 2,7 m$^2$K/W | 2,4 m$^2$K/W | 3,0 m$^2$K/W | - no data available |
| 2a | U-value windows (facades) (glass incl. frames) | 1,8 W/m$^2$K | 1,6 W/m$^2$K | 2,0 W/m$^2$K | - no data available (expected to be 10%-15% lower than design, due to double skin façade*) |
| 2b | U-value windows atrium | 5,0 W/m$^2$K | 4,5 W/m$^2$K | 5,5 W/m$^2$K | - no data available |
| 3 | G-value windows | 0,52 | 0,46 | 0,57 | - no data available |
| 4 | Infiltration | 0,30 dm$^3$/(s.m$^2$ floor) | 0,27 dm$^3$/(s.m$^2$ floor) | 0,33 dm$^3$/(s.m$^2$ floor) | - no data available |

* = The facades of the building are 'double skin' facades. The outer layer of the façade is transparent in front of each window. It is expected by design experts that this construction improves the thermal insulation value of the windows with 10-15%.

| ***Internal heat gains*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 5 | Internal heat production by occupants, appliances & lighting | 87 kW<br>*(12+45+30)* | 78 kW (-10%) &<br>44 kW (-50%) | 96 kW (+10%) &<br>131 kW (+50%) | 87 kW (estimated) |
| 6 | Sun blind control | 250 W/m$^2$ | 225 W/m$^2$ | 275 W/m$^2$ | - no data available |

| ***Comfort demand / user requirements*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 7a | Min. air temperature during office hours<br>- *Office zones / restaurant / entrance*<br>- *Stockroom / stairwells*<br>- *Technical room* | 22 °C<br>18 °C<br>15 °C | 19,8 °C<br>16,2 °C<br>13,5 °C | 24,2 °C<br>19,8 °C<br>16,5 °C | Different per zone:<br>21 - 23°C<br><br>-no data available<br>-no data available |
| 7b | Max. air temperature during office hours | 24 °C | 21,6 °C | 26,4 °C | Different per zone:<br>- Max. 23,5-25°C |
| 8 | Min. air temperature outside office hours<br>- *Zones with floor heating*<br>- *Remaining office rooms*<br>- *Technical room* | 20 °C<br>18 °C<br>15 °C | 18,0 °C<br>16,2 °C<br>13,5 °C | 22,0 °C<br>19,8 °C<br>16,5 °C | 20 °C<br>21 °C<br>- |
| 9 | Ventilation rate | 21.200 $m^3/h$ | 19.100 m3/h | 23.300 m3/h | 21.200 $m^3/h$ |

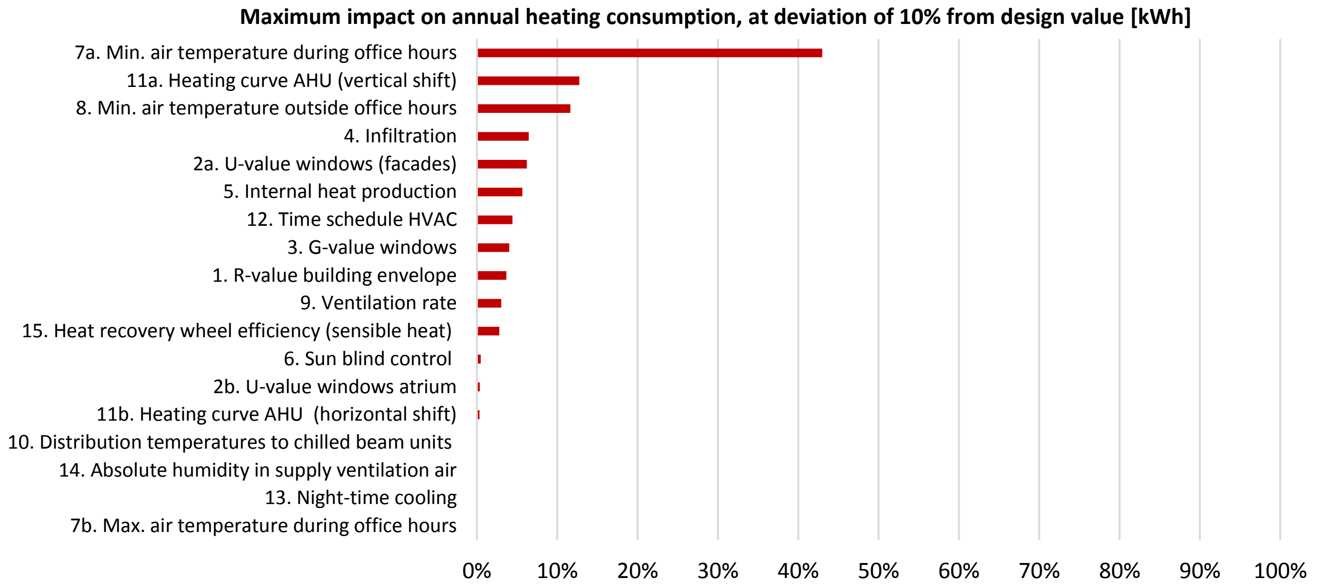
| ***Climate control settings*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 10 | Distribution temperatures to chilled beam units (heating/cooling) | 55°C / 15°C | 49,5°C / 13,5°C | 60,5°C / 16,5°C | 55°C / 15°C |
| 11a | Heating curve AHU ($T_{outside}$/$T_{supply\ air}$) (vertical shift) | -10/21 - 2/18 - 10/17 | -10/18,9 - 2/16,2 - 10/15,3 | -10/23,1 - 2/19,8 - 10/18,7 | -10°C/ 19°C<br>5°C /18°C |
| 11b | Heating curve AHU ($T_{outside}$/$T_{supply\ air}$) (horizontal shift) | -10/21 - 2/18 - 10/17 | -11/21 - 1,8/18 - 9/17 | -9/21 - 2,2/18 - 11/17 | -10°C/ 19°C<br>5°C /18°C |
| 12 | HVAC operation hours (time schedule office hours) | 15 h/day (6:00-21:00 h) | 14 h/day (7:00-21:00 h) | 17 h/day (5:00-22:00 h) | 15 h/day (6:00-21:00 h) |
| 13 | Night-time cooling | Activated | Deactivated | | Activated |
| 14 | Min. absolute humidity in supply ventilation air | - | - | - | - |

| ***Heat recovery*** | | **'Design' value** | **-10% deviation** | **+10% deviation** | **Measured value** |
|---|---|---|---|---|---|
| 15 | Heat recovery wheel efficiency (sensible heat) | 70% | 63% | 77% | 70-75% |

### 4.3.2 Ranking and scoring of parameters

In figure 4.3.2 the results of the sensitivity analysis are ranked by the impact on annual energy consumption, for heating and cooling.

The maximum value on the X-axis in each figure is the simulated annual energy consumption (in the reference NEN 5060 climate, because the sensitivity analysis is performed for this 'average' climate). In this way, it can easily be derived which parameters are relatively important and should be taken into account in the assessment of the identified energy performance gaps.



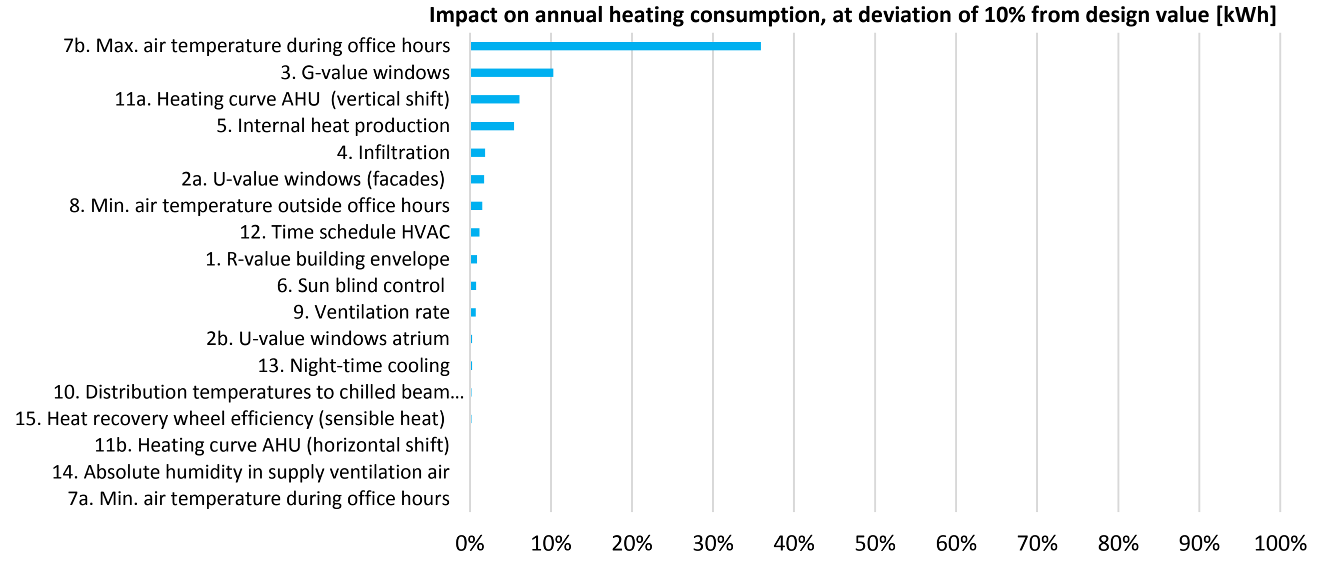


*Fig. 4.3.2: Tested parameters, sorted by impact on annual energy consumption (above: heating; below: cooling). The maximum value on the X-axis (100%) in each figure is the simulated annual energy consumption (reference NEN 5060 climate data). The energy consumption of this case study seems to be more robust, compared to Kropman Breda; the percentage impact of the most important parameters is smaller in this case study.*

From figure 4.3.2 it can be derived that there is 1 parameter, with a large percentage impact on the annual energy consumption, at a deviation of 10%: the indoor air temperature during office hours. This energy consumption seemed to be more robust, compared to the first case study.

Although the second and third parameter have less percentage impact on the annual energy consumption, they can still have a significant absolute impact. For cooling, actually only two parameters (air temperature during office hours and G-value of windows) are interesting in this case. The reason for this (unexpected) robustness of the cooling system is unknown, it can be caused by logical (unknown) physical reasons, by model limitations and/or by the used method of the sensitivity analysis.

In the sensitivity analysis (section 4.3.1), the internal heat production has additionally been analyzed with a sensitivity of +/- 50%. In that case, this parameter would have a large impact on the energy consumption. However, over a year, the assumed internal heat production has been estimated quite carefully and does not deviate for 50% over a year. But it is concluded from this result that this parameter can play a significant role in energy consumption when shorter time periods are considered. For example, over a day, the internal heat production can easily deviate 50% from the assumed daily internal heat production.

The most important parameters, which can make a real difference in energy performances are selected below from figure 4.3.2. These parameters should surely be taken into account in assessment of energy performance gaps.

| **Heating** | **Cooling** |
|---|---|
| • Min. air temperature during office hours | • Max. air temperature during office hours |
| • Heating curve AHU | • G-value of windows |
| • Min. air temperature outside office hours | |
| • Internal heat production by occupants, appliances & lighting<br>(only for energy assessment of relative short time periods) | • Internal heat production by occupants, appliances & lighting<br>(only for energy assessment of relative short time periods) |

## 4.4 Pareto analysis, step 6: Assessment of energy gap by selected critical parameters

In this section, the real share of the selected ‘critical parameters’ (§3.3) in the identified energy gaps, is assessed. In this way, it is investigated whether the theoretical ‘80/20-ratio’, according to basic principle of the Pareto analysis, is true for the energy gaps in this case study.

Section 4.4.1 deals with the analysis of the heating consumption, while the cooling consumption is analyzed in section 4.4.2.

### 4.4.2 Heating energy

Although the identified energy gap in heating consumption was not that large in section 4.1, the most important parameters, resulting from the Pareto analysis, are checked/assessed:

- Min. air temperature during office hours
- Heating curve AHU
- Min. air temperature outside office hours
- Internal heat production by occupants, appliances & lighting (only for energy assessment of relative short time periods)

The real values of these parameters are compared to the design values in table 4.4.1. Also the causes of the differences between the real values and the design values are analyzed, for a better implementation in the building model.

The real values of the critical parameters are implemented in the building model, as explained below. In figure 4.4.1 the results of this modified building simulation model are shown, besides the results of ‘design model’ and the measured heating consumption.

*Table 4.4.1: The critical parameters are compared with the design values. The critical parameters are analyzed as far as possible, with available data. Also the causes of the differences are analyzed.*

| Parameter | Design | Measured | Difference caused by: |
|---|---|---|---|
| Min. air temperature during office hours<br>- *Office zones / restaurant / entrance*<br>- *Stockroom / stairwells*<br>- *Technical room* | - Min. 22 °C<br>- Min. 18 °C<br>- Min. 15 °C | - Min. 21-23°C<br>- no data available<br>- no data available | No significant differences; average measured temperatures correspond to design settings. |
| Heating curve of supply air in the air handling unit | Breakpoints heating curve ($T_{outside}$/$T_{supply}$):<br>-10°C -> 21°C<br>2°C -> 18°C<br>10°C -> 17°C | Breakpoints heating curve ($T_{outside}$/$T_{supply}$):<br>-10°C -> 19°C<br>5°C -> 18°C | Heating curve modified in building management system |
| Minimum indoor air temperature outside office hours<br>- *Zones with floor heating*<br>- *Remaining office rooms*<br>- *Technical room* | - Min. 20 °C<br>- Min. 18 °C<br>- Min. 15 °C | - Min. 20 °C<br>- Min. 21 °C<br>- no data available | The air handling unit does hardly supply any heat during nights and weekends, which means that the floor heating system is responsible for the high temperatures during nights.<br>The floor heating supplies a constant heat load, instead of heat supply which is based on an outside air based heating curve (as described in the design documents).<br>The systems maintain a constant supply water temperature, which results in heat loads without correlations with the outside air and theoretical heating demand. |
| Internal heat production by occupants, appliances & lighting (only for energy assessment of relative short time periods) | 87 kW | - no data available | This parameter cannot be checked, since there is no data available about the occupancy in 2014. This parameter is estimated in average numbers, based on experience of employees in the case study building. Although this occupancy can have large fluctuations over small time periods, over a year this parameter is expected to be quite accurate. |

To identify to which extent these critical parameters are responsible for the energy gap and the different heating trend, they are implemented in the Vabi Elements building model. The internal heat production is not assessed, because no accurate data is available, as explained in table 4.4.1.

1. Air temperatures during office hours are not modified, because the measured values correspond on average with the design temperatures (22°C).
2. The heating curve of the air handling unit is just modified in settings of the model.
3. The settings of the floor heating are modified. In the 'design model', the floor heating had no own temperature set point, but was modeled as a secondary heating system, providing the heat demand together with the chilled beam units.
   In the modified model, the floor heating has an own temperature setting of 20°C. This way of floor heating controls the indoor air temperature on a constant minimum temperature of 20°C. This control is not completely corresponding to the real floor heating control (explained in table 4.6.1). But this modeled control (constant minimum air temperature of 20°C) does approach reality, because in practice, the minimum measured air temperature is 20°C in the rooms with floor heating.

The results of these modifications in the building simulation are shown in figure 4.4.1. It can be seen that he energy gap between 'design' and 'measured' is only relatively small (7%). The results of the modified building model (with implementation of the real values of the critical parameters) reduce this gap even more. However, in the LEAN Energy Analysis in this study, this figure turns out to be 'misleading'. Although over a year, there is only a small energy gap, it does not provide information about the fit of the building model. This is more explained and illustrated in sections 4.5-4.7 (steps of the LEAN Energy Analysis).

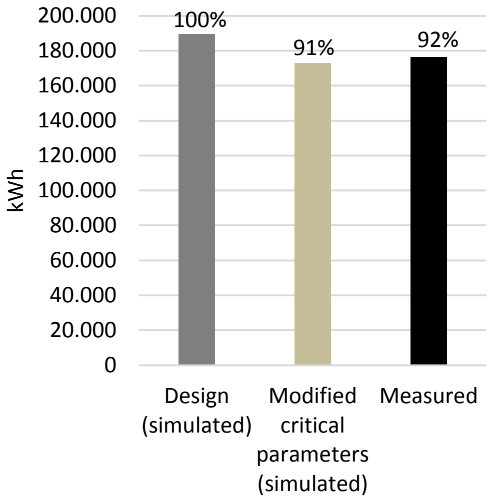


*Fig. 4.4.1: The energy gap between 'design' and 'measured' is only small. The results of the modified building model (with implementation of the real values of the critical parameters) reduce this gap even more. Although this indicates a quite well-performing heating system, during the LEAN Energy Analysis, it turned out that it is a false assumption.*

### 4.4.3 Cooling energy

In the cooling energy consumption, a large energy performance gap has been identified in section 4.1. In this section, the most important parameters in this case study building, as resulting from the Pareto analysis, are checked/assessed, with available data:

- Max. air temperature during office hours
- G-value of windows
- Internal heat production by occupants, appliances & lighting (only for energy assessment of relative short time periods)

The real values of these parameters are compared to the design values in table 4.4.2.

*Table 4.4.2: The design values of the most important parameters for cooling consumption are compared to the measured values. No significant differences are detected.*

| **Parameter** | **Design** | **Measured** | **Difference caused by:** |
|---|---|---|---|
| Air temperature during office hours<br>- *Office zones / restaurant / entrance*<br>- *Stockroom / stairwells*<br>- *Technical room* | - Max. 24 °C<br>- Max. 24 °C<br>- Max. 24 °C | - Max. 23-24 °C<br>- no data available<br>- no data available | No significant differences; on average a little lower than 24°C. |
| G-value of windows | 0,52 | - no data available | No sufficient data is available, but no significant deviations from product specifications are expected. |
| Internal heat production by occupants, appliances & lighting (only for energy assessment of relative short time periods) | 87 kW | - no data available. | Also here, this parameter can fluctuate a lot in small time periods, it cannot be the cause of the complete energy gap. The internal heat production cannot deviate that far from the estimations, made in the model. |

No significant differences have been found for the analyzed parameters. It is concluded that the critical parameters, as resulting from the Pareto analysis, are not the causes for the energy performance gaps. The cooling energy is further analyzed with the LEAN Energy Analysis (sections 4.5-4.7).

It is expected that the floor heating/cooling control, found in the previous section (§4.4.1), has impact on the cooling energy pattern. However, the maximum room temperatures do not deviate from the rooms without floor cooling and no uniform ‘maximum temperature’ (as was the case with the minimum temperature of 20°C) can be derived from the monitored air temperatures in the rooms with floor cooling. Therefore, the ‘design’ floor cooling control is taken into account in the simulation model.

## 4.5 LEAN Energy Analysis, step 1 & 2: collecting data & create baseline/benchmark models

Collecting utility and weather data is a continuous step in the analyzing process and is not specifically described in this report.

Therefore, this section deals with the identification of characteristic, independent variables for the creation of benchmark models, according to the LEAN principle, and already discussed for the first case study (section 3.5).

For the first case study, it was found that the correlation between heating consumption and the outdoor air temperature is too weak to assess measured energy performances. Section 4.5.1 shows that it is also the case for this case study.

Therefore, section 4.5.2 shows the correlations of the energy consumption with the outdoor temperature within characteristic time blocks, because these correlations were found to be useful for the first case study.

For this case study of Kropman Utrecht, both heating and cooling are considered, since they both play a significant role in the annual energy consumption.

### 4.5.2 Building heating/cooling as function of outdoor temperature

In figure 4.5.1 and 4.5.2 the heating and cooling consumption of Kropman Utrecht are shown as function of the outdoor temperature.

