A comparison between the calibration of low-resolution and detailed FDD simulation tools in the post-design phase

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Award date:
2015

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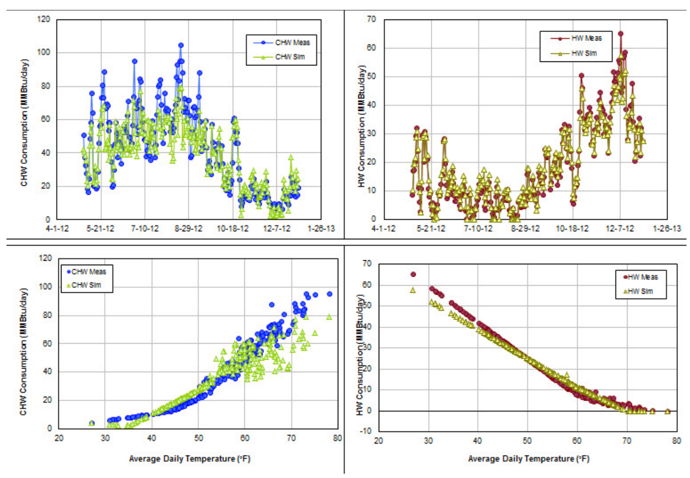

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NOMENCLATURE

ABCAT:	Automated Building Commissioning Analysis Tool
DFDD:	Dual Fan Dual Duct
DHW:	Domestic Hot Water
EP:	EnergyPlus
FDD:	Fault detection and Diagnosis
MBE:	Mean Bias Error
RMSE:	Root Mean Square Error
RMSE-CV:	Root Mean Square Error Coefficient of Variation
SDCV:	Single Duct Constant Volume
SDHC:	Single Duct Heating and Cooling = SDVAV
SDHR:	Single Duct Reheat = SDCV
SDVAV:	Single Duct Variable Volume

ABSTRACT

The purpose of this study is to investigate the differences between the calibration of a low-resolution tool and a FDD detailed tool that can be used in Fault Detection and Diagnosis (FDD). The low-resolution tool that is used is the Automated Building Commissioning Analysis Tool (ABCAT). The detailed tool that is used is EnergyPlus.

Literature review revealed building simulation tools that can be used in post-design phases. Based on insides of this literature review, a method has been drawn to compare the calibration tools. This method is tested using a case study. As case study the Spectrum building on the campus of the TU/e in Eindhoven is used.

Using the case study both tools were calibrated. The first results of the simulation showed that a detailed tool is more comparable to the measured data values. After the first simulation, the tools are calibrated with the aid of calibration and characteristic signatures. Finally, the tools were compared to each other. Results showed that low-resolution tools will not only reduce the time to calibrate, but also have a better RMSE and MBE value. In future research the calibrated files can be used for the FDD for the years after 2012.

1. INTRODUCTION

1.1 Motivation

Experience has shown that U.S. buildings on average may consume 20% more energy than required for occupant comfort [1]. Existing building commissioning has shown to be a useful method for reducing the amount of wasted energy in existing buildings. The average energy savings have been reported at levels greater than 20% [1]. In the research of Bynum [1] it is not mentioned if commissioning tools can be used for buildings with more innovative systems in the Netherlands. A question that can be asked is: What is 'innovative'? Generally speaking 'innovative' means: (Of a product, idea, etc.) featuring new methods; advanced and original; introducing new ideas; original and creative in thinking [2]. In this research the description of an innovative building is a building that differs from the systems that normally are used in the tools, just as SDCV, SDVAV etc.

1.2 Project description / problem definition

Usually during the design process the energy use of the building is simulated using different simulation tools., currently the role of simulation in the post-design phase is negligible [3]. When the measurements and predictions of the energy performance in the design phase are compared, differences of 50% are not uncommon[3]. The averages of the measured performances and the predictions are comparable, but there is a wide range in data.

This research focuses on the calibration of currently available tools for performance monitoring, fault detection and diagnosis (FDD) for whole building analysis. At this moment tools are available for performance monitoring and fault detection and diagnosis (FDD) for whole building analysis. This research will focus on the calibration of these tools. FDD tools are used for different standard, conventional buildings in the United States [4]. It provides information about energy performance, but lack information about comfort performances. Nowadays FDD tools offer limited capabilities to innovative building and system solutions. Innovative buildings rarely perform as predicted in the design, so a support tool for operation and management of more innovative buildings is required.

The major problem is the reference model which will be used for the prediction of the performance of the building. A solution for the problem is to use modeling and simulation for the predications of the case. The use of such models raises the issue of calibration.

For modeling and simulation low-resolution and detailed tools can be used. In this research a low-resolution tool (Automated Building Commissioning Analysis Tool (ABCAT)) and a detailed tool (Building Performance Simulations (BPS) tools) will be used for the prediction of faults. A case study will be used to compare the results of the simulations with the low-resolution and detailed tool and the real numbers.

As illustrated in Figure 1 two types of Fault Detection and models can be distinguished: Model-based and Data driven. In this research the focus will be on Model-driven Fault Detection and Diagnosis. The Model-driven FDD can be divided in a low-resolution and detailed category. This research will focus on the model driven part of the scheme.

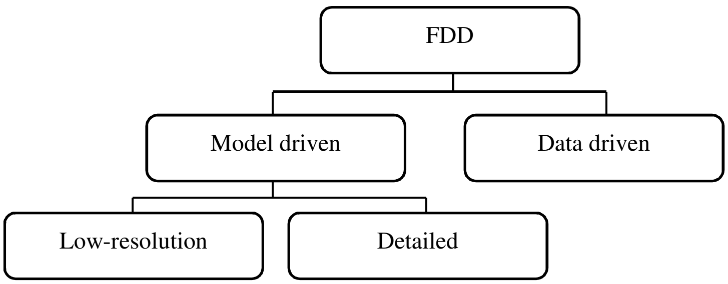

Figure 1 Types of models for Fault Detection and Diagnosis

1.3 Goal

The aim of this research is to make a comparison between the calibration of a low-resolution and a detailed tool, used for Fault Detection and Diagnosis.

On the one hand it is expected that the low-resolution tool will provide limited information and results. Only information on whole building level is given, making it difficult to appoint the exact fault.

On the other hand it is expected that the use of the detailed tool is a time consuming and thus expensive process. Due to the large number of inputs, calibration is difficult and results in an expected overwhelming number of outputs.

It is expected that the optimal solution is a combination of low-resolution and detailed tools.

1.4 Commissioning

Existing building commissioning is a useful method for reducing the amount of wasted energy. The reason why to commission is understanding why buildings and their systems are changed or will change. Some of those changes are common for all types of commissioning: improved system performance, energy savings, improved thermal comfort, extended equipment life and reduced warranty claims, increased occupant comfort, safety, productivity, decreased testing, adjusting, and balancing costs [5].

Four types of commissioning can be distinguished: Initial Commissioning (Cx), retro-commissioning (RCx), recommissioning and continuous commissioning [5], as illustrated in
Figure 2.

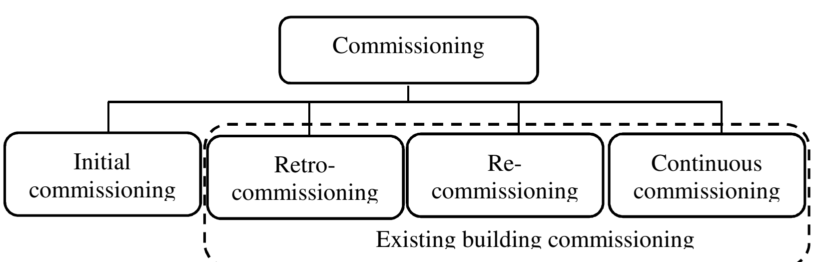

Figure 2 Four types of Commissioning

Initial Commissioning (Cx) is a process to verify and document that building systems meet the needs of the building operators [6]. The National Conference on Building Commissioning established an official definition of ‘Total Building Commissioning’ as follows: “Systematic process of assuring by verification and documentation, from the design phase to a minimum of one year after construction, that all facility systems perform interactively in accordance with the design documentation and intent, and in accordance with the owner’s operational need, including preparation of operation personnel” [7].

Retro-commissioning (RCx) is often used in older facilities that have never been through a commissioning process. Recommissioning is ideal to tune up buildings that have already been commissioned, bring them back to their original design intents and operating/energy efficiency.
Continuous commissioning commonly used in facilities with building automation systems (BAS), advanced metering systems, and advances organizations [5].

1.5 Fault detection and diagnosis

Fault detection and diagnostics (FDD) may be described as the process of establishing normal operating levels for measured parameters, monitoring these parameters to determine if the value exceeds established tolerances, and ascertaining the focus and cause of the fault [1]. To diagnose faults, simulation tools will be used. FDD develops calibrated simulation, it compares the simulated and measured energy consumption. If a significant difference is shown between the simulated and measured energy consumption the system should be investigated. [3]

Currently, the key barriers/challenges that have prevented energy diagnostics from being pervasively applied are [8]:

1. An integrated whole building energy FDD system does not exist.
2. Existing FDD methods are based on available data and simple, ad-hoc rules that do not adequately capture either the component or system functional and behavioral interactions.
3. Existing FDD methods, which are currently an ‘after thought’ add-on to building control systems, require manual intervention and labor-intensive analysis.
4. Most of the existing FDD systems to perform energy diagnostics are not scalable because they rely on manipulation of data by a limited number of experts which makes the scalability of the existing process to the entire industry infeasible.

1.4.1 Performance vs. predictions

At this moment most of the buildings have been simulated during the design phase, the actual performance is unknown. In the future feedback will be given, so the building predictions and actual performance can be compared.

The differences between the results of the prediction and the measurement can be up to 50%. On average the prediction and the real performance are comparable; there is a wide range in data. There are some causes for these differences: equipment failure, sub-optimal controls and prediction errors. Differences can be reduced by improving the prediction capability or use calibrated simulations for commissioning.[3]

A difference is not always a fault in the system, therefore another word is used for this difference: an 'anomaly' [9]. The difference between expected and realize energy performance has come to be known as the 'performance gap'[10].

2. LITERATURE REVIEW

2.1 Building performance simulation

Two types of models for FDD can be distinguished, namely data driven and model driven. The data driven models are also named 'black box' and empirically relate the model inputs to the model outputs. This research focused on the model driven part of the FDD.

Model based FDD can be distinguished in low-resolution and detailed models. The low-resolution model can be classified as a first principle driven method. The first principle models are also named 'white box' methods and are based on the fundamental physical relationships involved. The low-resolution models based on first principle analysis, like the Simplified Energy Analysis Procedure (SEAP) developed by Knebel [11], require less input and as a result are easier to calibrate. The low number of input will keep the data traffic and processing manageable [12]. This low-resolution model focusses on the whole building level. On the other hand the more sophisticated (detailed) model requires a large number of input and as a result are often difficult to calibrate [1].

In this research the differences between a low-resolution and a detailed tool will be investigated. In
Table 2, Table 3 and Table 1 the advantages and disadvantages of low-resolution and detailed models are summarized.

Table 1 Advantages and disadvantages of low-resolution and detailed models for FDD

Low-resolution models	Detailed models
Less costs	More costs
Small number of inputs	Large number of inputs
Easier to calibrate	More difficult to calibrate
Less accurate	More accurate

The low-resolution tool (such as ABCAT) requires input like weather data and simplified design parameters. The detailed tool (such as EnergyPlus) needs more detailed design parameters. The time resolution for the low-resolution tools is hourly, and for the detailed tools it is possible to choose for a sub-hourly time resolution. In Table 3 the summary for the benchmarking methods for the low-resolution and detailed tools is designated.

Detailed simulation methods are probably the most widely used method for energy estimation in design stage. Due to the comprehensiveness and wide acceptability, they are often used as a comparison case when testing new benchmarking methods. Researchers have shown that low-resolution methods can perform as an effective detailed simulation method in many energy benchmarking purposes. Developers of ABCAT have shown that modified bin method results in satisfactorily for energy benchmarking purpose in testing cases. [13]

In the research of Li, Han and Xu [13] a comparison between the modified bin method (low-resolution) and detailed energy simulation was performed. As expected the modeler experience should be higher for the detailed energy simulation and the calibration effort is also higher. The summery of the comparison is shown in Table 1. Please note that this is a comparison for the tools in the design stage and not for FDD tools.

Table 2 Summary of energy benchmarking models

Method	Input	Time resolution level	Application	Tool
Modified bin method	Weather data, simplified building design parameter	Hourly	Fault detection	ABCAT
Detailed simulation	Weather data, detailed building design parameters	Sub-hourly	Fault detection, monthly utility bill split, retrofit analysis, load prediction	EnergyPlus, Esp-r, DOE-2.1E, etc.

Table 3 Comparison between different benchmarking methods [13]

Method	Quantity of input data requirement	Modeler experience requirement	Calibration effort requirement	Quantity of training data requirement
Modified bin method	Medium	Medium (familiar with building physics)	Medium (relatively more parameters)	Medium

Detailed energy simulation	High	High (familiar with building physics and the particular software)	High (most parameters)	Low

A question that can be asked and is also important in this research in this research is: When should you use a low-resolution or a detailed tool? InAttachment 1 a flow chart has been proposed to help the modeler choose a proper benchmarking method. [13]. In this research detailed information of the building is available, so a white box method (left side of scheme) should be chosen.

It has been discovered that many methods, although simple, can achieve satisfactory performance. Choosing a proper method should be based on project requirement, available inputs, available monitoring data, and the modeler's experience.

2.1.1 Low-resolution tools

As mentioned in the previous paragraph the low-resolution tool gives information about the whole building's level of energy consumption. Three tools have seen significant development and testing: Performance And Continuous Re-Commissioning Analysis Tool (PARCAT) developed by Facility Dynamics Engineering, the Whole Building Diagnostician (WBD) developed under the guidance of the Pacific Northwest National Laboratory, and ABCAT developed at Texas A&M University. The tools PARCAT and WBD use a multiple variable bin method to predict energy consumption, a 'black box' method. One limitation is the large amount of data required to create the baseline using this approach in order to produce meaningful results. Another limitation of this approach is the inability of the model to predict consumption for conditions beyond the extent of that in the baseline data. Another option is ABCAT, which is unique in that it relies on a calibrated first principle based mathematical model, a 'white box' method, to predict the energy consumption under given weather conditions [1].

2.1.1.1 Introduction of ABCAT

As mentioned before an example of a FDD tool is ABCAT, which is based on the SEAP of Knebel [11]. This tool is a Microsoft Excel based tool, with multiple worksheets, chart sheets, and unique macros. A print screen of the tool is shown in Attachment 2.

The tool is 'white box', which means that it is based on the first principle and is very simple.

The whole building ABCAT tool requires the use of only three sensors: whole building electricity, whole building heating, and whole building cooling [1]. The low number of sensors helps achieve the tool's goals of being a cost effective and low-resolution alternative to the more complex systems. In Figure 3 a simplified scheme of metering positions in the ABCAT tool is shown.

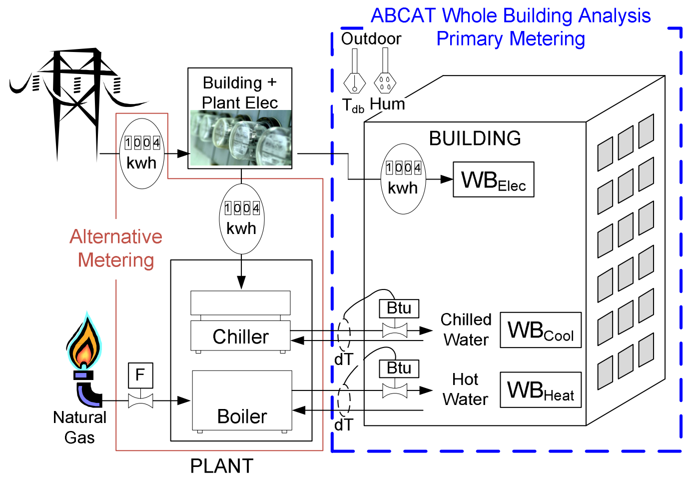

Figure 3 Consumption metering requirements for ABCAT

2.1.1.2 Systems in ABCAT

Four system types are currently available to simulate in ABCAT. These include SDRH (Single Duct Reheat = SDCV), SDHC (Single Duct heating and Cooling = SDVAV), DFDD (Dual Fan Dual Duct), and Dual duct [4]. Figures of the systems are shown in Attachment 3.

As can be seen there are more (innovative) systems that should be implemented in ABCAT. In this research the methods how to implement innovative systems in ABCAT will be investigated. Examples of sustainable systems that can't be put in the tool are floor heating/cooling, concrete core conditioning, climate ceiling, low temperature radiator, chilled beam, fan coil systems, induction units, displacement ventilation and hybrid ventilation [14].

2.1.2 Detailed tools

As mentioned in the introduction BPS tools will be used for simulations to predict the energy consumption of the building. These tools can give more accurate information, but need more inputs. Also this system is more difficult to calibrate.

