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HUMAN-IST
HUMAN CENTERED INTERACTION SCIENCE & TECHNOLOGY

Design and evaluation of a visual data exploration tool for multivariate building data

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Department of Informatics - Master Project Report

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Abstract

Building Automation Systems (BAS) provide monitoring and control for facility operators with purpose regarding maintenance, occupant comfort, equipment monitoring, safety and security. The traditional presentation formats for this monitored performance data, such as tables and graphs, are insufficient since they are not adaptable to the users cognitive capacity and do not allow analysis of the interaction between system parameters and performance indicators.

The presented data exploration application makes use of two well known multivariate data visualization techniques, parallel coordinates and circular heat map. They have been applied to a data set from a monitored office building, located in Switzerland. A 3d model of the building provides useful dimensional information about the data variables and is used at the same time to add or remove these variables to the visualizations.

The application has been evaluated by 11 experts with a building physics or engineering background and 1 visualization expert. They were able to report a multitude of observations concerning the buildings thermal comfort inside office rooms, heating and cooling behaviour, influence of outdoor variables, blinds operation and others. The experts reported the parallel coordinates visualization as 'very' useful for this kind of observations. Also the use of the abstract 3d building model has been very well received.

Keywords: Master thesis report, Human-IST Research Institute, building monitoring, information visualization, parallel coordinates, circular heat map

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1 Introduction

1.1 Motivations

Building Automation Systems (BAS) provide automatic control of different building related systems like heating, ventilation and air conditioning (HVAC), lighting, blinds and others. Additionally, they also provide monitoring and control for facility operators with purpose regarding maintenance, occupant comfort, equipment monitoring, safety and security [Yang and Ergan, 2014]. The monitoring of the mentioned systems produces multidimensional and multivariate data sets. Multidimensionality refers to the number of independent variables, and -variate to the number of dependent, possibly correlated variables. The traditional presentation formats for such monitored performance data sets are "insufficient, since they are not adaptable to the users cognitive capacity and do not allow analysis of the interaction between system parameters and performance indicators" [Struck et al., 2011].

There is a broad range of information visualization techniques that make use of the human cognitive capacity and are well fitted for multidimensional and multivariate data. Current research shows a trend to more interactive and sophisticated visualizations for building automation systems.

1.2 Goals

This project aims at the creation of a visual exploration tool for building related multivariate sensor data. To achieve this, the design and implementation of appropriate visualization techniques and interaction methods is required. Trough the use of multivariate visualization techniques, variable relationships are highlighted in order to understand the building's behaviour. Together with a 3d model that highlights the dimensionality of the data, the applications interaction possibilities lead the visual exploration process. To verify the usability and usefulness of the tool and the techniques used, the application has been evaluated by experts with building physics and engineering backgrounds.

1.3 Structure

This project is divided into three parts:

1. Acquisition of a monitored building's data set, alongside additional spatial information and floor plans.
2. Design and implementation of different multidimensional multivariate visualization and interaction techniques
3. Evaluation of the application with experts with a building physics and engineering background.

Likewise, this report has been structured. After this introduction, the second chapter provides the state of the art in multidimensional multivariate data visualization, interaction techniques and building monitoring. It highlights various needs of improvement for BAS visualizations, and provides so the foundation for the design and development of such an application. The monitored building and the obtained data set will be explained in detail in chapter 3. Chapter 4 then presents the system architecture and used technology for the application. The implemented application and its different parts are then explained in chapter 5. Chapter 6 presents the evaluation of the application done by experts. It will describe and interpret the results collected. Following this chapter, the conclusion will sum up the findings from the project.

2 State of the Art

This chapter presents the current state of research in multidimensional multivariate data visualization, interaction techniques and building monitoring. It provides the necessary foundation on which the application will developed in the next chapters.

2.1 Information visualization

Information visualization is defined by Card et al. [1999] as *the use of computer-supported, interactive, visual representations of abstract data to amplify cognition* or by Keim et al. [2006] as *(InfoVis) is the communication of abstract data through the use of interactive visual interfaces.*

This abstract data must be transformed from their original raw state into a representation, but not the visual representations themselves are its purpose, instead it is the gain of insight, rapid information assimilation or monitoring large amounts of data Card et al. [1999].

To choose the best representation for the abstract data is left to the researcher. In contrary to the field of scientific visualization, where the data often correspond to real-world objects and phenomena, there are no natural visual representations in information visualization Thomas [2005]. There are a number of well-known techniques for mapping the abstract data to the physical screen space, such as x-y plots, line plots and histograms. These techniques are mostly used for small and low dimensional data sets Keim et al. [2006].

2.1.1 Interaction Techniques

The analytical needs may not be satisfied by visual representations only. The addition of interaction techniques is needed. They will support the dialogue between the analyst an the data Thomas [2005]. This approach is called visual data exploration, in which the human is integrated in the data exploration process Keim et al. [2002]. It allows the user to directly interact with data, understand trends and anomalies, isolate and reorganize information, and engage in the analytical reasoning process Thomas [2005].

Another frequently used term is visual data mining. Data mining denotes the approach of finding and extracting valuable information hidden in data Keim et al. [1997]. In exploratory data analysis visual data mining has proven to be of high value Keim et al. [2002]. Especially for datasets that are little known, or the exploration goals are vague, visual data exploration is useful Keim et al. [2002]. The inclusion of the human in the process allows to shift and adjust the exploration goals as necessary Keim et al. [2002].

The human eye's broad bandwidth pathway into the mind is taken advantage of by visual representation and interaction techniques. It allows the users to see, explore and understand large amounts of information [Thomas, 2005].

The well known visual information-seeking Mantra *Overview first, zoom and filter, then details-on-demand* by Shneiderman [1996] provides design guidelines and a framework for designing information visualization applications.

More concrete, Card et al. [1999] identifies three primary uses of interaction for information visualization: to modify data transformation (filtering), to modify visual mappings, and to modify view transformation (i.e., navigation). Modifying data transformations can be achieved by:

- direct manipulation
- dynamic queries [Ahlberg et al., 1992], see figure 1
- brushing [Becker and Cleveland, 1987]

Brushing is the action of moving a rectangle with the mouse (called the brush) over a set of data points [Ahlberg et al., 1992]. It highlights selected data, and shadows out the other. The ability to change the size of the brush allows its user to select collections of data points.

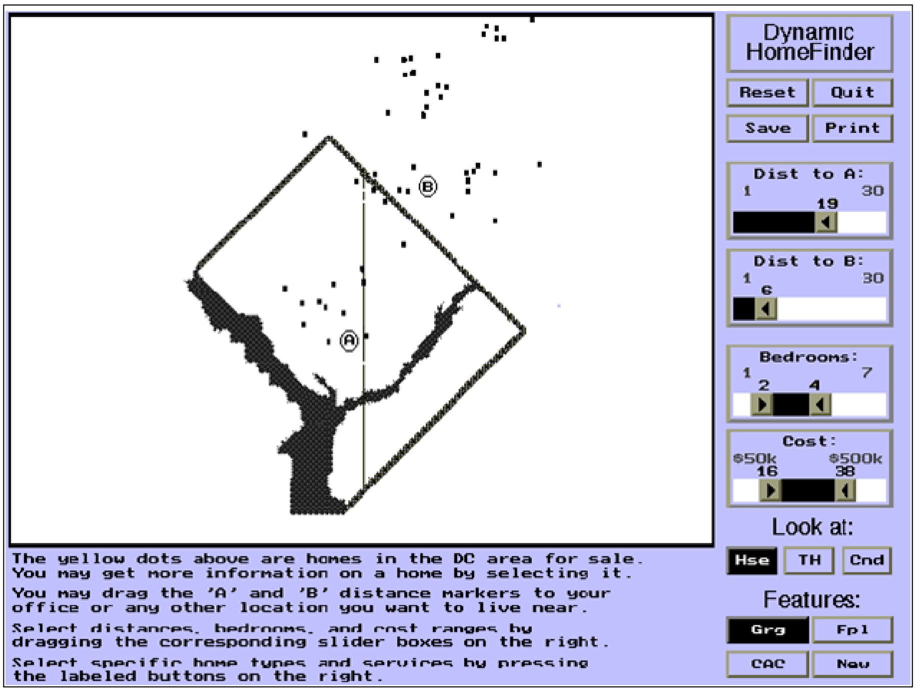

Figure 1: Dynamic Queries, visual sliders to query databases [Ahlberg et al., 1992]

2.1.2 Multidimensional multivariate visualization

Bergeron et al. [1994] gives us conventions for the frequently used terms multidimensional and multivariate. The term multidimensional refers to the dimensionality of the independent variables, and the term multivariate refers to the dimensionality of the dependent variables. A dependent variable is a function of another independent variable. Translated into an building example: a three dimensional volume space in which temperature and humidity are measured gives us 3- dimensional 2-variate data.

Many information visualization techniques for multidimensional and -variate data sets have been developed in the last two decades [Keim et al., 2006]. Wong and Bergeron [1994] summaries many of these techniques:

- Hyperslice
- Hyperbox
- Stick Figure Icon
- Autoglyph
- Color Icon
- Hierarchical Axis
- Dimension Stacking
- Worlds within Worlds
- Parallel Coordinates

- Circular View

Figure 2 shows examples of these techniques.

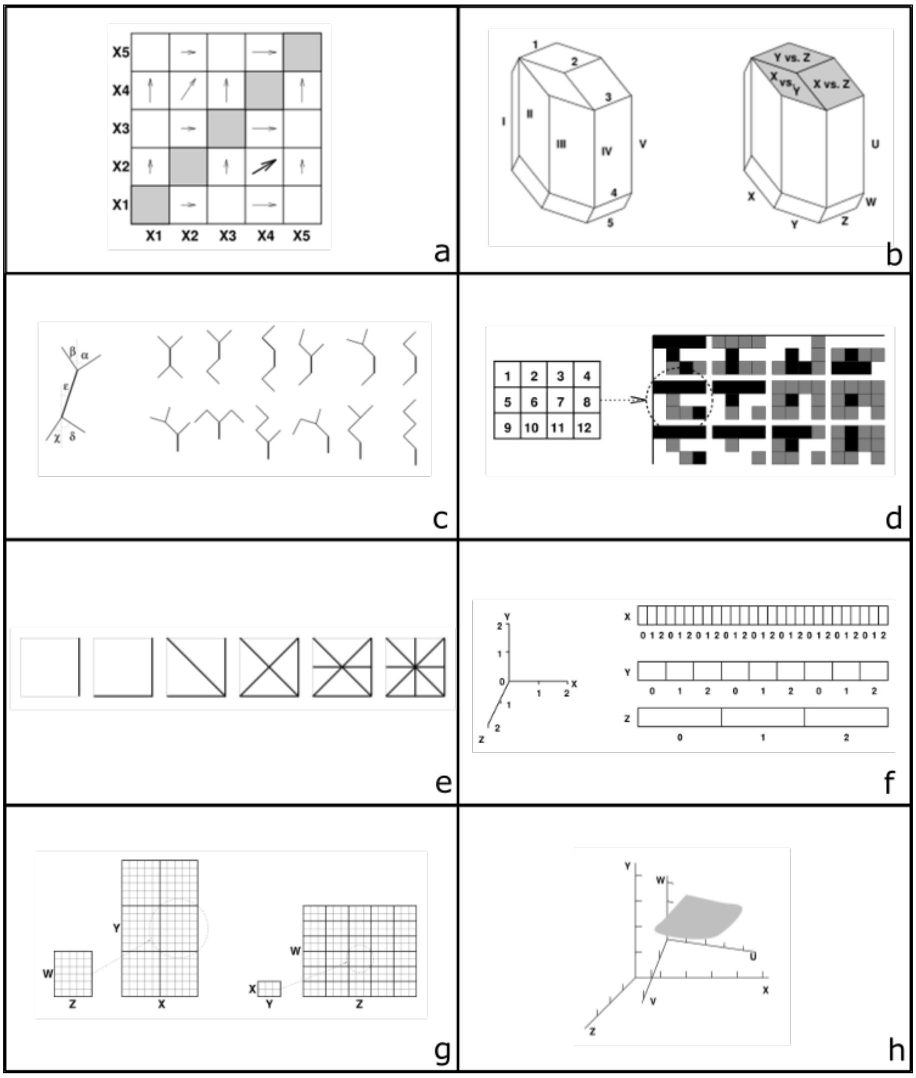

Figure 2: Multidimensional multivariate visualization techniques. a) Hyperslice b) Hyperbox c) Stick Figure Icon d) Autoglyph e) Color Icon f) Hierarchical Axis g) Dimension Stacking h) Worlds within Worlds. Source: [Wong and Bergeron, 1994]

The XmdvTool system developed by Ward [1994] implements a number of these techniques. The integration lets users explore users their multivariate data in different formats.

Guo et al. [2006] presents a visualization system for space-time and multivariate patterns. The techniques used include a parallel coordinate plot, several forms of reorderable matrices (including several ordering methods), a geographic small multiple display, and others. The a view of the system is shown in figure 3.

It uses coupling (linking) among the different techniques to leverage their independent strengths and facilitate a visual exploration of patterns that are difficult to discover otherwise. This

The two visualization techniques chosen for this work, parallel coordinates and circular view are explained in further detail.

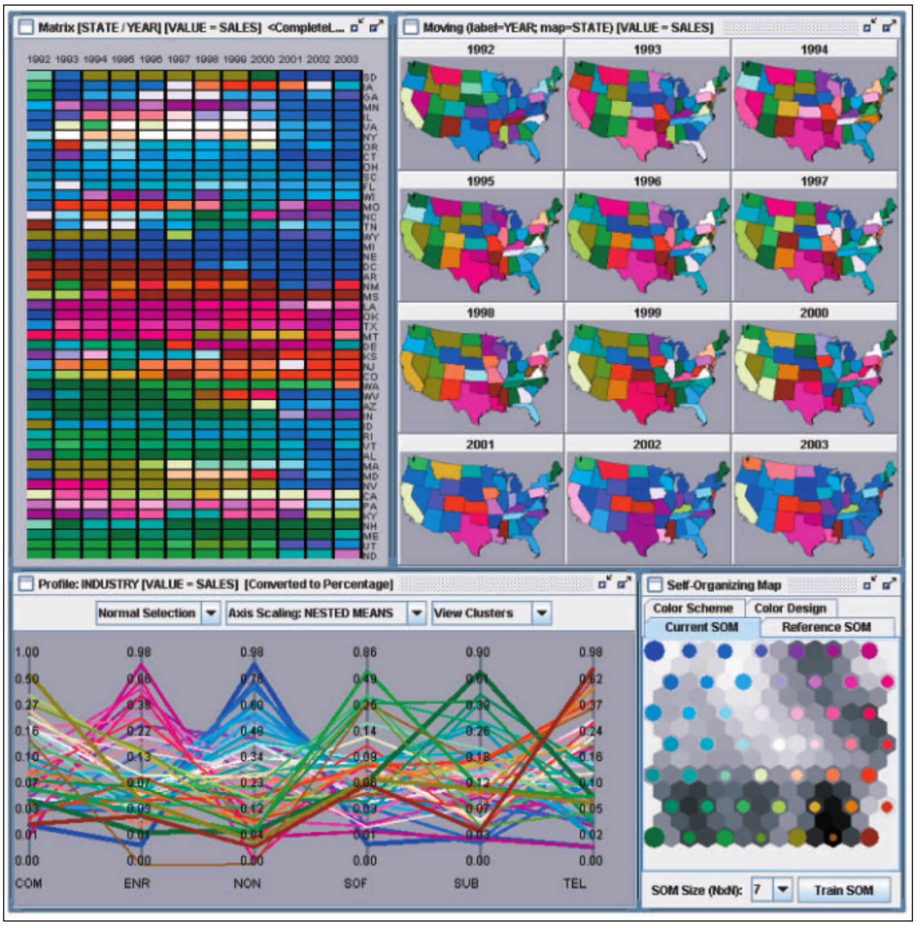

Figure 3: Different techniques used in the visualization system. (Top-left) The reorderable matrix, (top-right) map matrix, (bottom-left) multivariate legend-PCP, and (bottom-right) the SOM [Guo et al., 2006]

Parallel coordinates

Parallel coordinates have been invented in the 1970's and can be used for a broad set of multidimensional problems [Inselberg and Dimsdale, 1990]. They transform variable relations from multivariate data sets into 2-d patterns [Inselberg, 1997]. These patterns are well suited for visual data mining.