For heating consumption it is clear that the correlation is too weak to assess measured energy performances. For cooling consumption the correlation is more clear, but also in this profile some different trends can be seen (e.g. between 20 and 25 °C), which means that some other correlations should be taken into account. The cooling consumption at low outdoor temperatures is caused by the server room, which causes a constant cooling load.

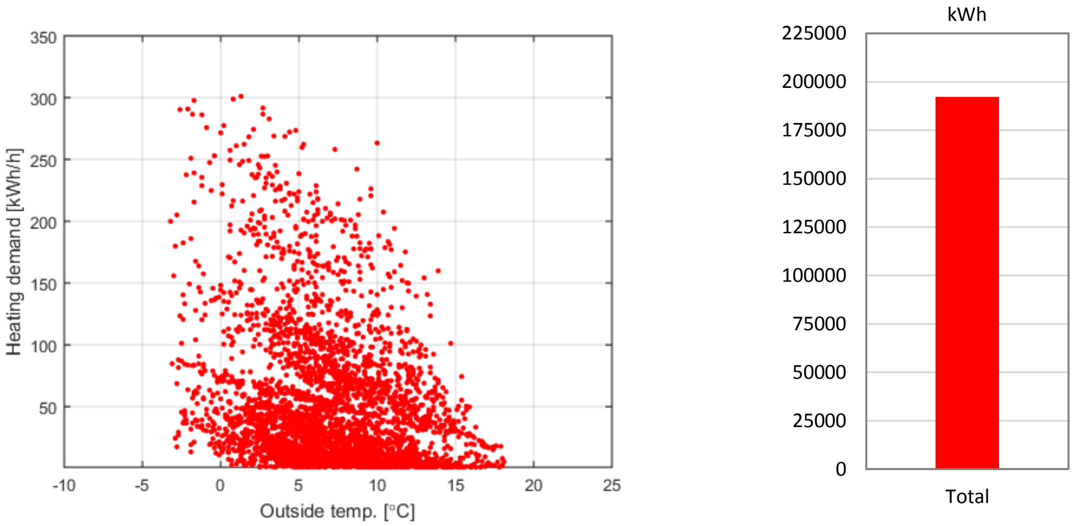


*Fig. 4.5.1:* **Left*:*** *annual simulated heating consumption as function of outdoor air temperature (Climate data of de Bilt, 2014). Each data point represents an hourly energy consumption. The correlations between the heating demand and outdoor temperature are too weak to assess measured energy performances.* **Right:** *sum of all simulated heating data points.*

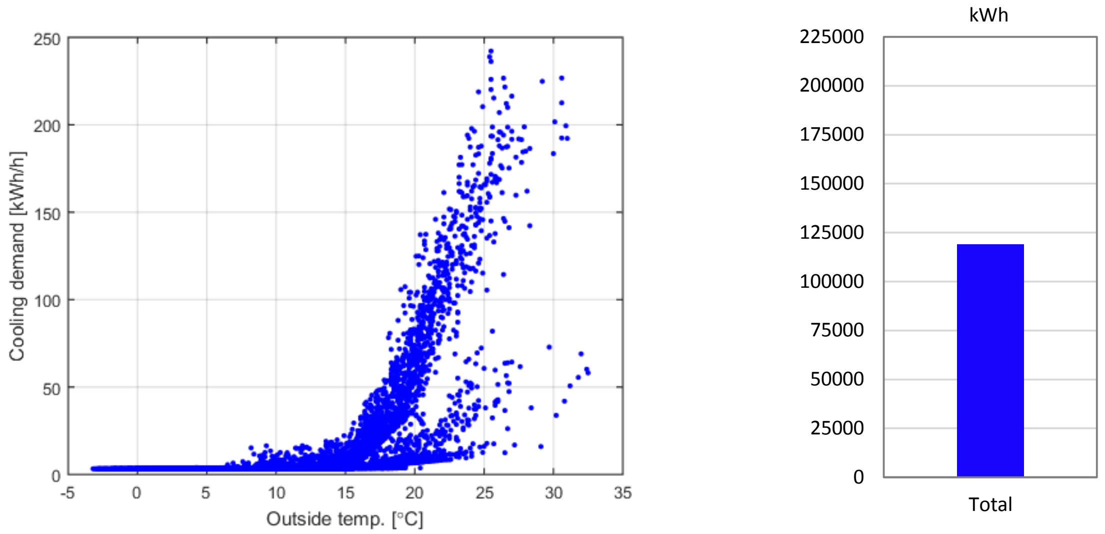


*Fig. 4.5.2:* **Left:** *annual simulated cooling consumption as function of outdoor air temperature (Climate data of de Bilt, 2014). The cooling load at lower outdoor temperatures is caused by a constant cooling demand of the server room.*
**Right:** *sum of all simulated cooling data points.*

## 4.5.3 Building heating/cooling as function of outdoor temperature & time

Because of the weak correlation between the heating/cooling energy consumption and the outdoor temperature, time is involved as second independent variable in the analysis of the energy consumption, following the successful results of the first case study. Time is considered as second variable, because of involved time-dependent parameters (e.g. solar irradiance, internal heat production by occupants, lighting and appliances, stored heat in the thermal building mass and different temperature settings between day and night). This section identifies typical time blocks for both case study buildings and combines them with the earlier analyzed variable of outdoor temperature.

In Kropman Utrecht, the system contains heat and cold water buffer vessels, to control/reduce the needed heat pump capacity. This means that there is no direct relation between the heating/cooling demand and the heating/cooling production. Therefore, based on the findings during the first case study, the heating/cooling demand is summed over a day within each time block. Which means that each time block has 365 data points over a year, instead of 8760. In this way, the dynamic behavior of the building system is better included within the time blocks.

First the heating consumption is divided in time blocks and analyzed. After that the cooling consumption is analyzed in the same way.

### *Time blocks in heating demand*

The ‘seasonal’ time blocks, as discussed for Kropman Breda, are also used in this case:

1. Winter: January, February & November, December
2. Spring/Autumn: March, April & September, October
3. Summer: May, June, July, August

In figure 4.5.3 the typical heating profiles of the simulated, daily heating consumption are shown. For Breda, an extra time block was selected for the heat up period on Mondays, since the heating system starts earlier on Mondays, compared to other weekdays. In the case of Kropman Utrecht, the heating system starts each working day (Monday-Friday) at 6.00 h. Therefore, for each working day the same time blocks are selected.

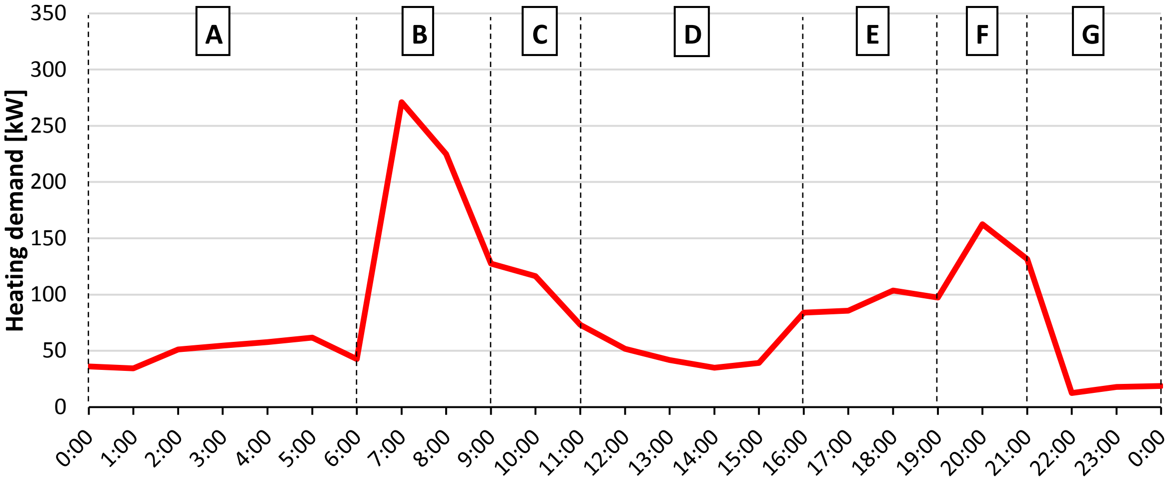


*Fig. 4.5.3: Typical profile of the simulated daily heating demand of Kropman Utrecht, in a winter day.*

The selected daily time blocks are:

A. 0:00- 6:00 h:
*The thermal mass of the building releases the stored heat and the indoor temperature is controlled at a set minimum temperature.*

B. 6:00-9:00 h:
*This block the heating system has to heat up building mass. In this hour also the internal heat production by employees, appliances and lighting is starting. Because different companies are settled in the building, with flexible working hours, this 'start' block is longer, compared to Kropman Breda.*

C. 9:00-11:00 h:
*The internal heat production is relatively constant and reduces the heating demand, but solar irradiation does not play a significant role in this block. In this period the building mass is heated up to a constant temperature.*

D. 11:00-16:00 h:
*In this block the heating demand is quite constant and relatively low, due to the solar irradiance and the fact that the building mass has reached a constant temperature and helps to reduce fluctuating heating demand. Furthermore, the occupancy rate is quite constant in this time block.*

E. 16:00-19:00 h:
*In this block, employees leave the building. Because of the flexible working hours, this is also a quite long period. Because the 'daytime operation' of the building system is from 6.00-21.00 h, the system needs to supply more heat, because of the reduction of internal heat production.*

F. 19:00-21:00 h:
*In this block, only a few (±5) employees are still in the building (telephone help desk). Because of the small internal heat production in this period, the heating system has still to supply a lot of heat.*

G. 21:00-0:00 h:
*Office is closed, building mass releases the stored heat to the indoor air.*

H. Weekend (Saturday 0:00 h. – Monday 6:00 h)
*Office is closed, the indoor temperature is controlled at a set minimum temperature.*

The correlations between the simulated heating demand (climate de Bilt, 2014) and the outdoor air temperature are considered again within these defined time blocks. The results are shown in the figures below.

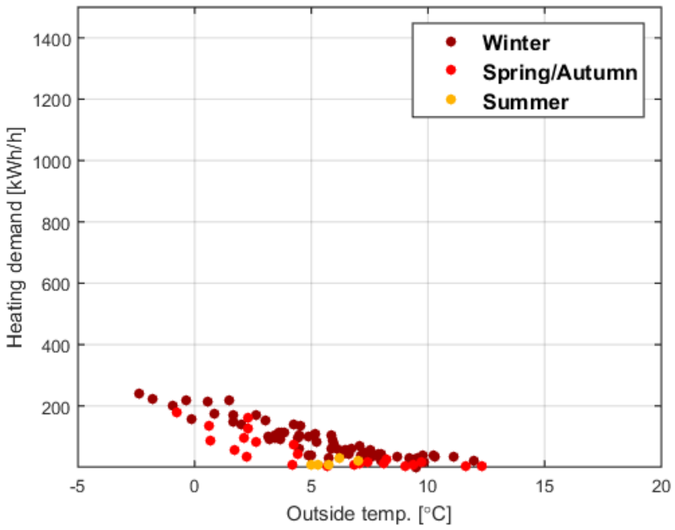


*Fig. 4.5.4. Simulated annual heating demand in time block A (0:00-6:00 h).*

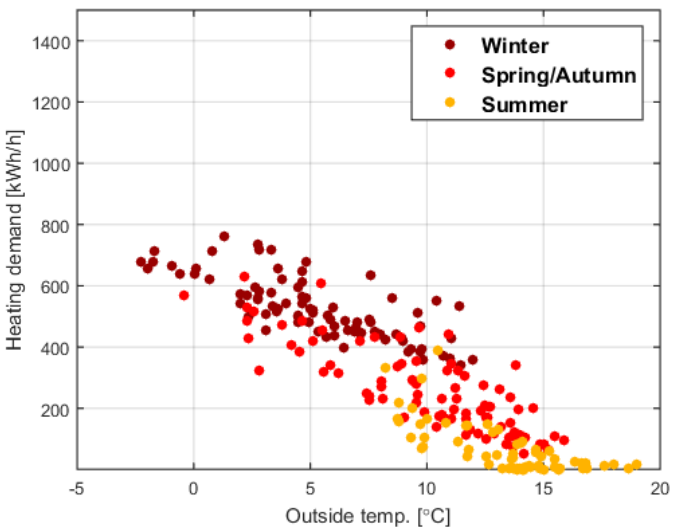


*Fig. 4.5.5. Simulated annual heating demand in time block B (6:00-9:00 h).*

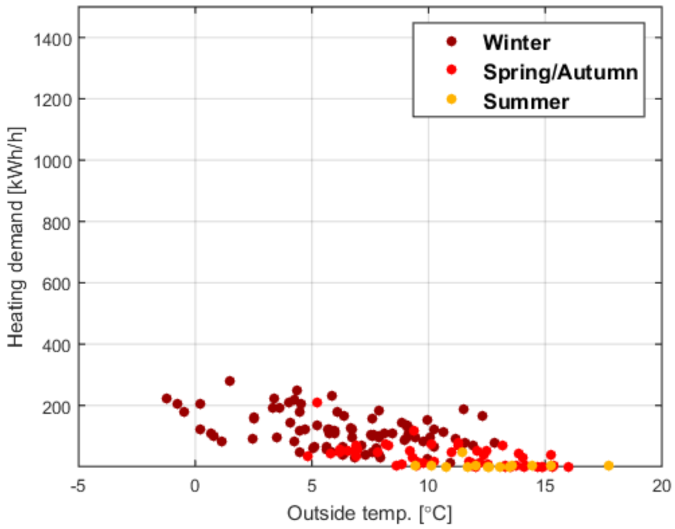


*Fig. 4.5.6. Simulated annual heating demand in time block C (9:00-11:00 h).*

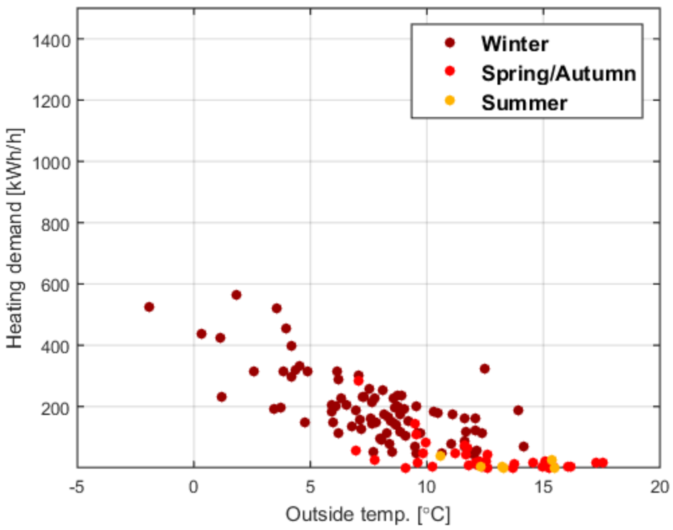


*Fig. 4.5.7. Simulated annual heating demand in time block D (11:00-16:00 h).*

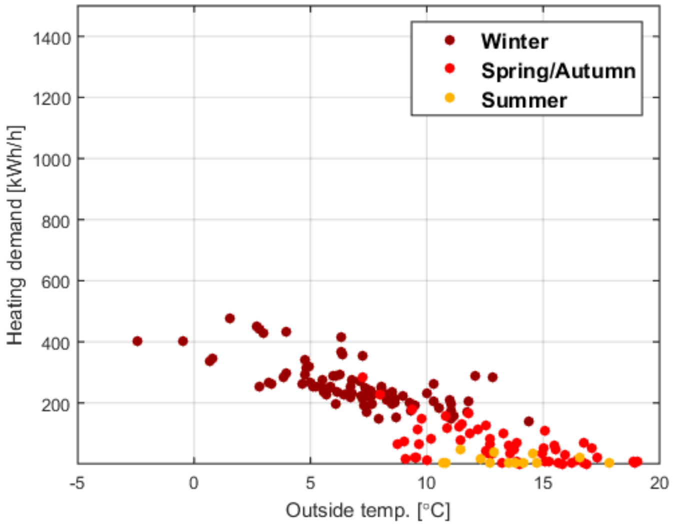


*Fig. 4.5.8. Simulated annual heating demand in time block E (16:00-19:00 h).*

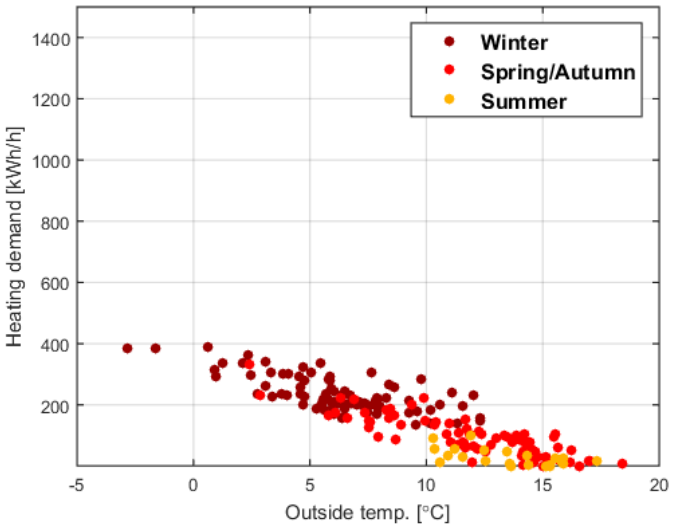


*Fig. 4.5.9. Simulated annual heating demand in time block F (19:00-21:00 h).*

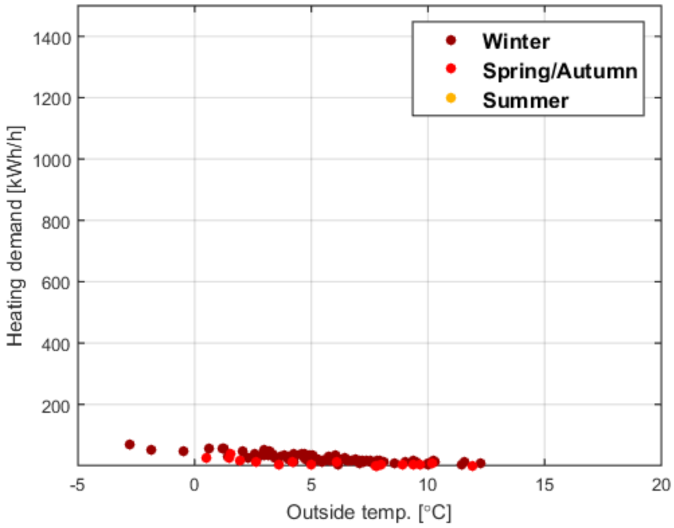


*Fig. 4.5.10. Simulated annual heating demand in time block G (21:00-0:00 h).*

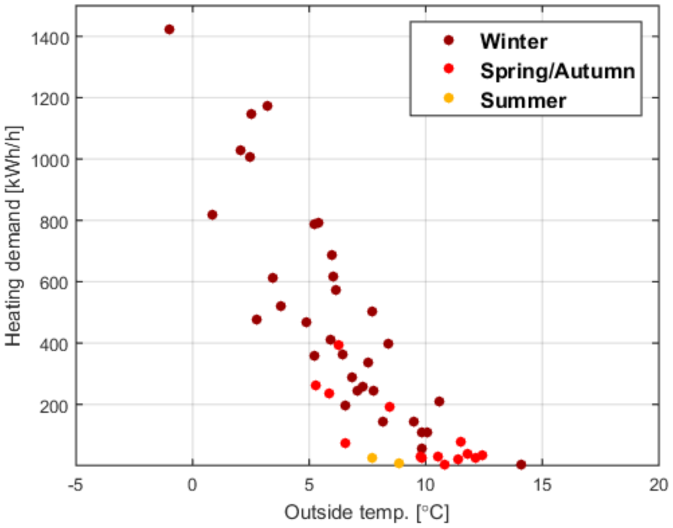


*Fig. 4.5.11. Simulated annual heating demand in time block H (Weekend; Saturday 0:00 h- Monday 6:00 h).*

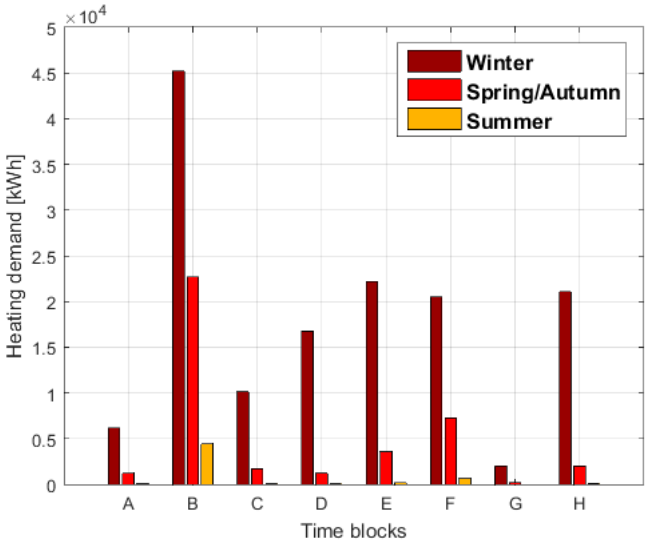


*Fig. 4.5.12: Sum of simulated annual heating demand, divided in the defined time blocks.*

Also for this case study, it is concluded from these figures that the correlation between the heating consumption and the outdoor air temperature is much stronger within the selected time blocks. Also the seasonal shift of the heating load can be derived. This shows that time can be considered as a sufficient, second independent variable in the assessment of energy performance (gaps).