There is a wide range of detailed tools that can be used. In the publication of Crawley [15] 20 BPS tools are compared for different capabilities. The publication of Attia [16] shows a comparison between ten tools, for example Design Builder, EnergyPlus, EQuest, DOE-2 etc.

2.1.2.1 EnergyPlus

As mentioned in the previous paragraph a comparison of BPS tools is found in the publication of Attia [16]. One of the best options to use as a BPS tool, according to engineers, is EnergyPlus. The best option was Design Builder, which is an interface for EnergyPlus.

According to Attia [16] EnergyPlus is the most accurate state of the art BPS tool that provides detailed and complex simulation capabilities. The strength of EnergyPlus lays in its transparency and various simulation capabilities including modular systems simulation and heat balance-based zone simulation. The tool also allows data exchange and facilitate third party interface development. [16]

In this research another interface is also used, namely OpenStudio, which makes EnergyPlus more user-friendly.

2.2 Previous research

The ABCAT tool is used for the calculation of the energy performance for different buildings. The buildings can be found on different locations around the world. ABCAT is used for the Sbisa Dining Hall in College Station Texas, Computing Services Building in Austin Texas [4], Bush Academic Building in College Station Texas, Gibb Gilchrist Building in College Station Texas and Koldus Building in College Station Texas [17]. ABCAT is also used for the prediction of the energy use for the Vertigo Building on the TU/e Campus in Eindhoven [9] and the Strukton Building in Maarssen, both in the Netherlands [18][12]. In the testing of Bynum [1], the ABCAT tool was used to successfully identify 24 significant energy consumption deviations in 5 retrospective applications and 5 significant energy consumption deviations in 4 live applications.

3. METHODS

3.1 In general

The aim for this research will be: Make a comparison between the calibration of low-resolution and detailed simulation tools in the post-design phase to provide recommendations for future development of FDD tools in buildings.

The results of a simple (ABCAT) and a detailed (BPS tool) simulation will be compared. The measured data will be provided by the Dienst Huisvesting (Real Estate Management and Development) and will be used for calibration of both low-resolution and detailed models. The capabilities of both approaches will be compared. Based on the comparison recommendations for future developments will be defined.

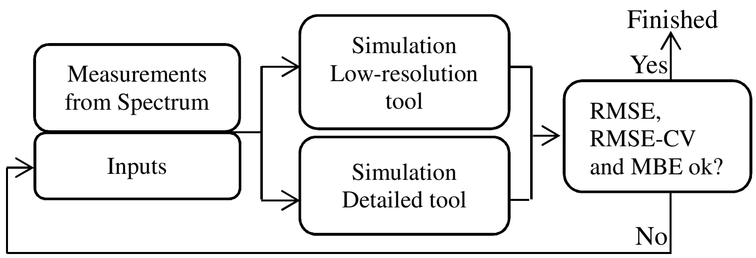

Figure 4 Scheme of the method of this project

Figure 4 shows a scheme of the method for this project. As mentioned the research starts with measurements. Together with the inputs a first simulation can be made. The results of the simulation can be the same as the measurement data. In that case the tool is calibrated.

It is expected that the outcome of the simulation is not aligned with the measurements, so the tool should be calibrated again. This calibration is done by changes in the inputs. This 'circle' will be going on, until the simulation is calibrated.

After the calibration the challenges in the processes will be compared. This way the calibration differences between the calibrations of the low-resolution and detailed tool can be demonstrated.

To evaluate the calibration of the simulations correctly, performance indicators are used. A performance indicator is a property of a product, building component or building, which closely reflects or characterizes its performance (state or progress towards an objective) in relation to the performance requirement that has been set. The indicator should be a quantitative, qualitative or descriptive parameter that can be readily assessed [19].

3.2 Case Study

In the project description the Spectrum Building was appointed to be the case building. The building was built in 2002 and has a gross floor area of 7200 m2. A picture of Spectrum is shown in Figure 5. The building consists of 3 floors, two with the same size and one floor with a smaller surface area. The floor plans for this building are shown in Attachment 4.

Spectrum makes use of the Aquifer Thermal Energy Storage (ATES) of the campus of the TU/e. This ATES is used for the heating and cooling of the building. The other source for heating is gas. Remarkable is that the majority of the gas comes from the Cascade building. All the energy uses for aquifer, gas and electricity are measured and will be discussed in the next chapter. At this moment no heat pumps are used in the building [21]. The drawings for the hot water and chilled water system are shown in Attachment 5.

Figure 5 Picture of the building Spectrum on the campus of the TU/e

3.2.1 Data analysis

As shown in Figure 4 measurement data will be used to compare with the results of the simulation with the low-resolution and detailed tool. This way the differences in prediction and real performance are shown.

The data of the Real Estate management (Dienst Huisvesting) of the TU/e consist of hourly measurement energy data for: warm and cold aquifer [kWh], gas use [m3], gas use from Cascade [m3], and electricity use [kWh]. A part of the electricity use is used for the cooling chiller. The electricity is measured at four different places. One of these places measures the heat but also others, like elevators and busbars.

For the low-resolution tool daily data is needed. The measured data is averaged per day and is copied in the ABCAT tool, so the differences between simulated and measured are calculated by the tool itself.

In the detailed tool no comparator has been included, so a new Excel file is generated to compare the measurement data and results of the simulations. For the detailed tool, the simulated hourly data are converted into daily data and compared with the daily data of the Real Estate Management.

Remarkable is that the data for heating and cooling are very high compared to reference buildings, which is shown in Table 4.

Table 4 Reference data for heating and cooling energy consumption

	Heating [kWh/m2.a]	Cooling [kWh/m2.a]
Measured	378.0	488.8
DOE1*	35.9	26.8

*Results of the DOE data bank: Energy use for universities, same climate and approximately the same gross floor area [20].

3.2.1 Charts of measured data of Spectrum

With the available data graphs are made. The axes show the temperature and the energy consumption. The graphs are made for the warm and cold aquifer, gas use, and electricity use. Some examples are shown in Figure 6, the charts for electricity and warm aquifer are shown in attachment 6. Remarkable is that some of the charts are not one cloud, but consist of two parts. In the next paragraph the graphs that consist of two parts are separated. The complete overview of charts is shown in Attachment 6.

As shown in Figure 6 the gas use will not have a zero value, not even when the temperatures are very high. The chart for the gas use shows a constant use at some point. This part is assumed to be for the domestic hot water and is removed from the data for heating. The next paragraph will explain which part of the chart is removed for the simulations.

The total energy consumption for heating is calculated by adding the gas use (converted into kWh) and warm aquifer. The total cooling energy is calculated by adding the aquifer cold, and electricity for the chiller multiplied by the COP.

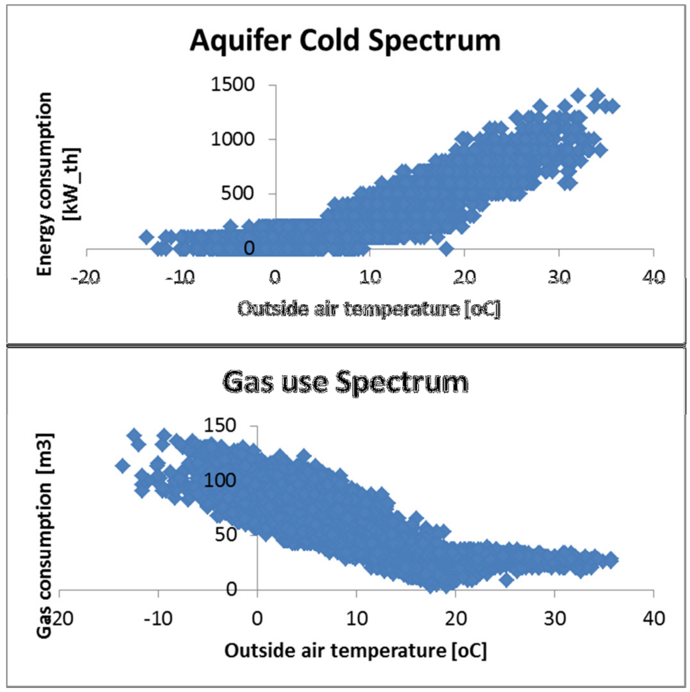

Figure 6 Charts of the measured energy consumption for the cold aquifer and for the gas use in 2012

3.2.2 Trend lines of the charts of measured data

As mentioned in the previous paragraph some of the charts are separated. In Figure 7 some examples are shown. The advantage of these graphs is that the two different trend lines can be used to fill the missing data points. The temperature can be filled in in the trend line equation and an energy consumption value is given.

The previous paragraph mentioned that it will be assumed that the gas use for higher values will be used for the heating of domestic water. The trend line for the temperatures higher than the intersection point shows a relatively straight line just above 26 m^3. This number is assumed to be the gas use for the heating of the dhw. The dhw part of the data is not included in the simulations (not possible in ABCAT).

3.2.2.1. Uncertainties

In the Year Report for Energy Consumption ('Jaarverslag TU/e') numbers for the energy use for the different aspects are given [21]. These numbers are compared with the total of the hourly measured data. The total energy consumption for electricity, warm and hot aquifer are comparable (in the range of sigma = 1). Remarkable is the difference for the gas use. In the Year Report this difference is also mentioned. The reason for this difference is the way of calculating the total by the energy supplier. They use a correction for the data for temperature and pressure, so an addition of the data can be made. Other reasons are the uncalibrated and old meters. [21]

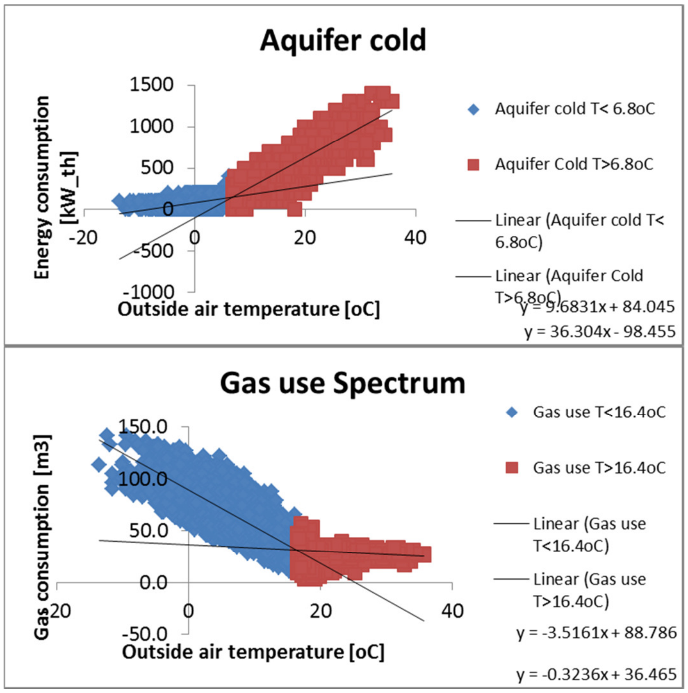

Figure 7 Change-point charts for the cold aquifer and gas use

3.3 Simulation tools

As mentioned BPS tools can be used for FDD, like a low-resolution tool as ABCAT and a detailed tool as EnergyPlus. In this paragraph the methods to use these tools for FDD are shown.

3.3.1 Low-resolution

In this research the tool ABCAT will be used as a low-resolution tool for FDD. The ABCAT tool requires simple inputs. The inputs for this research are shown in Table 5. To calculate the solar transmission another file was needed, this was not as simple as expected for a low-resolution tool. The temperature was found in the data of the KNMI [22]. Remark: The units that are used in the table are US-units, because this should be put in the (US) tool.

Table 5 Inputs for the low-resolution tool (ABCAT)

System	Single Duct VAV
Total floor area	5745 m^2
Thermal mass definitions (SWR)	415 kg/m^2
Cooling coil set point temperature schedule	Tset1:16°c, T1:16°C, Tset2:13°C, T2:27°C
Heating coil set point temperature schedule	Tset1:43°C, T1:5°C, Tset2:32°C, T2:16°C
Occupancy schedules	Week day: 8:00-18:00, Weekend: 12:00-16:00
HVAC schedules	0:00-24:00
Volumetric flow rates	1.24 (l/s)/m^2
U-value walls	3.00 m^2.K/W
U-value windows	1.5 W/m^2.K
Solar transmission	q-Jan: 0.0085 kW, q-July: 0.0158 kW/hr
Weather data	Temperature

3.3.2 Detailed

EnergyPlus will be used as the detailed tool that can be used for FDD. This tool requires, as expected, more detailed inputs. The inputs for this research are shown in Table 6. For this tool an epw-weather file should also be imported. For Eindhoven there was no epw-weather file available. As starting point the epw-weather file for Beek has been used. This csv-file is opened in Excel, whereupon the known parameters of Eindhoven according to the KNMI [22] are put in.

Table 6 Inputs for the detailed tool (EnergyPlus)

System	Single Duct VAV
Floor area and materials	As drawings
Cooling coil set point temperature schedule	Auto size
Heating coil set point temperature schedule	Auto size
Occupancy schedules	Week day: 8:00-18:00, Weekend: 12:00-16:00
HVAC schedules	0:00-24:00
Volumetric flow rates	3 ACH (auto size)
R_c-value walls	3.00 m^2.K/W
U-value windows	1.5 W/m^2.K
Weather data	Weather file Eindhoven

3.4 Calibration of the models

When the (assumed) inputs are imported in the tool, the simulation will give energy consumption numbers as an output, which can differ from the measured data. The tools should be calibrated. To get a good calibrated tool, the period from the 1st of May 2012 until the end of 2012 is used for calibration. The year 2013 can be used for the FDD part of the research. During this graduation project there was not enough time to simulate also for this year. More information will be given in the chapter about 'further research'.

In an earlier research at the TU/e a schematic overview for the calibration process for ABCAT is created [12]. This overview is shown in Figure 8. The method of this scheme can be found in the book *Building Performance Simulation Design Operation* of Jan Hensen [23].

The first step of the calibration is to simulate the calibration period (05-01-12 – 12-31-12). The result of this simulation should be compared with the measurement data. If the result are comparable the tool can be used, if not the tool should be calibrated again.

In Figure 8 the *Calibration signature* and *Characteristic signature* are mentioned. These signatures will be used to see what parameter should be adjusted to get a calibrated simulation. The way of calculating the calibration and characteristic signature is shown in Equation 1 [24].

In some situations, when the weather is comparable to the weather location in the manual, the characteristic signatures in the manual can be used.

The weather in Eindhoven is not comparable to the climate in Passadena, Sacramento or Oakland, so new characteristic signatures should be made. These signatures are made for both the low-resolution and detailed tool.

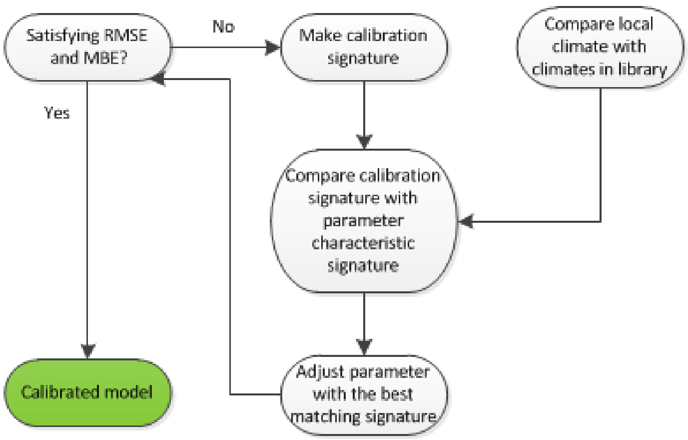

Figure 8 Schematic overview of the calibration process for ABCAT. All steps in this overview are treated in more detail in the text [22]

$$\text{Calibration signature} = \frac{-\text{Residual}}{\text{Maximum measured energy}} \times 100\,\%$$

$$\text{Residual} = \text{Simulated consumption} - \text{Measured consumption}$$

$$\text{Characteristic signature} = \frac{\text{Change in energy consumption}}{\text{Maximum energy consumption}} \times 100\,\%$$

Equation 1 Equation to calculate the Calibration Signature and Characteristic Signature [24]

To compare the results the RMSE, RMSE and MBE are calculated. According to Claridge [24] the RMSE preferred lies between 5 and 10 MMBtu/day (1465-2930 kWh/day, the MBE is preferred to have a number as low as possible. The equations for the RMSE and MBE are shown in Equation 2.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} Residual_i^2}{n-2}} \qquad MBE = \frac{\sum_{i=1}^{n} Residual_i}{n}$$

Equation 2 Formulas to calculate the RMSE and MBE

Claridge [24] mentioned that simulation with a small RMSE and a high MBE might indicate an error in the simulation inputs. When the simulation has a large RMSE, but a small MBE it indicates that there are no errors in simulation inputs.

4 RESULTS

4.1 Calibration of ABCAT

The way of calibrating the ABCAT tool is described in Figure 8. First is a baseline simulation performed with some assumptions. The inputs for this simulation are shown in Table 5. The results for this simulation are shown in Figure 9. This chart shows that the heating part of the simulation is comparable for the warmer periods. In the winter situation there is a difference of a factor two. In the upper charts in this figure, the energy consumption during the year is shown. The figure left above shows in blue the measured energy, and in green the simulated energy. The above chart on the right shows in red the measured heating energy and in yellow the simulated one. The charts below show the energy consumption in comparison with the temperature. The temperature is shown on the x-axes. A larger version of this figure is shown in Attachment 7.