A set of n-dimensional data points is shown in the following way: the visualization consists of n parallel axes in a vertical arrangement, where each axis represents a dimension. A data point is represented as a polyline, connecting vertices on the axes. Figure 4 shows a set of mathematical functions organized in a parallel coordinates plot.

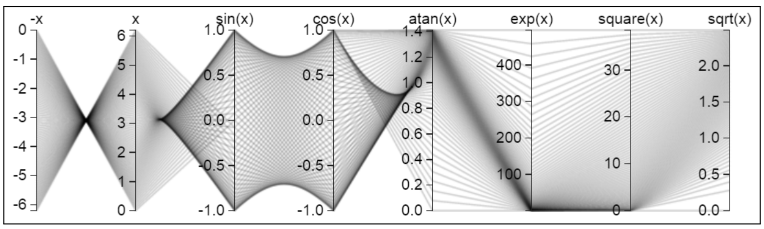

Figure 4: Mathematical functions visualized with Parallel coordinates [Chang, 2012]

The advantage of parallel coordinates is the transformation of high dimensional geometric properties into simple 2-d patterns. With this transformation, some loss of information is expected. A limitation is that each axis can have at most two neighbouring axes. So in a n-dimensional data set, at most n-1 relationships can be shown. The order of the axes is an important factor in finding features in the dataset. However, since these axes don't have a natural order, often many different orderings need to be tried in an data analysis [Yang et al., 2003].

According to Inselberg [Inselberg, 1997], the relationships between the axes can be read in the following way: parallel lines between two axes suggests a positive relationship between those dimensions, crossing lines in a x-shape suggests a negative relationship and if lines cross mostly randomly there is no relationship.

There are a few publicly available libraries that implement parallel coordinates, notably Protovis.js [1], D3.js [2]. D3.Parcoords.js[3] is a library based on D3.js and focuses on the creation of parallel coordinates graphs.

Circular heat map

A new visualization technique called Circle View [Keim et al., 2004] combines the popular pie chart with arrangement of time events on circle segments. It's used for the problem of analysing multidimensional or multivariate time-referenced data sets. The variables are plotted on a slice of a circle. Each of these slices is divided further, according to the distribution over time, shown in figure 5. The variable values are encoded in some statistical colouring.

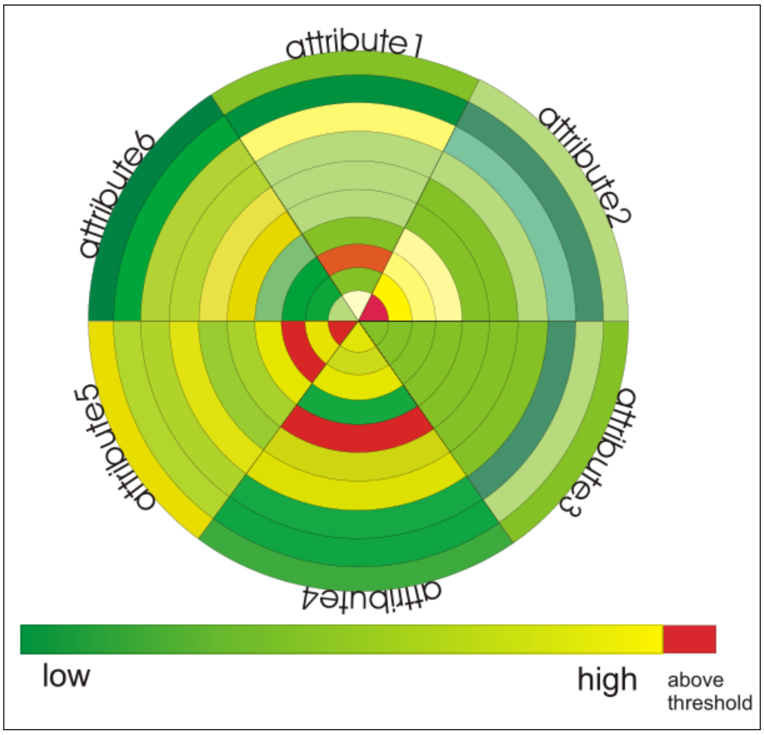

Figure 5: Circle View showing the evolution of multiple attributes over time [Keim et al., 2004]

A variation of this Circle View is presented by Cook [2013], called Circular Heat Chart. It uses the circle segments and its subsegments as time axes. An example is shown in figure 6 where the

[1] http://mbostock.github.io/protovis/ex/cars.html
[2] http://mbostock.github.io/d3/talk/20111116/iris-parallel.html
[3] http://syntagmatic.github.io/parallel-coordinates/

circle is divided into 24 hours segments and the subsegments display weekdays. Again, the variable values are then encoded in some statistical colouring.

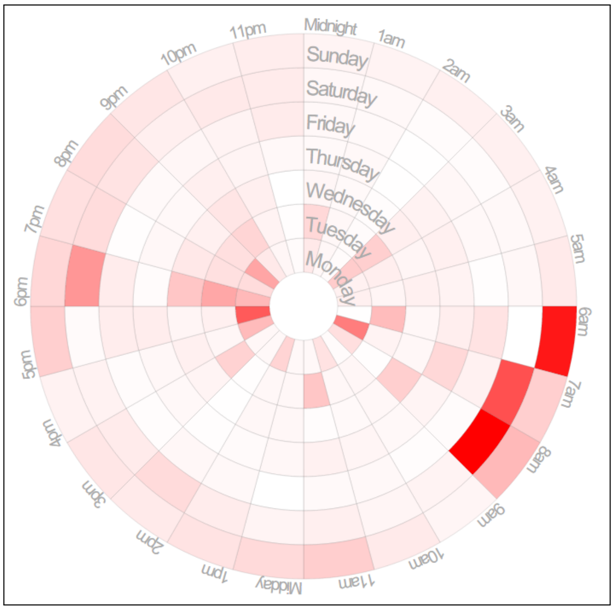

Figure 6: Circular heat chart example by [Cook, 2013]

Cook [2013] provides an JavaScript implementation of this heat map chart, d3-circularheat [4], based on d3.js.

2.2 Building monitoring and automation

The term building automation refers to the automatic centralized control of different building related systems like heating, ventilation and air conditioning (HVAC), lighting, blinds through a building management system (BMS) or building automation system (BAS).

Modern BAS's using direct digital control (DDC) not only provide automatic control of indoor environments, but also allow remote monitoring and control for facility operators. The purpose of this control has many purposes, most notably: facility maintenance, occupant comfort, equipment monitoring, safety and security [Yang and Ergan, 2014].

BAS's have to systems to support its operators in his monitoring task: alarm and warning systems and data visualization programs [Seem, 2007]. For the first type of systems, the calibration of the thresholds and warnings is a difficult tasks. Seem [2007] presents a method for detecting abnormal energy consumption in buildings based on daily readings of energy consumption and peak energy consumption.

Different kind of visualizations systems and their studies are presented in the following subsection.

2.2.1 User Interfaces and Visualization systems

Lehrer and Vasudev [2011] reviewed seven software products available for visualizing energy consumption information in commercial buildings and conducted a study with experts about attitudes and practices regarding visualization. The goal was to identify the optimal methods for visualizing

[4]http://prcweb.co.uk/lab/circularheat/

building performance information. They reported a common number of unmet information needs. One particular interesting concerning this work is the "integration of energy visualization features with data analysis: Many users rely on data downloaded from BMSs and manipulated in spreadsheet programs. The ability to filter and generate energy analyses in tabular or graphical form directly from the energy monitoring system would be a great time saver for these users."

An ideal energy visualization tool according the expert users would include a high-level overview with drill-down capabilities. One mentioned limitation of current tools is the lack of integration, none of the tools used by this group of subjects could combine multiple energy sources.

Another survey conducted by Chien et al. [2011] had the objective to "capture the views of the potential receivers of building monitoring information regarding the relative importance of different kinds of information and the modes and means of presenting and visualization such information."

Zach et al. [2012] presents a vendor and technology independent toolkit for building monitoring, data processing and visualization. It includes applications for data aggregation, display, visualization and analyses that simplify the use of building data. The author states that the currently available BMS could be improved in numerous ways, one being the presentation of performance data in a structured spatial and temporal manner. The authors argue that independence from the building market developments can be increased by using open-source technologies. They mention also that the visualization of data in a two or three dimensional building model is being explored. In future work, they'd also like to enhance the web visualizations to simplify the usage for non technical skilled users.

Yang and Ergan [2014] presents a research study motivated by a case study about visualization techniques for BAS's in a greenhouse facility. Their evaluation showed that there are challenges faced by facility operators that impede their efficiency and accuracy of their responses. These challenges revolve around:

- lack of spatial context for the monitored sensor readings and equipment statuses
- information overloading

The case study evaluated the current in-use interface of the BAS in the greenhouse facility, together with a sample set of other BAS interfaces in other greenhouse facilities or regular buildings, shown in figure 8 and 7. The authors hypothesize that visualization techniques could enhance facility operators' accuracy and efficiency during their monitoring tasks. The results of the tests showed "the accuracy and efficiency of operators' decisions during monitoring tasks are affected by how the information is displayed to them." The interfaces shown in the previous figures resulted in better accuracies and efficiencies, compared to the current tabular interfaces.

Struck et al. [2011] argues that "the traditional display formats, such as tables and graphs, are insufficient to communicate dynamic performance data since they are not adaptable to the users cognitive capacity and do not allow analysis of the interaction between system parameters and performance indicators." And Spence [2001] states that the use of interactivity can considerably enhance interpretation.

Raftery and Keane [2011] presents a visualization technique for effective analysis of building data. It combines binning with carpet plots, and is called carpet-contour plot, shown in figure 9.

The approach is most applicable on two independent variables. The author states further that an useful aspect is that the plots can sometimes highlight erroneous conclusions when two variables are slightly correlated.

The presented research clearly shows a trend towards more interactive and sophisticated visualizations for building automation systems. Parallel coordinates and circular heat charts are well known visualization methods for multivariate data. Their usefulness in a building data visualization application will be investigated, together with a brush interaction technique and a three dimensional building model.

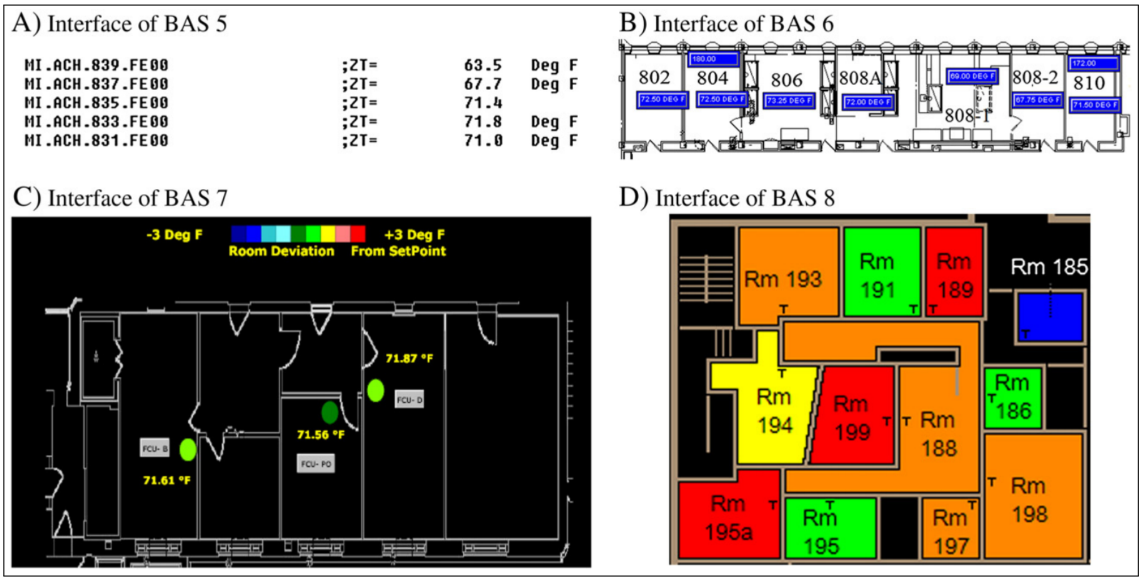

Figure 7: Sample set of BAS interfaces used for regular commercial building monitoring. [Yang and Ergan, 2014]

2.3 Thermal comfort

According to ASHRAE [5] , the term 'thermal comfort' describes the condition of mind that expresses satisfaction with the thermal environment. This satisfaction is assessed by subjective evaluation [ANSI/ASHRAE, 2013]. Humidity and temperature combine with personal factors (clothing) and work-related factors (physical activity) influence your thermal comfort [Health and Safety Executive, 2015].

ASHRAE defines an adaptive comfort model which is based on the idea that the outdoor climate influences indoor comfort because humans can adapt to different temperatures during different times of the year [De Dear and Brager, 1998].

The Société des Ingénieurs et Architectes suisses (Swiss society of engineers and architects, short: SIA) drafts and publish standards on buildings. It was funded in 1837, its members are mostly architects and civil engineers. Their publications include rules and directives, standards and technical reports. The role of the SIA standards are: design and control tools, summary of the state of the art and are used in court as reference.

The role of the SIA 180 standard is the protection against moisture and indoor climate in buildings. The first version appeared in 1970, and has been revised in 1988, 1999 and lastly in 2014. One of its objectives is the definition of an acceptable range of perceived temperature, shown in figure 10.

The standard differs between rooms with heating, cooling or mechanical air conditioning (violet) and rooms with natural ventilation, without cooling or heating (red).

For the rest of this thesis, thermal comfort refers to this SIA 180 standard from 2014.