### *Time blocks in cooling demand*

Solar irradiation is the largest external factor that plays a key role in cooling consumption. Besides the annual curve of solar strength, the solar irradiation has a characteristic curve over a day. Based on these curves, the daily time blocks are selected (figure 4.5.13). The 'seasonal' time blocks are again:

1. Winter: January, February & November, December
2. Spring/Autumn: March, April & September, October
3. Summer: May, June, July, August

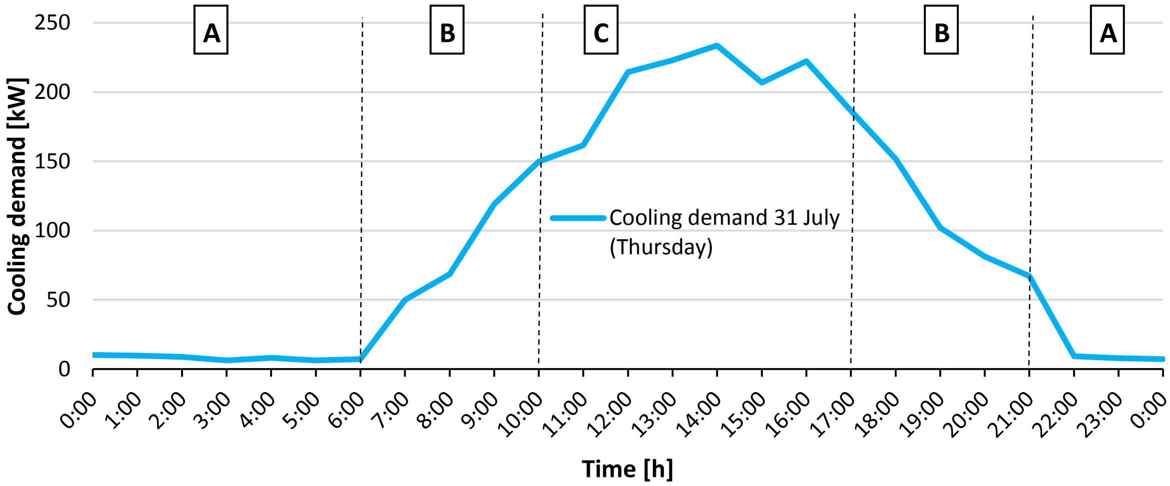


*Fig. 4.5.13: Typical profile of the simulated daily cooling demand of Kropman Utrecht, in a summer day.*

The selected daily time blocks are:

A. 0:00-6:00 h & 21:00-0:00 h:
*Office is closed; neither solar irradiation nor internal heat production by occupants, appliances and/or lighting do play a role. The maximum indoor temperature is controlled with nigh ventilation.*

B. 6:00-10:00 h & 17:00-21:00 h:
*Solar intensity is relatively low in this block, but there is internal heat production by occupants, appliances and lighting.*

C. 10:00 -17:00 h:
*Solar intensity is high in this block. The cooling demand is determined by this solar irradiation, as well as by the other internal heat gains.*

D. Weekend (Saturday 0:00 h – Monday 6:00 h):
*Office is closed, the maximum indoor temperature is controlled with night ventilation.*

The correlations between the simulated cooling demand (climate data of de Bilt, 2014) and the outdoor air temperature are considered again within these defined time blocks. The results are shown in the figures below.

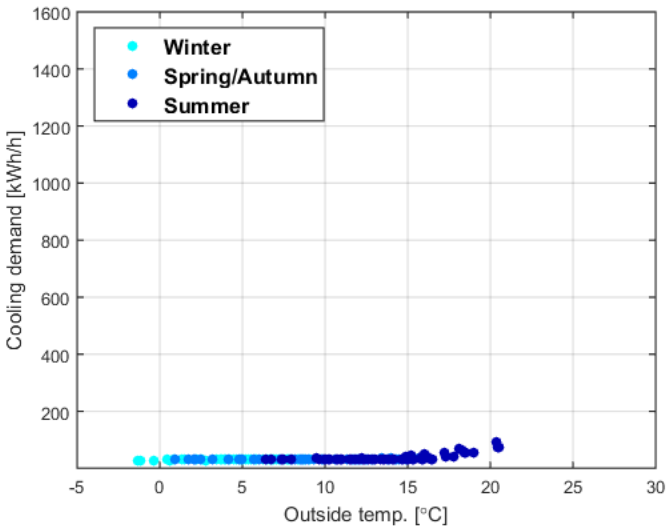


Fig. 4.5.14. Simulated annual cooling demand in time block A (0:00-6:00 h & 21:00-0:00 h).

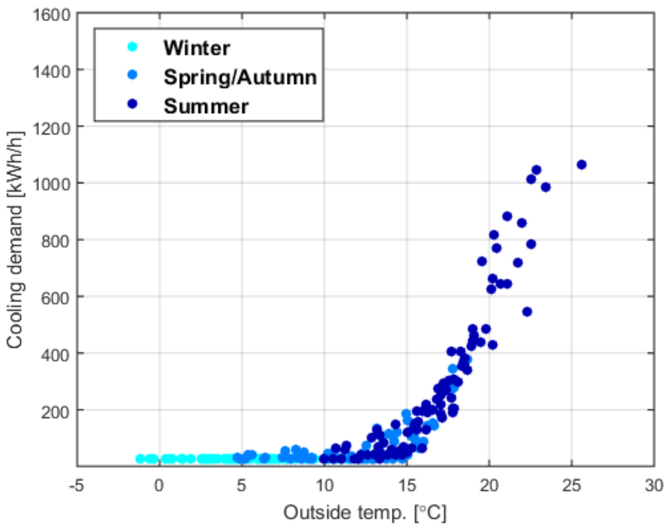


Fig. 4.5.15. Simulated annual cooling demand in time block B (6:00-10:00 h & 17:00-21:00 h).

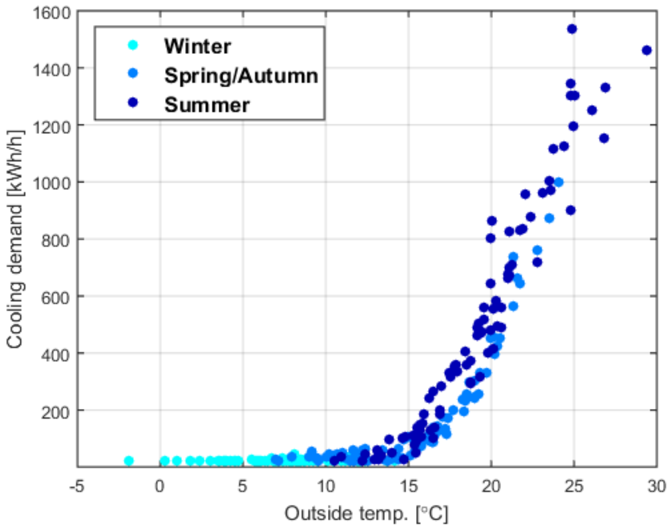


Fig. 4.5.16. Simulated annual cooling demand in time block C (10:00-17:00 h).

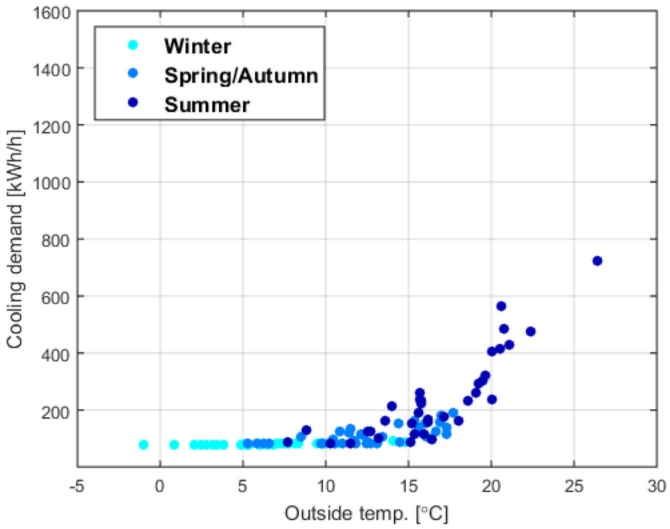


Fig. 4.5.17. Simulated annual cooling demand in time block D (weekend).

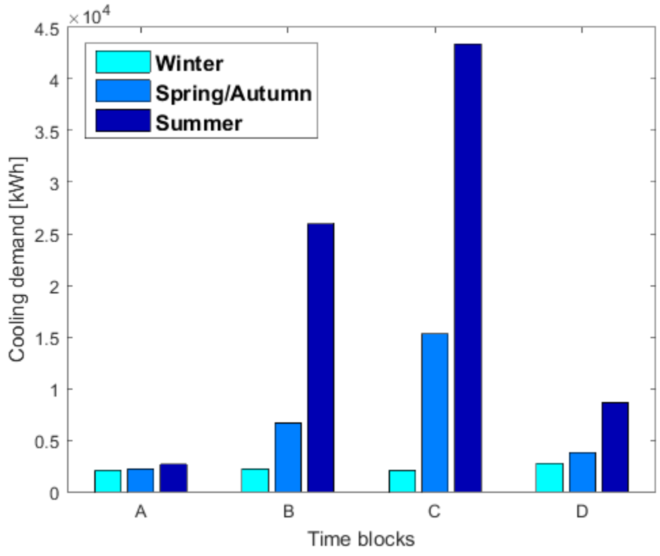


Fig. 4.5.18: Sum of simulated annual cooling demand, divided in the defined time blocks.

These figures show that the correlations between the outdoor temperature and the cooling demand are stronger when characteristic time blocks are considered. Also the seasonal shift of the cooling load can be derived. This shows that time can be considered as a sufficient, second independent variable in the assessment of energy performance (gaps), due to the involved time-dependent parameters, mentioned before.

## 4.6 LEAN Energy Analysis, step 3: Identify energy performance gaps

In section 3.6.1 is explained that it was found that regression analysis reduce the ability to assess the measured energy consumption, because information about the physical behavior of building (system) from energy data profiles is lost when the energy profiles are reduced to regression lines. For that case study, the energy gap had successfully been identified with the cumulative energy assessment in the identified, characteristic time blocks. Therefore, this method is also used for this case study.

For Kropman Utrecht, the measured data is harder to analyze. The main system of heat and cold energy is the aquifer thermal energy storage system (ATES), in combination with a heat pump. Because a heat pump produces cold and warm water at the same time (cold evaporator side and warm condenser side). In case, there is only a heating demand in the building, the produced cold from the evaporator side is stored in the aquifer system. When there is only cooling demand in the building, produced heat (condenser) is stored in the aquifer system. When there is simultaneously a heating and cooling demand in the building, a part of the energy is used to heat/cool the building, while a remaining part flows back to the aquifer system. Within the building system, several strategies are implemented in the software of the building system to control these flows. In Appendix II a schematic overview is provided of the heating and cooling energy flows in different system states.

Besides this aquifer system and the heat pump, other ‘generators’ have to be taken into account: a part of the heat is supplied by district heating and night-time cooling (by mechanical ventilation) supplies additional cooling during nights and weekends.

Because most energy flows are measured on a more centralized level, the rough heating/cooling data from the heat pump is filtered to get the heating/cooling flows to and within the building and create a straight-line comparison with the simulated energy consumption:

- Heating consumption: $(Q_{condenser} – Q_{stored\_heat\_ATES}) + Q_{district\_heating}$
- Cooling consumption: $Q_{ATES} + (Q_{evaporator} – Q_{stored\_cold\_ATES} – Q_{regeneration\_ATES}) + Q_{night\text{-}time\_cooling}$

In this section the measured and simulated heating and cooling consumption are compared for each identified time block.

### 4.6.2 Heating consumption

Because a part of the energy gap is already explained by the results of the Pareto analysis (the selected most critical parameters), the results of the modified building model (with the implemented real values of the critical parameters) are also shown. With this comparison, it can be seen in which time blocks the critical parameters have the largest impact and which part of the energy gap is not explained by the results of the Pareto analysis. Based on these findings, the further analysis can be continued more specific and effective.

In tables 4.6.1 – 4.6.3, the simulated heating consumption (both, the design situation and the modified building model, based on the results of the Pareto analysis) and the measured heating consumption are compared for each time block. Table 4.6.1 shows the results for the winter period, figure 4.6.2 the spring/autumn period and table 4.6.3 shows the summer period.

*Table 4.6.1: Comparison of measured and simulated heating consumption in winter period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 6:00 h** | 6.200 | 15.000 | 13.700 |
| **B** | **6:00-9:00 h** | 45.200 | 16.500 | 28.900 |
| **C** | **9:00-11:00 h** | 10.200 | 8.200 | 8.300 |
| **D** | **11:00-16:00 h** | 17.600 | 14.100 | 14.800 |
| **E** | **16:00-19:00 h** | 22.200 | 9.600 | 17.200 |
| **F** | **19:00-21:00 h** | 21.000 | 8.000 | 15.600 |
| **G** | **21:00-0:00 h** | 2.000 | 8.600 | 6.100 |
| **H** | **Weekend (Saturday 0:00 h. – Monday 6:00 h)** | 21.000 | 31.600 | 31.500 |

*Table 4.6.2: Comparison of measured and simulated heating consumption in spring/autumn period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 6:00 h** | 1.200 | 8.200 | 3.300 |
| **B** | **6:00-9:00 h** | 22.700 | 7.200 | 13.200 |
| **C** | **9:00-11:00 h** | 1.700 | 4.800 | 1.700 |
| **D** | **11:00-16:00 h** | 1.200 | 8.300 | 1.600 |
| **E** | **16:00-19:00 h** | 3.600 | 4.300 | 2.700 |
| **F** | **19:00-21:00 h** | 7.300 | 3.700 | 5.200 |
| **G** | **21:00-0:00 h** | 200 | 3.400 | 600 |
| **H** | **Weekend (Saturday 0:00 h. – Monday 6:00 h)** | 2.000 | 10.700 | 4.300 |

*Table 4.6.3: Comparison of measured and simulated heating consumption in summer period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** | **Modified critical parameters, resulting from Pareto analysis (simulated) [kWh]** |
|---|---|---|---|---|
| **A** | **0:00- 6:00 h** | 100 | 700 | 200 |
| **B** | **6:00-9:00 h** | 4.400 | 1.700 | 2.600 |
| **C** | **9:00-11:00 h** | 100 | 2.000 | 200 |
| **D** | **11:00-16:00 h** | 100 | 4.500 | 200 |
| **E** | **16:00-19:00 h** | 200 | 2.600 | 200 |
| **F** | **19:00-21:00 h** | 600 | 1.500 | 600 |
| **G** | **21:00-0:00 h** | 0 | 500 | 0 |
| **H** | **Weekend (Saturday 0:00 h. – Monday 6:00 h)** | 100 | 700 | 300 |

The most relevant seasons are shown in figure 4.6.1 (winter) and 4.6.2 (spring/autumn).

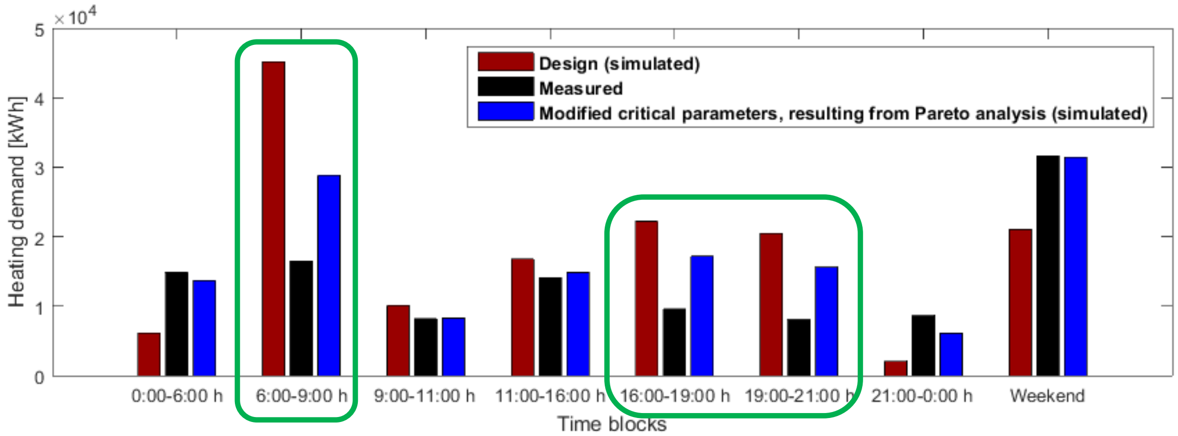


*Fig. 4.6.1: Identification of the heating energy gaps in different time blocks in winter period (January, February, November and December). Although the assessed critical parameters (blue bars) explain the major part of the deviating heating pattern, there still exist significant energy gaps in the start and end of the office day (6:00-9:00 and 16:00-21:00 h).*

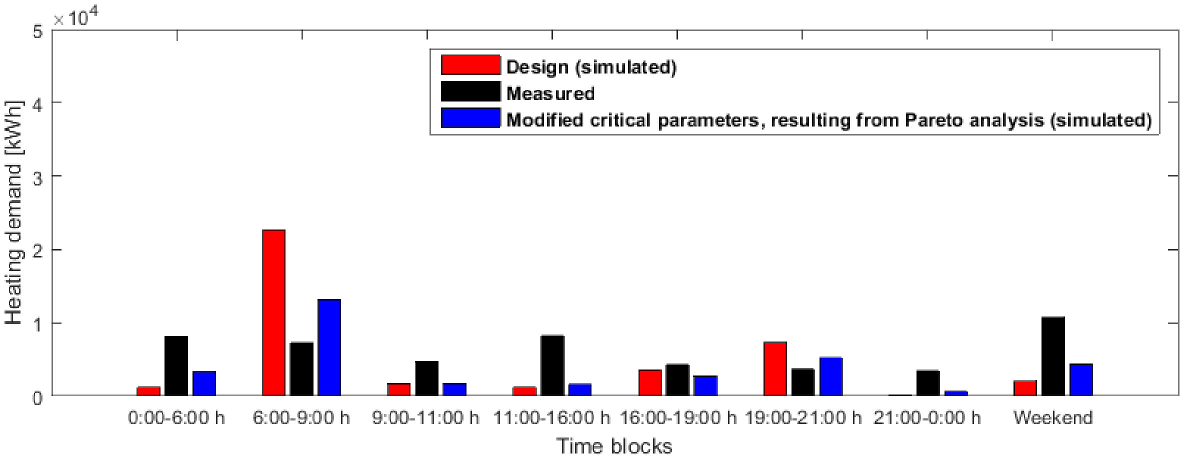


*Fig. 4.6.2: Assessment of the heating energy gaps by the critical parameters, in spring/autumn period (March, April, September and October). Although the measured heating consumption is not very high, the pattern of the load over a day is still different from the simulated heating load, after implementation of the real values of the critical parameters (blue bars).*

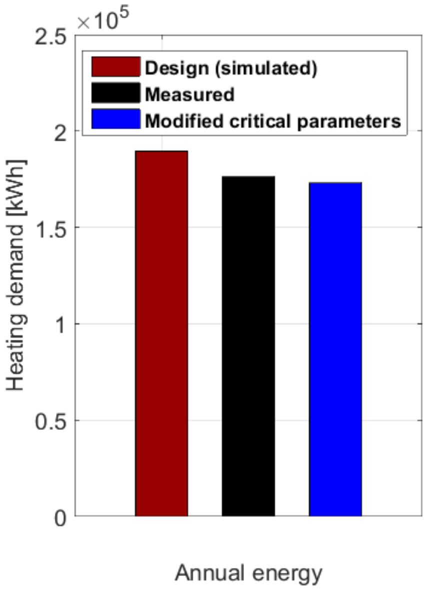


*Fig. 4.6.4: annual heating consumption: simulations vs measured. Although the annual energy gap is only small, it is found that there are large differences in the heating pattern over a day.*

In the figures it can be seen that the model of the 'original design' situation does not represent the real situation, although the total energy gap is only small (figure 4.6.4). There is a completely different trend of the heating load over a day. The simulated heating load after implementation of the critical parameters (resulting from the Pareto analysis), corresponds much better with the measured heating load over a day (0:00 – 24:00 h). The main effect is caused by the floor heating control, discussed in the assessment of the critical parameters (section 4.4).