For the cooling situation the differences are bigger. Only for the colder temperatures the measurements and simulation are comparable. For the warmer periods the measured cooling consumption can be a factor 25 higher.

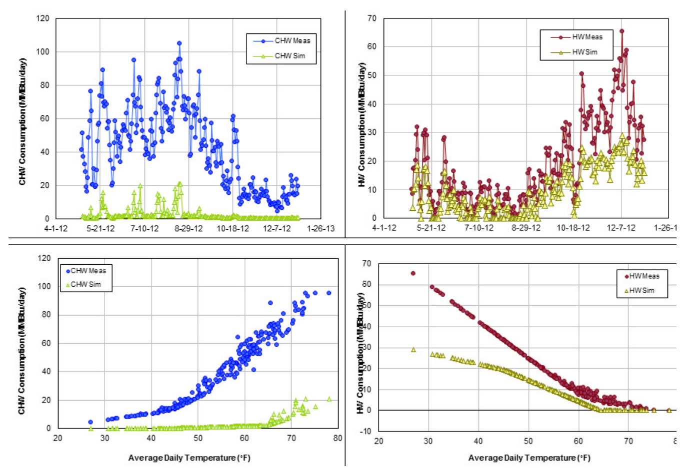

Figure 9 Result of the baseline simulation.

First the calibration signature for this situation is calculated. In Figure 10 this calibration signature is shown. This calibration signature should be zero when the measured data and the simulated numbers are the same. In this situation the simulated heating energy is for the lower temperatures too low. For the higher temperatures the simulated cooling energy is too low.

To calibrate the simulation some of the inputs can or should be changed. The '*Manual of procedures for calibrating simulations of building systems*' [24] gives a guideline for changeable inputs that has been found to be of major importance in calibrating a simulation. For these inputs characteristic signature are calculated. Two examples are shown in Figure 11. The rest of the characteristic signatures are shown in Attachment 9.

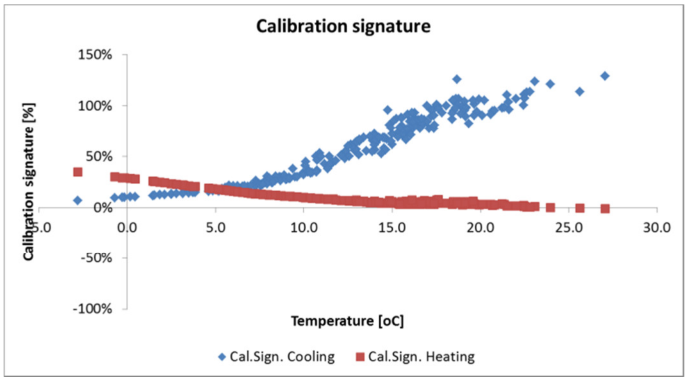

Figure 10 Calibration signature for the low-resolution tool (ABCAT). A larger figure is shown in Attachment 8.

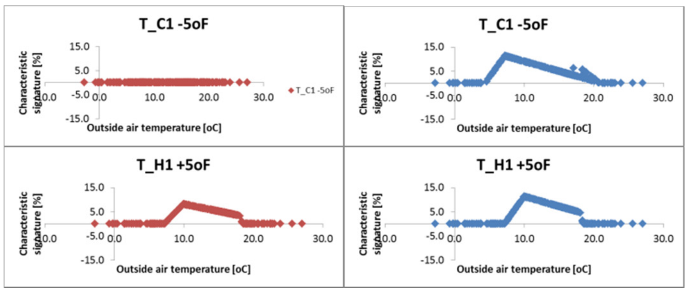

Figure 11 Characteristic signature [in %] when coil set point temperatures are changed. In red the characteristic signatures for heating, the blue lines are for cooling. On the x-ases the temperature [in ºC] is shown.

The characteristic signatures of Figure 11 show the influence when a parameter is changed. The most influencing parameters according to the signatures are the flow rates and the coil set point temperatures. The other parameters are not influencing the result very much.

The found parameters are changed and the calibration signature was calculated again, until the RMSE is acceptable according to the preferred RMSE. In Table 7 the calculated RMSE, RMSE-CV and MBE are shown. The result after the calibration of ABCAT in charts is shown in Figure 12.

Figure 8 shows the method for this research project. In this paragraph the results of the simulations are shown and the figures and tables have shown the way of calibrating the tool.

Table 7 RMSE, RMSE-CV and MBE for the ABCAT simulations

	RMSE [kWh/day]	RMSE-CV [%]	MBE [MMBtu/day]
Base cooling	13070	107.0 %	-39.1
Base heating	3282	27.0 %	-9.0
Calibrated cooling	3106	25.5 %	-3.2
Calibrated heating	645	5.3 %	0.09

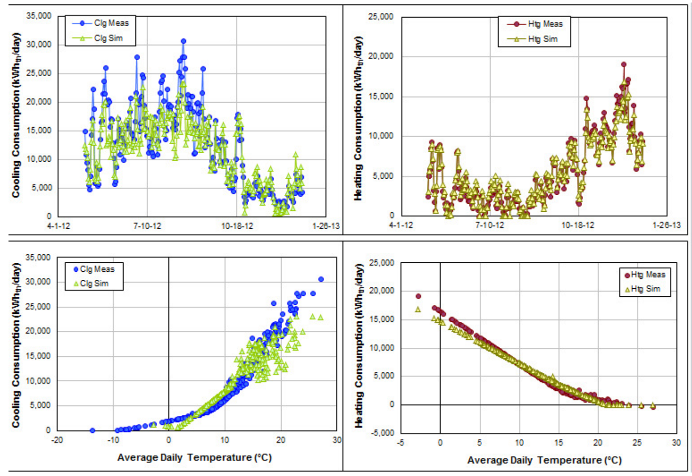

Figure 12 Results of the calibrated simulation of ABCAT: A larger figure is shown in Attachment 10.

4.2 Calibration of EnergyPlus

The calibration phase for EnergyPlus starts also with a baseline simulation. The (assumed) inputs of Table 6 are put in the simulation. The results for the first simulation are shown in Figure 13. This figure is made in Excel, because in the EnergyPlus tool the output is a numerical csv-file. The numbers of these files are copied to Excel, averaged to daily numbers and placed in a chart. Averaging to daily numbers is recommended according to Claridge [24]. It is also possible to use the hourly number if the researcher prefers.

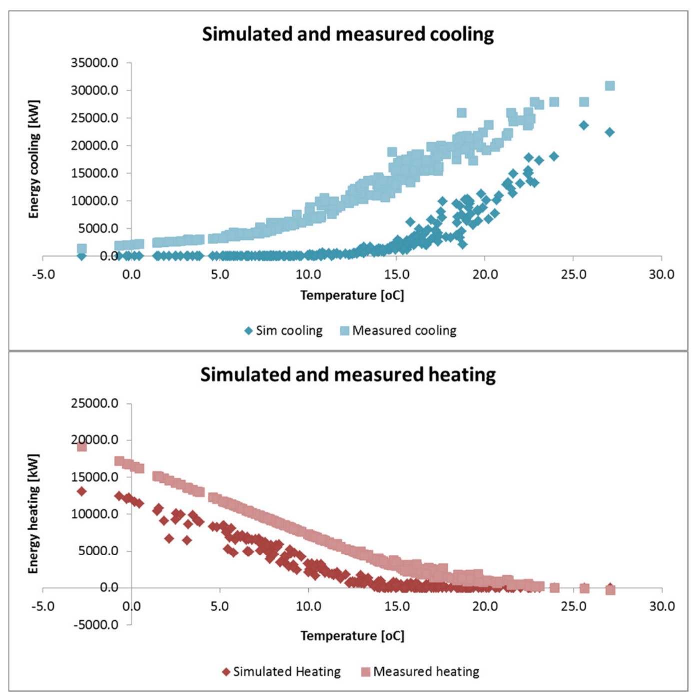

Figure 13 Results of the baseline simulation for EnergyPlus. The larger figures are shown in Attachment 11.

This results in a calibration signature, which is shown in Figure 14. These baseline charts have the same shape as for the low-resolution tool. The calibration signature has a lower value, so the simulated and measured values are more comparable.

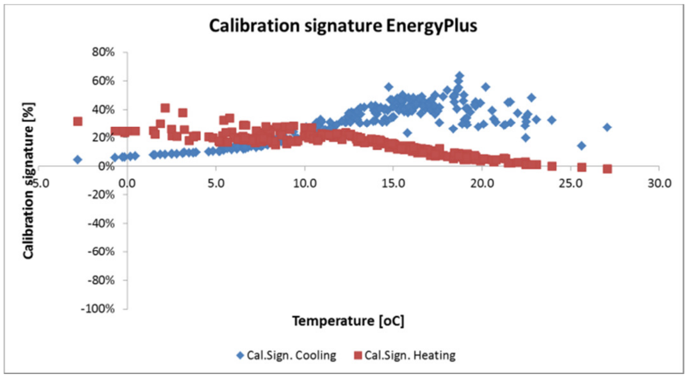

Figure 14 Calibration signature for the detailed tool (EnergyPlus). A larger figure is shown in Attachment 12.

For the detailed simulation characteristic signatures are also made. Some of the characteristic signatures are shown in Figure 15. Other characteristic signatures are shown in Attachment 13. Also for this the tool, the most influencing parameters are the flow rates and coil set point temperatures.

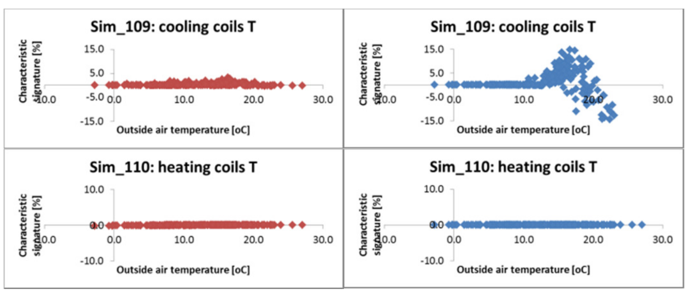

Figure 15 Characteristic signatures [in %] when the coil set point temperature is changed. In red the lines for heating, the blue lines are for cooling. On the x-ases the temperature [oC] is shown.

Remarkable for the signatures of Figure 15 is that when the temperature for the number for the heating coil is changed, the influence is minimal. When the parameters for cooling are changed, the characteristic signature for cooling changed. For heating the characteristic signature is almost zero in that case. This is comparable with the signatures of ABCAT (see Figure 11).

The found parameters are changed and the calibration signature was calculated again, until the RMSE is acceptable according the preferred RMSE. In Table 8 the calculated RMSE, RMSE-CV and MBE are shown. The result after the calibration of ABCAT in charts is shown in Figure 16.

Table 8 Results in SI-units

	RMSE [kWh/day]	RMSE-CV [%]	MBE [kWh/day]
Base cooling	10298.1	84.2	-9332.0
Base heating	3369.6	27.6	-3021.3
Calibrated cooling	3965.4	32.4	-2931.1
Calibrated heating	4081.8	33.3	-2099.9

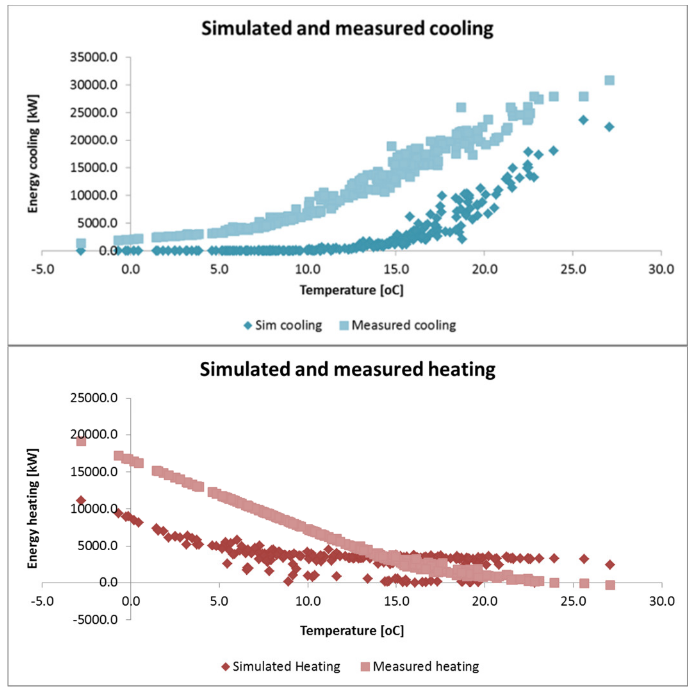

Figure 16 Results of the calibrated simulation for EnergyPlus. The larger figures are shown in Attachment 14.

The numbers of Table 8 seem to be very high. It should be noted that these numbers are SI-units. To compare the numbers with the RMSE-numbers of the preferred RMSE of the Claridges calibration manual, the results are converted to US units. These results are shown in Table 9.

Table 9 Results in US-units

	RMSE [MMBtu/day]	MBE [MMBtu/day]
Base cooling	35.1	-31.8
Base heating	11.5	-10.3
Calibrated cooling	13.5	-9.9
Calibrated heating	13.9	-7.2

5 DISCUSSION

5.1 Data

A big part of the process is the data analysis. Two types of gas consumption were available, the most detailed type was chosen. .

Remarkable is the big amount of cooling consumption that is measured. Reference buildings show than the cooling energy consumption is in most cases less that the heating consumption. Recommended is to simulate a building with an energy consumption for heating and cooling comparable to the reference buildings. It is expected that in that case the simulation outputs will be more equal to the measured data.

The energy consumption for heating is calculated by adding the gas use and warmth of the aquifer. For the gas use a part of the data is removed, because it was expected to be for the domestic hot water. This was an assumption, because numbers are not available for the domestic hot water. Preferably, more information should be available in a next research.

The system has rounded the energy consumption for the warm aquifer, what makes these measurements less accurate. Preferably in a following research this numbers will be more accurate.

Another assumption is made for the cooling energy for the chiller. The COP for the chiller was found as a constant value for all the temperatures, according to the information of the Real Estate Management. In further research this number can be a varying value, depending on the temperature.

5.2 Tools

For the low-resolution tool daily averages are needed. This was also an extra step that needs to be taken in comparison with the detailed tool. To get a good comparison, the detailed tool is also converted into daily numbers. This was also recommended in the calibration manual [24]. This was an extra step and took some time.

5.3 First simulations

The first results for both simulation tools, shows a better agreement with the measurements for the detailed tool. The low-resolution tool shows an unexpected difference for cooling.

For EnergyPlus there is a better match with the measurements.

5.4 Calibration and characteristic signatures

Some remarks can be made for the characteristic signatures for ABCAT and EnergyPlus. For ABCAT a change in a heating parameter, will result in a change in heating and cooling signatures. When a cooling parameter is changed, only the cooling will change noticeably.

When in EnergyPlus setback temperature parameters are changed, the characteristic signatures will only show a noticeable difference for the heating or cooling. So if the heating setback temperature is changed, the cooling characteristic signatures will be nearby zero. If the cooling setback temperature is changed, the heating characteristic signature will be nearby zero for all temperatures.

The most influencing parameter for both simulations is the flow rate outside air. The characteristic signatures for this parameter is very high in comparison with the signatures for other parameters. Remarkable is the difference in characteristic signature for ABCAT and EnergyPlus. A change in input for the flow rate outside air is 7 times more influencing for ABCAT than for EnergyPlus.

5.5 Calibrated results

The results for the simulations are shown in tables. These tables show that the calibration for ABCAT is the better one.

Also remarkable is the degradation in the RMSE for the heating in EnergyPlus. This was the only possibility to get an acceptable RMSE for cooling.

The first result of EnergyPlus was very promising, but calibrating was more difficult. Maybe for a building with an equal heating and cooling consumption the results will differ.

5.6 Comparison:

To get calibrated ABCAT results it took 50% of the time, which was used for the calibration of EnergyPlus. The disadvantage of ABCAT is that all the numbers you should put in, are US-units. This makes it difficult to give an opinion about the outcome and if these are realistic.

To calibrate EnergyPlus it costs less time than was expected. If some experience is present. The disadvantages of the program is that other software (for example Sketchup) should be used to see what the building looks like. If only EnergyPlus is used it's difficult to see what numbers are connected with each other.

What was not expected is that the result of the final calibration of ABCAT is much better. The RMSE, RMSE-CV and MBE are very acceptable in comparison with the results of EnergyPlus. A remark is that the first result of EnergyPlus was very promising. The calibrated heating result of EnergyPlus was worse than the uncalibrated result. Contrary to the expectations, ABCAT has the most accurate results for calibration.

6 CONCLUSION

This research was about the calibration of two different simulation tools, namely the low-resolution tool (ABCAT) and a detailed tool (EnergyPlus). In the introduction was mentioned that the best tool will be a combination of the tools.