[5] https://www.ashrae.org/

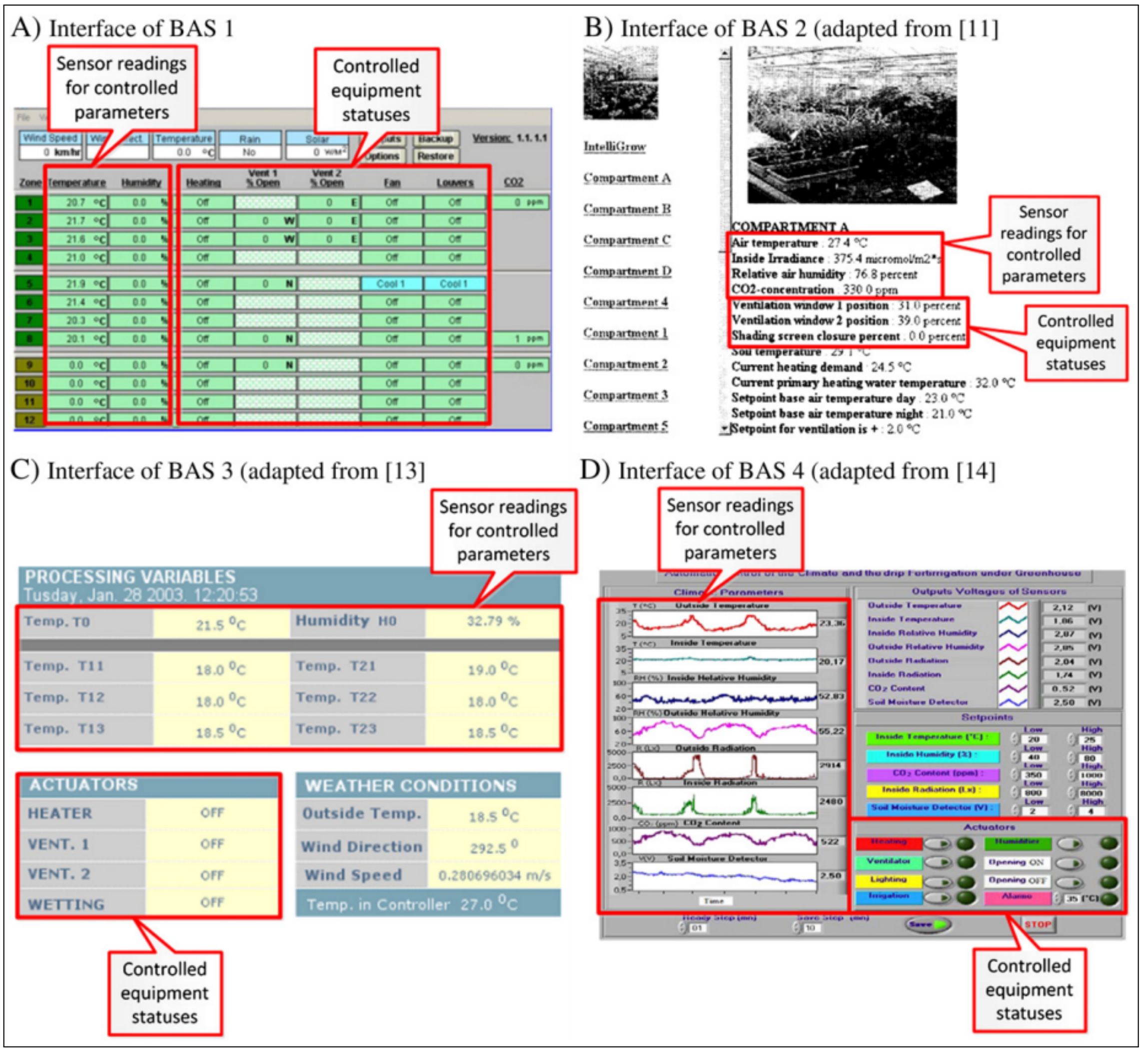

Figure 8: Sample set of BAS interfaces used for greenhouse building monitoring. [Yang and Ergan, 2014]

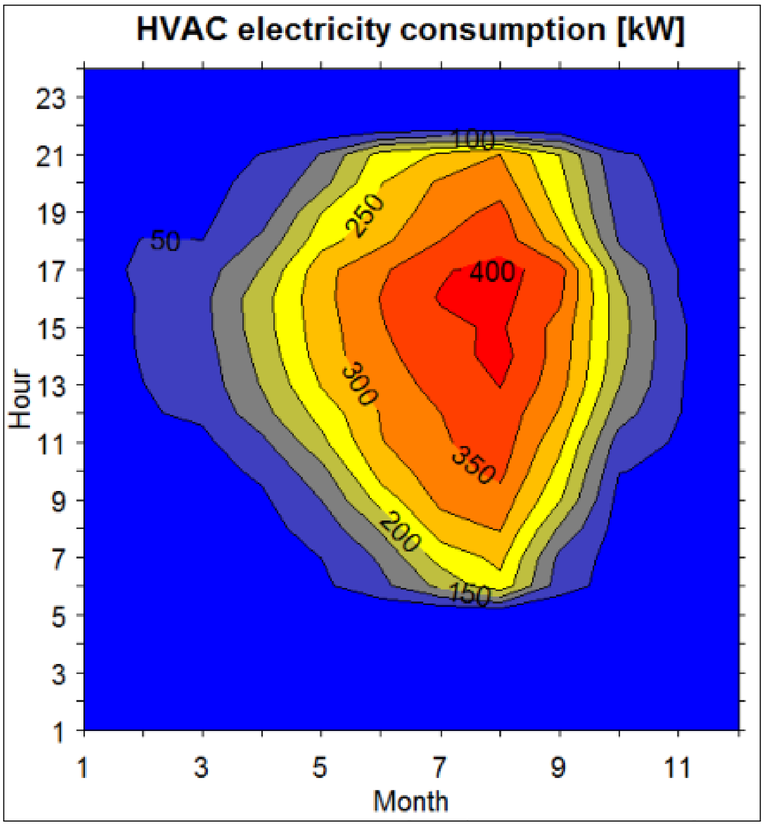

Figure 9: carpet-contour plot showing mean value of HVAC consumption against hour of day and month of year. [Raftery and Keane, 2011]

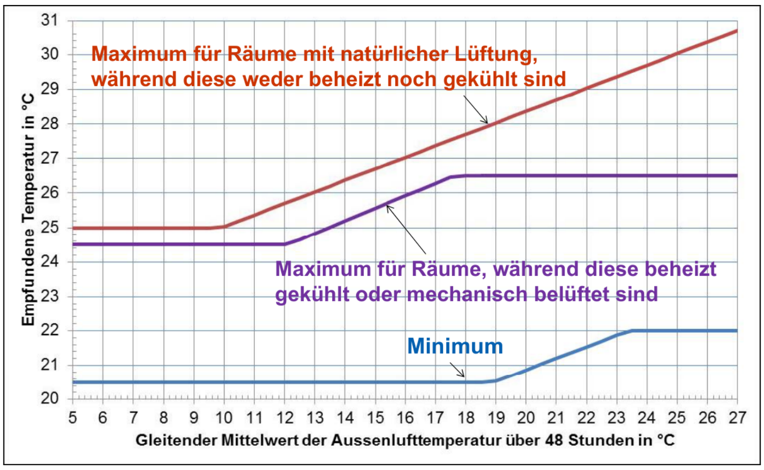

Figure 10: SIA 180: acceptable range of perceived temperature. Source: [Huber, 2014]

3 Monitored building: case study

The following section explains the monitored building in detail. This includes the building's use and system technology, various floor plans and the data set obtained from the monitoring.

3.0.1 Synergy BTC AG

Synergy BTC AG [6] is consulting agency with focus on Software-as-a-Service for buildings, located in Bern, Switzerland. The company specializes in complex planning and monitoring processes to support flexible, as well as distributed and growing data sets without compromising the quality or security of data.

The company acquired a dataset over several years from a monitored building and made it available for this project. The presented work will use this data for the proposed visualization system.

3.1 Building layout and System technology

The data set from the monitored building along with the additional information about it was provided by Synergy BTC AG.

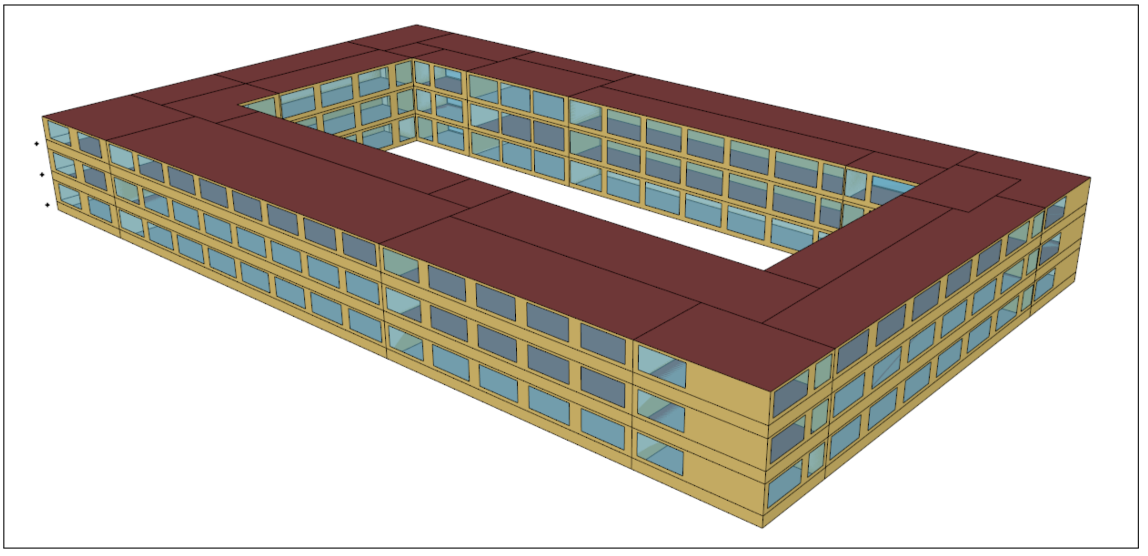

Figure 11: Model of the monitored building

The monitored building is located in eastern Switzerland. Figure 11 shows a model of the building. The following part summaries information about building use and system technology. Floor plans are also provided to explain further the zoning, mechanical ventilation system, and heating/cooling.

3.1.1 Information on building use and system technology

- Gross floor area: 9560 m^2
- Number of floors: 3
- Location: Eastern Switzerland, industrial area

[6] http://www.synergy.ch/

- Use: Office and administrative building

3.1.2 Building Shell

- Outside Walls: $U = 0.24\ W/m^2K$, massive
- Glazing: $Uf = 1.1\ W/m^2K$, $Ug = 0.65$, $g = 0.40$
- Interior walls: $U = 2.0\ W/m^2K$, lightweight

3.1.3 Space (zoning) per floor

- 13 office areas (mostly open space)
- 6 meeting rooms
- 5 border zones (traffic area, toilet, stairs)

Figure 12 shows the room layout for a floor of the office building. It's divided into three different zones: meeting rooms (red), office areas (green) and border zones (blue). For every floor, the zoning is the same.

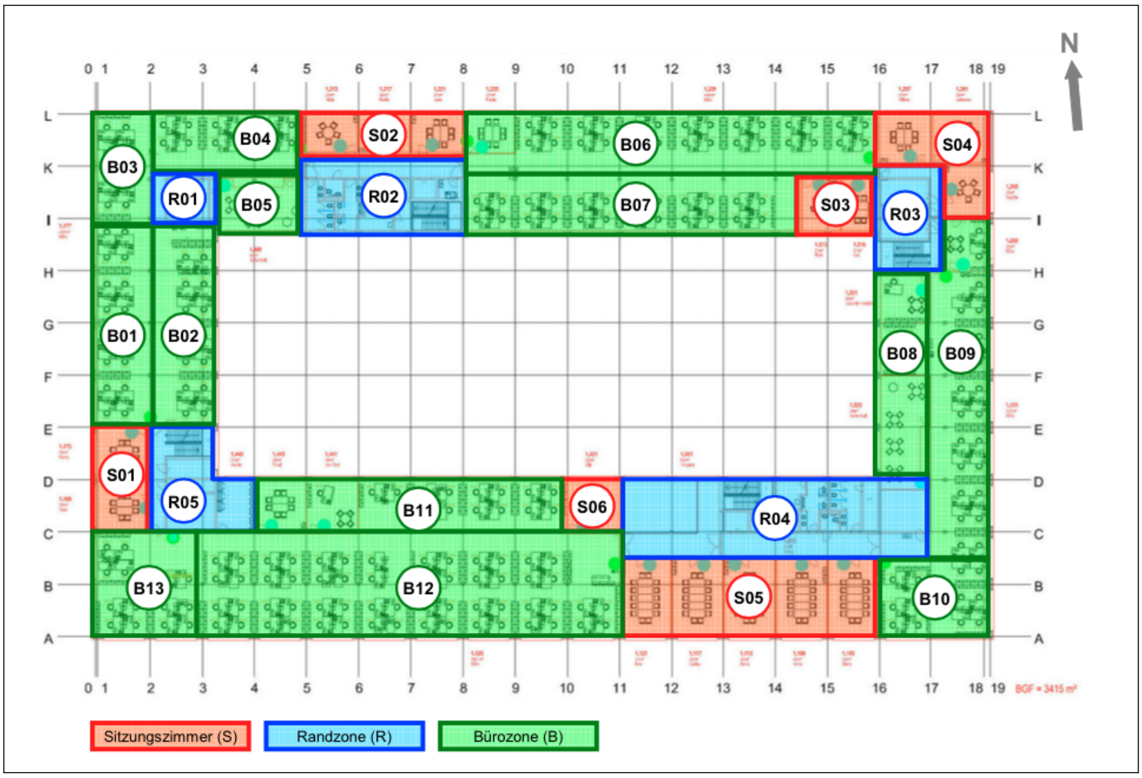

Figure 12: Room layout / zoning

3.1.4 Mechanical Ventilation System

The building is supplied by two mechanical ventilation systems (yellow and blue), as shown in figure 13. One ventilation system supplies all floors of the corresponding building side.