It is concluded that the critical parameters in the winter period are obviously the major causes of the different heating load. From the assessed critical parameters, the floor heating control, as discussed in table 4.6.1, has the largest impact. Although the different heating pattern over a day is mainly explained by the critical parameters, there still exist energy gaps:

- In winter period, during the start and end period of the office hours (6:00-9:00 h and 16:00 – 21:00 h). A reasonable explanation for (a part of) the energy gaps in these blocks, is the simulated occupancy pattern. Because of the presence – based climate control in the building, the heating load is very hard to predict in these periods. The occupancy pattern is based on an estimated, average pattern. Over the whole day, this assumed occupancy rate cannot be very different from the real one, but in the start and end period of an office day, it can have relatively large deviations. The real occupancy pattern cannot be analyzed, since this is only monitored in a few rooms.
- In the spring/autumn and summer period, the measured heating consumption shows still (relatively small) energy gaps in each time block (also nights and weekends). Because many parameters cane be responsible for this different heating load pattern, this gap cannot be assessed with the results of the Pareto analysis.

In section 4.7, these remaining energy gaps are analyzed by trend analysis, to identify the cause(s) of them.

### 4.6.3 Cooling consumption

In the measured data, electricity for the server room (by the split unit) has not been involved. Therefore, the cooling load for this server room is also excluded in this section for the simulated cooling load, to create a straight-line comparison.

In Tables 4.6.4 – 4.6.6, the simulated cooling consumption and the measured heating consumption are compared for each time block. Only the design simulations are shown, because the results of the Pareto analysis did not explain any part of the energy gaps. Table 4.6.4, shows the results for the winter period, table 4.6.5 the spring/autumn period and table 4.6.6 shows the summer period. The simulations are performed with climate data of de Bilt, 2014.

*Table 4.6.4: Comparison of measured and simulated cooling consumption in winter period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** |
|---|---|---|---|
| **A** | **0:00-6:00 h &<br>21:00-0:00 h** | 0 | 6.100 |
| **B** | **6:00-10:00 h &<br>17:00-21:00 h** | 0 | 11.000 |
| **C** | **10:00 -17:00 h** | 100 | 13.000 |
| **D** | **Weekend (Saturday 0:00 h – Monday 6:00 h)** | 0 | 8.200 |

*Table 4.6.5: Comparison of measured and simulated cooling consumption in spring/autumn period.*

| | | **Design (simulated) [kWh]** | **Measured [kWh]** |
|---|---|---|---|
| **A** | **0:00-6:00 h &<br>21:00-0:00 h** | 2.200 | 17.900 |
| **B** | **6:00-10:00 h &<br>17:00-21:00 h** | 6.700 | 22.900 |
| **C** | **10:00 -17:00 h** | 15.300 | 34.200 |
| **D** | **Weekend (Saturday 0:00 h – Monday 6:00 h)** | 4.200 | 14.700 |

*Table 4.6.6: Comparison of measured and simulated cooling consumption in summer period.*

| | | Design (simulated) [kWh] | Measured [kWh] |
|---|---|---|---|
| **A** | **0:00-6:00 h &<br>21:00-0:00 h** | 400 | 20.100 |
| **B** | **6:00-10:00 h &<br>17:00-21:00 h** | 23.400 | 45.000 |
| **C** | **10:00 -17:00 h** | 41.100 | 59.100 |
| **D** | **Weekend (Saturday 0:00 h – Monday 6:00 h)** | 5.600 | 14.000 |

The results are visualized in figure 4.6.5-5.6.7.

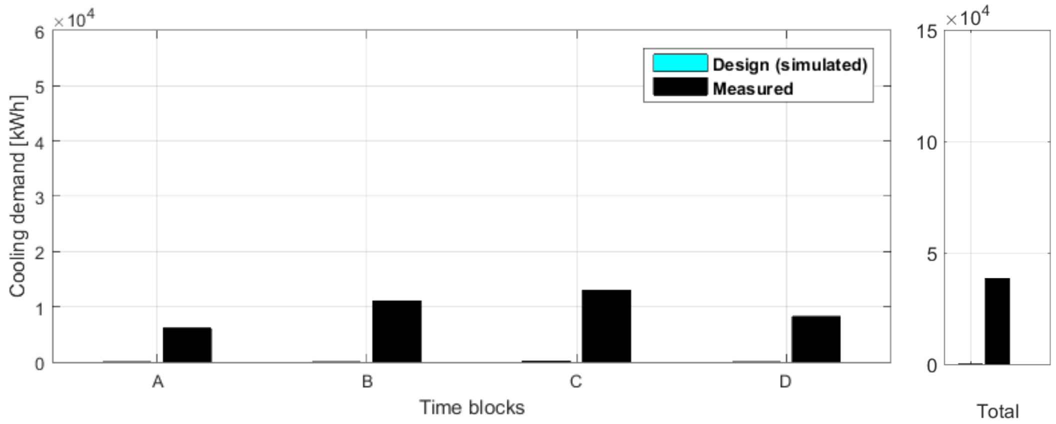


*Fig. 4.6.5: Winter season (January, February, November & December): comparison of the simulated and the measured cooling consumption in the defined time blocks of Kropman Utrecht.*

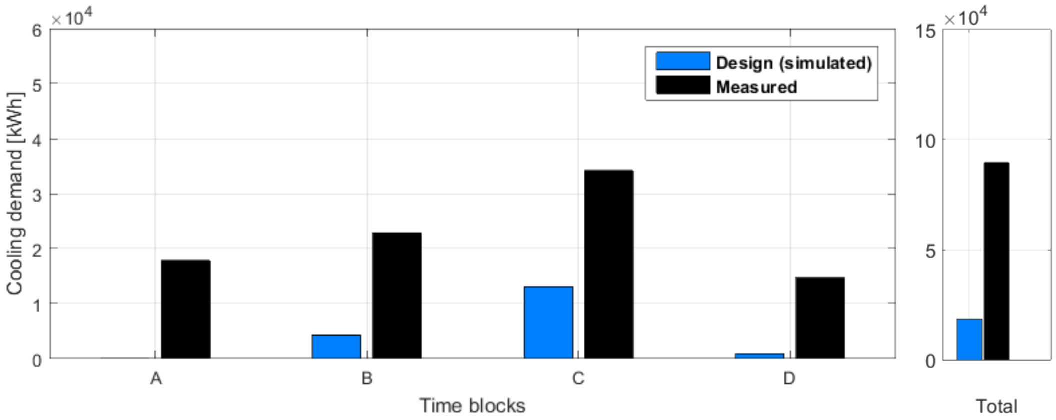


*Fig. 4.6.6: Spring/Autumn season (March, April, September & October): comparison of the simulated and the measured cooling consumption in the defined time blocks of Kropman Utrecht.*

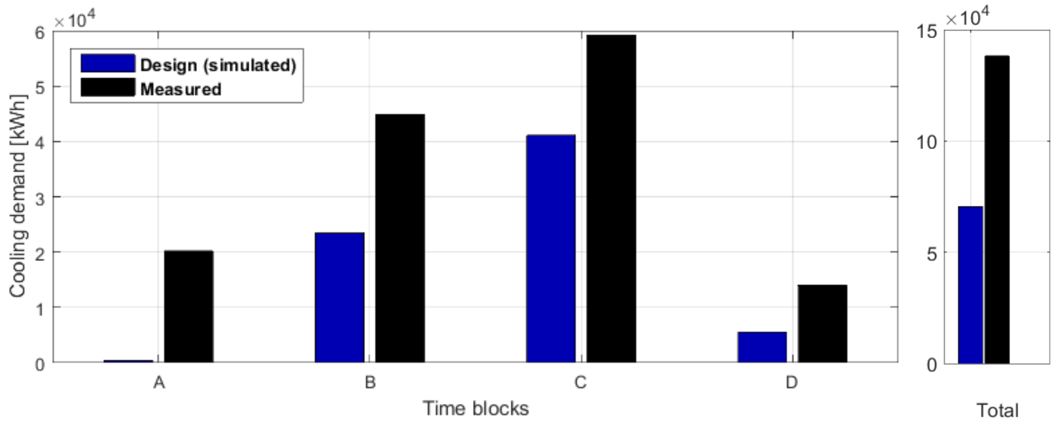


*Fig. 4.6.7: Summer season (May – August): comparison of the simulated and the measured cooling consumption in the defined time blocks of Kropman Utrecht.*

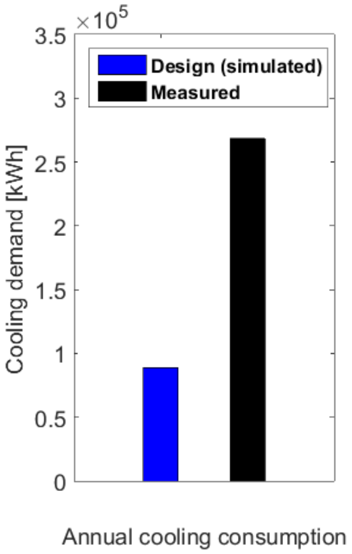


*Figure 4.6.8: The simulated and measured annual cooling demand. The large energy gap shows a significant difference between the design model and the real situation.*

The figures show a large energy performance gap between the simulated (design-based) and measured cooling consumption in every season and each time block. In figure 4.6.8 it can be seen that the annual measured cooling consumption is about 2,3x higher than the simulated cooling consumption (268.000 kWh vs 119.000 kWh). This means that there are serious differences between the original design of the building and the real situation. In section 4.7, the cooling consumption is further analyzed to identify the main causes of this large energy gap.

## 4.7 Assessment of remaining energy gaps (which cannot be explained by the results of the Pareto analysis)

This section deals with the last step of the LEAN Energy Analysis (assessment and opportunities). This last step is to identify the causes of the remaining energy gaps (which cannot be explained by the results of the Pareto analysis) in a specific and effective way. This is possible due to the results of the steps before, in which the energy gaps are identified within specific time blocks.

Section 4.7.1 deals with the identification of the causes of the remaining energy gaps in heating consumption, by trend analysis. In section 4.7.2 this analysis is performed for cooling consumption.

### 4.7.2 Assessment of remaining energy gaps in heating consumption

In step 3 of the LEAN Energy Analysis (section 4.6), the following remaining energy gaps are identified:

- In winter period, in the start and end period of the office hours (6:00-9:00 h and 16:00 – 21:00 h). A reasonable explanation for (a part of) the energy gaps in these blocks, is the simulated occupancy pattern. Because of the presence – based climate control in the building, the heating load is very hard to predict in these periods. The occupancy pattern is based on an estimated, average pattern. Over the whole day, this assumed occupancy rate cannot be very different from the real one, but in the start and end period of an office day, it can have relatively large deviations. The real occupancy pattern cannot be analyzed, since this is only monitored in a few rooms.
- In the spring/autumn and summer period, the measured heating consumption shows still (relatively small) energy gaps in each time block (also nights and weekends).

The conclusion that the remaining energy gaps occur in each time block in the spring/autumn and summer period, makes it is useless to analyze each time block separately. Therefore, the heating consumption is shown in seasonal energy profiles, in figure 4.7.1, 4.7.2 and 4.7.3.

Figure 4.7.1 shows the results for the winter period (January, February, November and December), 4.7.2 the spring/autumn period (March, April, September and October) and 4.7.3 shows the summer period (May-August). The simulated energy profiles are based again on climate data of de Bilt (2014).

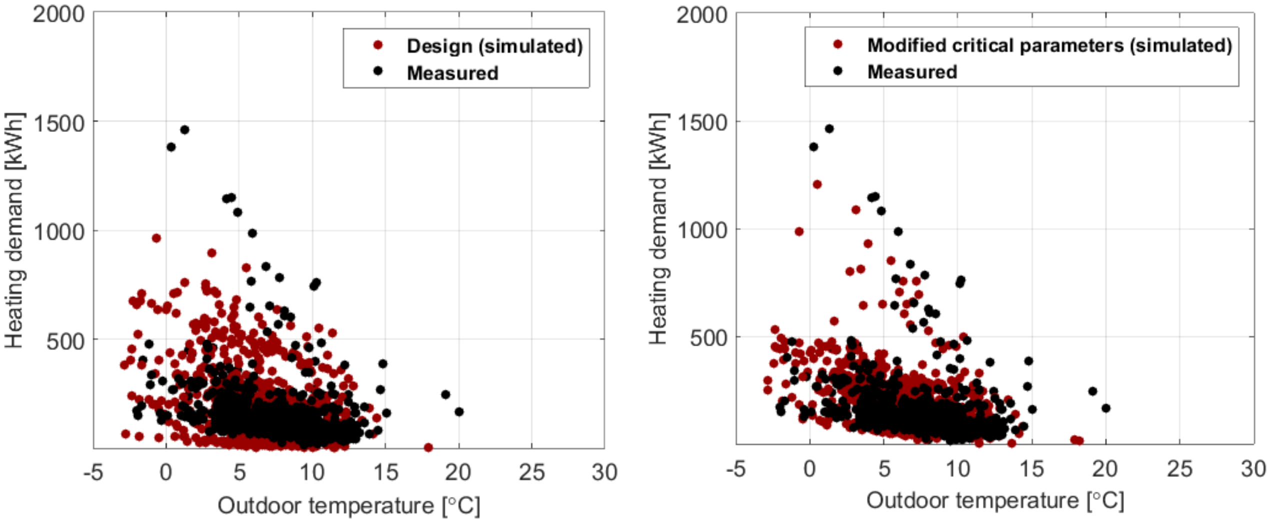


*Fig. 4.7.1: Winter period. **Left:** measured (black) vs. simulated heating (design situation). **Right:** measured (black) vs. simulated heating (building model with modified critical parameters).Althought the figure underlines that the measured heating load is much better represented with the results of the Pareto analysis (right), no conclusions can be drawn about the remaining energy gaps in the start and end time blocks of the office days (6:00 -9:00 h and 16:00 – 21:00 h).*

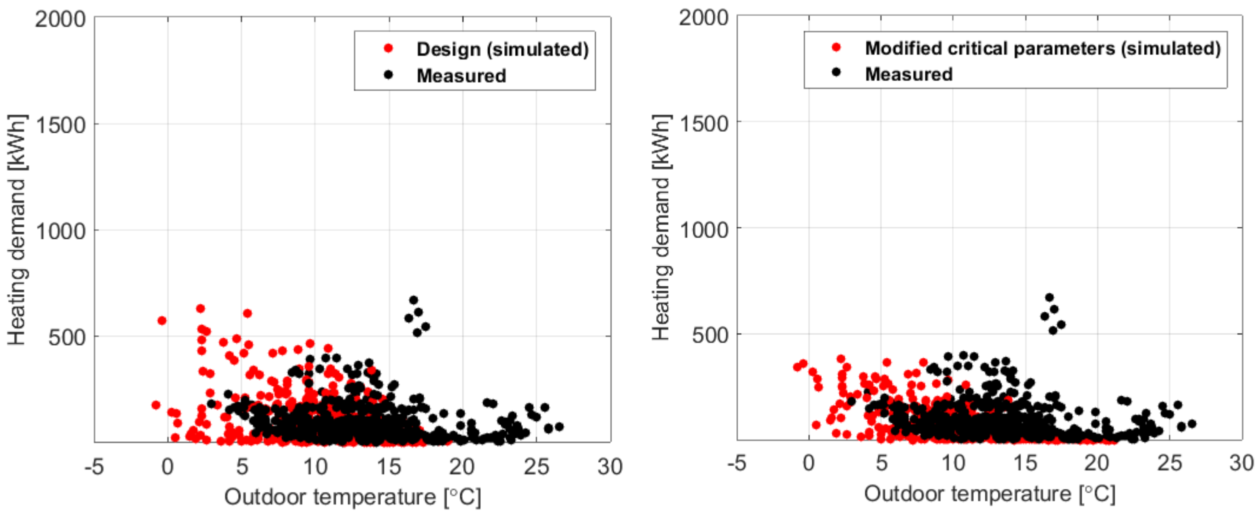


*Fig. 4.7.2: Spring/autumn period.* ***Left****: measured heating (black) vs. simulated heating (design situation).* ***Right****: measured heating profile (black) vs. simulated heating consumption (building model with modified critical parameters). There is no clear correlation between the measured heating consumption and the outdoor temperature; the heating load at 5°C is more or less simultaneously to the heating load at 17-26°C.*

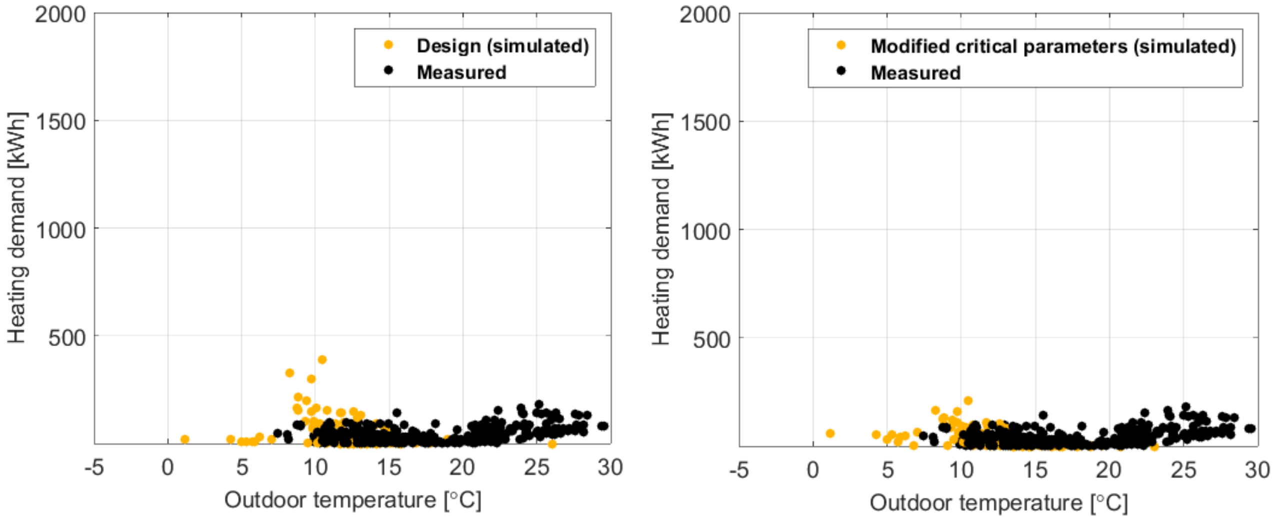


*Fig. 4.7.3: Summer period.* **Left:** *measured heating profile (black) vs. simulated heating consumption (design situation).* **Right:** *measured heating (black) vs. simulated heating consumption (building model with modified critical parameters). The measured heating load is more or less constant. The real cause cannot be identified from the available data, but seem to indicate unexpected (non-modeled) heat losses in the building system.*

Figure 4.7.1 underlines the earlier conclusion that the measured heating load is much better represented with the results of the Pareto analysis, but no conclusions can be drawn about the remaining energy gaps in the start and end time blocks of the office days (6:00 -9:00 h and 16:00 – 21:00 h). The most reliable hypothesis has already been mentioned before, namely the modeling of the presence-based climate control.