The results of the simulation show a different view. The first results of the detailed tool are the most comparable to the measured data. However the final results of the calibration shows that ABCAT has the best results for RMSE, RMSE-CV and MBE. According to Claridge [24] the RMSE should be preferably under 10 and the MBE as low as possible. For ABCAT the first requirement is achieved, but the MBE for cooling is not very low. This may be the result of the case building choice. As mentioned the heating and cooling consumption for the Spectrum building is higher than similar buildings with the same size and climate.

It is recommended to follow the steps of this research for a building with energy consumption comparable to the reference numbers.

7 FURTHER RESEARCH

This research was about the calibration of the tools. The FDD part of the project should be investigated in further research. In this research new data can be put in the tools and the new years can be simulated. If there is no error in the calibration and the data, the charts of measurements and simulations will be the same. If an error will happen at a certain point, the charts will show an anomaly.

8 ACKNOWLEDGMENTS

The author would like to thank John Bynum for his advice and supervision during the first phase of this research. Furthermore the author would like to thank Mohamed Hasan, who took over the task of advisor. Also Thijs Meulen from the Real Estate Management of the TU/e has helped a lot by the provision of the measurement data. Finally the author would thank the members of the group BPS on the TU/e, who asked questions and gave suggestions during the monthly progress meetings.

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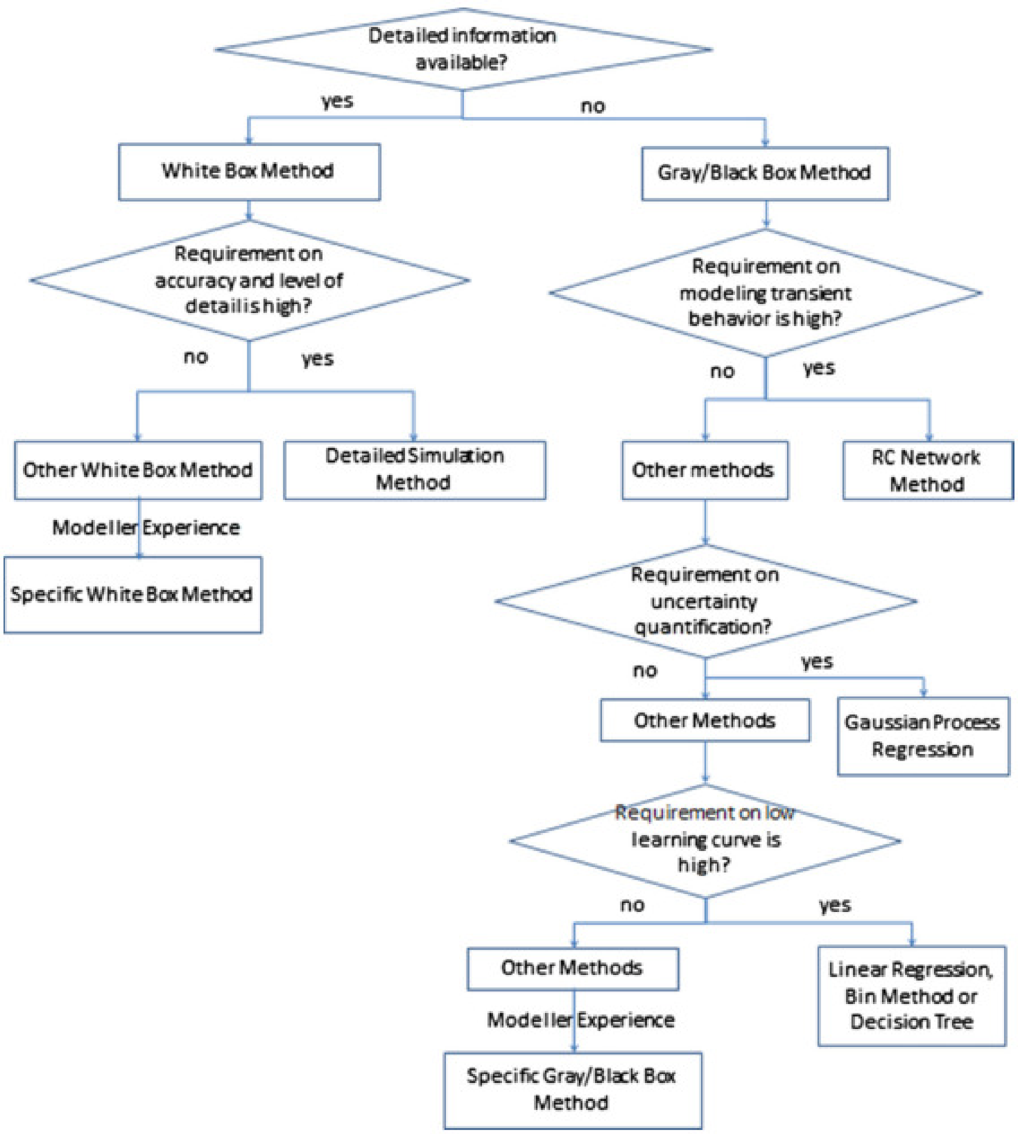
Attachment 1

Benchmark



Attachment 2

Print screens of ABCAT

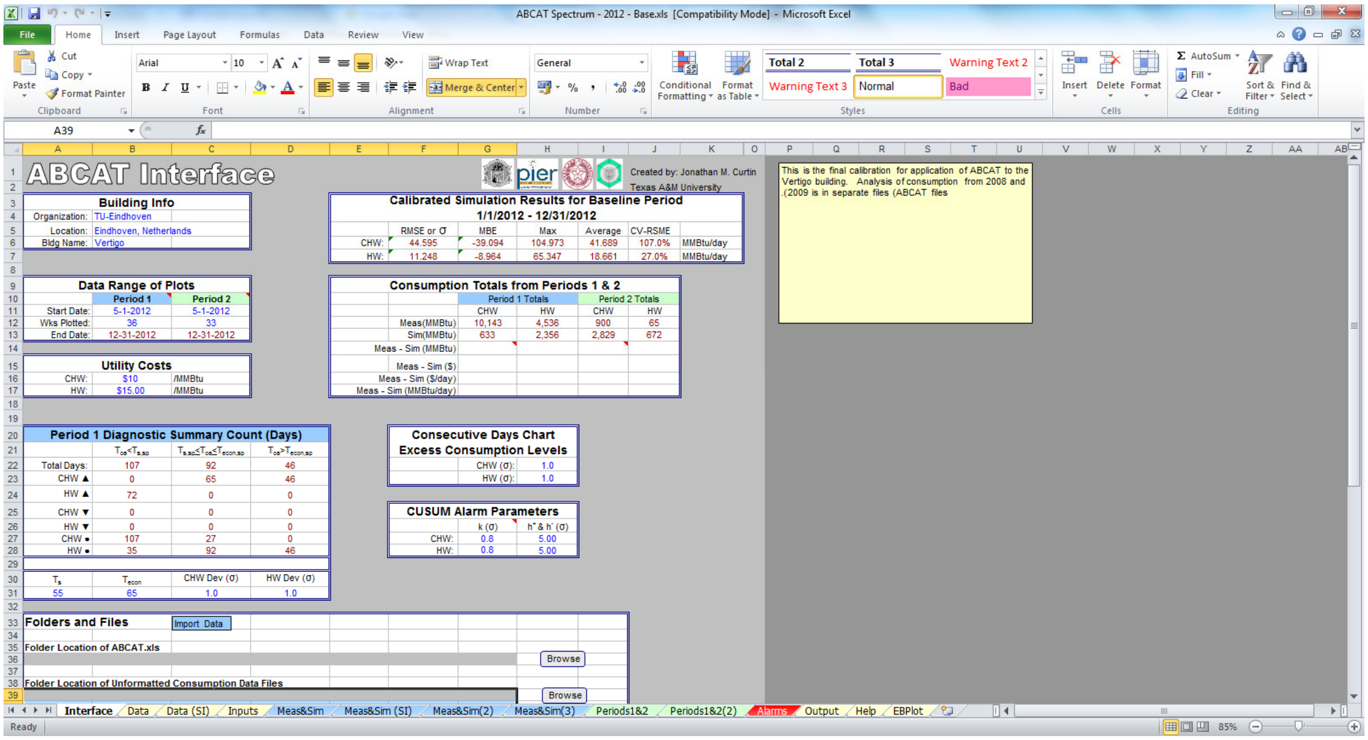


Figure 17 Interface of ABCAT

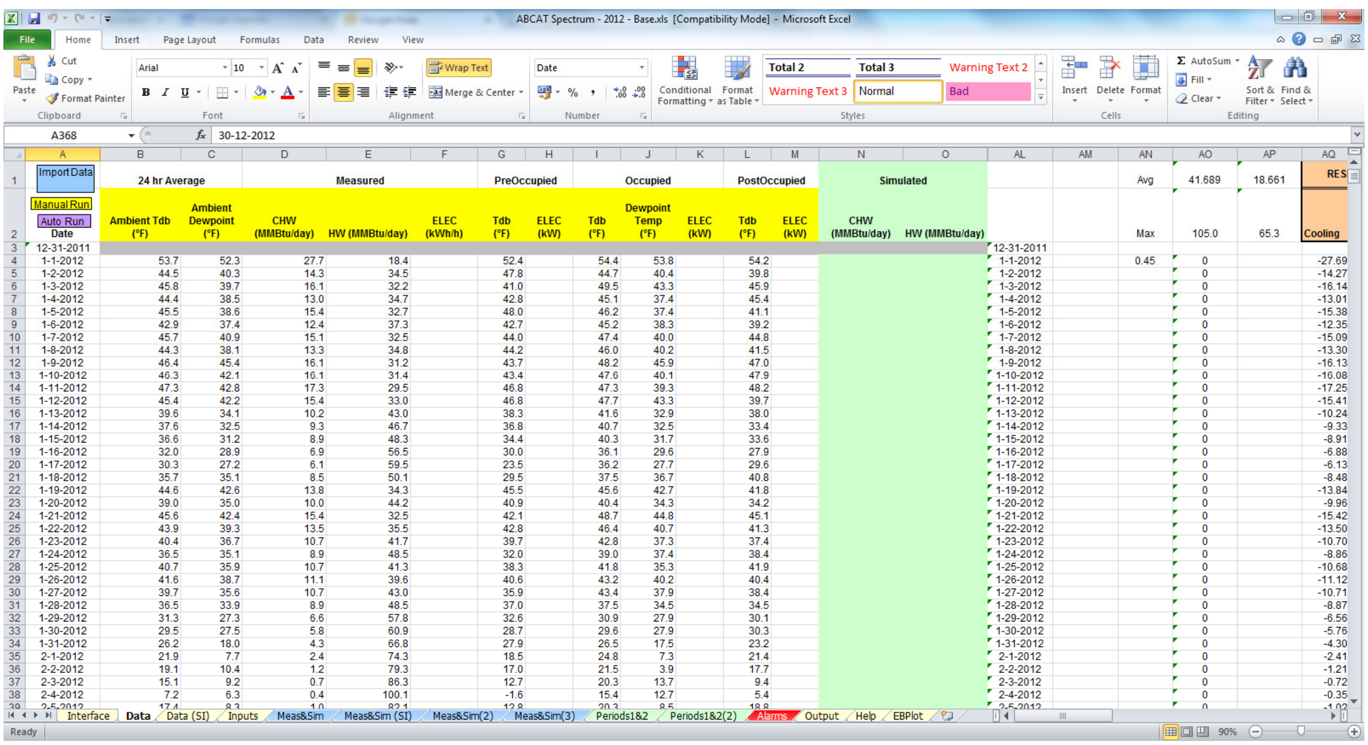


Figure 18 Data screen of ABCAT

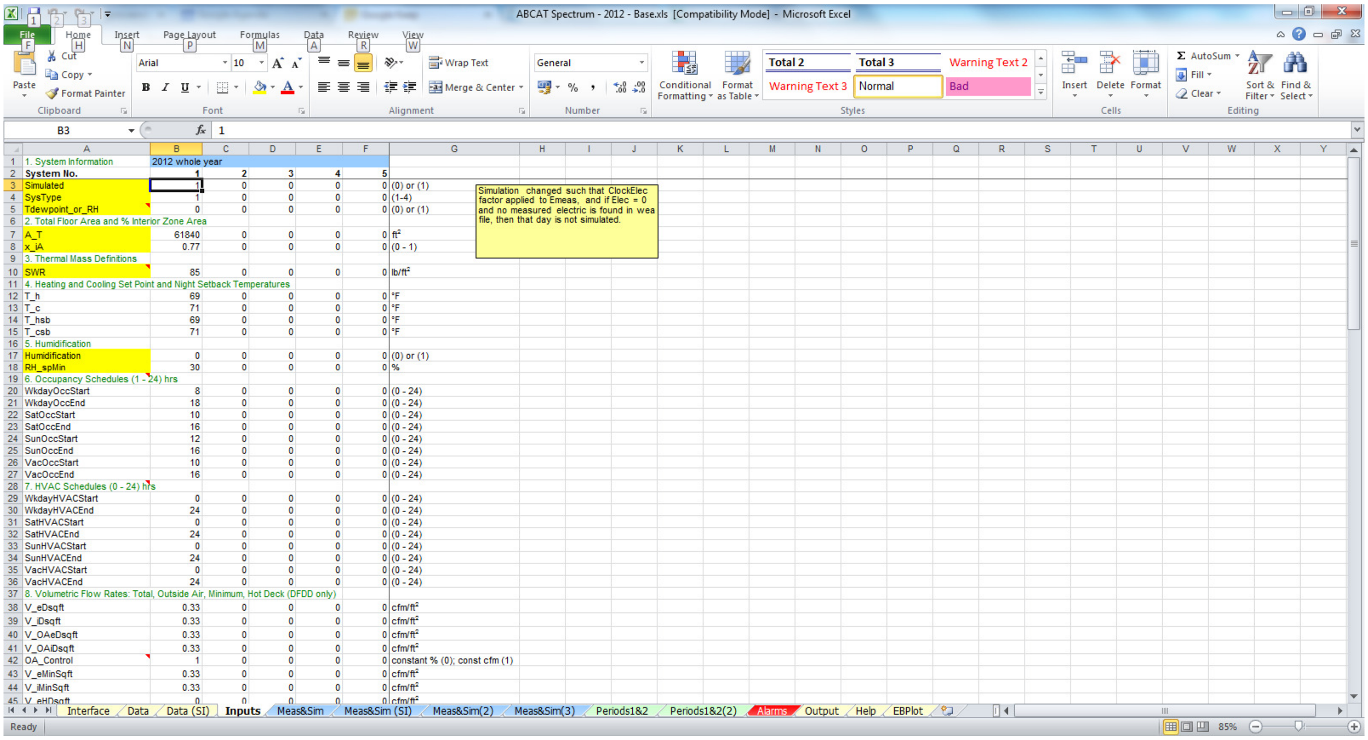


Figure 19 Inputs screen of ABCAT

Attachment 3

Systems that can be simulated in ABCAT

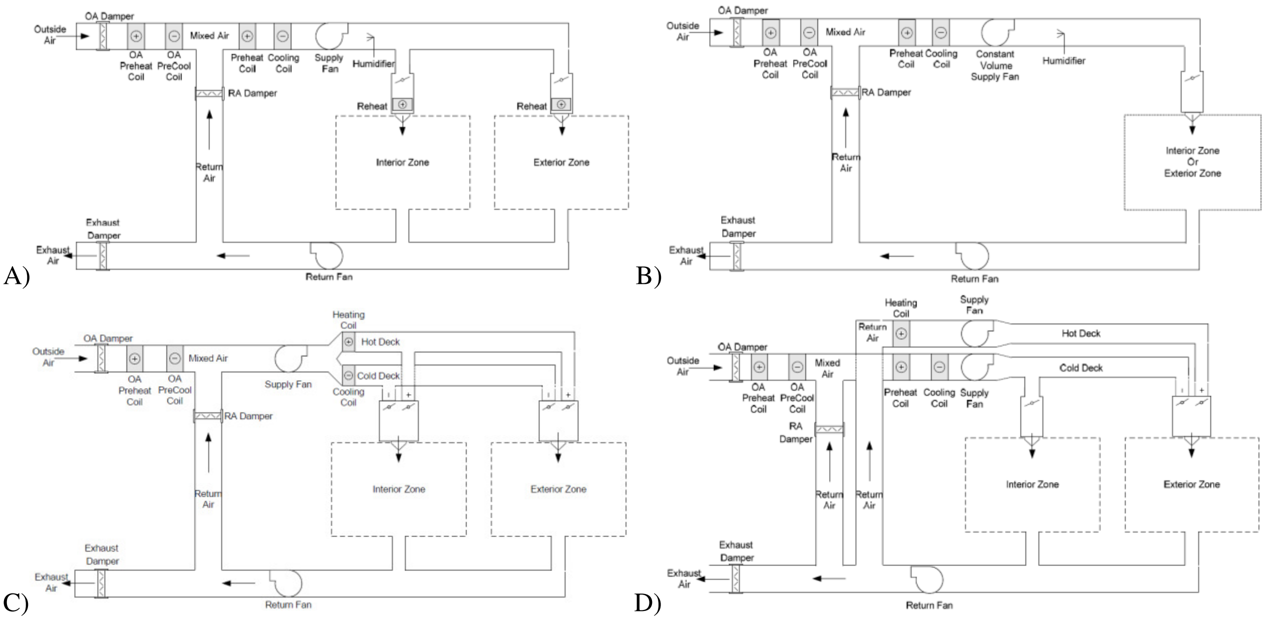


Figure 20 Systems in ABCAT: A) Single Duct with Terminal Reheat (SDRH/SDCV) System Diagram, B) Single Zone Heating and Cooling (SZHC/SDVAV) System Diagram, C) Dual Duct (DD) System Diagram, D) Dual Fan Duct Dual (DFDD) System Diagram [4]