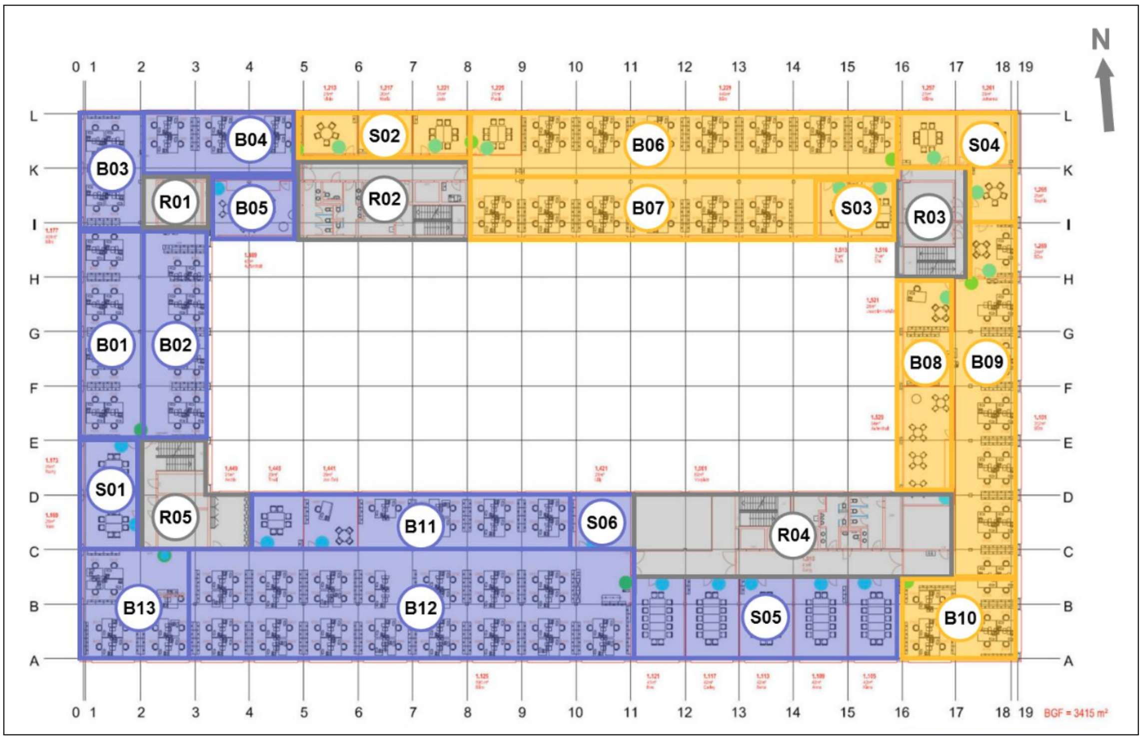

Figure 13: Mechanical ventilation system floor plan

3.1.5 Heating and Cooling

The buildings heating and cooling take place through thermally-activated building systems (TABS). Again, the building is supplied from two different systems (red and green), as shown in figure 14. One TABS zone supplies all floors of the corresponding building side.

There are some differences in zoning of the mechanical ventilation systems and the heating and cooling system. For example, room B10 is in the north/east zone of the ventilation system, but in the south/west zone of the heating and cooling system. The use of a building model, explained later in section 3.1, will help to provide a clear understanding of the zones layout during the application use. Fortunately, the 4 monitored rooms per floor correspond to the north/east south/west labelling.

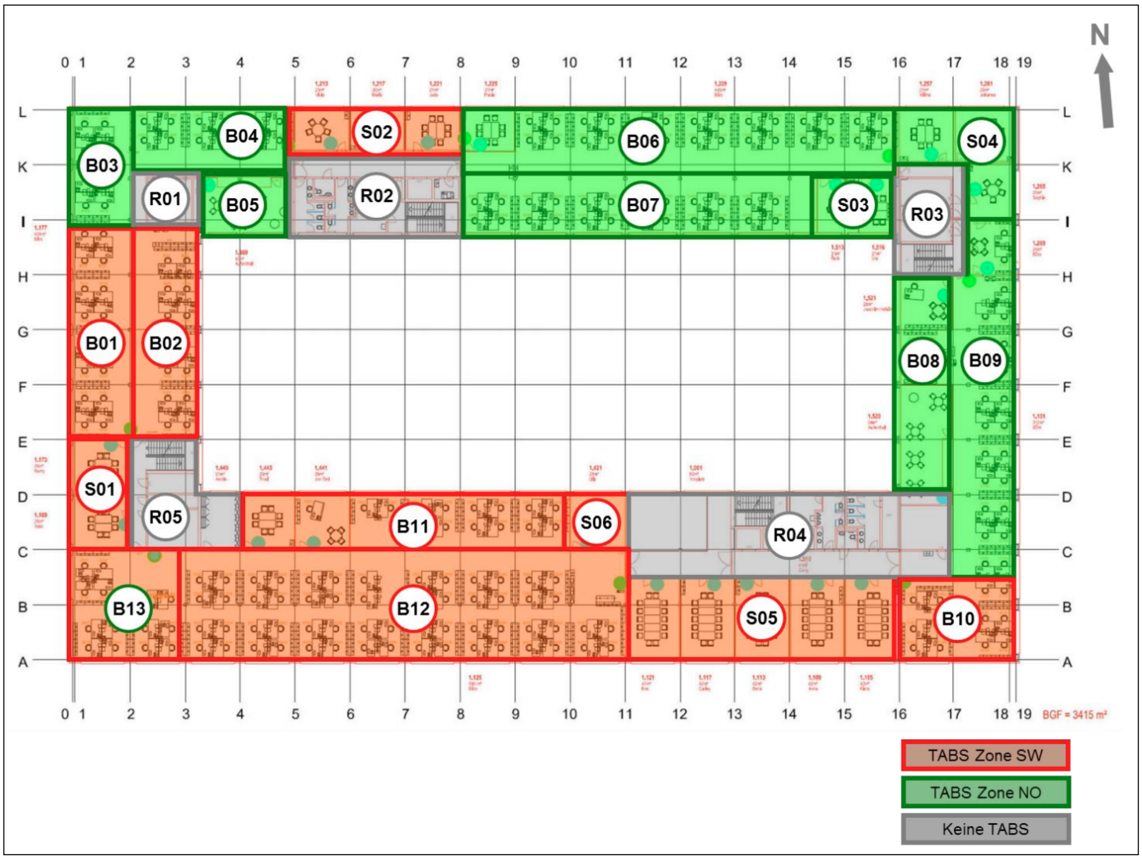

Figure 14: Heating and cooling systems floor plan

3.1.6 Room temperature and humidity

Four rooms on every floor are equipped with temperature and humidity sensors. Their location is shown in figure 15.

3.1.7 Mechanical sunblinds

- Outer slat blinds
- Automatic control depending on radiation and wind
- User intervention: can override blinds position
- All windows per building side are controlled in parallel
- Eight sectors (N/E/S/W inner courtyard, N/E/S/W outer road)

3.2 Building data

The data has been provided in a .csv file. The variables include room temperatures, window blind heights and angles, heating and cooling powers, CO^2 exhaust air and others. Table 1 shows a summary of the different variable categories, together with their units.

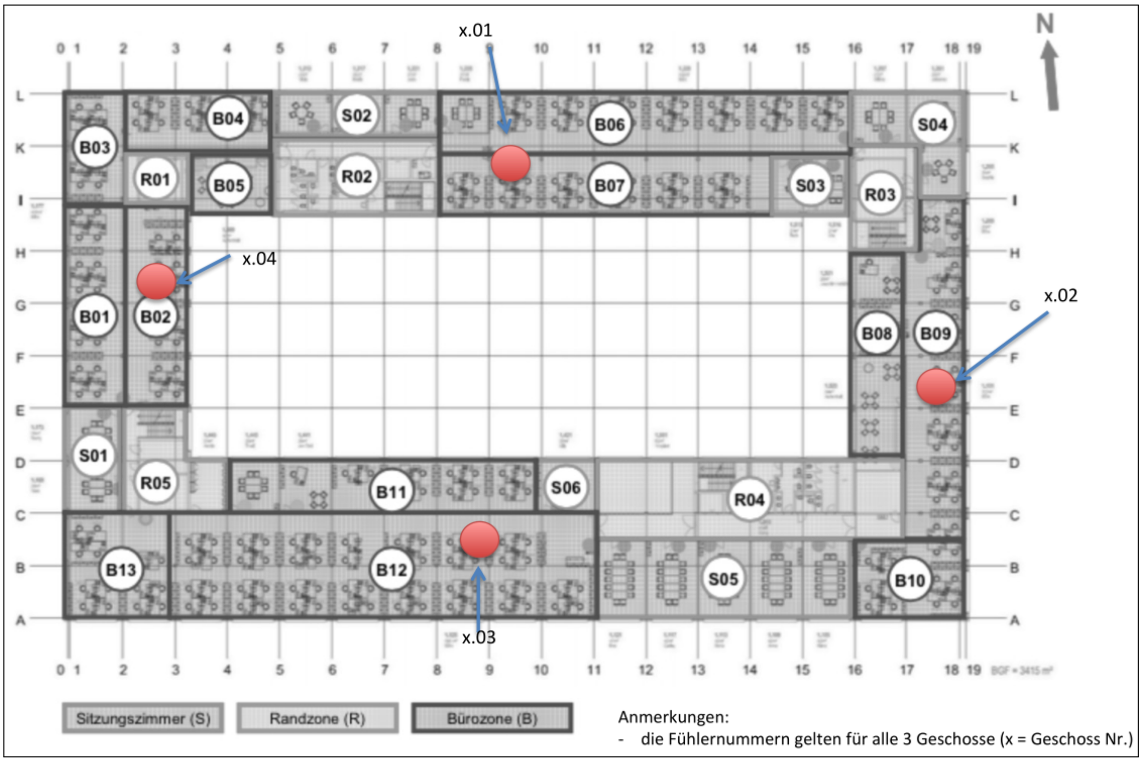

Figure 15: Room temperature and humidity sensors positioning (red dot)

Variable name	**unit**
CO^2 exhaust air	ppm
Humidity exhaust air	%
Temperature exhaust air	°C
Temperature intake air	°C
Cooling TABS	kWh
Heating TABS	kWh
Blinds height	%
Blinds angle	%
Blinds status	0/1
Room temperature	°C
Room humidity	%
Outdoor temperature	°C

Table 1: Monitored data variable categories with units

These variable categories may contain multiple variables. For example, the category 'Cooling TABS' contains 2 variables, one for each TABS zone. Or the category Room temperature, it contains a total of 12 variables (4 for each floor). The whole variable list contains a total of 61 variables. It can be found in appendix A. The data ranges over 3 years, from mid of 2012 until mid of 2015 with hourly measurements.

Additionally, the data set has been enriched with outdoor weather data. The buildings nearest weather station is Zürich-Kloten, for which the data has been acquired from the *Bundesamt für Meteorologie und Klimatologie Meteo Schweiz*. The variables are outdoor temperature (°C), precipitation (mm) and sunshine hours (min).

The hourly measurements are averaged over a day. This is a necessary step because of the application's performance. The refresh rate of the display is too slow in its current implementation with 3 years worth of hourly measurements. But the daily hours chosen for this average can be changed, explained later in section 5.1.4.

The data set is anonymous, no more information about the buildings location or surrounding area is available.

4 System Architecture and Technology

This chapter presents the general system architecture and technology used. First it gives an overview over the architecture and its different parts. Then it introduces the software and libraries used for the application.

4.1 Overview

The application developed is a web application. The reasons for this choice is the availability of powerful visualization libraries and reusability. The application uses a traditional three-tier architecture: a back-end database, an application web server and the front-end content rendered by the clients browser, as shown in figure 16.

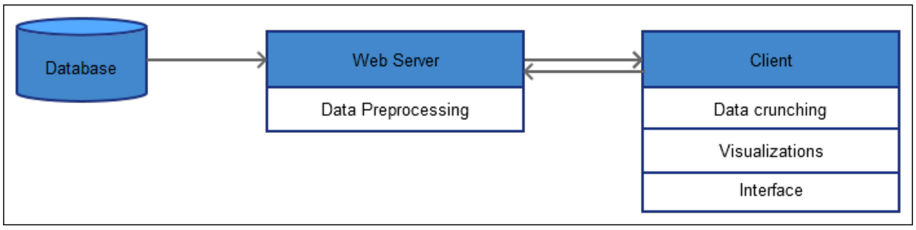

Figure 16: Three Tier System Architecture

This architecture has been chosen for performance and reusability reasons. The data crunching on the client side requires computational power, especially because of some of the interaction possibilities (filtering). With this architecture choice, the other two tiers can run on different machines, reducing some load for the client. The application could also be hooked to a (live) database from another building. Assuming the same data structure and a new corresponding building model, the application could then work with this new data set.

Starting with the database, the following subsections will explain the different parts of the system architecture in more detail.

4.2 Database

The data tier holds and retrieves information from a database. MongoDB [7] has been chosen as a database implementation. MongoDB is an open-source document database. It provides high performance, high availability and automatic scaling [MongoDB Inc., 2015].

Records in a MongoDB database are called documents and are key value pairs. Values may include other documents. Analogue to tables in relational databases, documents are stored in collections. These records are stored in a binary JSON format, called BSON [Quinstreet Enterprise, 2015].

PyMongo [8] is a Python [9] Module, containing the tools necessary to work with MongoDB from a Python application.

4.3 Server-side software

Flask [10] is a micro web framework written in Python. It has no database abstraction layer or form validation. But there are several extensions to add application features. One of such extensions

[7] https://www.mongodb.org/
[8] https://docs.mongodb.org/getting-started/python/client/
[9] https://www.python.org/
[10] http://flask.pocoo.org/

is the PyMongo modul. It facilitates the retrieving and storing of records in the database. It also provides the views and controller for the client-side, in form of HTML files, CSS files and JavaScript libraries. The retrieved data records are transferred to the client machine in JSON format.

4.4 Client-side software

The client-side content is retrieved from the web server and rendered in the clients browser. The application is created with common web technologies, namely HTML, CSS, SVG and JavaScript. The latter provides useful libraries:

- queue.js [11] is an asynchronous helper library for JavaScript. It is used to retrieve the data records from the web server.
- jQuery [12] is a feature-rich JavaScript library. In this application it is used to do minor data crushing.
- crossfilter.js [13] is a library created for the purpose of exploring large multivariate data sets in the browser. It uses sorted indexes for fast filtering of large data sets. This library does the major part of the data crushing.
- d3.js [14] is a popular JavaScript library for web visualizations. It allows to bind arbitrary data to a Document Object Model (DOM), and then apply data-driven transformations to the document.
- d3.parcoords.js [15] facilitates the creation of parallel coordinates visualizations with the help of the d3.js library. It is used, with some modifications explained later in section 5.1.1, to create the parallel coordinates visualization.
- circularHeatChart.js [16] is a library for the creation of circular heat maps with the help of the d3.js library. With some modifications made explained later in section 5.1.2, this library provides the means for the desired circular heat map visualization.

The building model received, explained in section 3.1, was provided in the SKP format. This is a three-dimensional model created by SketchUp [17] software. It has been exported in SVG format to be viewed in the web browser. The exact locations of the different building zones and rooms have been extracted with the help of Inkscape [18].

With the help of these libraries and tools the front-end application is created, explained in the next section.

[11] https://github.com/mbostock/queue
[12] https://jquery.com/
[13] http://square.github.io/crossfilter/
[14] http://d3js.org/
[15] http://syntagmatic.github.io/parallel-coordinates/
[16] https://github.com/prcweb/d3-circularheat
[17] http://www.sketchup.com/
[18] https://inkscape.org/en/

5 Proposed system

The following section explains the different parts of the application. The first part is dedicated to the visualizations used, the parallel coordinates, the circular heat map and the building model. It presents the implemented visualizations in detail. The second part then presents the interface of the application and highlights interaction possibilities.