For the energy gaps in the spring/autumn (fig. 4.7.2) and summer period (fig. 4.7.3), the measured heating profiles show a relative constant heating load over time, without clear correlations between the heating load and the outdoor air temperatures. Although the root cause cannot be derived from the available data, the trend of these measured heating profiles seem to indicate (non-modeled) heat losses in the building system. Because there are no clear correlations with the outdoor air temperature, it is not likely that the cause will be found in the building envelope. Because no sufficient data is available to analyze this on a more detailed level, this hypothesis has not been checked. Additional, detailed measurements are needed to identify the root cause and the locations of this heat loss/consumption.

**Concluding assessment of energy gap in heating consumption**

As partial conclusion for this section, it can be stated that the major part of the energy gaps in the heating consumption is explained by the analyzed critical parameters, identified with the Pareto analysis. The cumulative energy gap was only small, but the simulated heating consumption showed a completely different daily heating pattern. In the analysis is found that this difference is mainly caused by the floor heating control.

In the winter period, there are still energy gaps in the start and end periods of the office hours (6:00-9:00 and 16:00-21:00). It is quite reasonable that these gaps are caused by the simplified occupancy pattern in the model. Namely, in reality, the climate control is presence-based. Therefore, the heating load is very hard to predict in start and end periods of the office days. These hypothesis cannot be assessed, because no sufficient data is available for the presence pattern in 2014.

In spring/autumn and summer period, there still remain energy gaps in all analyzed daily time blocks. The results of the Pareto analysis do not provide sufficient information about possible causes for these energy gaps. Therefore, trend analyses, according to the LEAN Energy Analysis, have been used to analyze the heating energy profiles. Although the root cause cannot be derived from available data, the heating profiles seem to indicate unexpected (non-modeled) heat losses in the building system. To check this latter hypothesis, additional, detailed measurements are needed.

### 4.7.3 Assessment of remaining energy gaps in cooling consumption

For the cooling consumption a large energy performance gap was identified, which cannot be explained by the results of the Pareto analysis. In this section the energy gaps are further analyzed by trend analysis.

In §4.6 it is found that the energy gaps occur in all seasonal and daily time blocks. Therefore, in first instance, the cooling consumption is only divided in two categories: 'within office day' (6:00-21:00 h) and 'outside office hours (nights and weekends).

In figure 4.7.4, the simulated (climate data: de Bilt) and measured cooling profiles are compared. It shows that the energy gap occurs in both the day (left) and night/weekend (right) profiles, mainly in the temperature range between 0 and 17°C, when only a small cooling load is simulated. In first instance, it seems to be a system-based problem, instead of a (constant) building-envelope based problem, because the simulated and measured curve correspond to each other in the 'normal' cooling temperature range (> 20°C).

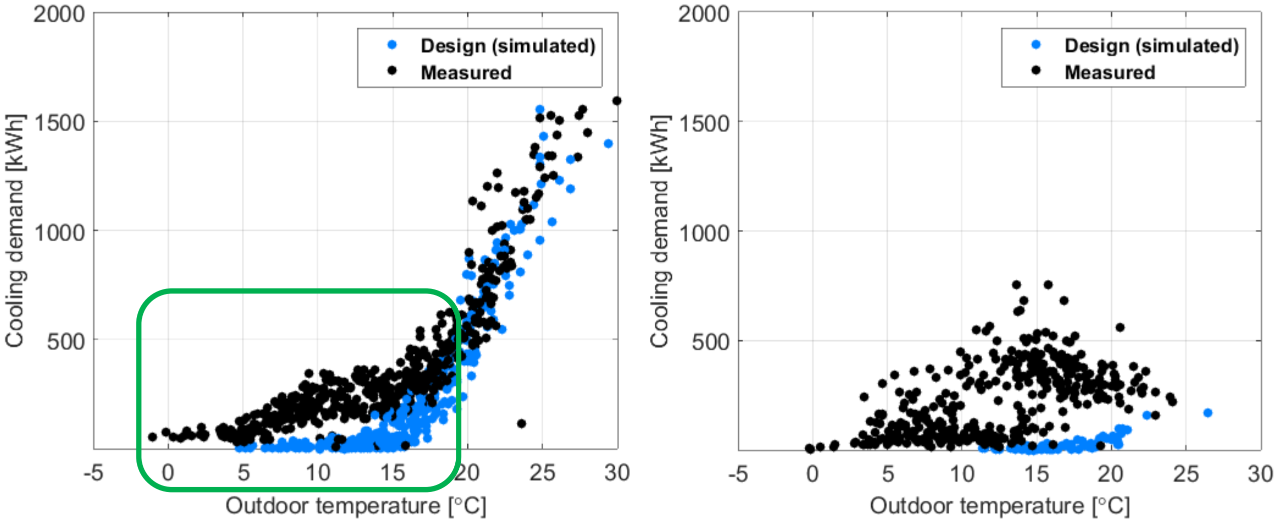


*Fig. 4.7.4: Comparison between the annual simulated and measured cooling profile.* **Left***: cooling profile within office hours (6:00 – 21:00 h).* **Right:** *cooling energy profile outside office hours (nights and weekends). The energy gap occurs in both the day (left) and night/weekend (right) profiles, mainly in the temperature range between 0 and 17°C, when only a small cooling load is simulated.*

To find causes for these energy gaps, first the night/weekend profiles are analyzed, because in this period, there are better starting points for an analysis, compared to the daytime profiles. During days, a large variety of possible causes can be responsible for an energy gap. During nights and weekends, there is only a relatively small amount of main causes which can be responsible for cooling during nights. The measured cooling profile is created with data, which is filtered according the earlier mentioned equation:

- Cooling consumption: $Q_{ATES} + (Q_{evaporator} - Q_{stored\_cold\_ATES} - Q_{regeneration\_ATES}) + Q_{night\text{-}time\_cooling}$

Because cooling is only provided by the air handling unit in this case, within the measured data frame, there are three main options for the cooling load during nights and weekends:

1. There is a cooling demand from the building, supplied by the air handling unit
2. There is no cooling demand from the building, which means that that a cooling load is 'lost' somewhere in the building system.
3. The regeneration strategy is different from the design strategy (design: regeneration at outdoor temperatures <4°C)

**Energy gap outside office hours (nights and weekends)**

As mentioned above, there are only a limited amount of options, which can be responsible for the cooling load during nights and weekends.

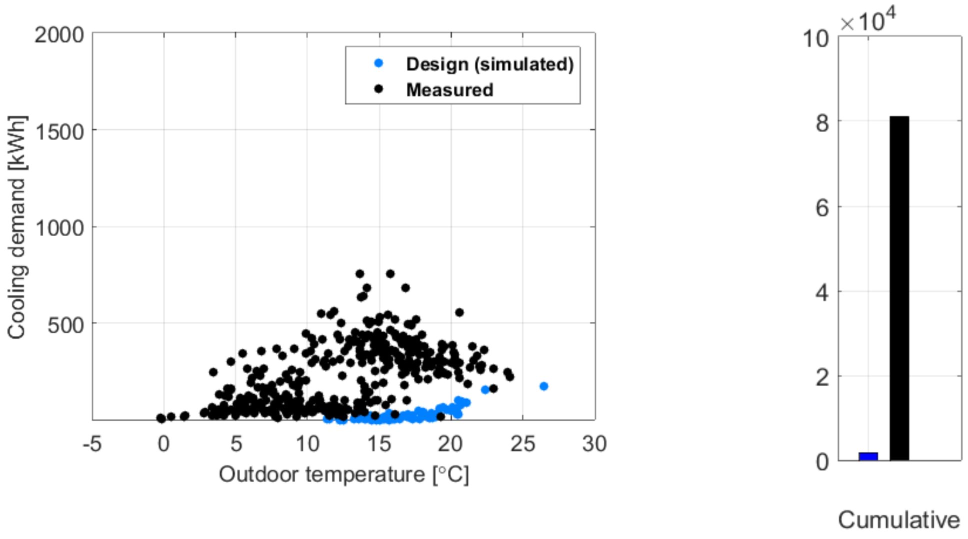
*1. Cooling demand from the building, supplied by the air handling unit (night-time cooling)*

First the cooling supplied by the air handling unit, is analyzed. According to the design of the building system, only a cooling demand is allowed during nights for night-time cooling: supply of outdoor air by mechanical ventilation, to cool down the building during nights, if the indoor air temperatures are high.

To assess the role of the night-time cooling in this energy gap, this night-time cooling is filtered out of the measured cooling profile. The night-time cooling data is filtered out with the following conditions:

- Time = 22:00 h – 6:00 h (nights) during weekdays, Saturday and/or Sunday
- Supply air temperature – return air temperature < 0 °C
- Rotational speed of supply fan: >40% of maximum speed
- Cooling coil does not supply cooling

For the simulations, also the night-time cooling is excluded (by running the simulations without the nigh-time cooling strategy). The profiles of the design and measured cooling load are compared in figure 4.7.5.



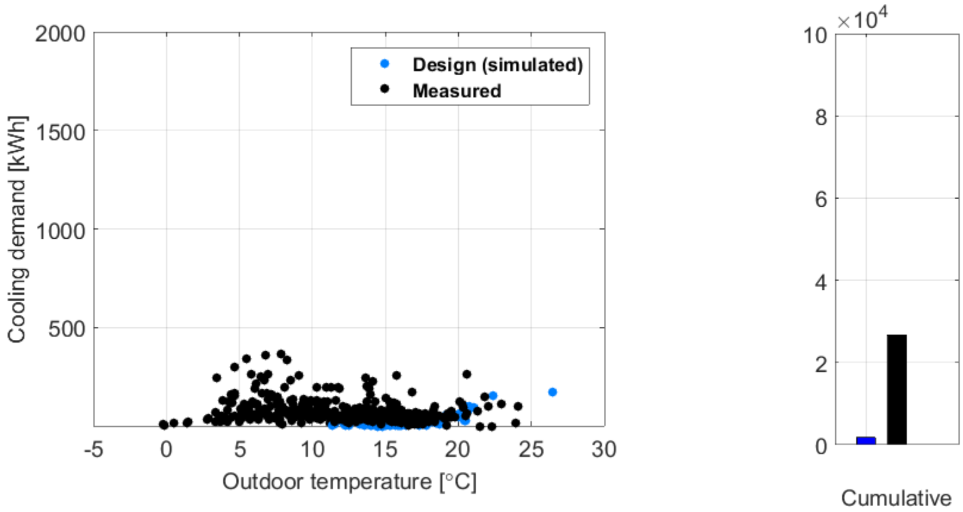


*Fig. 4.7.5: Filtering of 'night-time cooling' data.* ***Above:*** *total cooling load (simulated vs measured).* ***Below:*** *Simulated vs measured cooling load, without night-time cooling data. It can be seen that this night-time cooling is responsible for a large part of the energy gap during nights/weekends.*

In figure 4.7.5, it can be seen that this night-time cooling is responsible for a large part of the energy gap during nights/weekends. Based on the results of this figure, a technical, detailed investigation has been performed on the reason for this 'unusual' high night-time cooling load: night-time cooling is used for regeneration of the ATES-system, by a 'cooling bypass' in the air handling unit. The outdoor air has to cool down water, without involving of the building itself. However, valves of the chilled beam units are open sometimes, while rooms are unoccupied and temperature set points are lowered. This results in a cooling demand when mechanical ventilation is activated.

Although a large part of the energy gap during nights/weekend has been explained, there is still a quite constant cooling load from 0 – 25°C. Therefore, the second option for energy gaps in the cooling load, during nights/weekends, is analyzed:

2. *There is no cooling demand from the building, which means that that a cooling load is 'lost' somewhere in the building system.*

To detect 'unintended' cooling load, the data is filtered by the 'cooling state' of the ATES system. In other words, only data is shown where the ATES-system delivers cooling to the building (and thus heat is stored in the aquifer system). In this case, only measured data remains when there is an active cooling demand from the building.

This data is filtered by the following conditions, based on an earlier performed study on the aquifer system of this case study building (Hoving, 2015):

- The flow between the building and the aquifer system: > 2 $m^3/h$
- The temperature of the flow from the building to the ATES: > 12°C
- Temperature difference between flow in and out the ATES-system ($T_{in}$- $T_{out}$): ≥ 1°C

The profiles of the measured cooling data 'in cooling state' (without night-time cooling data) and the design cooling load are compared in figure 4.7.6.

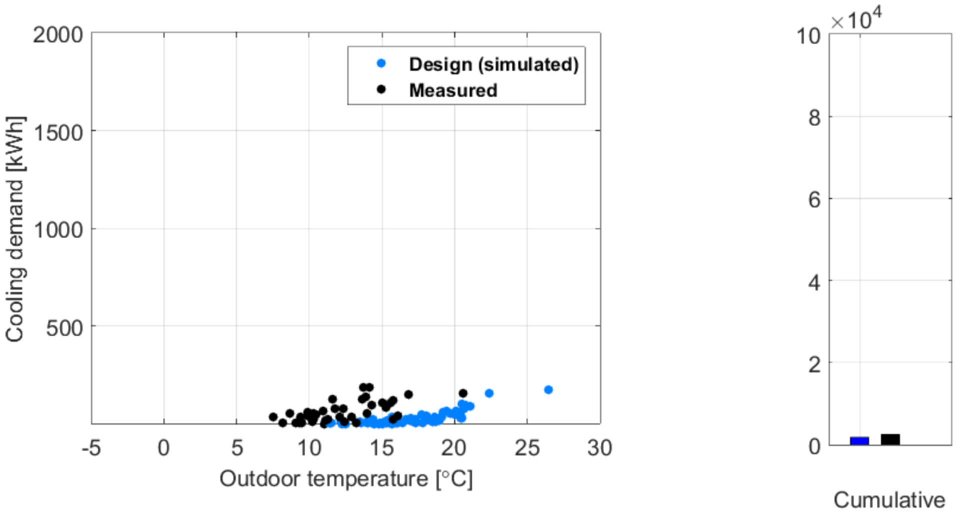


*Fig. 4.7.6: simulated vs measured cooling load data. The measured cooling load data is filtered: besides excluded night-time cooling, only data is shown where the ATES-system is 'in cooling state', which means that there is a meant, active cooling demand from the building. The remaining cooling load is negligble, which means that the energy gap occurs when there is no cooling demand for the ATES-system.*

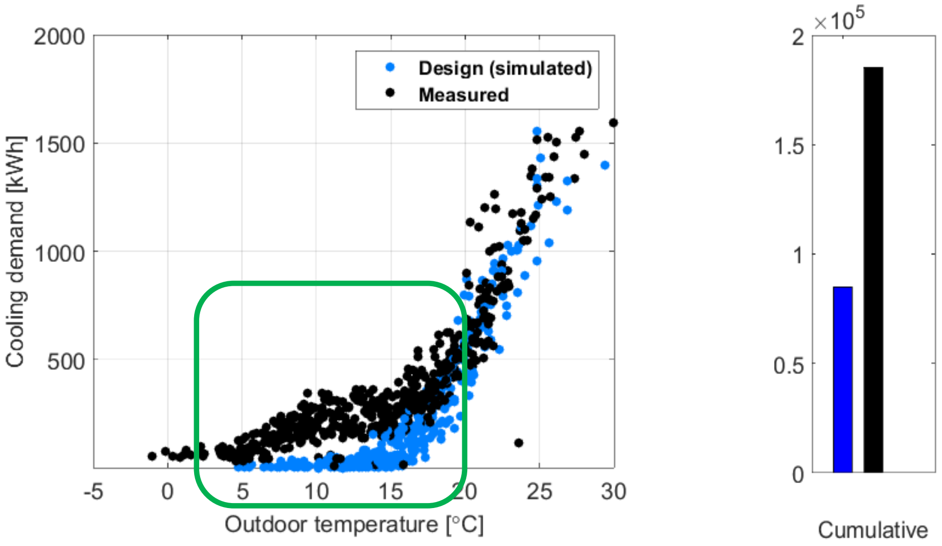
In figure 4.7.6, it can be seen that the remaining cooling load is negligible when the ATES system is in 'cooling state', which means that the remaining energy gap occurs when there is no cooling demand for the ATES-system. So it can be derived that a significant amount of cooling is produced when there is no cooling demand from the ATES-system, which means that cooling (produced by the evaporator of the heat pump), is not stored in the ATES-system, but is lost somewhere in the building system.

A more detailed analysis for the exact location of these losses is not performed in this study, because no sufficient data is availble, but it is recommended to carry out measurements, to detect the energy losses.

With the latter 'cooling state' filter, the energy performance gap outside office hours has been explained. Below, the energy gap during office hours (daytime) is analyzed.

**Energy gap during office hours**

Because loss of cooling energy is detected in the night/weekend block, with the 'cooling state' filter, the same data filter is applied during office hours. In figure 4.7.7 the impact of this data filter is shown.



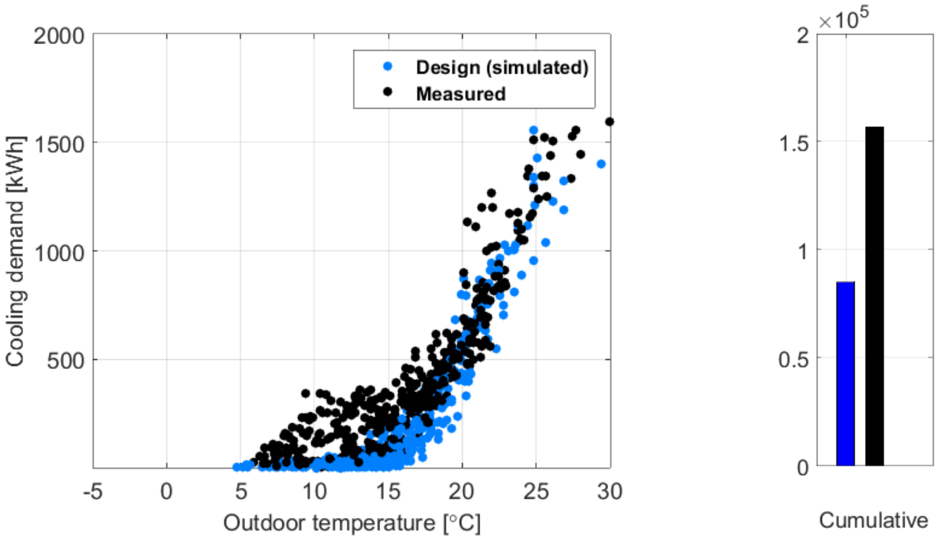


*Fig. 4.7.7: simulated vs measured cooling load data. Measured data outside 'cooling state' of the ATES-system is filtered out, to exclude unintended cooling load. This filter explains only a relative small part of the energy gap. The major part of the cooling energy gap remains and cannot be explained by this cause.*

In figure 4.7.7 it can be seen that the 'cooling state' filter explains only a relative small part of the energy gap. For example cooling data in the range of 0-6°C is disappeared, which means that this cooling load is caused by cooling energy losses. Possibly, these losses have also impact on the heating consumption, but this hypothesis is not been checked in this study, since no sufficient data is available. However, the major part of the cooling energy gap remains and cannot be explained by this cause. Therefore, the analysis is continued with another possible cause, also following from the findings in the 'night/weekend' block.