Attachment 4

Floor plans Spectrum

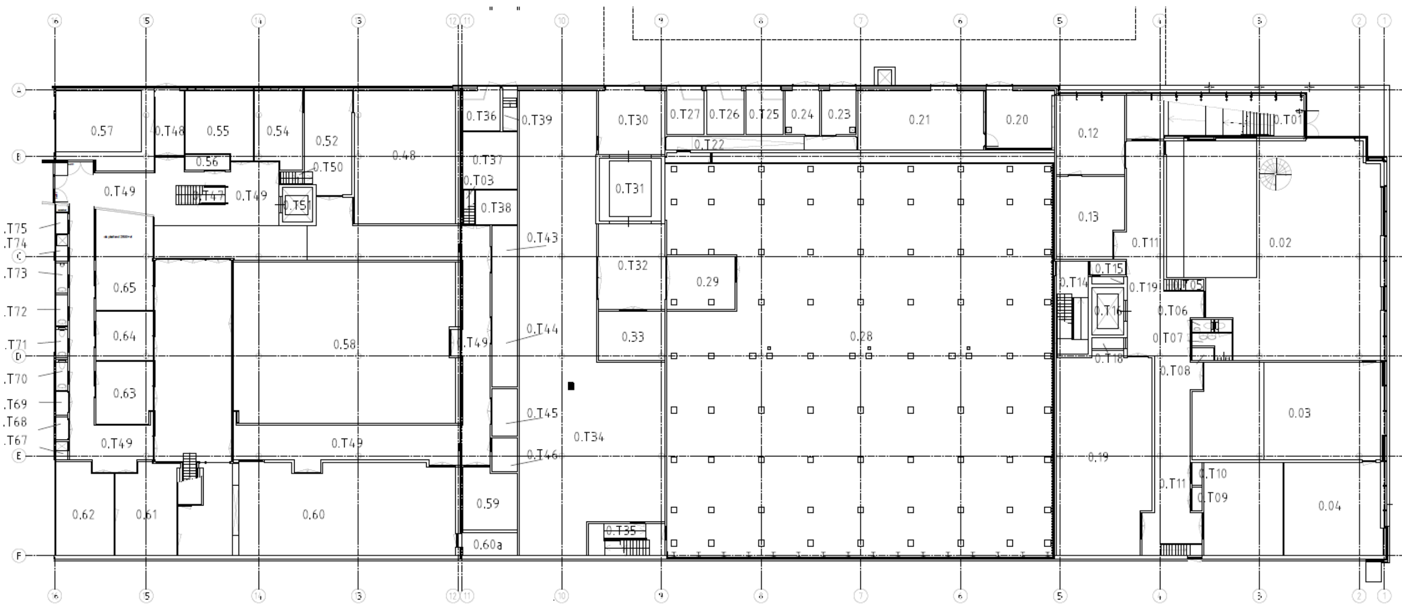


Figure 21 Floor plan of the first floor of the Spectrum building

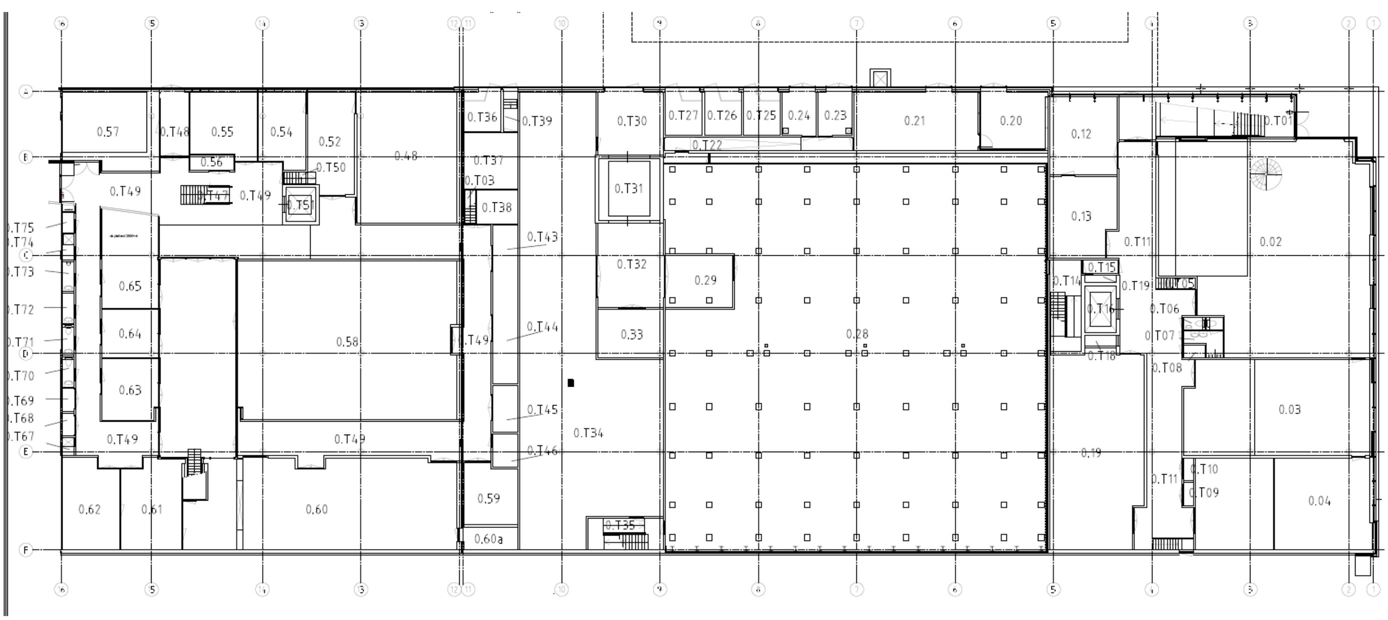


Figure 22 Floor plan of the second floor of the Spectrum building S

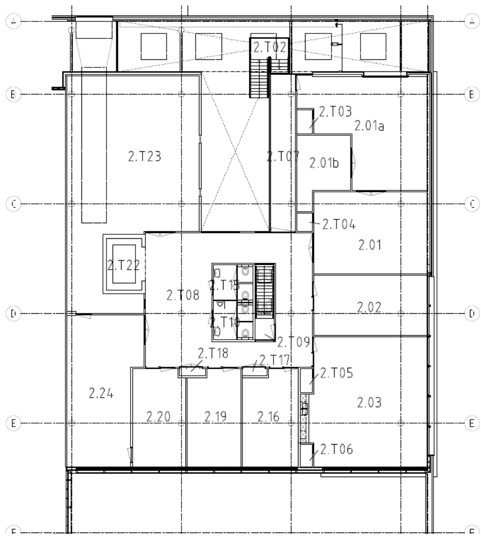


Figure 23 Third floor of the Spectrum building

Attachment 5

Drawings of hot water and chilled water for the Spectrum building

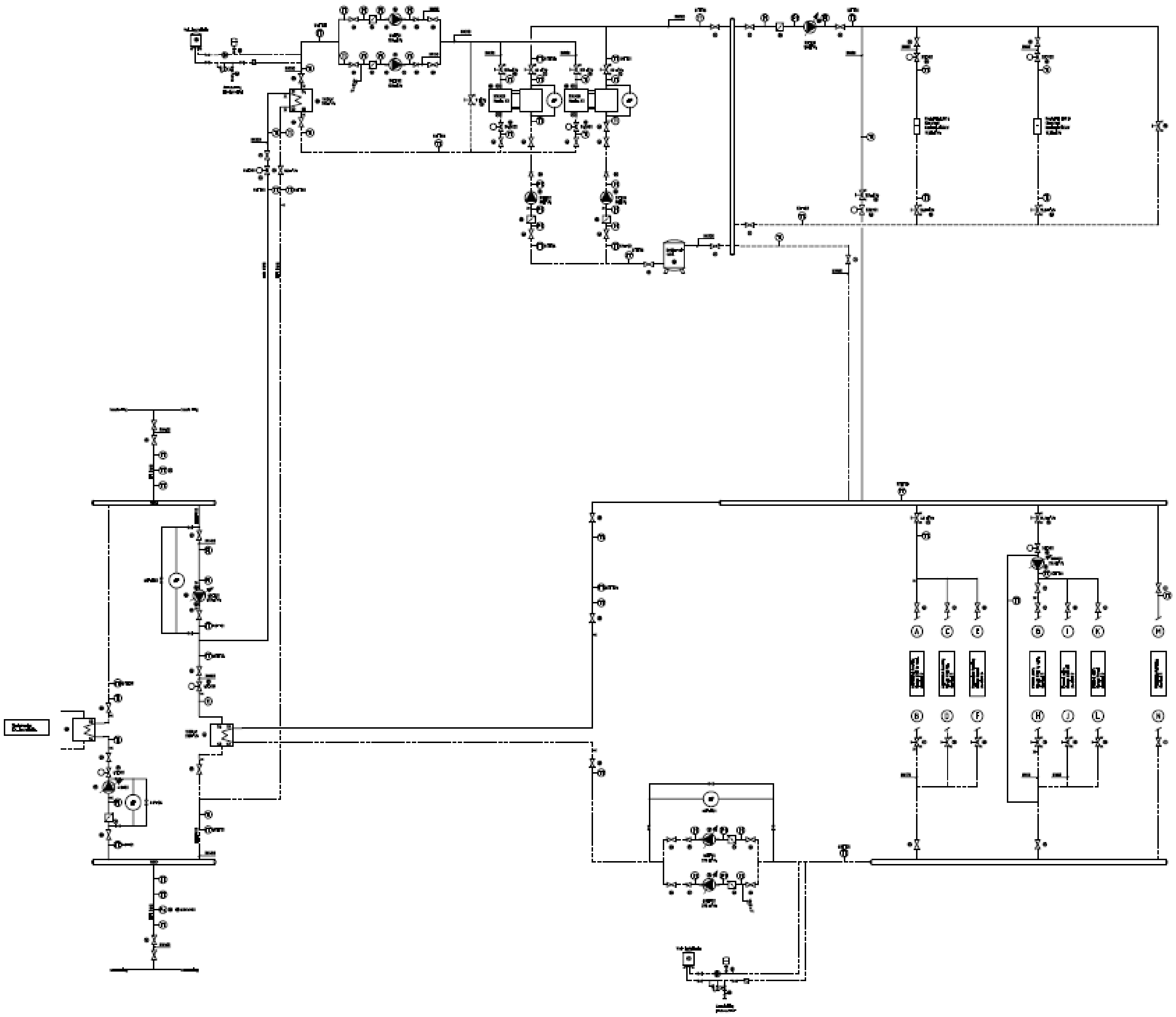


Figure 24 Drawing for the cooled water circuit in the Spectrum building

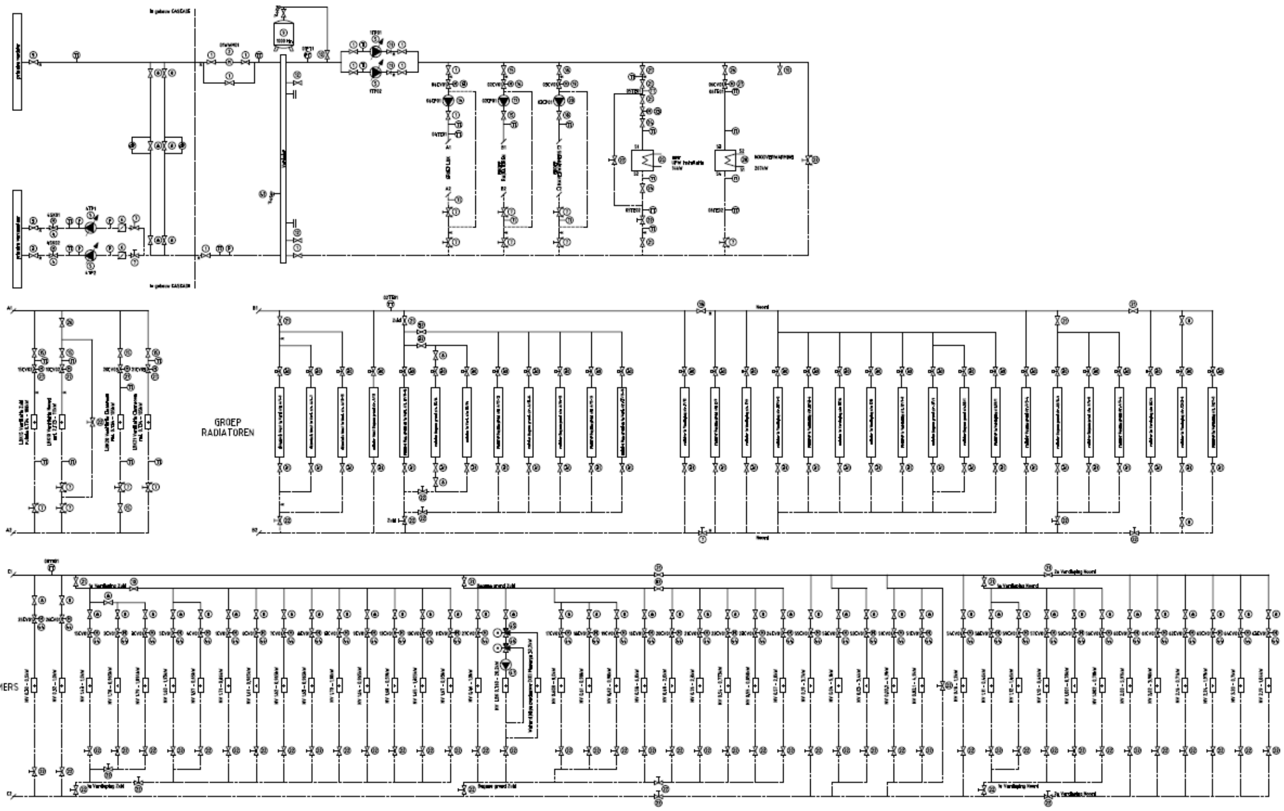


Figure 25 Drawing of the hot water circuit in the Spectrum building – part 1

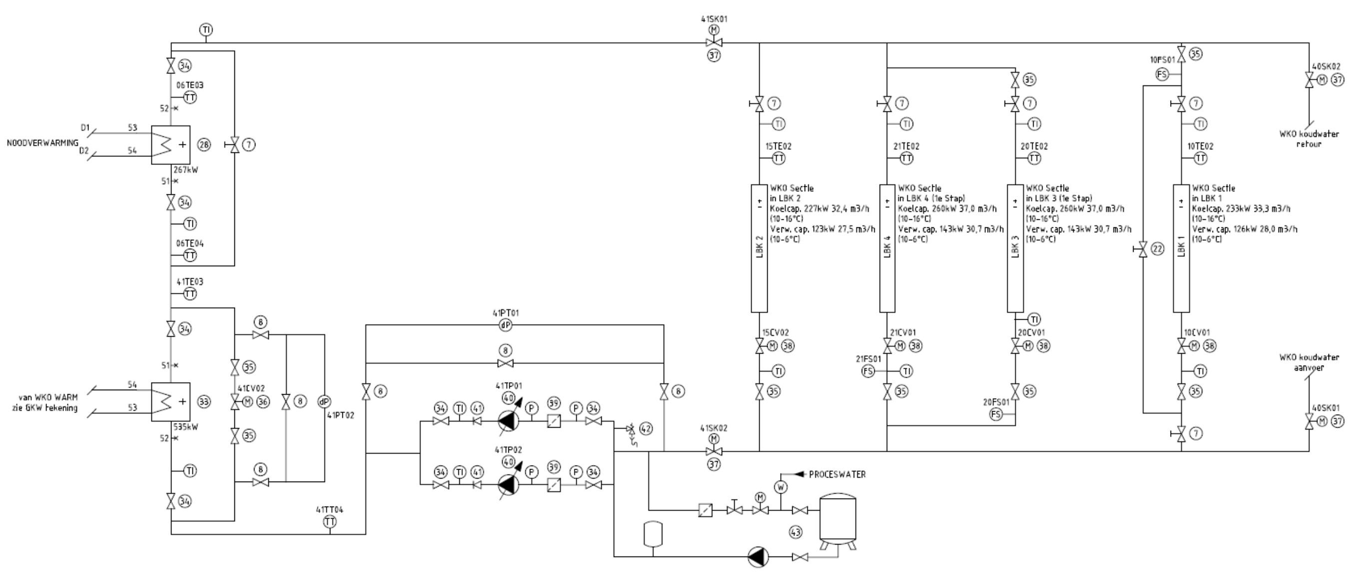
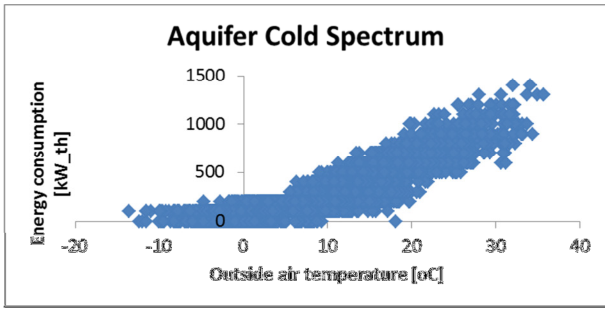