Figure 17 shows a screen shot of the application with the different parts in place. The parallel coordinates plot is located on the top left, the circular heat map plot on the top right. In the bottom left one can find the building model and on the bottom right the time chart.

Different variables can be added or removed from the visualizations by clicking on them in the building model. The current view shows 3 selected variables, sunshine hours in yellow, room 203 comfort in green and TABS heating south/west in magenta. The data range of the variables can be filtered by brushing on the axis on the parallel coordinates visualization. The circular heat map is linked to the applied filters, displaying the same data as the parallel coordinates, in another representation.

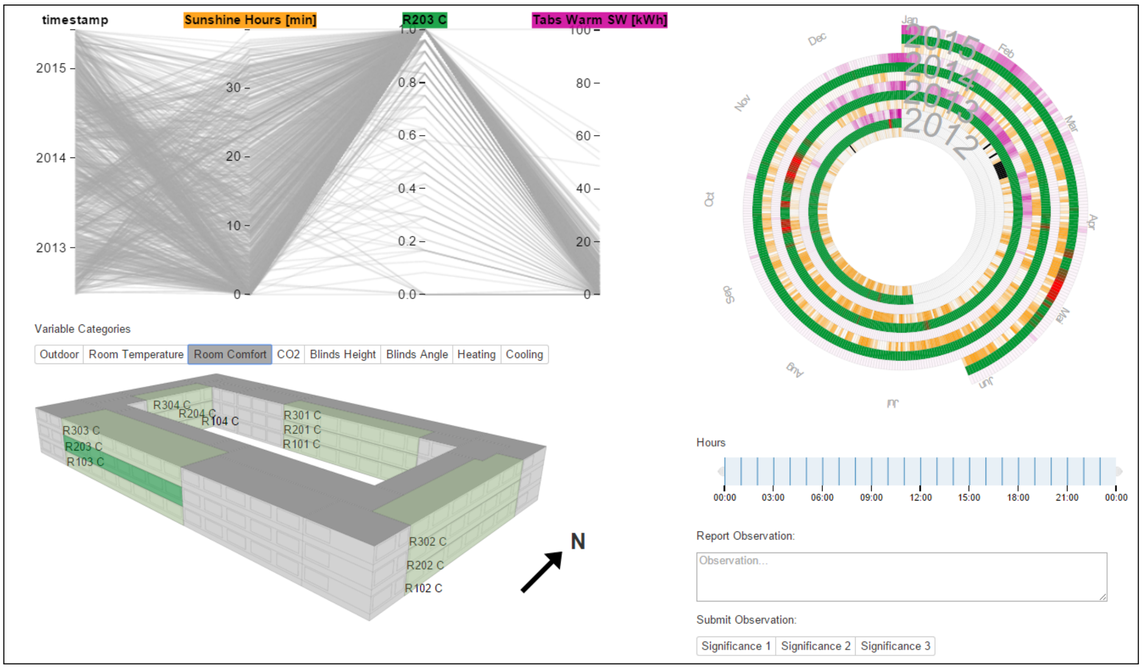

Figure 17: Full Application Screen Shot

5.1 Visualizations

5.1.1 Parallel coordinates

With the library *d3.parcoords.js* mentioned in section 4.4, the application visualises the building data in a parallel coordinates plot, as shown in figure 18.

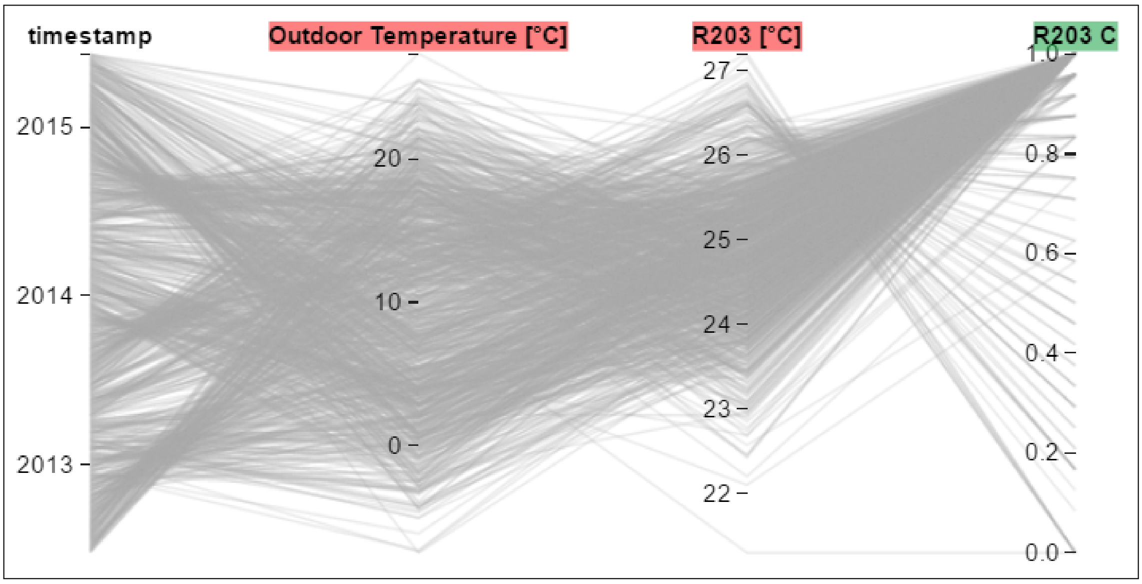

Figure 18: Parallel coordinates plot

The first axis on the left side displays the timestamp for each measurement made, or to be more precise for each daily average. This axis includes the time dimension of the data into the visualization. Because of its importance, it is always displayed. The other axes display different variables, each labelled with name and unit. Which variables are displayed is up to the user. A polyline connects each measurement, starting from the timestamp axis to the first selected variable, continuing over every selected variable. As mentioned in section 2.1.2, parallel lines between two axes suggests a positive relationship between these variables, crossing lines in a x-shape suggests a negative relationship and if lines cross mostly randomly there is no relationship.

Brush-interaction on an axis allows to apply a filter on the variables data range. For example, a user may want to have a look at high outdoor temperatures. Figure 19 shows such a brush on the outdoor temperature variable. The actual brush is surrounded by a red rectangle to highlight it.

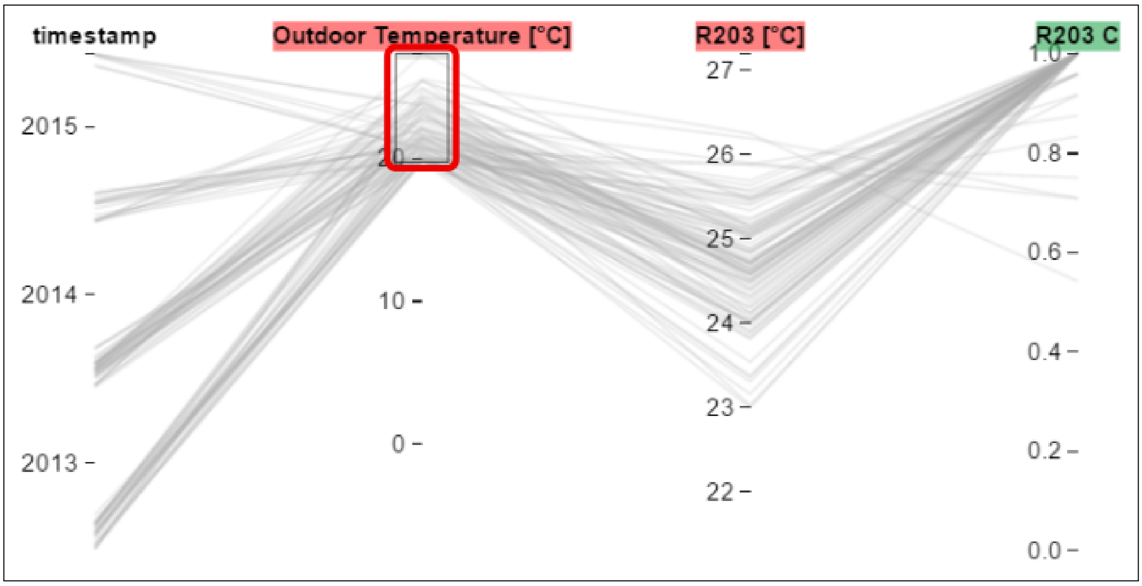

Figure 19: Parallel coordinates plot with brush (highlighted by a red square)

It is also possible to switch the axis ordering, to better understand the relation between neighbouring variables. The addition or removal of variables takes place via the building model, explained later in this section.

Some additions or modifications have been made to the library to extent its functionality. First, the axis label's background have been coloured to match the ones used in the building model and circular heat map. Second, the colouring of the lines connecting the axis can be changed to match a selected variables range. The color scheme chosen is a classic traffic light colouring. Red indicates a high value, green a low one. Figure 20 shows the colouring of the connecting lines by outdoor temperature. Low temperature values are coloured in green, medium ones in yellow and high ones in red. As expected, low temperature values occur during the winter months on the timestamps axis, high ones during summer months. Interestingly, there is not a positive relationship between outdoor temperatures and room temperatures (variable R203). Both the highest, and lowest outdoor temperatures lead to average (23-26 °C) room temperatures. Not surprisingly, the heating system (TABS Warm) is active during low outdoor temperatures, but there are some interesting outliers worth investigating.

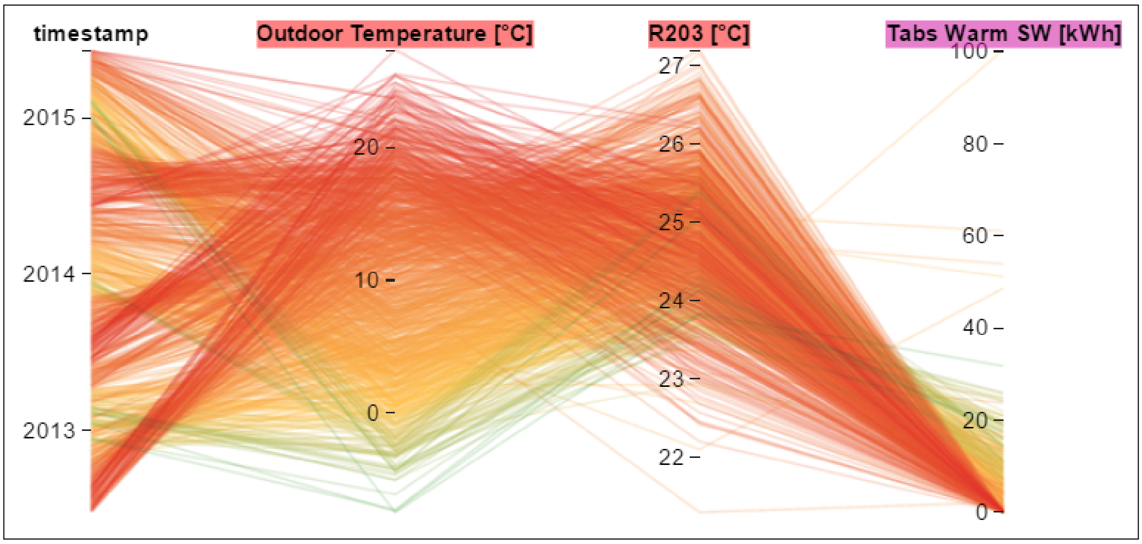

Figure 20: Parallel coordinates plot with coloured lines by variable outdoor temperature

Third, the axis labels are now interactive, a click on them highlights the respective variable category and building part in the model, see section 5.2.

5.1.2 Circular heat map

The circular heat map plot has been implemented with the library *d3-circularheat* mentioned in section 4.4. Some modifications have been made in the library that the visualization now can display any number of variables, instead of just one. Figure 21 shows the modified visualization with three variables. The visualized variables are: TABS heating (magenta), outdoor temperature (green-red) and sunshine hours (yellow).

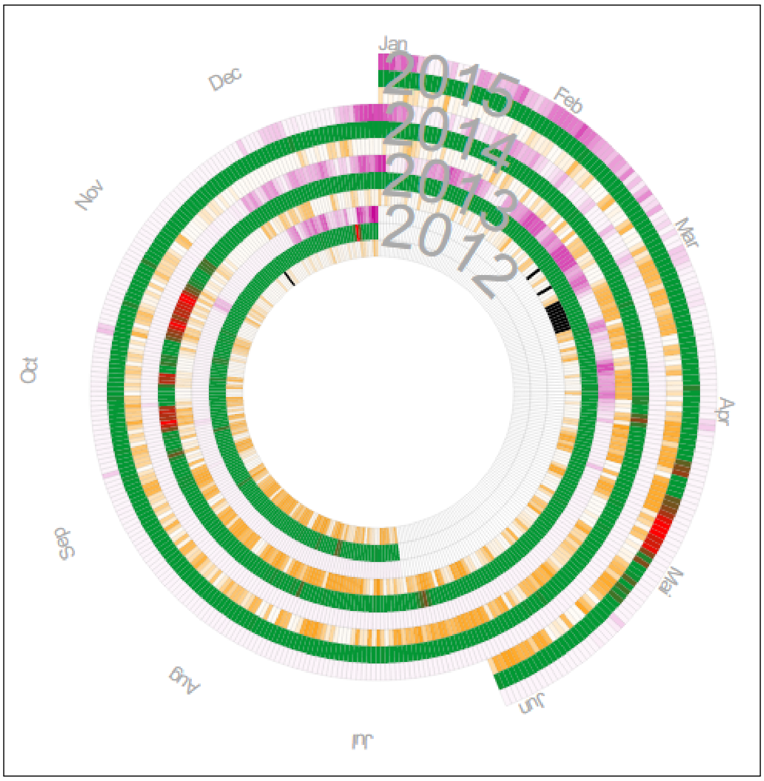

Figure 21: Circular heat map plot

Starting at 12 o'clock with January, a data range of one year takes one clock cycle. Further cycles display more years worth of data.

The colors used in the visualization have been selected with colorbrewer [19]. The variables are coloured in the same colors as on the parallel coordinates plot and building model plot. The values are coded in different shades of its variable color. Dark indicates a high value, light a low value. Exception being the colors for room comfort and temperature. For room comfort, the color ranges from green (comfortable) to red (uncomfortable), for temperature it ranges from red (high temperature) to blue (low temperature). The purpose of this colouring is to give these variables a more intuitive way of interpreting them.

[19] http://colorbrewer2.org/

5.1.3 Building model

The application includes a model of the monitored building, shown in figure 22.