*Cooling demand from the building, supplied by the air handling unit*

In the night/weekend period, it was found that there was a relative large cooling demand from the building during nights/weekends. Based on this finding, a more detailed/technical investigation is carried out and it turned out that this cooling demand is caused by open valves, during periods where these should be closed (already mentioned in figure 4.7.5).

A more detailed explanation:

The presence-based climate control is based on signals '0', '1' and '3'.

- '0' means: the room is occupied. In that case, the climate is controlled on workable climate settings (e.g. temperature between 22°C and 24°C, lights activated, etc.).
- '3' is the signal which is normally used in this building to indicate an unoccupied room.
- The signal '1' is also used to indicate unoccupied rooms for a relatively small time period (from 17th of February – 27th of June). Although the exact different meaning between the signals '1' and '3' is not found, the effects are found. In this period, the valves are open when the signal '1' is measured. Because the set points for the required indoor temperatures are lowered for unoccupied rooms, this results often in a cooling demand for the building.

There is no sufficient data to analyze on a detailed level in which rooms this unintended cooling load occurred. Therefore, to analyze the impact of this unintended cooling demand, the period where this '1' signal is used, is filtered out, namely from 17th of February – 27th of June. In figure 4.6.11, the results are shown.

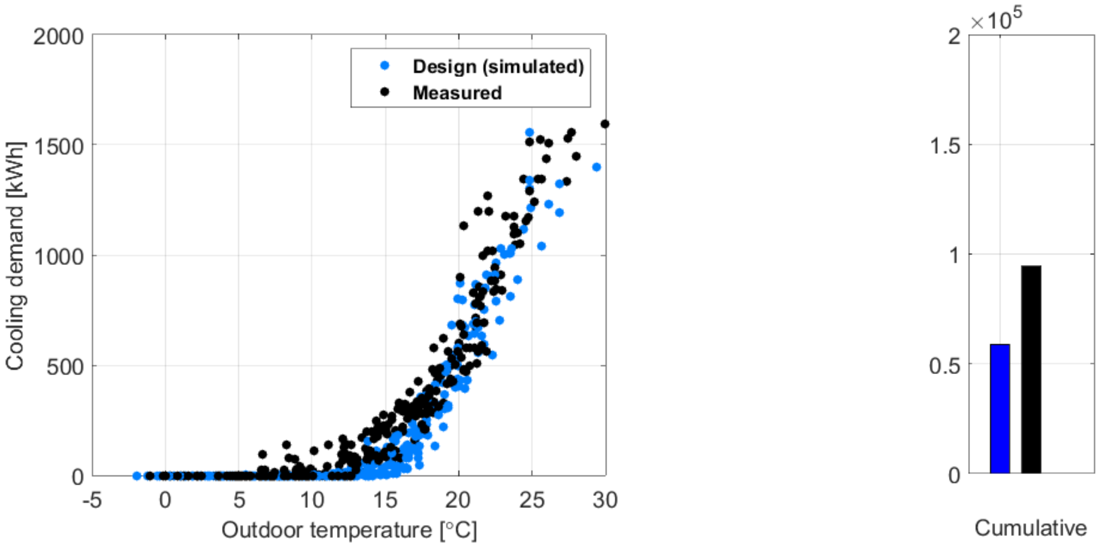


*Fig. 4.7.8: simulated vs measured cooling load data .To analyze the impact of the uninted cooling load in unoccupied rooms, as discussed above, the data from 17th of February – 27th of June is filtered out. The shape of the measured cooling profile corresponds much better with the simulated profile in this case, which means that this discussed 'error' in the presence-based climate control have been caused a large energy gap.*

Figure 4.7.8 shows that the shape of the measured cooling profile corresponds much better with the simulated profile in this case, which means that this discussed 'error' in the presence-based climate control have been caused a large energy gap. Although the energy gap is not completely explained by these factors, the trend of the profiles mainly corresponds to each other, which means that the trend analysis cannot provide more information for this energy gap. The major part of the energy gap is explained by the discussed causes. The remaining gap can be caused by multiple possible (combined) parameters, but cannot be explained with the used Pareto analysis and LEAN Energy Analysis.

### Concluding assessment of energy gap in cooling consumption

As partial conclusion for the assessment of the cooling energy gap, it can be stated that the results of the Pareto analysis are insufficient for the assessment of it. The parameters, identified as most important for the cooling energy consumption, are not the causes of the energy gap in this case.

Therefore, an additional trend analysis is performed. Because a trend analysis does not provide information about a specific parameter or cause, the analysis is started for the night/weekend periods, because in these periods, there are better starting points for a trend analysis, compared to the daytime profiles. During days, a large variety of possible causes can be responsible for an energy gap. During nights and weekends, there is only a relatively small amount of main causes which can be responsible for cooling during nights, as explained more detailed earlier in this section.

In this way different possible options/causes are analyzed and eliminated, to find the causes for the energy gap. It turned out that the energy gaps outside office hours (nights/weekends) are caused by the same 'root causes' as during office hours.

The first main cause is a software 'error' in the presence-based climate control, which resulted in unintended cooling in unoccupied rooms. Furthermore, it turned out that a large energy gap had also been caused by cooling energy losses in the building system. Cooling is produced when there is no cooling demand from the building. Possibly, the cooling energy from the evaporator of the heat pump is not stored in the ATES system, but is lost somewhere. This cooling losses are not investigated further in this study, since no sufficient data is available (for 2014) to analyze this more detailed. It is recommended to perform measurements to find the exact cause and location of these energy losses.

## 4.8 Findings from case study 2

**Findings from the Pareto analysis:**

In step 1 of the Pareto analysis (§4.1), for heating consumption only a relatively small energy gap was found between design-based simulated and measured annual energy consumption (gap = ±7%). For cooling consumption, this annual energy gap is much bigger: the measured cooling is about 2,3x higher than the simulated cooling consumption.

In the second step of Pareto (§4.2), a selection of 15 parameters has been made again, based on the building model input. Although most parameters are generally applicable, some ones are different from the first case study. The impact of these parameters on the annual heating and cooling consumption has been analyzed with the same sensitivity analysis as performed for the first case study (§4.3). By comparison of the results with the sensitivity analysis in case study 1, it turned out that the percentage impact of parameters are different. Especially in case of heating consumption, the heating system in Kropman Utrecht seems to be more robust, compared to Kropman Breda. Also for this case study, it turned out that a fluctuation of 50% of internal heat production has a large impact on energy consumption. Although the average internal heat production over a year will not deviate that much, when energy is considered over short time periods, it is a decisive parameter.

Cooling energy also seems to be quite robust, which was also the case in Kropman Breda. This robustness of the cooling energy, compared to heating energy, was not expected. The exact reason for this unexpected robustness is unknown. This robustness can be an (unexpected) 'logical' cause of the building system. If not, it can be caused by model limitations or the used method of the sensitivity analysis. More detailed research is needed to explain this finding.

The actual effect of the selected critical parameters on the energy performances of Kropman Utrecht has been investigated (§4.4).

For heating, only a small energy gap was identified from the annual simulated and measured consumption. This energy gap can be partly explained by the critical parameters. The main effect is caused by the floor heating/cooling control. For cooling, no significant deviations between the 'design' and real values of the critical parameters were identified. It is concluded that the results of the Pareto analysis provide insufficient information to explain this energy gap.

**Findings from the LEAN Energy Analysis:**

The same way of energy assessment (energy profiles within characteristic time blocks), has been used in this case study, since it proved to be successful for case study 1.

It was found that energy profiles with hourly data do not well represent the dynamic behaviour of the building systems (due to inertia of the system and use of heat/cold buffer vessels). Therefore, the heating demand has been summed over a day within each time block. That means that each time block has 365 data points over a year, instead of 8760. In this way, the dynamic behavior of the building system is better included within the time blocks.

Furthermore, it was found that time blocks for energy assessment can be selected as small and detailed as possible. However, in a small time block, the dynamic behavior of the system and occupancy rate become dominant in the energy consumption, which make assessment much too complicated and useless for wide ranged application. On the other hand, they should be small enough to provide sufficient information about correlations with outdoor temperature and time. Therefore, the selected time blocks in this study have to be based on their 'physical meaning', the time-dependent parameters.

Using the different characteristic time blocks, energy gaps in several time blocks of the heating consumption are identified. Although the annual sum of the simulated and measured heating energy corresponds to each other, a different heating pattern was identified. In some time blocks, the measured heating load was much lower than the simulations, while in other time blocks it was much higher. From this finding, it is concluded the total amount of consumed energy can be 'misleading', when energy is considered over longer periods (e.g. a year). Causes of energy gaps can be canceled out by each other, over longer periods. In that case, energy inefficient system control would not be found if energy is assessed only over a long period.

The remaining energy gaps in heating consumption, have been analyzed with trend analysis. The major causes seem to be model simplifications (simplified occupancy pattern) and (non-modeled) heat losses in the building system (§ 4.7.1). To check these hypotheses, additional detailed measurements are recommended.

For the assessment of the energy gaps in cooling consumption, it is concluded before that the results of the Pareto analysis are insufficient for the assessment of it. Using this trend analysis, different causes of the energy gaps are found (§ 4.7.2), resulting in an explanation of the major part of the energy gaps. It is hard to define the percentage of the explained part of the energy gap, because no sufficient data is available to check the specific effect of an identified cause.

It is expected that the floor heating/cooling control, which causes a main effect on the daily heating pattern, also has impact on the cooling energy pattern. In this study, this hypothesis has not been checked, since these consequences for the cooling consumption cannot be derived from available data. On the other hand, during the analysis of the energy gap in cooling consumption, unintended loss of cooling energy was found. It is expected that this also influence the heating load of the building. Although this cannot be checked with available data, it possibly explains (partly) the remaining (unexplained) energy gaps.

# 5 Method evaluation

In an evaluation of the used Pareto analysis and LEAN Energy Analysis, the strengths and weaknesses of both methods are evaluated (§5.1). In section 5.2 a combined method is recommended, using the strengths of both methods.

## 5.1 Strengths and weaknesses of the used Pareto analysis and LEAN Energy Analysis

In table 5.1.1 and 5.1.2, the strengths and weaknesses of both methods are evaluated, based on the results of both case studies.

*Table 5.1.1: Pareto analysis: evaluation of the strengths and weaknesses, based on the study results.*

| **+ (strengths)** | **- (weaknesses)** |
|---|---|
| • Leads systematically to parameters with a high risk to cause energy performance gaps.<br>• Identification of the 'critical parameters' in building energy consumption improves the effectivity of energy monitoring, leading to a few essential points which should be monitored for a useful energy assessment.<br>• The results improve the functionality of 'quick energy scans' in existing buildings, they are useful in assessment of the most relevant parameters.<br>• Effective analysis for multi parameter problems like this, by focusing only on the main problems and main causes. | • Hard to define '100%' of involved causes for an energy performance gap, because of the quantity of interdependent parameters. That makes it hard to define a selection ('20%') of parameters which can really explain 80% of the energy performance gaps.<br>• The interdependency of parameters makes it hard to generalize conclusions about real 'critical parameters'. The percentage impact of parameters is not similar in each building. More case studies are needed to investigate the correlations between the critical parameters and the characteristics of a building (system). |

*Table 5.1.2: LEAN Energy Analysis: evaluation of the strengths and weaknesses, based on the study results.*

| **+ (strengths)** | **- (weaknesses)** |
|---|---|
| • Heating and cooling data profiles are suitable for energy assessment, if the heating/cooling energy is considered as function of outdoor temperature and time. The use of characteristic time blocks, based on involved time-dependent parameters, improves the ability to assess measured energy performances.<br>• Trend analysis (using energy profiles in individual, characteristic time blocks), can efficiently lead to the real causes of energy gaps if it is started from global, overarching causes to specific causes, e.g. system components or settings (discussed more detailed in §4.8). | • Reducing energy profiles (within specific time blocks) to regression lines, results in loss of useful information about energetic behavior of the building (systems). (Discussed more detailed in §3.6.1)<br>• Regression coefficients (e.g. slope of a regression line) only provides very general information about efficiency of energy consumption. Because many parameters influence this efficiency (and slope of regression lines), no reliable conclusions can be drawn about the causes of deviating energy efficiency.<br>• Detailed energy data (e.g. on component, room and/or floor-level) is needed to identify the real causes from trend analysis. |

The strengths and weaknesses of both methods, listed in tables 5.1.1 and 5.1.2, are 'summarized' to an assessment of the functionality and feasibility for both the Pareto analysis and the LEAN Energy Analysis, shown in table 5.1.3.

*Table 5.1.3: The strengths and weaknesses of the Pareto analysis and the LEAN Energy Analysis are 'summarized' to an assessment on the functionality and feasibility of both methods.*

| | **Functionality** *(identification of energy gaps and their causes)* | | **Feasibility** *(systematics, applicability and required amount of data)* | |
|---|---|---|---|---|
| **Pareto analysis** | **+/-** | Because of the interdependency of involved parameters, it is hard to define a few major parameters which can be generally considered as the 'critical parameters' and really explain the major part of energy gaps. On the other hand, it provides useful information about 'risky' parameters, improving the functionality of quick energy scans in existing buildings. | It consists of a clear, stepwise approach. By repeating this analysis for multiple case studies, correlations between building (system) characteristics and critical parameters can be investigated. With more generalizing conclusions about critical parameters, the required amount of data for an energy assessment, will decrease. | **+** |
| **LEAN Energy Analysis** | **+** | Causes of energy performance gaps are successfully identified by trend analysis of energy consumption within characteristic time blocks | A systematic approach helps in trend analysis, but it leads less rapidly to specific causes, compared to the Pareto analysis. Furthermore, detailed energy data (e.g. on component, room and/or floor-level) is needed to identify the real causes from trend analysis. | **+/-** |

Based on this section, a combined energy assessment method is recommended in section 5.2, using the strengths of both methods.

## 5.2 Recommended energy assessment method, using strengths of Pareto analysis and LEAN Energy Analysis

Based on the strengths of both used methods (Pareto analysis and LEAN Energy Analysis) and gained insights during this study, a stepwise approach is recommended for efficient assessment of energy performance gaps:

1. Identify a reference situation for the building. If the original design is selected as the 'reference' situation, check if important modifications are implemented during the operational phase of the building. Otherwise, the reference situation is basically outdated.
2. Define in general terms the main parameters, involved in the energy consumption of the building.
3. Analyze the sensitivity of these parameters and reduce the quantity of 'major parameters' to only a few 'critical parameters', with the highest risk to cause a significant energy performance gap.
4. Identify characteristic time blocks in the demand of the energy function, based on the involved time-dependent parameters (solar irradiation, internal heat production, etc.). Classification of characteristic daily and seasonal time blocks have been proved to be useful in this study.
5. Compare the measured energy consumption with the energy consumption of the reference situation, within the characteristic time blocks. In this step, a few aspects should be taken into account:
    - Accuracy and completeness of measured data. The accuracy of the data has to be checked and/or taken into account. For example, if temperature data or (automatically calculated) energy data is used for analysis, a relatively small inaccuracy can have large consequences for the results when these data is cumulated over a long period. Also accurate weather data monitoring on a building is important, since heating curves are often based on outdoor

  temperature. Furthermore, the completeness of data should be checked. For example, meters or system components can fail during certain periods by technical breakdowns.
  - A general, but very important point: before starting the analysis of an energy gap between measured and simulated data, it must be sure that both measured and simulated are based on the same ‘assessment framework’. For example, is the measured energy consumption of the generator (e.g. heat pump) the produced energy (which excludes generation efficiency) or the consumed energy (which includes generation efficiency)? Although this seems to be a logical point, in a more detailed level, it is very important to be aware of this point in each comparative analysis.

6. Check the identified critical parameters in the building. When there is a deviation between the reference and measured value of the parameter, a specific investigation can be started to identify the cause(s) of this difference. In this way, major causes of an energy gap can be identified in an efficient way.
7. When the identified critical parameters do not contain the real causes of the energy gap, an additional trend analysis can be performed. Based on this study, the following aspects are recommended for an efficient trend analysis:
   - A successful way for assessment of energy is the consideration of it as a function of outdoor temperature and time. The timescale (small or large time blocks) is dependent on the building characteristics and the distribution of the energy gap over a period. Basically, the question is in here: in which seasons and on which moment of the day (or in which pattern over a day) does the energy gap occurs? When this first question is answered, causes of the energy gap can be identified much more efficient.
   - To identify a cause of an energy gap, the analysis starts from global, overarching causes to specific causes, e.g. system components or settings. For example, a first question can be: which system components do play an active role in the specific time blocks in which energy gaps are identified? This leads to a more specific (group of) system component(s). For further analysis, for example, a next question can be: what is the primary function of this component, is the energy supplied to the right rooms, on the right moments? In this way, a part of the possible causes can be eliminated without a detailed investigation and the real cause can be identified in an efficient and targeted way.

# 6 Discussion, conclusions and recommendations for further research

## 6.1 Discussion

**Sensitivity analysis**
From the sensitivity analysis, which is used to identify the most critical parameters in the energy performances of buildings, two points of discussion are derived:

- In the used way of the sensitivity analysis, interdependence between parameters is included, which means that some 'critical parameters' are important only in combination with certain other parameters. Although these correlations are present in reality, it makes it hard to generalize conclusions about real 'critical parameters', since the percentage impact of the parameters is not the same for each building. This sensitivity analysis can be used in future, but in that case, more case studies are needed to investigate the correlations between the most important parameters and the characteristics of a building (system), for more general conclusions about critical parameters.
- The straight-line comparison of all parameters, with a deviation of +/- 10%. This method was chosen to get an indication of the sensitivity of different parameters/values, but during this study it becomes clear that this method is not that realistic for all parameters. For some parameters, 10% deviation will hardly occur in practice, while for other parameters, 10% is only a small deviation in practice.

**Simulation tool**
The limitations of the simulation tool: the tool is not aimed at the dynamic behavior of the building systems (distribution losses, inertia of the system (control), generation efficiency, etc.). Over periods, where the energy demand of the building is quite constant, acceptable estimations for the distribution and generation efficiency can be made by indication values from literature (e.g. in periods where occupancy is quite constant). However, in 'heat up' and 'cool down' periods (e.g. during start & end of the office hours), the limitations of the simulation tool play a more significant role. In these periods, the dynamic behavior of the building system is decisive for the energy consumption. During these 'heat up' and 'cool down' periods, the simulated energy profiles deviate relatively much from the measured energy profiles.

## 6.2 Conclusions

Based on the results of this study and the points of discussion (chapter 5), the main research question is answered in this section.