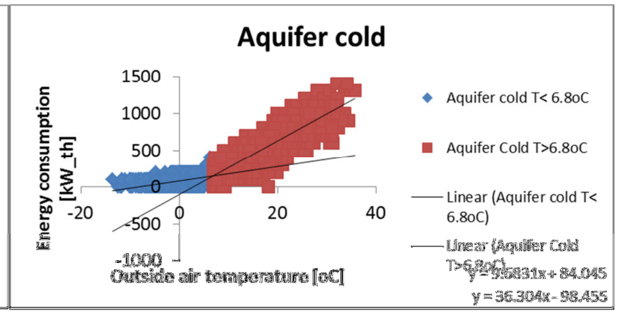
Figure 26 Drawing of the hot water circuit in the Spectrum building - part 2

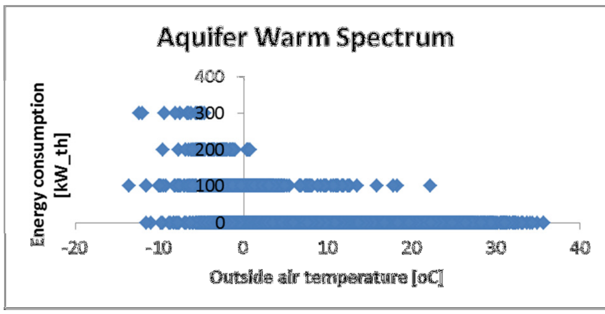
Attachment 6

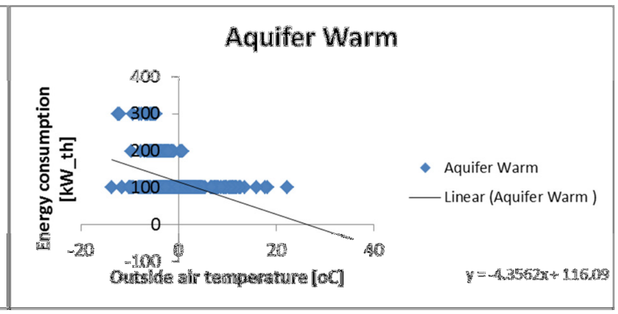
Complete overview of charts of data from Dienst Huisvesting

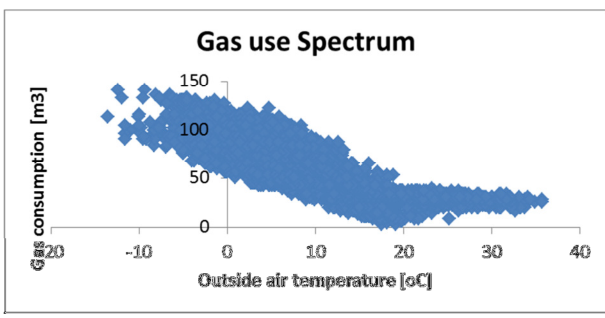
Normal charts and change point charts

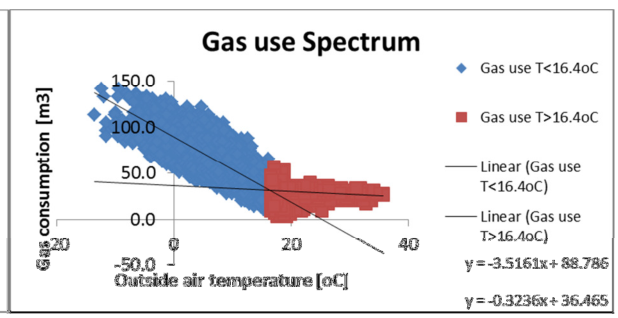


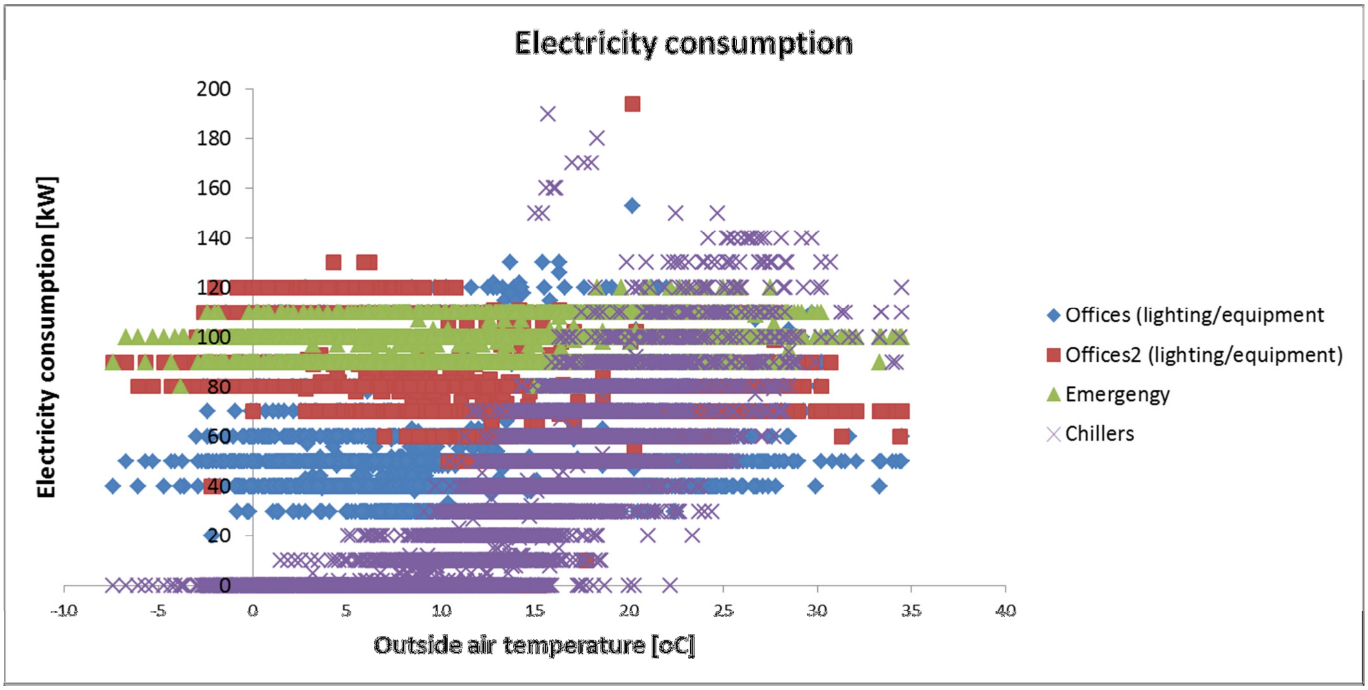






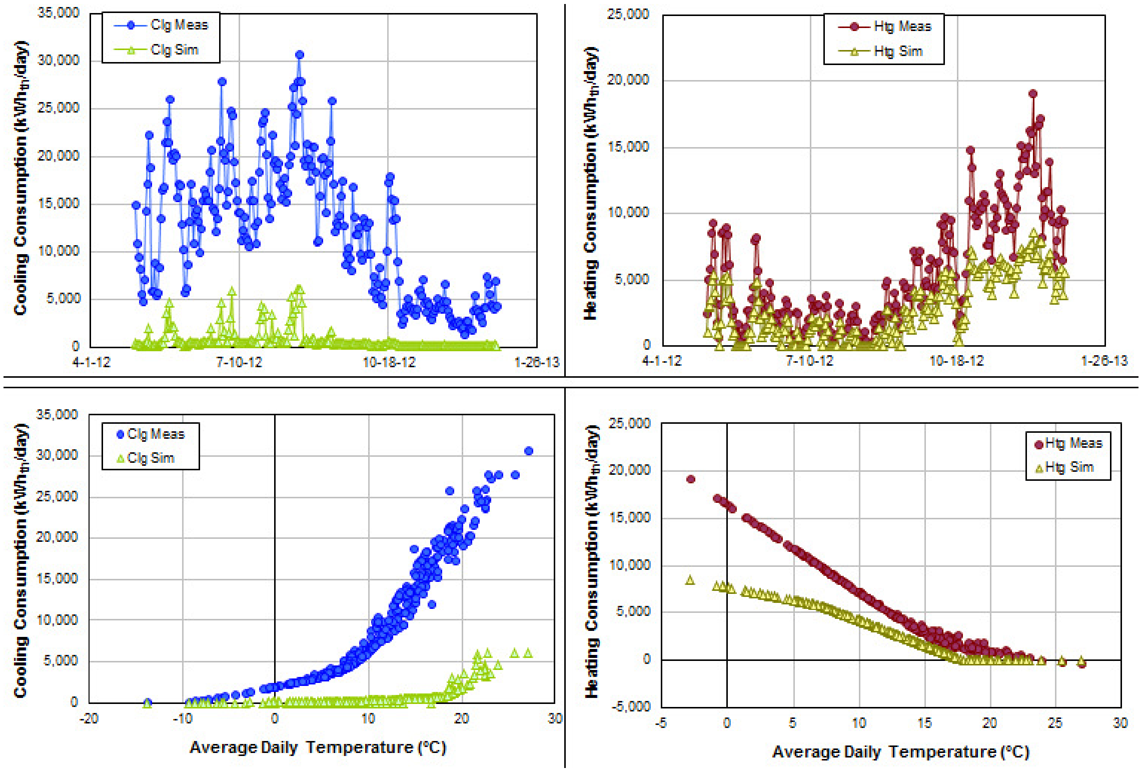





Electricity consumption
Electricity consumption [kW]
200
180
160
140
120
100
80
60
40
20
0
-10
-5
0
5
10
15
20
25
30
35
40
Outside air temperature [oC]
Offices (lighting/equipment
Offices2 (lighting/equipment)
Emergengy
Chillers

Attachment 7

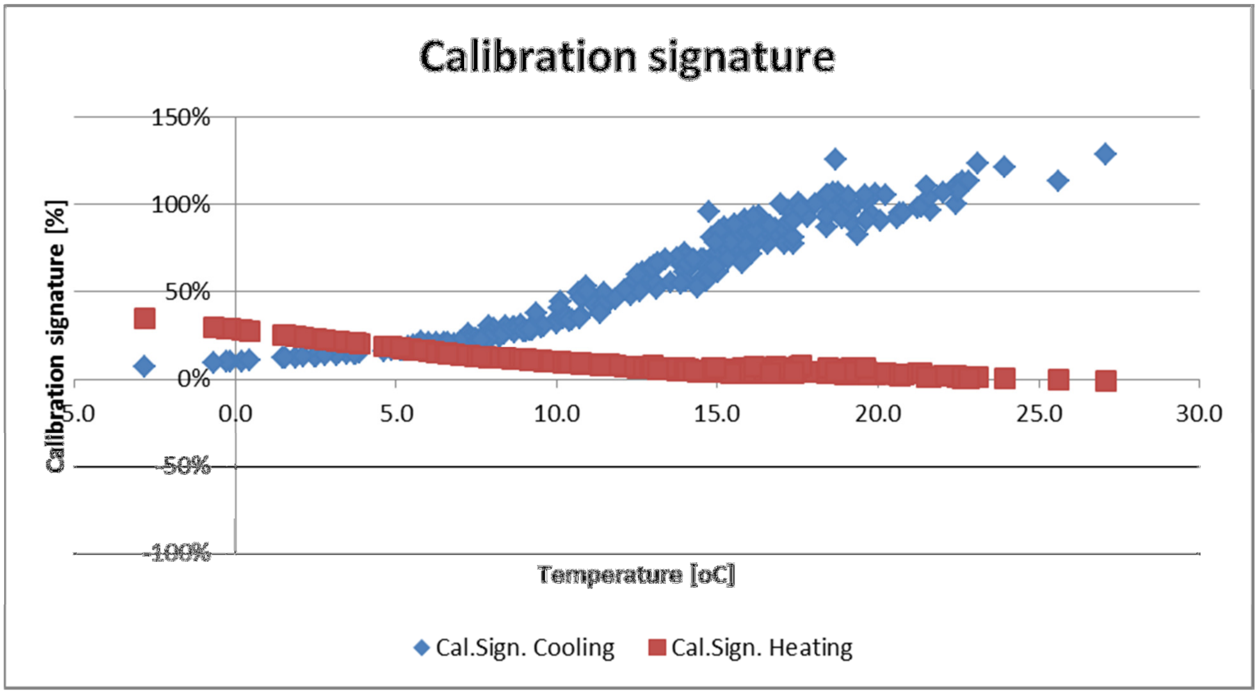
First results of ABCAT



Abbreviations:
CHW: Chilled water
HW: Hot water

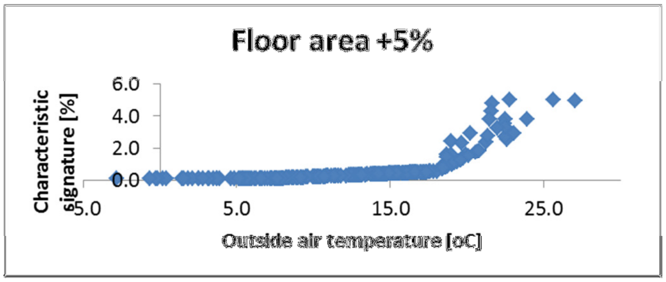
Attachment 8

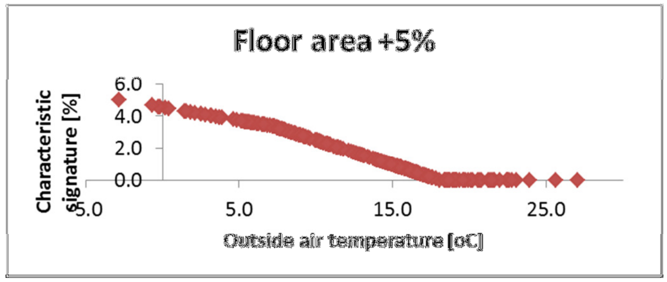
Calibration signature for the low-resolution tool