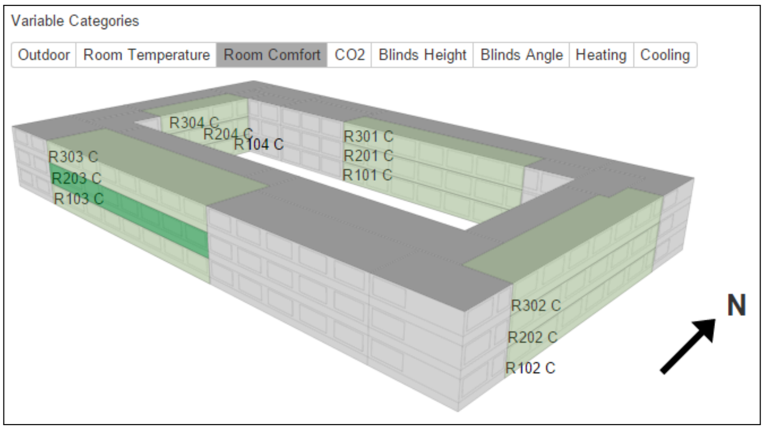

Figure 22: Building model plot

The models purpose is manifold. First, it gives the user a general idea about the layout of the building. Second, it highlights the different rooms or zones a variable stands for and gives meaning to their spatial dimension. The different zones are shown in figure 23 and correspond to the ones shown on the floor plans in section 3.2. And third, it allows to add or remove variables to the parallel coordinates and circular heat map plot.

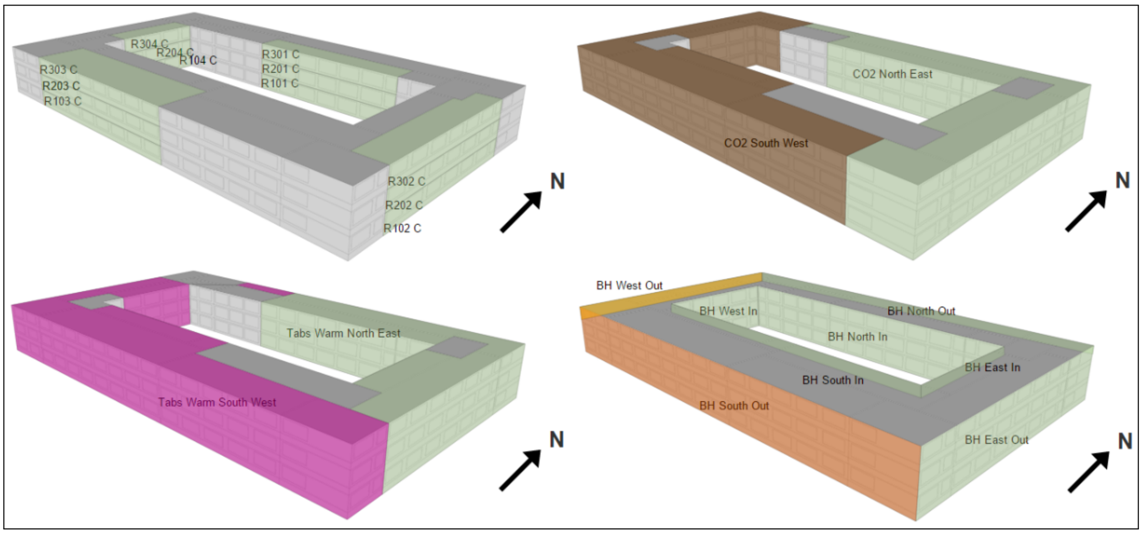

Figure 23: Different rooms and zones highlighted or selected in the building model. Top left shows the monitored rooms, top right ventilation system zones, bottom left TABS zones, bottom right window blinds

5.1.4 Hour time chart

The application displays computed daily averages of the measured data. A modified time chart is used to display the hours of a day, shown in figure 24. With the use of a brush, the daily hours chosen to compute this average can be modified. For example a comfort value may be only interesting if people are present. So this time chart will allow the selection of office hours, ranging from 07:00 to 17:00.

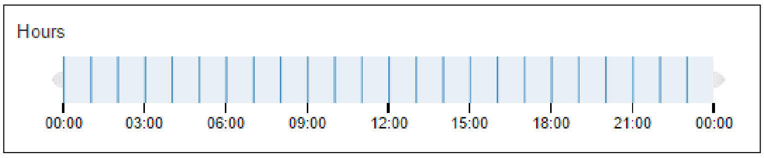

Figure 24: Hours time chart plot with brush selection

5.2 Interface

Interaction possibilities within the application are always indicated with a change of the mouse cursor. The cursor changes to a pointer for button, building model and axis clicks. For the parallel coordinates filtering it changes to a crosshair. The resizing of the time chart hour selection is indicated by a resize cursor.

Located above the building model are a series of buttons labelled with the variable categories. A click on one of them changes the view of the model to the corresponding zoning. Hovering over a part of a zone highlights its dimension. By clicking on a zone, the variable for which the zone stands for gets added or removed to the parallel coordinates and circular heat map plots.

For the parallel coordinates, the different axes can be switched around by dragging the axis label. A single click on an axis label switches to the corresponding variable category of the building model and highlights the specific zone or room. Control + click on an axis labels changes the colouring of the parallel coordinates lines, according to the classic traffic light colouring explained earlier. By dragging the mouse cursor on an axis, a filter can be applied. These filters will also be applied on the circular heat map plot. Both plots display always the same data, in a different visual representation.

By dragging, a filter can be applied to the hour time chart. Doing so will recalculate the average values visualized, corresponding to the selected hours.

Figure 25 shows the application in full screen mode.

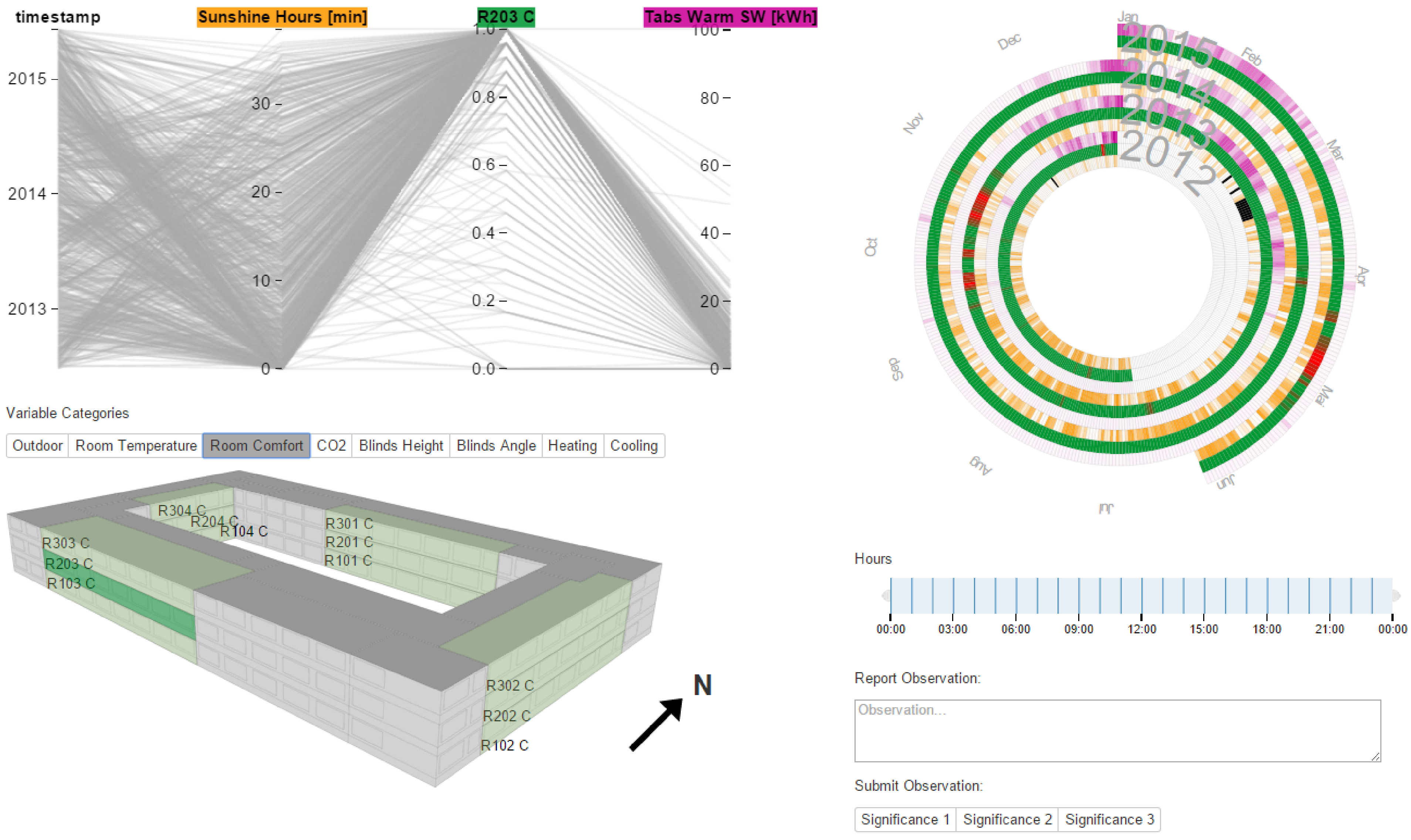

Figure 25: Application in full screen

6 Evaluation and testing

This chapter describes the qualitative testing done to evaluate the application. The first part describes the experiment environment. A number of experts have been asked to evaluate the application by testing it and by answering a short questionnaire. The testing was done in an exploratory manner; no strict protocol was presented to the participants. The visual exploration process has the purpose to gain insight, which would be difficult to measure with controlled experiments, suggested by Saraiya et al. [2005]. The participants were asked to report observations made during their application testing. The second part of the chapter deals with the analysis the collected results. The application will be evaluated in terms of usability and usefulness. A short conclusion summaries the most important findings.

6.1 Experiment environment

In order to test the applications usability and usefulness, an evaluation has been set up. A number of experts from different organizations haven asked to participate in the evaluation. A short questionnaire has been created to estimate the participants experience in building physics, monitoring and data visualization, and to rate the usability and usefulness of the different parts of the application. After answering the first part of the questionnaire, the application was tested with each participant. They were asked to report observations they could make within the data. The interaction with the application by the participants has been logged in order to reconstruct and understand the actions made by the participants. After this testing, the second part of the questionnaire was answered by the participants. The purpose of this second set of questions is collect feedback concerning the usability and usefulness of the application.

6.1.1 Participants

A total of 12 experts have been asked to participate in the evaluation of the application. They are from 4 different organizations:

- 5 experts from an engineering office for environment and safety with a building physics background
- 5 experts from a research laboratory for smart buildings with a building physics background
- an expert for building engineering from a consulting agency with focus on Software-as-a-Service for buildings
- a visualization expert from an University

Although from the same group, the individual participants are skilled in different domains. The first part of the questionnaire will help to understand these individual strengths and weaknesses.

6.1.2 Procedure

The evaluation done with every participant has been subdivided into 4 parts.

1. Introduction and Information about building use (3')
2. Questions about participants background (2')
3. Application Evaluation (15'-20')
4. Questions about Interface and Application Performance (2')

The first part was a short introduction into the evaluation, the test building, system technology and ethical concerns about user data recording. For the second part, the participants were asked to answer four questions about their background:

1. How comfortable are you using a new software or computer?
2. How familiar are you with Building Physics?
3. How familiar are you with Building Monitoring Systems?
4. How familiar are you with Data Visualization?

The questions could be answered on a 5-point Likert Scale [McLeod, S. A., 2008] ranging from *not at all* to *extremely*. These questions had the goal to estimate the users skills with computers in general and his/her familiarity with building physics, monitoring and data visualizations. The third part of the evaluation was the actual application testing. The users were asked to test the application out and discover its functionality. Because of the visual exploration purpose of the application, no strict protocol was presented that told the users how to proceed. If they made an observation concerning variable relationships, system behaviour, outliers, etc. they were asked to record it in a special field within the application, shown in figure 26. They were also asked to rate the significance of the observation made on a scale from 1 to 3.

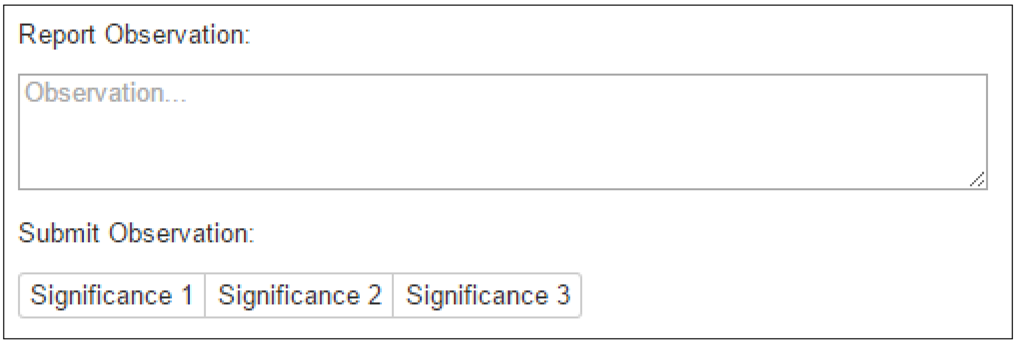

Figure 26: Textfield and buttons to report an observation

For the fourth and last part of the evaluation the participants were asked again to answer five questions:

1. How would you rate the usefulness of the parallel coordinates visualization?
2. How would you rate the usefulness of the circular heat map visualization?
3. Did you find the linking between the two visualizations above useful?
4. How good is the interaction with the application?
5. Did you find the interaction with the 3D-building model useful?

Again, the questions could be answered with the same Likert Scale as for the previous questions.

6.1.3 Questionnaire

The actual questionnaire handed out the the participants of the evaluation can be found in the appendix A.

6.1.4 Logging

For the evaluation, a system has been set in place to record the participants actions during the testing of the application. Each user action within the application (button clicks, slider movements, etc.) has been recorded with its timestamp. Together with the user made observations, this data was posted back to the web server for further analysis. Figure 27 shows such an example log file.

```
{
    "2015-11-03T09:19:49.547Z": "VarOverButton13",
    "2015-11-03T09:19:49.567Z": "VarOutButton13",
    "2015-11-03T09:19:49.713Z": "VarOverButton13",
    "2015-11-03T09:19:49.753Z": "VarOutButton13",
    "2015-11-03T09:19:49.783Z": "VarOverButton13",
    "2015-11-03T09:19:50.326Z": "VarClickButton13",
    "2015-11-03T09:19:50.989Z": "VarOutButton13",
    "2015-11-03T09:19:52.525Z": "VarOverButton5",
    "2015-11-03T09:19:53.168Z": "VarClickButton5",
    "2015-11-03T09:19:53.949Z": "VarOutButton5",
    "2015-11-03T09:20:01.853Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:03.342Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:04.190Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:05.215Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:06.425Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:07.252Z": "Axis click: Tabs Warm SW [kWh]",
    "2015-11-03T09:20:17.776Z": "VarClickButton46",
    "2015-11-03T09:20:18.409Z": "VarOverButton46",
    "2015-11-03T09:20:19.556Z": "VarOutButton46",
    "2015-11-03T09:20:19.557Z": "VarOverButton45",
    "2015-11-03T09:20:27.479Z": "VarOutButton45",
    "2015-11-03T09:20:27.836Z": "VarOverButton46",
    "2015-11-03T09:20:28.165Z": "VarOutButton46",
    "2015-11-03T09:20:51.795Z": "SubmitClick:1, finding: Raumtemperatur R203 grösser R103, kleiner R303"
}
```


Figure 27: Sample log file of one observation concerning

In terms of usefulness, the log files purpose it to reconstruct the observations made by the user and the comparison of different user behaviours. In terms of usability, the log files may highlight interface problems. The interpretation and visualization of these log files is discussed in the next subsection.