**Pareto analysis**
It is concluded that the use of the Pareto analysis has led to a structured and clear approach in this multi-variable topic. The Pareto analysis is aimed to identify 20% of all involved causes, which are responsible for 80% of the problem. In this study, it was found that it is hard to select a literal percentage 20% of all involved causes in building energy performances. Because many control settings and fluctuating parameters in user behavior are involved and interdependent, it is very hard to define 100% of all causes. Therefore, although the parameters cannot be considered as a literally percentage of 20%, in this study it has led to the identification of a few critical parameters, containing a high risk to cause energy performance gaps in buildings.

In the performed analysis in this study, the parameters are specifically aimed at the use of the building (system). Therefore, these few 'critical parameters' can be considered as major parameters in the use of the building (system). If these parameters can explain the energy performance gaps, than the use of the building (system) is deviating from the assumed use (in the design). The part of the energy gaps which cannot be explained by the critical parameters, represent the dynamic behavior and underlying control of the building (systems). In that part, the building (system) is used 'as expected', but energy is consumed ineffectively.

In case study 1, the results of the Pareto analysis leads to identification of an unnecessarily high air humidification setting. Based on this finding, this setting is lowered, which will result in energy savings. For heating, only a small part of the energy performance gap could be explained by the results of the Pareto analysis. The actual values of the selected critical parameters did not deviate significant from the 'design' values.

In case study 2, the major part of the energy gap in heating consumption could be explained by the results of the Pareto analysis. Although the annual energy gap in heating consumption was only negligible, it turned out (in the LEAN Energy Analysis) that the heating pattern over a day was significantly different from the simulated pattern, due to the floor heating/cooling control. In cooling energy a large energy gap was identified, but cannot explained by the results of the Pareto analysis. Although it is expected that the floor heating/cooling control has effect on the cooling load pattern, no sufficient data is available to check this hypothesis.

Because the used sensitivity analysis to identify the most important parameters includes interdependence between parameters (discussed in chapter 5), these 'critical parameters' are not the same for each building. Therefore, to draw general conclusions about these critical parameters, there are two major options:

- More case studies should be analyzed to identify the correlations between building (system) characteristics and resulting critical parameters.
- Another type of analysis, which excludes interdependence between different parameters, can be used for a more independent consideration of the involved parameters (although it must be taken into account that these correlations are present in operating buildings).

**LEAN Energy Analysis**
The LEAN Energy Analysis is useful for the identification of characteristic correlations in energy consumption, which can be used for efficient energy assessment. In this study, by use of this method it was found that energy consumption can efficiently be assessed by a combination of outdoor temperature and time. Time is a sufficient, independent variable, due to several involved time-dependent parameters (solar irradiance, internal heat production, stored heat in thermal building mass and different temperature settings during day and night)

Regression analysis, which is commonly discussed and recommended in publications about the LEAN Energy Analysis, did not improve the ability to assess energy consumption in this study. By use of regression analysis and regression coefficients, information about the dynamic behavior of the building system is lost. Therefore, assessment by energy profiles within characteristic time blocks has been successfully used in this study.

To derive specific causes of energy gaps from trend analysis, a systematic approach is needed, starting from global, overarching causes to specific causes (components or settings). The required amount of (detailed) data is a disadvantage in this method.

In case study 1, the trend analysis led to identification of an unexpected large heating load, supplied in the 'heat-up' period of the boiler. This strongly indicates large (non-modeled) heat losses through the building envelope. Additional measurements are recommended to check this hypothesis.

In case study 2, trend analysis showed unexpected heating consumption, which indicates (non-modeled) heat losses within the building system. The exact reason and location of the heat losses cannot be derived from available data. Therefore, additional measurements are needed to analyze these heat losses more detailed. For cooling consumption, the LEAN Energy Analysis led to explanation of the major part of the energy gap. Losses of cooling energy, as well as unintended building cooling during nights, have been identified as major causes. It is expected that this cooling energy losses has influence on the heating load of the building, but no sufficient data is available to analyze this more detailed. Probably (a part) of the remaining, unexplained energy gap can be explained by this fact.

**Combination of Pareto analysis and LEAN Energy Analysis**
Using the strengths of both methods results in a successful, combined method for analysis of energy performance gaps in existing buildings. Although more research is needed to draw generalize conclusions for 'critical parameters' in energy performances of office buildings, the analysis have been proven to be clear and useful. If this method is applied on more case studies, it will result in more effective energy monitoring and less required data for assessment of energy performances in existing buildings. The LEAN Energy showed that identification of characteristic time blocks and trend analysis is useful in the identification of specific inefficient energy consumption in building (systems). For this analysis, a lot of (detailed) data is needed to identify the causes. This latter disadvantage can be reduced by more generalizing conclusions about the critical parameters in energy performances. In that case, trend analysis can be performed more targeted on specific system

components. A stepwise analysis, based on the study results and strengths of the Pareto analysis and LEAN Energy Analysis, has been recommended in section 5.2.

## 6.3 Recommendations for further research

Some recommendations for further research are listed below:

- In this study, the selection of ‘critical parameters’ in building energy performance, has been limited to the use of the building and building systems. Critical parameters in the control of the building system (parameters in the generation efficiency and efficiency of the distribution system) are not involved in the performed analysis. It is worth to investigate the most important parameters in this more dynamic behavior of the building system for a more complete, quick energy assessment.
- For more general conclusions about the most important parameters in building energy performances, more case studies should be analyzed to identify the correlations between building (system) characteristics and resulting critical parameters.
- It is recommended to assess the used sensitivity analysis in this study by performing an additional sensitivity analysis with another method. The limitations of the used sensitivity analysis have been discussed already in §6.1.

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| | |
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# Appendices

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|---|---|
| Appendix I | Design situation of case study building I (Kropman Breda). |
| Appendix II | Design situation of case study building II (Kropman Utrecht). |
| Appendix III | Technical analysis of gas fired boiler in Case study I (Kropman Breda). |

## Appendix I: Office building Kropman Breda (case study 1)

The appendix is modified from de Bont (2014). In this study the office building of Kropman Breda is used as case study. The most relevant information about the office building has been discussed already in the report. In this appendix, more detailed information about the building systems is provided.

**Heating**
The supplied hot water for heating and others is supplied by a conventional gas boiler (1-1KK1) the circulation pump valve will be started and opened when at least 1 of the groups has a heating demand. These groups are:

- Radiator group north-east
- Radiator group south-west
- Heater Air Handling Unit (AHU)
- Heater storage room

The radiators in the rooms are located on the floor by the window openings. When to outdoor temperature is below 17 ˚C the radiator groups will be released and (PI-) controlled to a weighted indoor temperature (room sensor north-east, rooms sensor canteen, room sensor office) of 21.2 ˚C. Further details are not required for this research.

*Heat exchanger (heat recovery wheel)*
The heat exchanger works as cooler when the outside air temperature is 1K lower than the averaged space temperature. And the heat exchanger works as heater when the outside air is 1K higher than the averaged space temperature.

*Heating generator*
The desired supplied air is determined by a heating curve and PID-controlled. Starting setpoints between X1 = -10 ˚C and X2 = 10 ˚C. Regardless if the AHU is running or not. If the temperature at the heating surface will become below zero, the freezing thermostat will start the following components: Supply fan off, exhaust fan off, outside air valves closed, circulation pump in and valve heater 100% open.

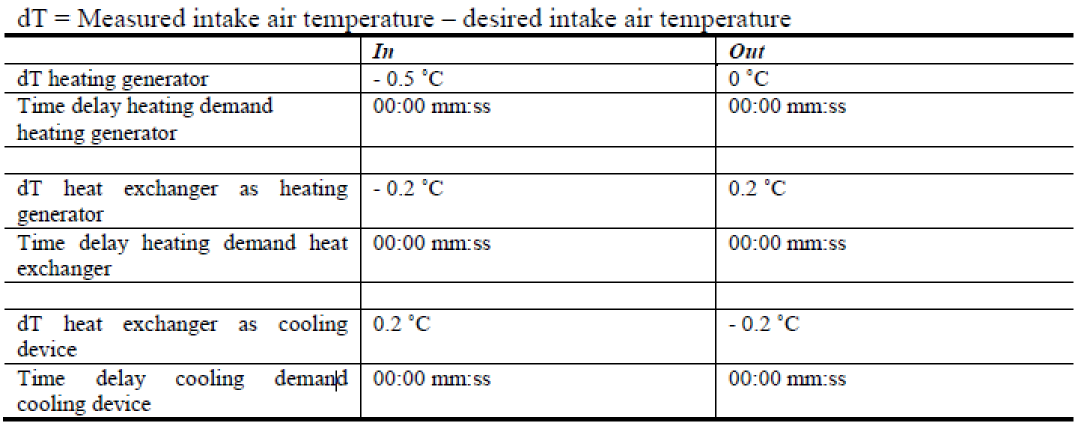
**Cooling**
Cooling is usually been used during summer time or when it’s required. The system has been divided into 3 cooling groups.

- North
- South
- Drawing room

These groups are the same for ventilation since cooling the rooms will be achieved through the air. The cooling machine (1-4KM01) will be released when there is a cooling demand and outdoor temperature is at least 1 hour above 18 ˚C. Since this research is about winter time cooling loads are not taken into account.

**Night-time cooling**
Free cooling will only start between 22:00 – 05:00 and when the averaged space temperature is higher than 23 ˚C and the outside air is 3 ˚C lower. The night-time cooling program stops when the outside air temperature is below 12˚C and when the averaged inside air temperature reaches 21˚C.

**Ventilation**
Supply air temperature controlled by the heat exchanger and the heating generator with the following settings:



dT = Measured intake air temperature – desired intake air temperature

| | *In* | *Out* |
|---|---|---|
| dT heating generator | - 0.5 °C | 0 °C |
| Time delay heating demand heating generator | 00:00 mm:ss | 00:00 mm:ss |
| | | |
| dT heat exchanger as heating generator | - 0.2 °C | 0.2 °C |
| Time delay heating demand heat exchanger | 00:00 mm:ss | 00:00 mm:ss |
| | | |
| dT heat exchanger as cooling device | 0.2 °C | - 0.2 °C |
| Time delay cooling demand cooling device | 00:00 mm:ss | 00:00 mm:ss |

**Energy consumption in 2013-2015.**

The analysis in the study is based on 2014, because at the start of the study, this year had the most complete measured data sets. In figure I.1 a comparison is made with the energy data of 2013 and 2015. In 2013, energy was measured from June to December (roughly half a year). The annual energy consumption is estimated, by multiply the measured energy by a factor 1,9. 2015 is added later on. This measurement data set is complete.

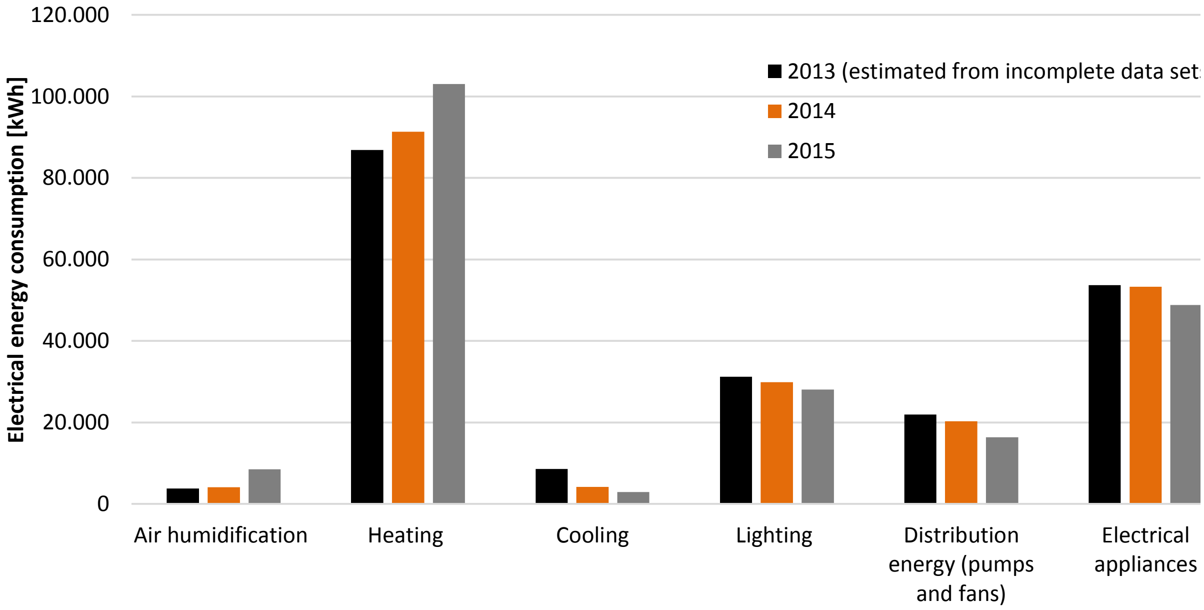


*Fig. I.1: energy consumption in 2013-2015. The consumption in 2013 is estimated from incomplete data sets: measurements were complete only from June-August.*

## Appendix II: Office building Kropman Utrecht (case study 2)

The appendix is modified from Hoving (2015). In this study the office building of Kropman Utrecht is used as case study. Most relevant information about the office building is taken from this study.

### Building

This office building houses approx. 150 employees. The building is constructed in 2004 and has a GFA (gross floor area) of roughly 5500 m$^2$. The GFA is divided in 3300 m$_2$ office space and 2200 m$^2$ for storage, restaurant, entree hall and other general spaces. The building has two wings, both holding 4 floors, which are separated by a large atrium. The atrium is closed in by the wings and two towers containing staircases, elevators, toilets and the majority of the technical installations. The wings contain large open offices with small (meeting) rooms and offices at both ends. The building is constructed using the industrial, flexible & demountable (IFD) building method. Buildings constructed with the IFD method are constructed with straightforward industrial methods as a bolted steel frame and prefab concrete floors. The design is based on large open floors without any internal walls. This makes the buildings highly flexible in their use and easy to readjust to future needs.

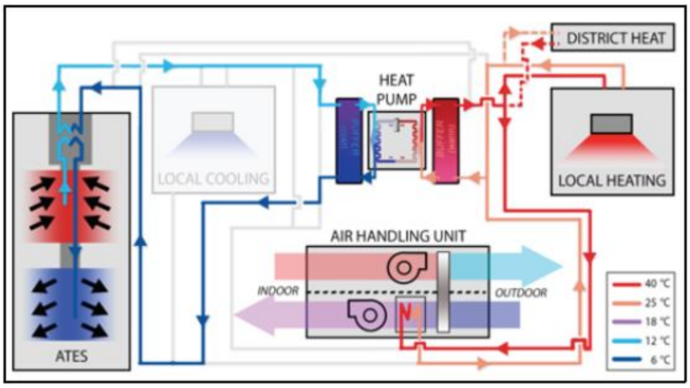
### Building system states

The states of the distribution network are defined by the buildings control software. This software is based on a technical description that describes how the system should operate. The model is constructed according to the states described in this original document. In reality there are some deviations between the original description and the actual software. These deviations are caused by bugs, manual overridden settings or faults in the implementation. This section introduces the states as they were intended in the original design. The tables below show the states during office hours and outside office hours.

***Building states during office hours (weekdays 6.00-21.00 hour)***

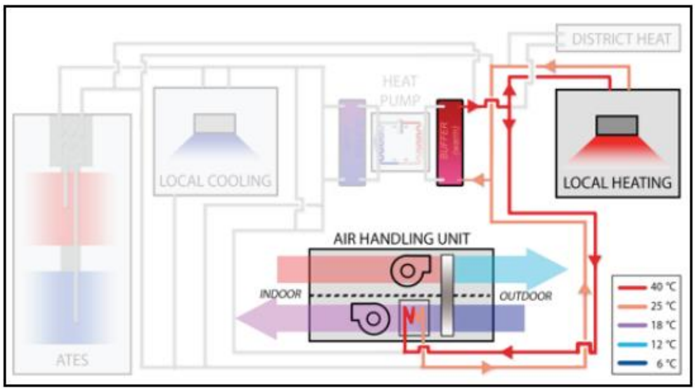
**State 1a. Only heating (estimated < 5 °C) - Heat pump active**

If the air temperature after the heat recovery wheel is lower than the required temperature according to the heating curve, additional central heating in the AHU is supplied. Chilled water produced by the heat pump is stored in the ATES system. When the heat pump cannot deliver enough heating capacity, the district heating supplies the needed additional heating power.



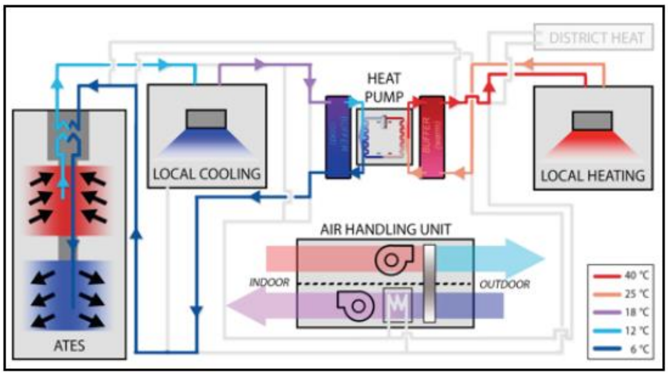
**State 1b. Only heating (estimated < 5 °C) - Heat pump inactive**

If the total heat load is lower than the heating capacity of the heat pump, the surplus of produced heat is stored in the buffer vessel. When the buffer vessel has reached the setpoint temperature, the heat pump and ATES are shut down. The heating load is supplied from the buffer vessel.



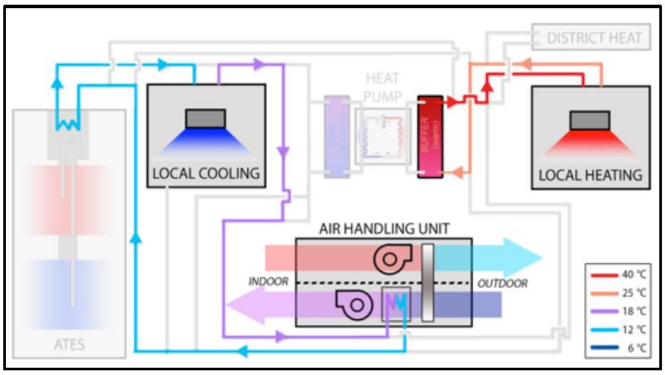
### State 2a. Redistribution of heat (estimated 5-13 °C) – Heat pump active

If no central heating is required, the supply water pump of the local cooling group is started. The water supplied to the heat pump is preheated by the local cooling. If in this state the local cooling demand is lower than the chilled water production by the heat pump, the surplus is of cold is stored in the ATES.



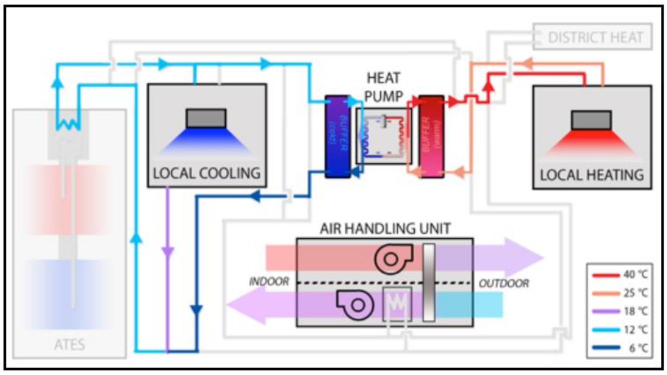
### State 2b. Redistribution of heat (estimated 5-13 °C) – Heat pump inactive

If the heated water buffer is filled, the heat pump is switched off and the local heating load is supplied by the buffer vessel. The return water from the local cooling system is transported to the AHU coil and used to preheat the air. The more heat supplied by the local cooling, less heat needs to be recovered by the heat recovery wheel.