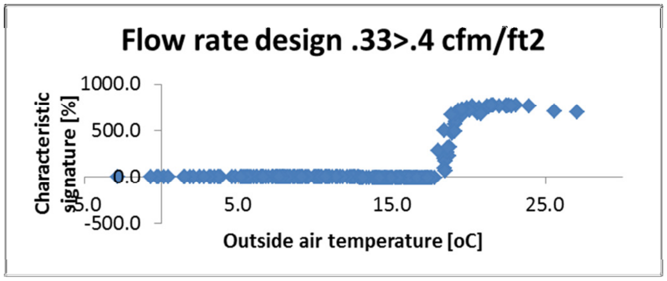


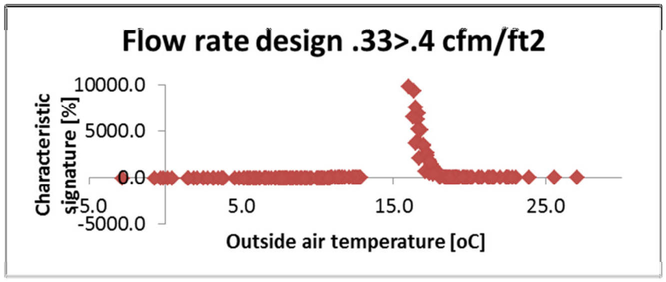
Attachment 9

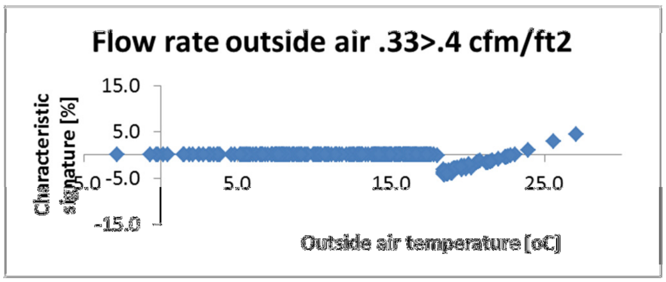
Characteristic signatures ABCAT

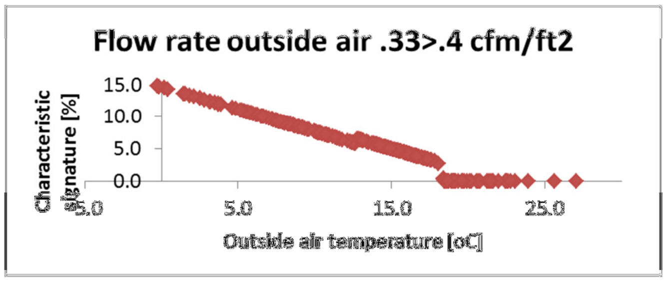


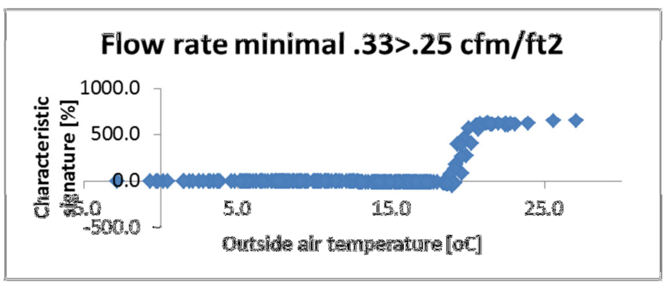


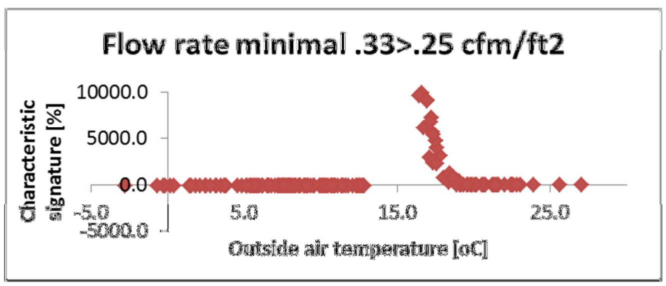


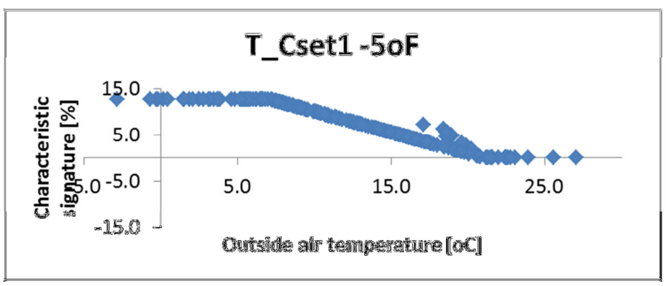


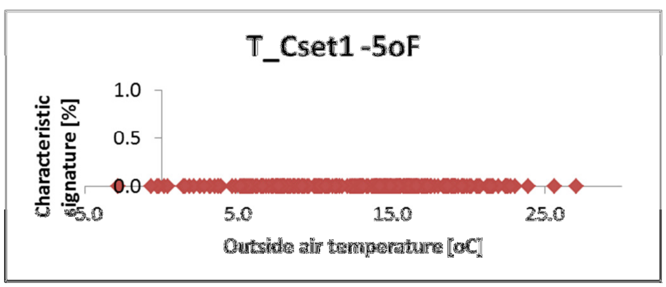


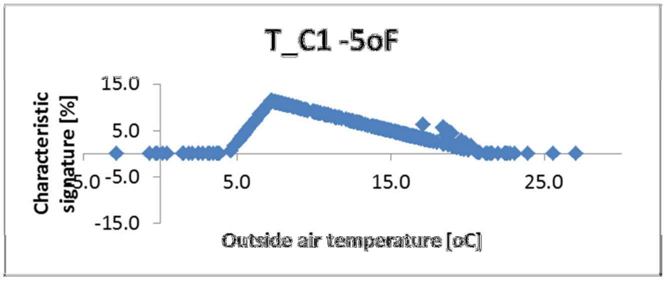


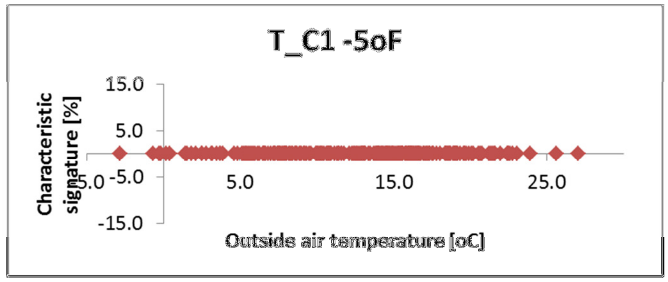


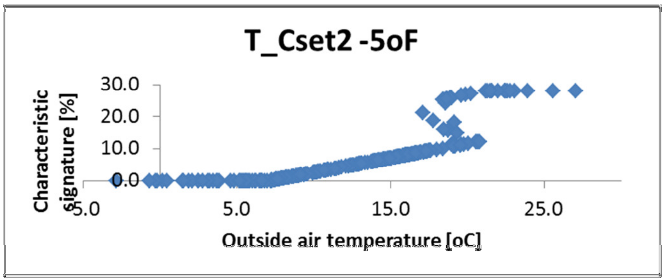


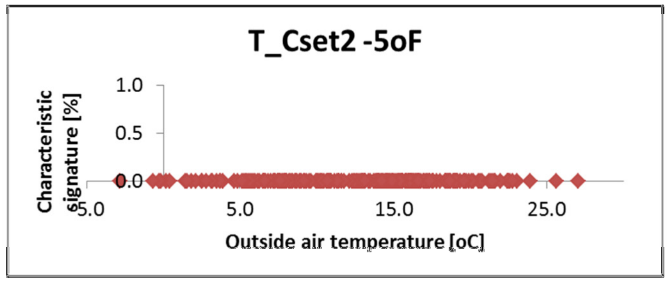


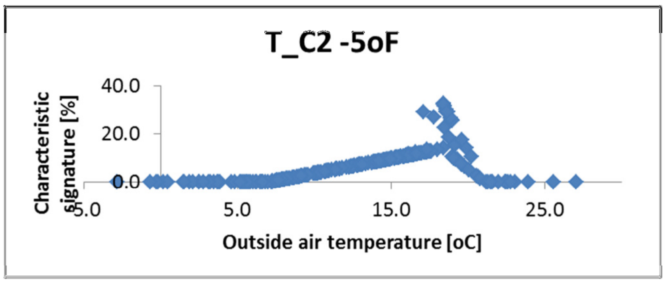


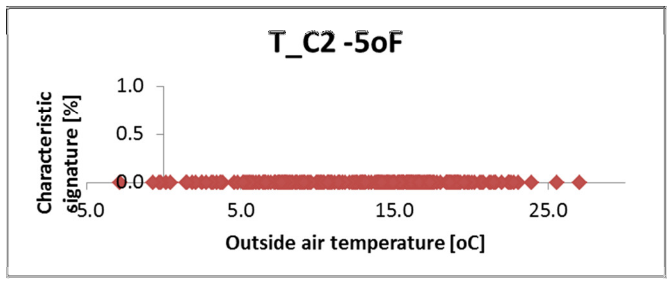

T_C1 -5oF
Characteristic signature [%]
15.0
5.0
-5.0
-15.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

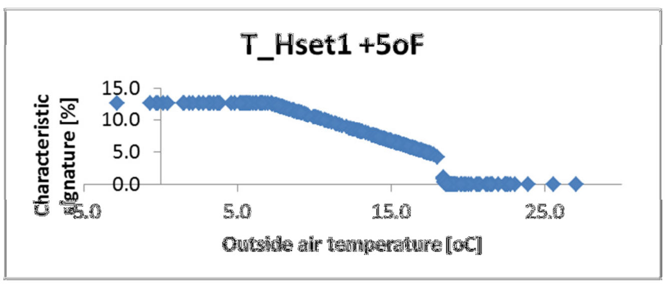

T_C1 -5oF
Characteristic signature [%]
15.0
5.0
-5.0
-15.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

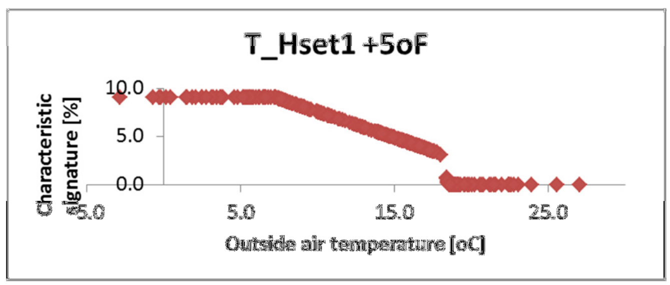

T_Cset2 -5oF
Characteristic signature [%]
30.0
20.0
10.0
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

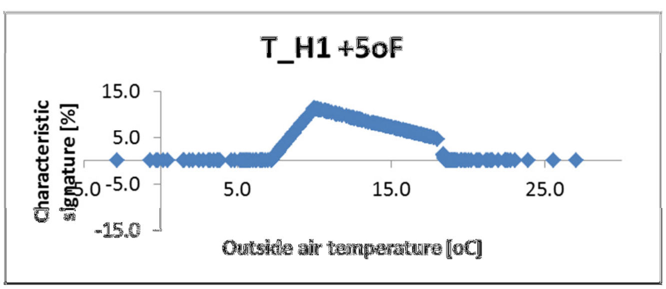

T_Cset2 -5oF
Characteristic signature [%]
1.0
0.5
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

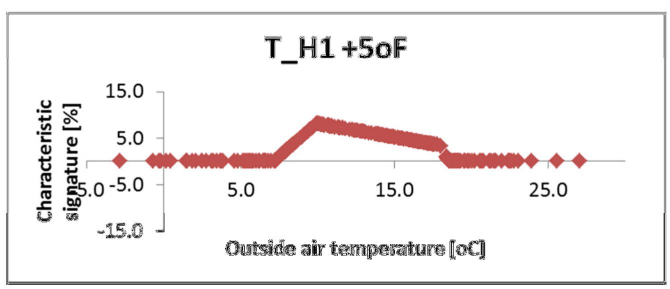

T_C2 -5oF
Characteristic signature [%]
40.0
20.0
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

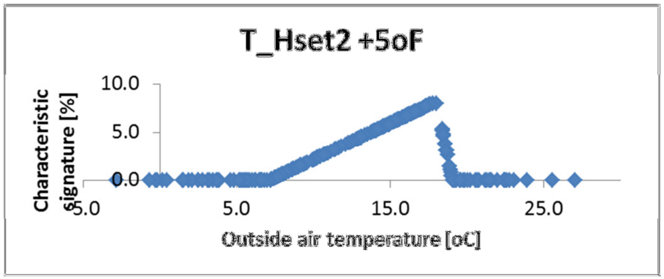

T_C2 -5oF
Characteristic signature [%]
1.0
0.5
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

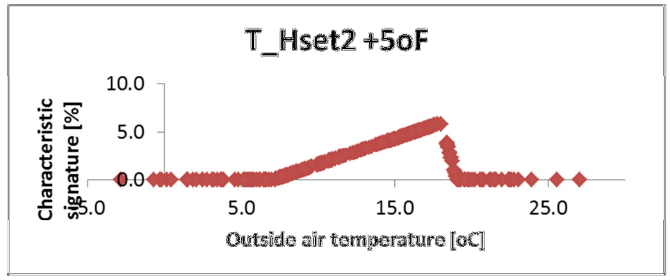

T_Hset1 +5oF
Characteristic signature [%]
15.0
10.0
5.0
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

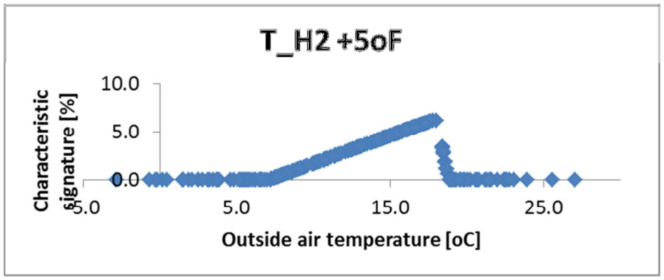

T_Hset1 +5oF
Characteristic signature [%]
10.0
5.0
0.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

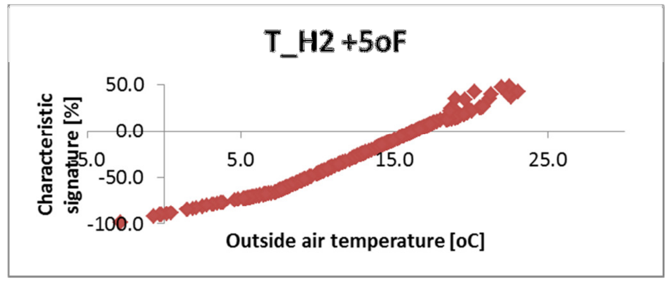

T_H1 +5oF
Characteristic signature [%]
15.0
5.0
-5.0
-15.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


T_H1 +5oF
Characteristic signature [%]
15.0
5.0
-5.0
-15.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]







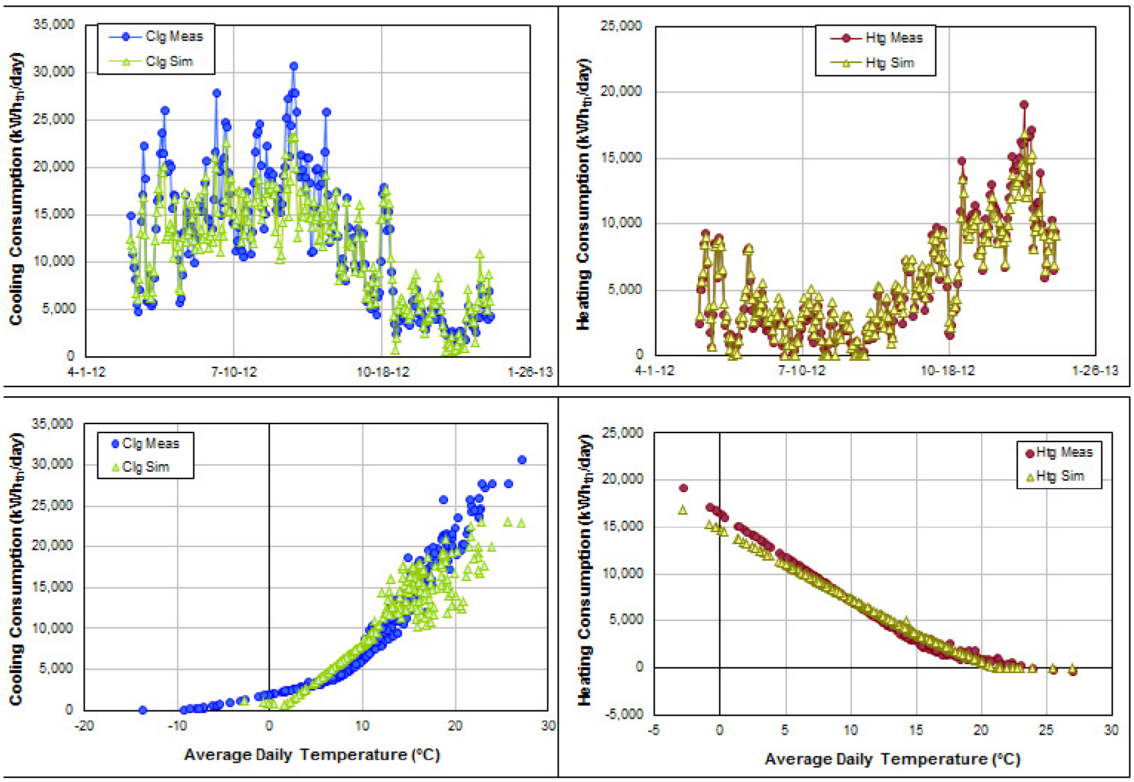


Abbreviations:

T_Cset1: cooling coil set point temperature corresponding to low ambient temperature T_C1
T_C1: low ambient temperature condition for T_Cset1
T_Cset2: cooling coil set point temperature corresponding to high ambient temperature T_C2
T_C2: high ambient temperature condition for T_Cset2
T_Hset1: heating coil set point temperature corresponding to low ambient temperature T_H1
T_H1: low ambient temperature condition for T_Hset1
T_Hset2: heating coil set point temperature corresponding to high ambient temperature T_H2
T_H2: high ambient temperature condition for T_H2