6.2 Results

This subsection presents the collected results and interprets them. It's divided into two parts, the usability and usefulness of the application. Figure 28 summaries the collected responses from the questionnaire.

ID	Question	Median	Mode
Q1	How comfortable are you using a new software or computer?	very	very
Q2	How familiar are you with Building Physics	moderately/very	moderately
Q3	How familiar are you with Building Monitoring Systems	slightly/moderately	slightly
Q4	How familiar are you with Data Visualization?	slightly/moderately	slightly
Q5	How would you rate the usefulness of the parallel coordinates visualization?	very	very
Q6	How would you rate the usefulness of the circular heat map visualization?	moderately	moderately
Q7	Did you find the linking between the two visualizations above useful?	moderately	moderately
Q8	How good is the interaction with the application?	moderately	moderately
Q9	Did you find the interaction with the 3D-building model useful?	very	very
Obs_Total	Total Observations	3.5	3

Figure 28: Questionnaire statistics: median and mode

The first four questions had the goal to estimate the participants skills in areas important for this evaluation. It shows that many participants are comfortable with new software or computers. Moderately to very familiar with building physics, and moderately to slightly familiar with building monitoring systems and data visualization. Figure 29 shows a matrix for spearman correlation [Lehman, 2005]. Highlighted in green are strong correlation values.

There is a strong correlation (0.83) is between question Q1 and the number of observations by a

spearman	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Obs_Total
Q1	1.000	-0.091	0.034	0.762	0.811	-0.270	-0.079	0.512	0.579	0.828
Q2	-0.091	1.000	0.759	-0.251	-0.102	0.287	0.287	0.301	0.305	0.109
Q3	0.034	0.759	1.000	0.090	-0.039	0.238	0.379	0.321	0.423	0.289
Q4	0.762	-0.251	0.090	1.000	0.554	-0.281	-0.272	0.159	0.463	0.636
Q5	0.811	-0.102	-0.039	0.554	1.000	0.020	0.282	0.510	0.534	0.684
Q6	-0.270	0.287	0.238	-0.281	0.020	1.000	0.729	0.247	0.077	-0.229
Q7	-0.079	0.287	0.379	-0.272	0.282	0.729	1.000	0.533	0.043	-0.133
Q8	0.512	0.301	0.321	0.159	0.510	0.247	0.533	1.000	0.242	0.311
Q9	0.579	0.305	0.423	0.463	0.534	0.077	0.043	0.242	1.000	0.774
Obs_Total	0.828	0.109	0.289	0.636	0.684	-0.229	-0.133	0.311	0.774	1.000

Figure 29: Questionnaire statistics: spearman correlation matrix

participant. As one might expect, the more comfortable a user is with handling a new software, the faster he/she is able to use it in an effective manner. This holds also true for this application. Another strong correlation (0.81) between question Q1 and Q5. The more comfortable a user is using a new software or computer, the more useful he/she has rated the parallel coordinates visualization and interaction. This shows a similar finding as the previous correlation; the parallel coordinates visualization could be used by the participants according to their skill with new software. Also the correlation value (0.78) between question Q9 and number of observations made shows that the interaction with the building model is useful and leads to more observations in a shorter time. There are other correlations between the different skills (Q1-Q4 and Q2-Q3) that may be related to the users education/experience.

6.2.1 Usability

For the usability results, the question Q8 about the interactions with the application from the questionnaire and the comments made by the participants during and after the evaluation are considered. The median and mode for this question are both moderately. The following list shows the participants commentaries concerning the usability of the application. A number in brackets indicates if the comment has been made by multiple participants.

- Testing time too short (4)
- Adding a new variable resets the axis filters (3)
- Legend for circular heat map (3)
- Axis dimension: same data range for similar variables (2)
- Pop-up by hovering circular heat map: more details (2)
- Multi-filter possibility for parallel coordinates axis
- Visualisations too small
- Calendar for precise date selection
- Variable names confusing
- additional statistical information about selected data
- 3D building model: rotation and environment
- Export-function for selected data

- Same color for similar variables: hard to spot tendencies on circular heat map
- Interaction with parallel coordinates not intuitive

The first point mentions that the testing time was too short for a number of participants. This was recorded after the first 6 evaluations. So the application testing time for the other 6 participants has been extended for another 5 minutes to 20 minutes.

A problem is the resetting of the filters in the parallel coordinates plot if a variable gets added or removed. This is an implementation problem, if a new variable gets added or removed, the parallel coordinates plot is destroyed and recreated. One would need to store the brush values, recreate the plot, and re-apply them.

Another problem is the lack of a legend for the circular heat map. The variable colors among the different plots of the application do correspond, but the shading in the circular heat map plot may be not intuitive. This can be solved by adding a variable legend.

The next point mentioned by 2 participants is the axis dimension for similar variables: the axes get scaled from their minimum to maximum variable value. Two different rooms may not have the same minimum or maximum values, making it difficult to compare them. This can be solved by scaling them to a fixed, predefined size.

There are other points mentioned which would be valuable additions or improvements to the application, like the possibilities for multiple filters on the same axis. This would make a new range of comparisons possible. A calendar for more precise date selection could also be useful.

6.2.2 Usefulness

The other questions (Q5,Q6,Q7,Q9) were asked to evaluate the usefulness of the application. Together with the observations made by the participants and log files recorded, the usefulness of the application will be estimated.

The median and mode for the question Q5 about the usefulness of the parallel coordinates are both 'very', indicating a good usefulness. Question Q6 about usefulness of the circular heat map received a 'moderately' rating. This difference between the two questions may be explained due to the interaction possibilities with the parallel coordinates, were as the circular heat map has none. Also the lack of a legend and the size of the visualization as mentioned in the usability subsection may influence this further.

The usefulness of the linking between the parallel coordinates and circular heat map visualizations received a 'moderately' rating. The correlation value between this question and the previous one (Q6 - Q7) is 0.73, found in figure 29. This encourages the improvement of the circular heat map visualization.

The interaction with the building model is perceived as 'very' useful by most of the participants, as the median and mode for question Q9 show. As intended, the model provides the dimensions for the variables inside the building. Especially because each participant had only 15 to 20 minutes testing time, this kind of interaction was very valuable and has been well received, commented by multiple participants.

Participant T6: reconstruction of logging files

In order to reconstruct and understand the observations made by the experts, a number of graphs have been produced from the recorded user actions. There is one figure per participant, the ones not referenced here can be found in the appendix C. Figure 32 shows the log files from participant T6. The y axis features the monitored variables, the x axis displays the testing time. Red bars show selected variables and the duration of this selection. Brush events are marked in green, the smaller the brush amount, the smaller the marker. Observations are marked with a vertical yellow line and attached to it is the actual observation text. He/she could observe the following:

- By comparing the variables TABS Warm NE and TABS Warm SW, there seems to be a high positive correlation between them. That may indicate that, even if there is a different system for each zone, they seem to run at the same time.
- There is a high negative correlation between TABS Warm and sunshine hours, with some interesting outliers.
- The next observation investigates these outliers: TABS Warm is very high on certain dates, but is not explained by the Sunshine Hours. Why so much heating on these days?
- The investigation continues, the brush now selects only the highest value, a value of more than 100 kWh of TABS Warm NE. It's not obvious what causes this outlier. The outdoor temperature and room temperature at this date aren't different from the rest of this winter period, shown in figure **??**.

After some initial data exploration, the participant T6 found an interesting outlier. Most of the remaining testing time was then committed to investigate this further.

This outlier couldn't be explained from the data alone. Maybe this is some kind of maintenance behaviour of the TABS system, the building/system manager could provide more information most probably.

Particularly interesting is the fact that this participant was the visualization expert. He/she has rated his familiarity with building physics and monitoring 'not at all', yet still was able to investigate interesting building behaviour.

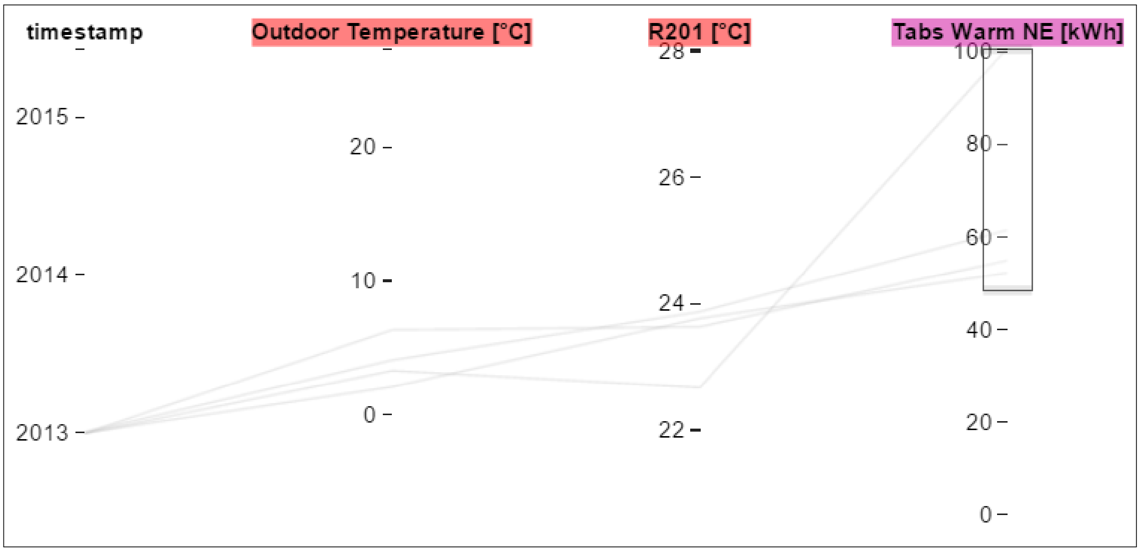

Figure 30: Evaluation log reconstructed: TABS Warm outliers at end of December 2012

Participant T7: reconstruction of logging files

Figure 33 shows the log files from participant T7. The figure shows that the participant immediately started investigating a variable (room temperature), and made an observation. The selection of new variable is usually followed by some brush events, followed by an observation. This behaviour indicates that the participant has a high amount of practice with building monitoring data, which is affirmed by his/her responses to the first part of the questionnaire. In 16 minutes, the participant was able to report 13 observations, that's one observation every 1.2 minutes. This is an impressive number, regarding to the size of the data set and that the participant used the application for the first time.

The participant could make the following observations:

- Room temperature in 203 mostly over 23°C
- R203 temperature values bigger then R103, smaller then R303
- Room 203 seems to be most prone to overheating
- By adding the Blinds Height variable, it was observed that if the blinds height are smaller than 100%, the room 203 overheats. Why are they not closed?
- Room 203 overheats in April-May, October-November, but the TABS Cold is not active in these periods, which could prevent that.
- These overheating occurs during office hours
- There are also occurrences where the TABS cold are cooling, yet R203 still overheats. Cooling power too small?
- Longer cooling periods in 2014 then 2013. Higher outdoor temperatures?
- Heating active from December till Mars
- Low, steady heating level from 2013
- R101, R201, R301 high room comfort level, some outliers in the summer months

Investigating the 4th observation made by this participant yields some interesting things: first, let's only investigate office hours, from 7 a.m. to 6 p.m. By filtering for high outdoor temperatures, one can observe that overheating only occurs at 4 dates. At all these days, the cooling system was active, yet the room 203 still overheated. Excluding these high outdoor temperature dates, the remaining days are all during spring or fall. On a few days, the system was cooling, yet the rooms overheated again. Filtering for days without high outdoor temperatures and without cooling, one can have a look at the sunshine hours and blinds height. These two variables seem to correlate, the more sun, the longer are the blinds closed. Filtering out days with high amount of sunshine, there are still about 20 days left with room temperatures bigger than 26°C. Figure **??** shows this investigation. These overheating dates can not be explained through outdoor weather data. By comparing room 203 to 103 and 303 (located a floor below and above 203), one can observe that room 303 never exceeds 26°C and room 103 only slightly at a few days. A possible explanation could be the number of people present in this room. The CO^2 values from the mechanical ventilation system could serve as a presence indicator, unfortunately these values are for a whole building zone. By adding them to the parallel coordinates plot, no new information can be gained.

There are a number of interesting observations made by the other participants, listed in table 2. All observations made by the participants during the evaluation can be found in the appendix D, table 5.

Expert Group	**Observation**	**Significance rating**
1	Cooling was not active - thermal comfort not satisfied because of this	2
1	Room temperature depended on high sunshine hours values in summer	2
1	North room temperatures cooler than south	1
1	Comfort not satisfied during heatwave in summer	1
1	High power usage of TABS system during 2013	2
1	Its was extraordinary warm in room 203 during October/November compared to the other rooms	2

1	Even with low/no heating in room 203, the room temperature is always high	2
1	High temperatures (26-27 °C) have been recorded in spring and autumn. Overheating?	3
2	It seems that the building need to be heated when the outside temperature is below 10°C	3
2	The building seems also to be cold starting from 10°C, so the range of outside temperature where it is not cold end heated is very low	2
2	Winter days in the north room: To have a good comfort you don't need any heating system!	2
2	The sunshine data indicates that the solar gain of the building mainly appears in March, April, May, June and July. The highest one appears in May, June.	1
2	With the same sunshine condition, the indoor temperatures of the rooms located in north and west side are almost the same, and slightly lower then the rooms located in the south.	2
2	outdoor temperature is indicated without any relations to the CO^2 in door, which may means the need of ventilation may not related to the outdoor temperature.	3

Table 2: Interesting observations reported during evaluation

These observations highlight some interesting building behaviours: There are cases were the thermal comfort for some rooms is not satisfied because the TABS cooling was not active. On the other hand, there are cases were the TABS cooling was active, yet the thermal comfort was still not satisfied. In some cases, heat waves may be the cause of the latter. But the former clearly shows some optimization potential for the TABS cooling system. Interesting is also the fact that during some winter dates, the north rooms don't need any TABS heating for comfortable indoor temperatures. Some observations also confirm expected behaviour: rooms located on the north side are mostly cooler than south side, or that the room temperature is depended on high sunshine hours values during summer.

Comparison between expert groups

To compare the different expert groups in terms of interest towards variable categories, the variables mentioned in each reported observation get counted and divided by the total of observations made by this group. Table 3 shows the ratio between observations concerning different variable categories and total observations by this group.