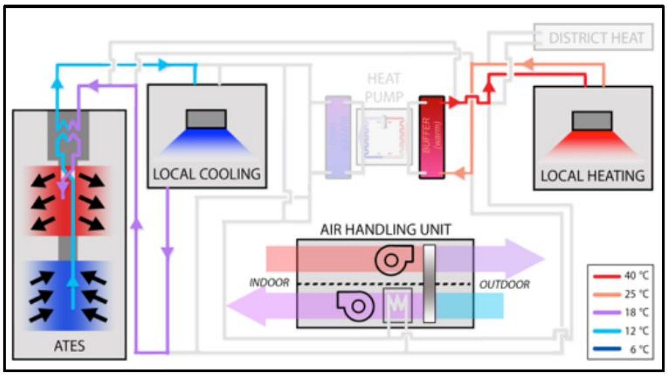
### State 3a. Redistribution and ATES cooling (estimated 13-17 °C) - Heat pump active

If the heat pump cooling capacity and the local cooling load are roughly equal, both return flows will mix to water with a temperature of roughly 12°C. Significant deviation are corrected by the ATES system. Between 13 and 17 °C the heating load is very low, so this state will not occur very frequently.



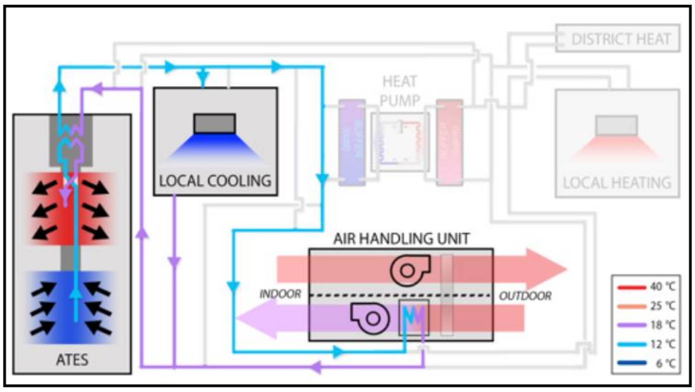
### State 3b. Redistribution and ATES cooling (estimated 13-17 °C) - Heat pump inactive

If the heat pump is not active, the ATES is used to provide the chilled water for the local cooling group. The heat load is supplied from the buffer vessel.



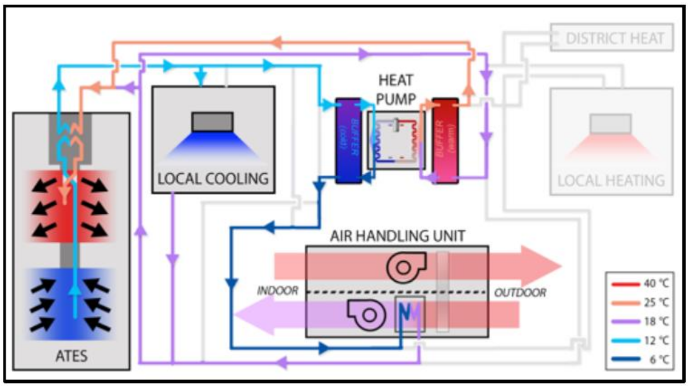
### State 4a. Full ATES cooling (estimated 17-25 °C) - Heat pump inactive

If central cooling is needed in the AHU (to reach the heating curve setpoint), the local heating system is turned off. Both central as local cooling are provided by the ATES system.



### State 4b. Full ATES cooling with additional heat pump cooling (estimated > 25 °C)

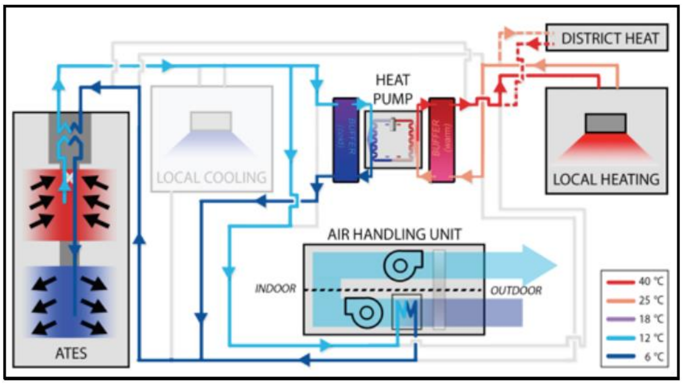
If the supply temperature of the ATES water is too high to reach the AHU heating curve setpoint, the heat pump is used to precool the water. The generated heat is transported to the return water from local and central cooling and is stored in the ATES.



## *Building states outside office hours (21.00-6.00 hours & weekends)*

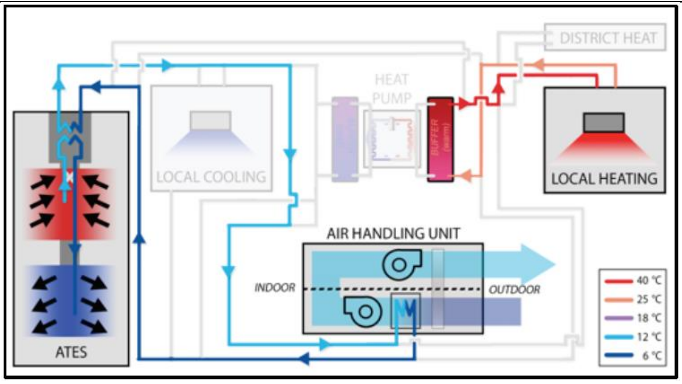
### State 1a. Regeneration of the ATES system (below 4°C) – Heat pump active

Depending on the setpoint to start regeneration (4°C) the bypass in the AHU is opened and the cold airflow is used to supply cold water to the ATES. Parallel to this flow the heat pump is used to supply heat to the building. The district heating is used if the heating load is higher than the maximal heat pump capacity.



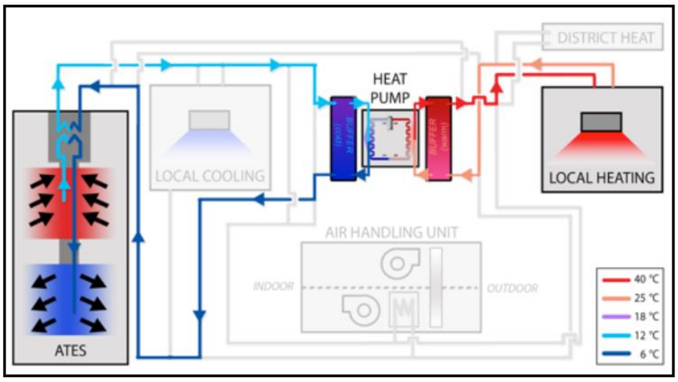
### State 1b. Regeneration of the ATES system (below 4°C) – Heat pump inactive

Same as above, but with heat pump inactive.



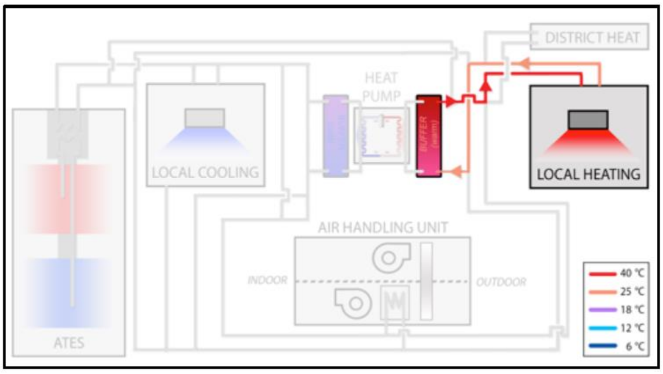
**State 2a. Only heating (4-15 °C) - Heat pump active**

Only local heating is active using the heat pump. Cold is stored in the ATES system. The rest of the system is inactive.



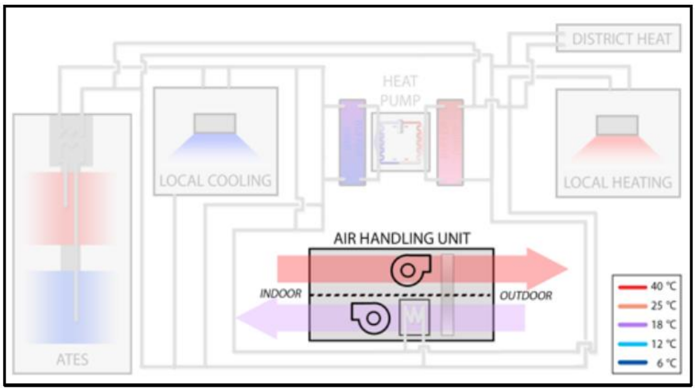
**State 2b. Only heating (4-15 °C) - Heat pump inactive**

Same as above, but with heat pump inactive. The heat is supplied from the buffer vessel and the rest of the system is inactive.



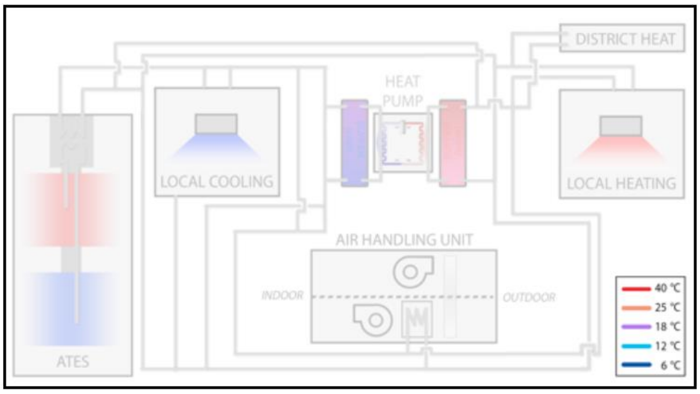
**State 3. Night-time cooling (15-23 °C)**

The colder outdoor air is used to cool down the building upon the average room temperature gets below a predefined temperature setpoint. When this setpoint is reached the AHU is turned off and the building is in rest (state 4). The behavior during this state is not important for ATES simulation, because both states do not directly influence the ATES system.



**State 4. Rest (>23 °C or when night-time cooling has cooled the building sufficiently)**

All systems inactive.



## Appendix III: boiler efficiency Kropman Breda

### Average energy efficiency

The average efficiency over a year (January-December 2014) is 90%. This efficiency is based on the average hourly return water temperatures when heating has been supplied by the boiler (figure III.1). It can be seen that in a large part, the return water temperature is above or hardly below the condensation temperature of the gas (± 57°C for Dutch gas). That means that the 'High-Efficiency' effect of the boiler is unused in a large period. Frequently turning on and off the boiler has also a negative impact on the average efficiency of the boiler. This effect is excluded in the defining of the average efficiency, which means that in practice, the average efficiency can be lower than 90%.

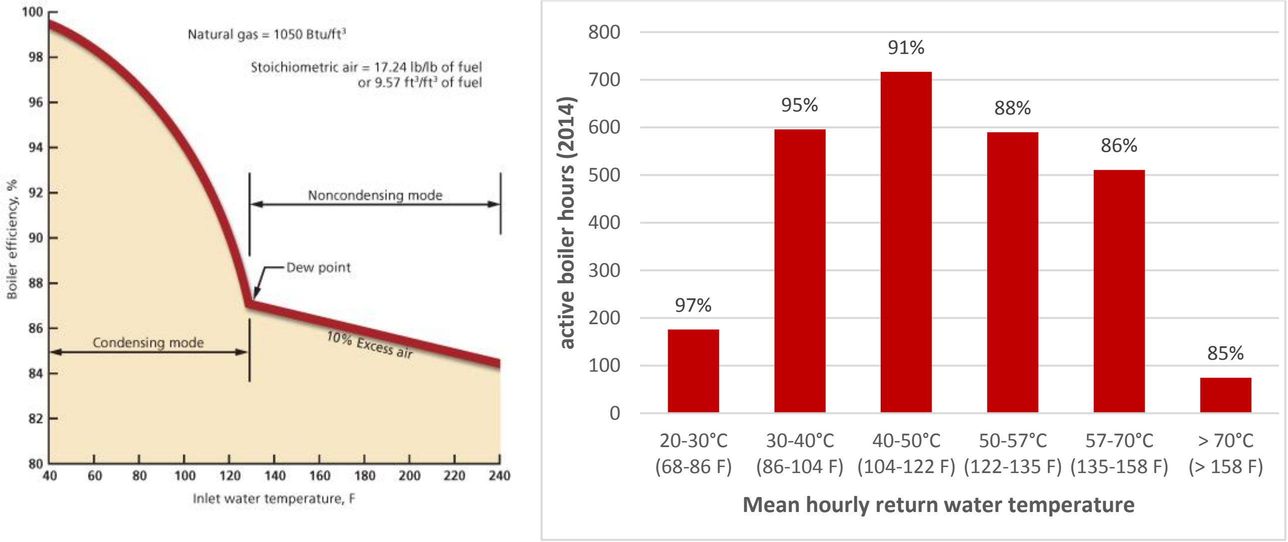


*Fig. III.1: indication of boiler efficiency in Kropman Breda, based on mean hourly return water temperatures.*

### Behavior of boiler efficiency

Figure III.2 shows the effect of the modified heating curve of the boiler on the supply water temperatures of the boiler. The figures shows average hourly outdoor temperatures and average hourly supply water temperatures. Only data is shown when heat is supplied by the boiler. The figure is based on the heating curve in table III.1

*Table III.1: heating curves boiler*

| *Current set heating curve radiator groups* | *Outdoor temperature [°C]* | *Supply water temperature* |
|---|---|---|
| | *-5 °C* | *90°C + 5°C offset for boiler* |
| | *20 °C* | *20°C + 5°C offset for boiler* |
| *Designed heating curve radiator groups* | *-10 °C* | *85°C +5°C offset for boiler* |
| | *20 °C* | *15°C + 5°C offset for boiler* |

Figure III.3 shows that the temperature difference between supply and return water temperatures is relatively small. Even with high supply temperatures, the average hourly temperature difference is between 5 and 10 °C. A small difference can lead to unstable control behavior, due the relatively low power demand. This effect has a negative impact on the efficiency of the boiler, but this effect is hard to quantify over a year. In figure III.4, an example of unstable control is shown from measured data of the boiler.

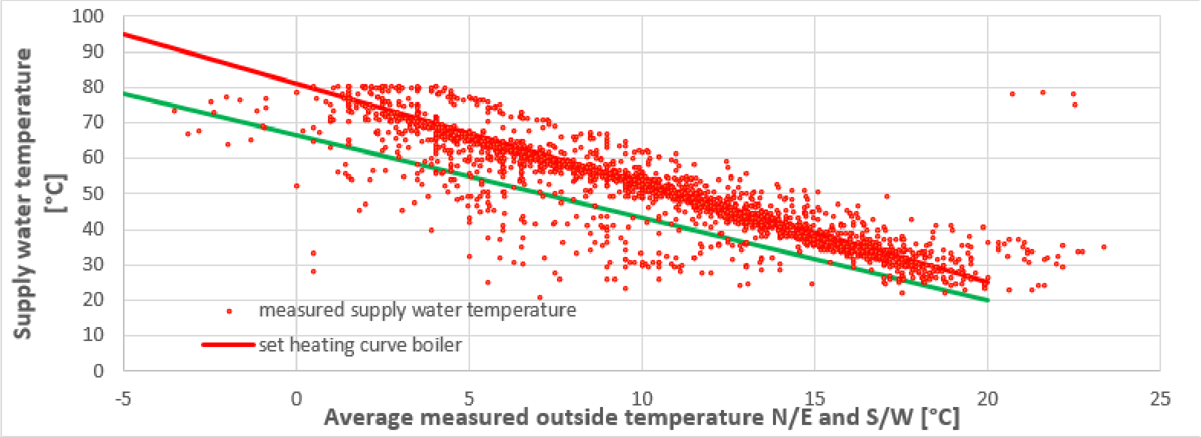


*Fig. III.2: Boiler supply water temperatures during active boiler hours, versus outside temperature (average hourly values).*

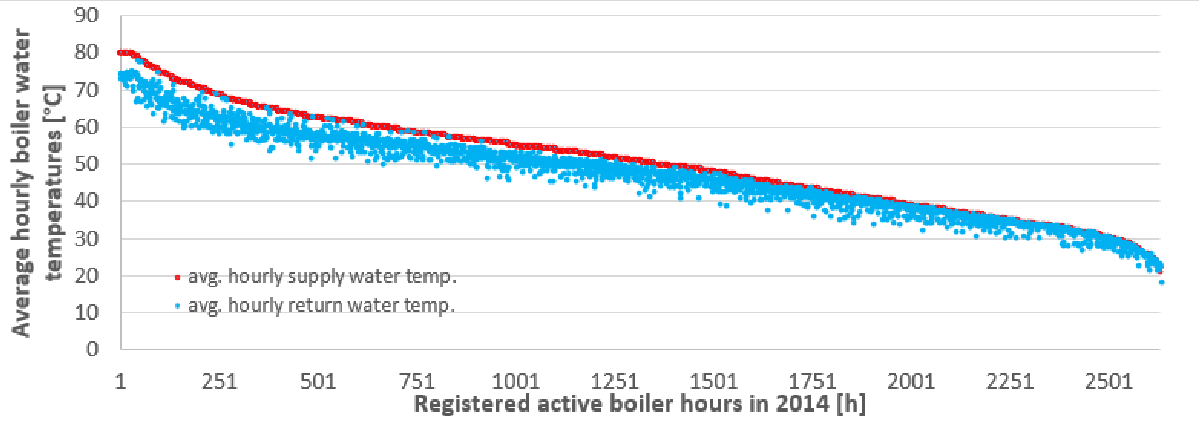


*Fig. III.3: Boiler supply and return water temperatures during active boiler hours (average hourly values).*

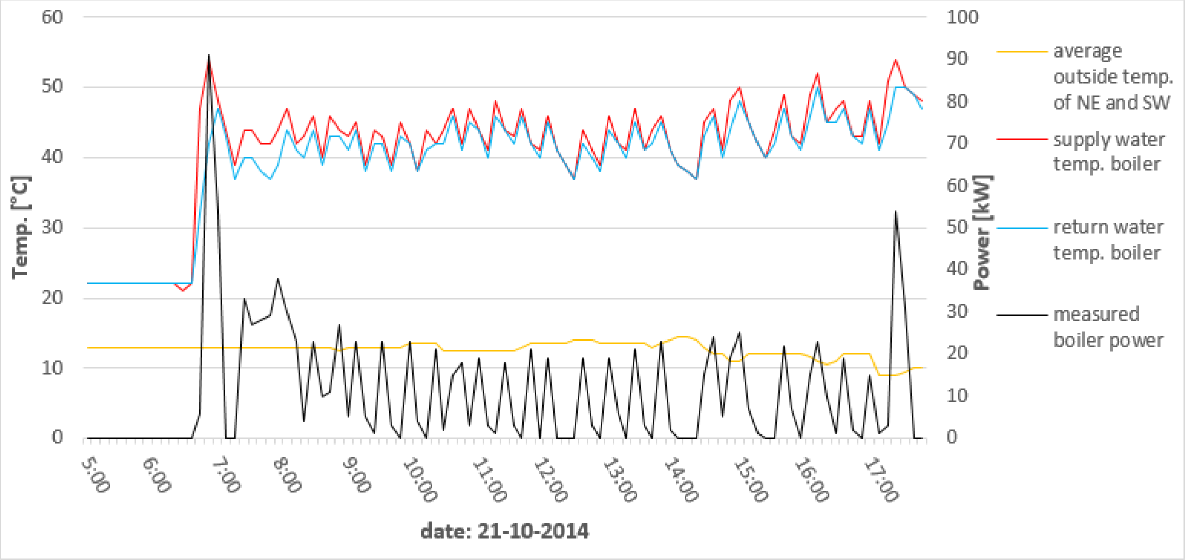


*Fig. III.4: Boiler supply and return water temperatures and the resulting measured boiler power.*