Attachment 10

Calibrated result ABCAT



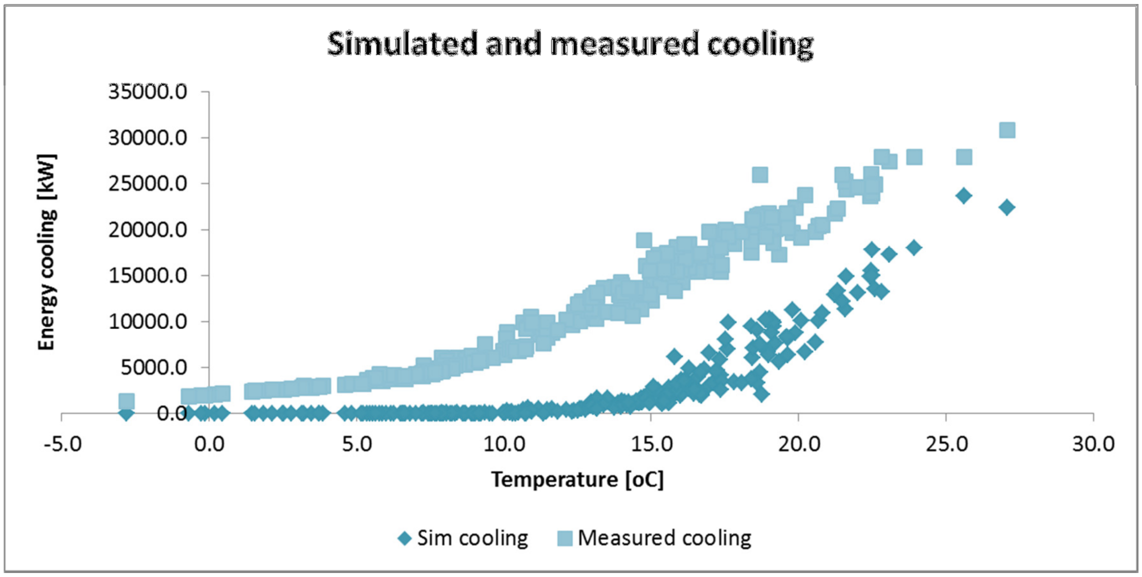
Abbreviations:

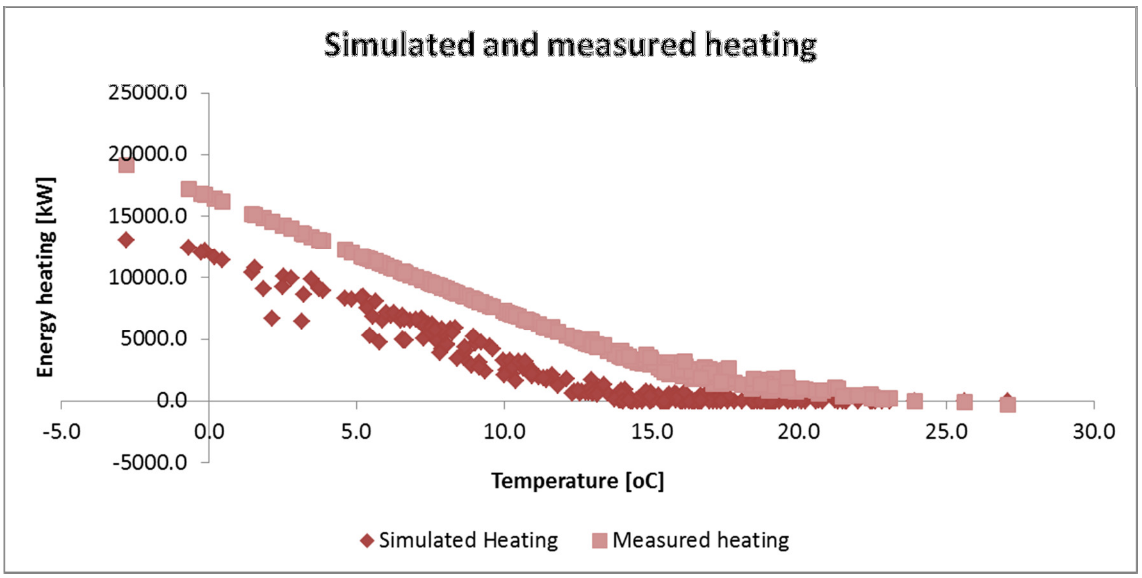
CHW: Chilled water

HW: Hot water

Attachment 11

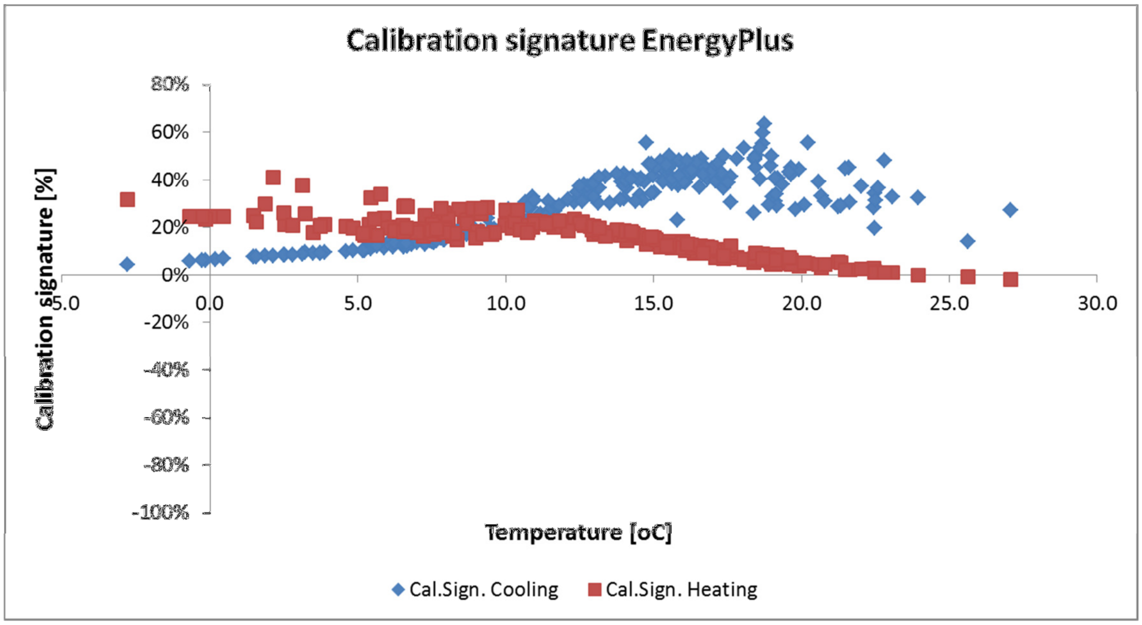
First results EnergyPlus





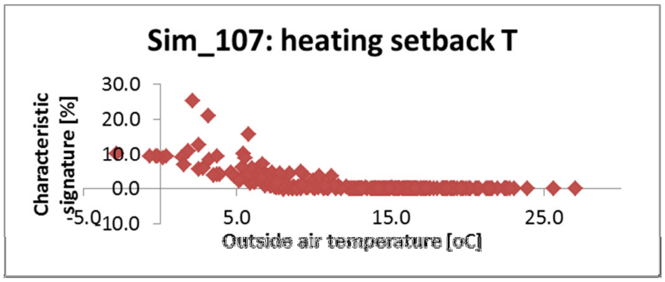
Attachment 12

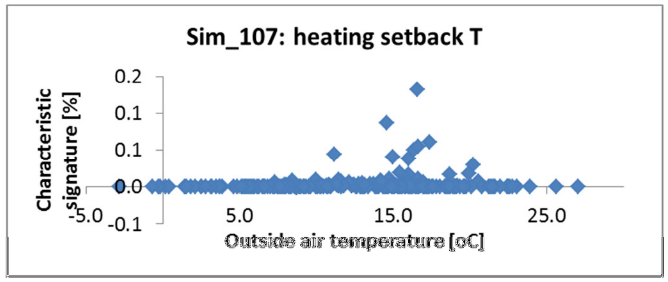
Calibration signature EnergyPlus

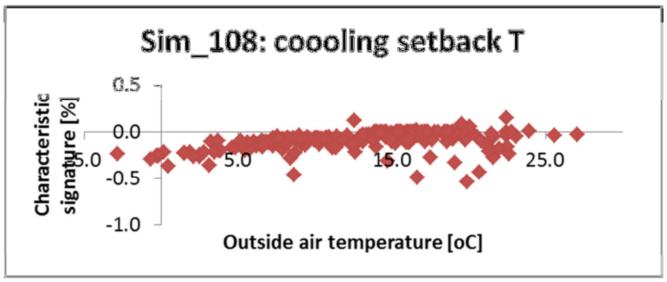


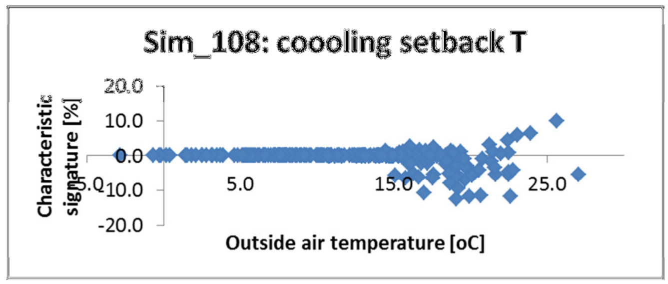
Attachment 13

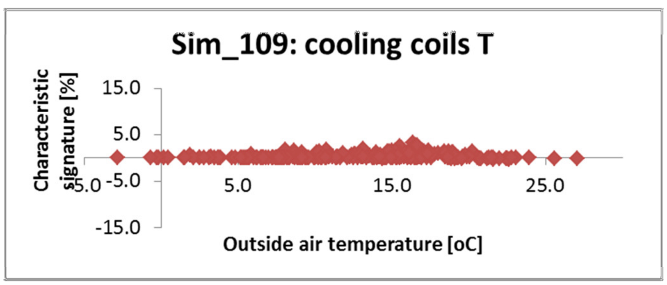
Characteristic signatures EnergyPlus

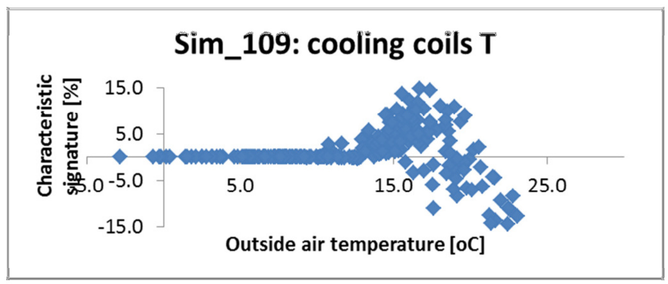


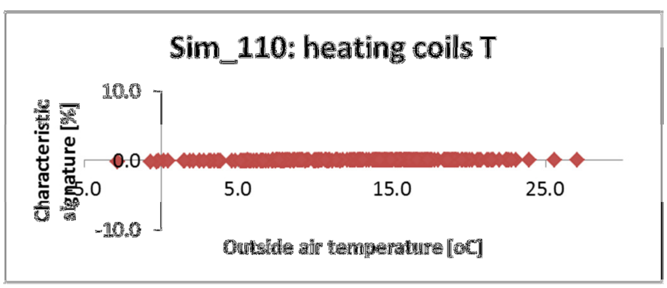


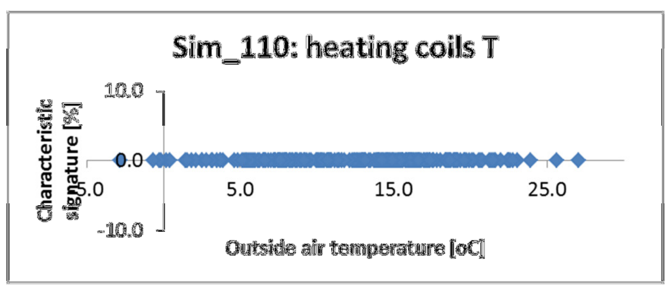


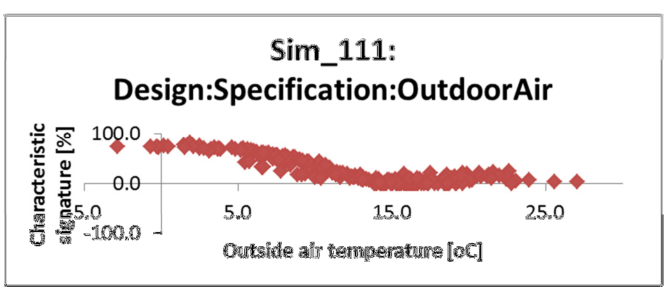


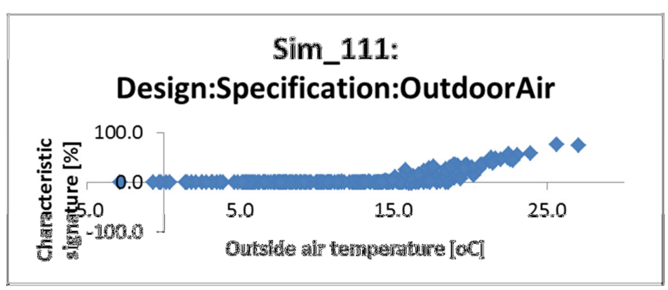


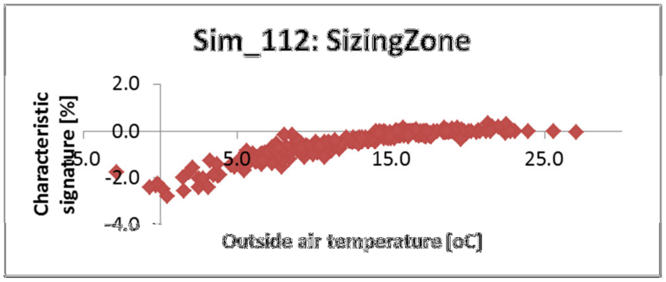


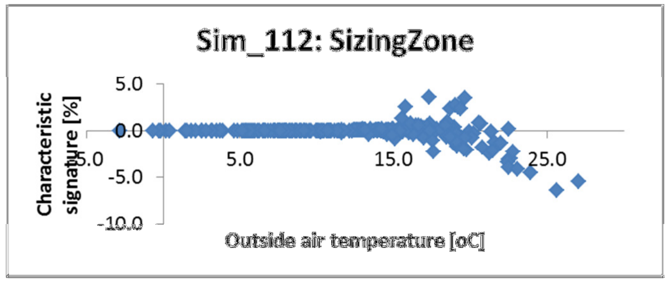


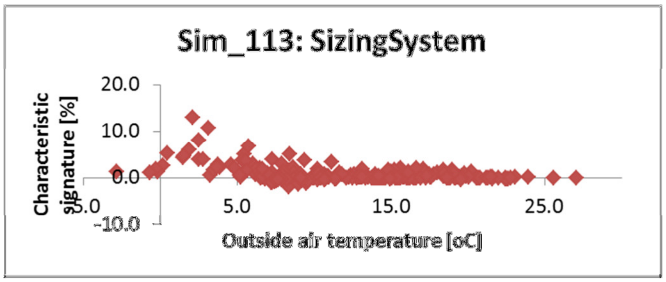


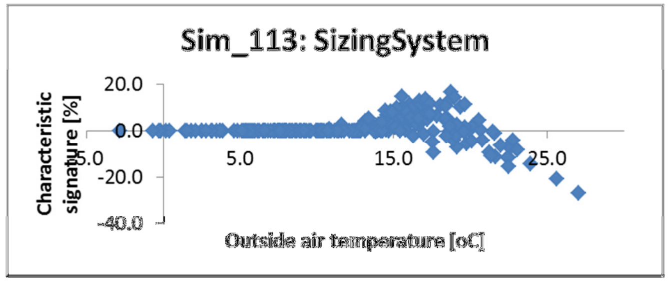


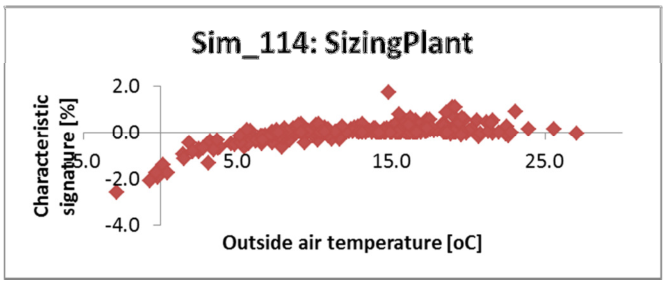


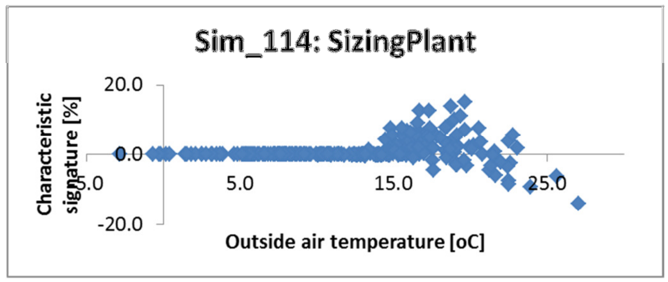

Sim_112: SizingZone
Characteristic signature [%]
2.0
0.0
-2.0
-4.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


Sim_112: SizingZone
Characteristic signature [%]
5.0
0.0
-5.0
-10.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


Sim_113: SizingSystem
Characteristic signature [%]
20.0
10.0
0.0
-10.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


Sim_113: SizingSystem
Characteristic signature [%]
20.0
0.0
-20.0
-40.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


Sim_114: SizingPlant
Characteristic signature [%]
2.0
0.0
-2.0
-4.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]


Sim_114: SizingPlant
Characteristic signature [%]
20.0
0.0
-20.0
-5.0
5.0
15.0
25.0
Outside air temperature [oC]

Attachment 14

Results EnergyPlus