Expert Group / **Variable Category**	**1**	**2**	**3**	**4**
Room Comfort	0.56	0.47	0.67	0.20
TABS	0.38	0.47	0.50	0.6
Outdoor	0.31	0.47	0.08	0.6
Blinds	0.14	0.18	0.08	0
CO^2	0	0.06	0	0
Total	22	28	16	7

Table 3: Ratio between reported observations in each variable category and total observations by this group, for each expert group

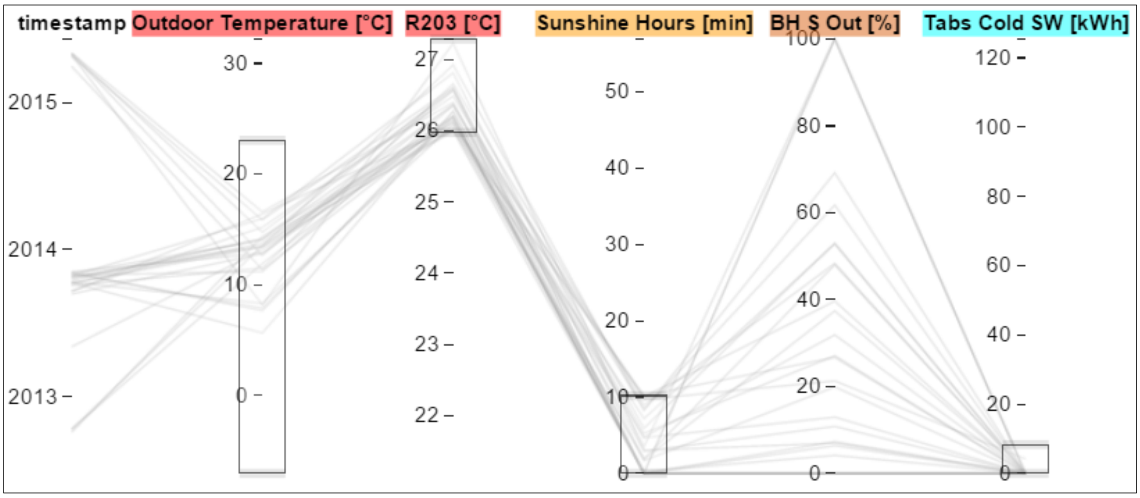

Figure 31: Participant T7 Observation 4 overheating investigation

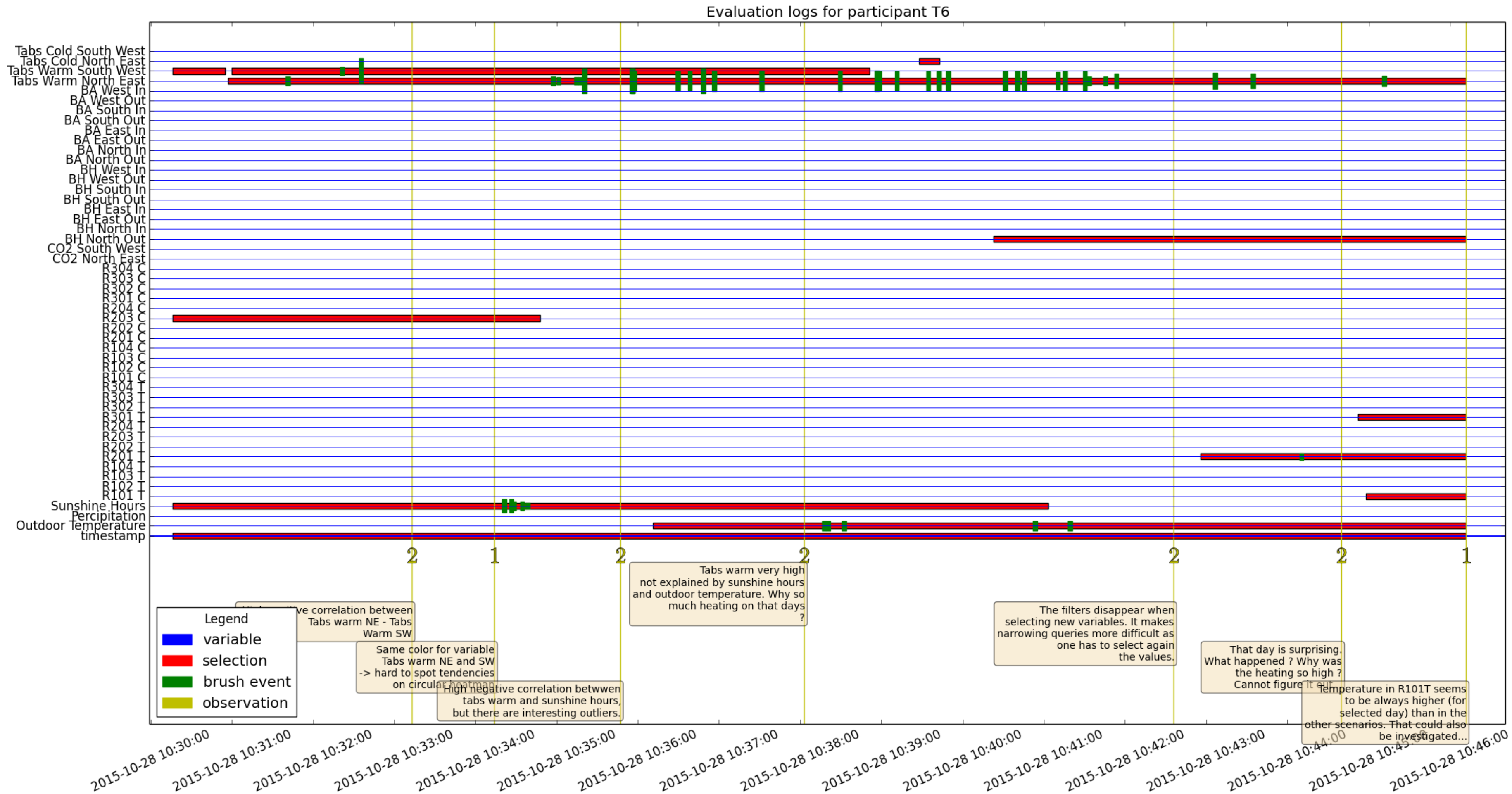

Figure 32: Log file visualised for participant T6

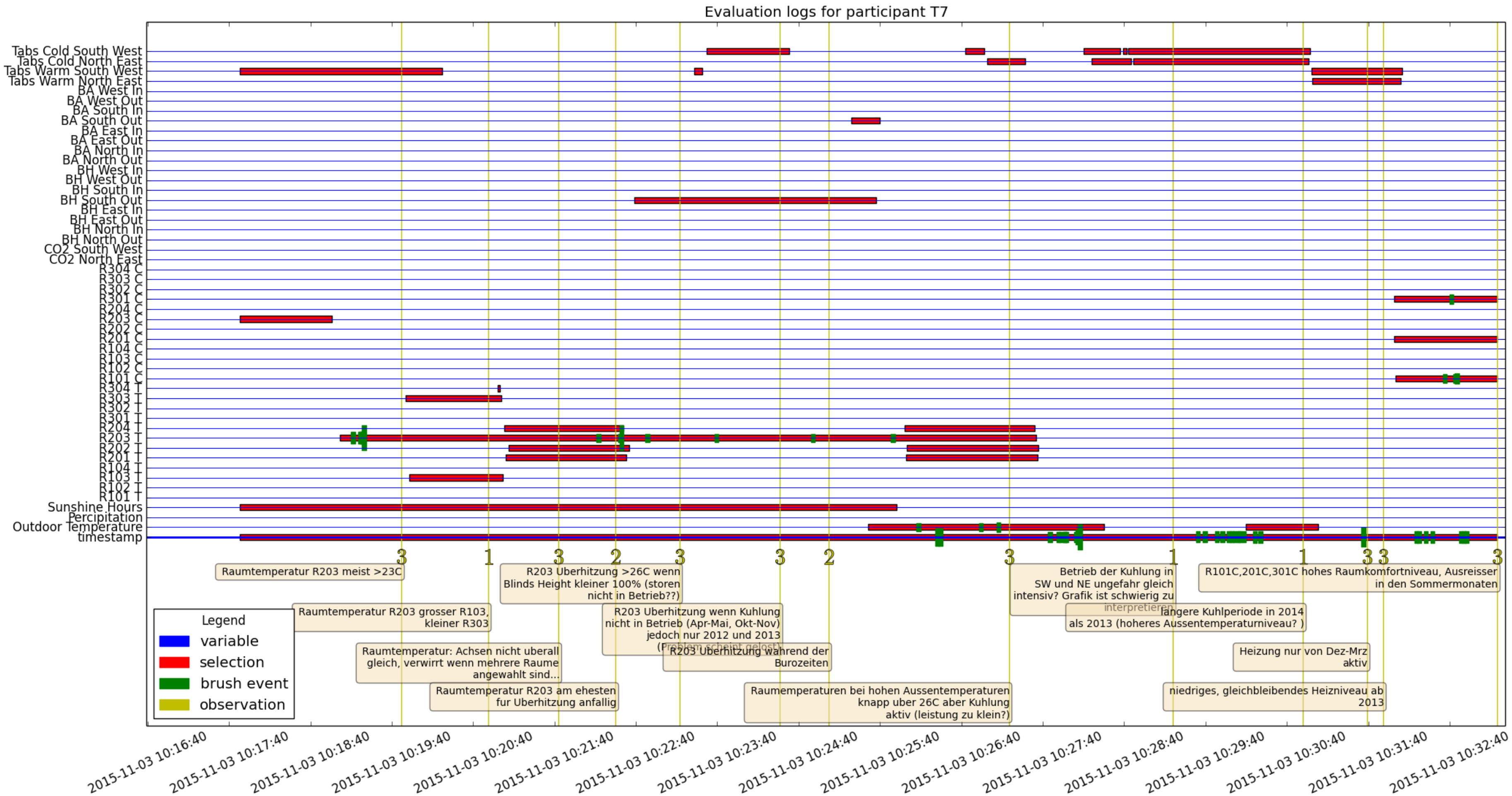

Figure 33: Log file visualised for participant T7

The first expert group was mostly interested in room temperatures and comfort (0.56), to a smaller amount in TABS cooling/heating and Outdoor variables(0.38, 0.31). The second group shows equal interest in these 3 categories (0.47). It's the only group that had one observation concerning CO^2. Group 3 was mostly interested in Room Comfort and temperatures and TABS (0.67, 0.50). Only group 4 hasn't reported many observations regarding room comfort (0.20), instead more interest was dedicated towards TABS and Outdoor variables (0.6).

Comparison between different skill levels

Figure 35 shows the a comparison between the users T1, T11 and T7.

These three participants have been selected according to their different level of skill regarding handling new software, building physics, building monitoring and data visualization. The questionnaire answers (Q1-Q4) are displayed in a bar chart. The answers for participant T1 report mostly 'slightly', for T11 'moderately' and 'very' and for T7 'very' and 'extremely'. The other part of figure 35 shows the evaluation logging files in a comparative manner. Interesting is not only the number of observations reported per user (T1: 2 Observations, T11: 4 Observations, T7: 13 Observations), but also the style of interaction with the application. The logs for T1 show barely any interaction with the building model, only at the end another variable gets selected. There are some brush interactions, and it took the participant several minutes until a first observation was reported. The logs for participant T2 show more interaction with the building model, more brush interactions, also the functionality of the hour time chart was used, which T1 didn't touch. For participant T7, the logs show the highest amount of interaction, which correlates with the number of observations reported.

To investigate this difference between different skill levels further, figure 34 shows the distribution of the participants by using the average response from the first four questions (Q1-Q4).

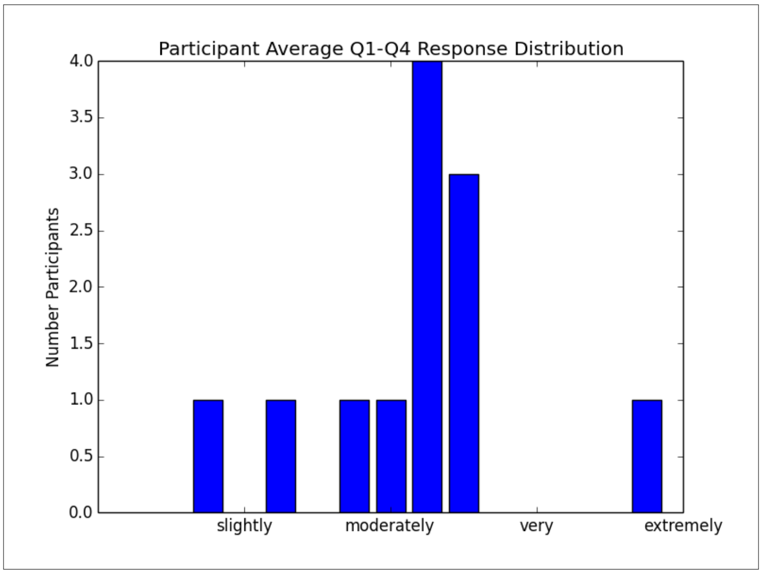

Figure 34: Participant distribution by average questionnaire answers Q1-Q4

Out of this distribution, 3 three different skill groups (low, medium, high) are formed, each containing 4 participants. Again, table 4 shows the ratio of variable categories in the observations and total observations made by this skill group, for each skill group.

Skill Level Group / Variable Category	low	medium	high

Room Comfort	0.36	0.42	0.67
TABS	0.73	0.53	0.33
Outdoor	0.18	0.42	0.38
Blinds	0	0.21	0.10
CO^2	0	0	0.05
Total	14	30	32

Table 4: Ratio between reported observations in each variable category and total observations by this skill group, for each skill group

Participants from the 'low' group reported mostly observations concerning TABS variables (0.73) and about a third concerning room comfort (0.36) and a few outdoor variables (0.18). The 'medium' group reported evenly distributed among the categories room comfort, TABS and outdoor (0.42,0.53,0.42). They had the highest amount of observations concerning blinds variables among the other groups (0.21). The third group 'high' reported about two thirds of the observations regarding room comfort variables (0.67) and about a third in TABS and outdoor each (0.33,0.38). In average, less observations were about blinds variables (0.10) then group 'medium', but they had one observation concerning CO^2 (0.05).

Still, participants from the different groups of skill level were able to make similar observations, yet the ones from the 'medium' and 'high' group investigated more variable categories. Also the number of observations per group increased with the skill level from 11 to 19 to 21.

6.3 Evaluation conclusions

The usability section has shown that there are several points in which the application can be improved. Especially the circular heat map needs refining.

In terms of usefulness, the application has passed its test by the experts. They were able to observe various building behaviours, variable relationships and conduct detailed investigations during their first use of the application and short testing time. The more comfortable by using new software and familiar with building physics, monitoring and data visualization, the more observations could be reported by the participants. The division of experts into three different skill groups has shown that the two groups 'medium' and 'high' are relatively close together in terms of number of observations made and in the distribution of variable categories investigated. This shows that two thirds of the participants were able to handle the application in an expected manner. And even the 'low' group was able the make some observations.

Valuable feedback was collected to further improve the application. The responses about the parallel coordinates and 3d building model were especially positive. The experts reported them to be very useful within short time. They seem to be very well fitted for this kind of visual data exploration and worth further investigation.

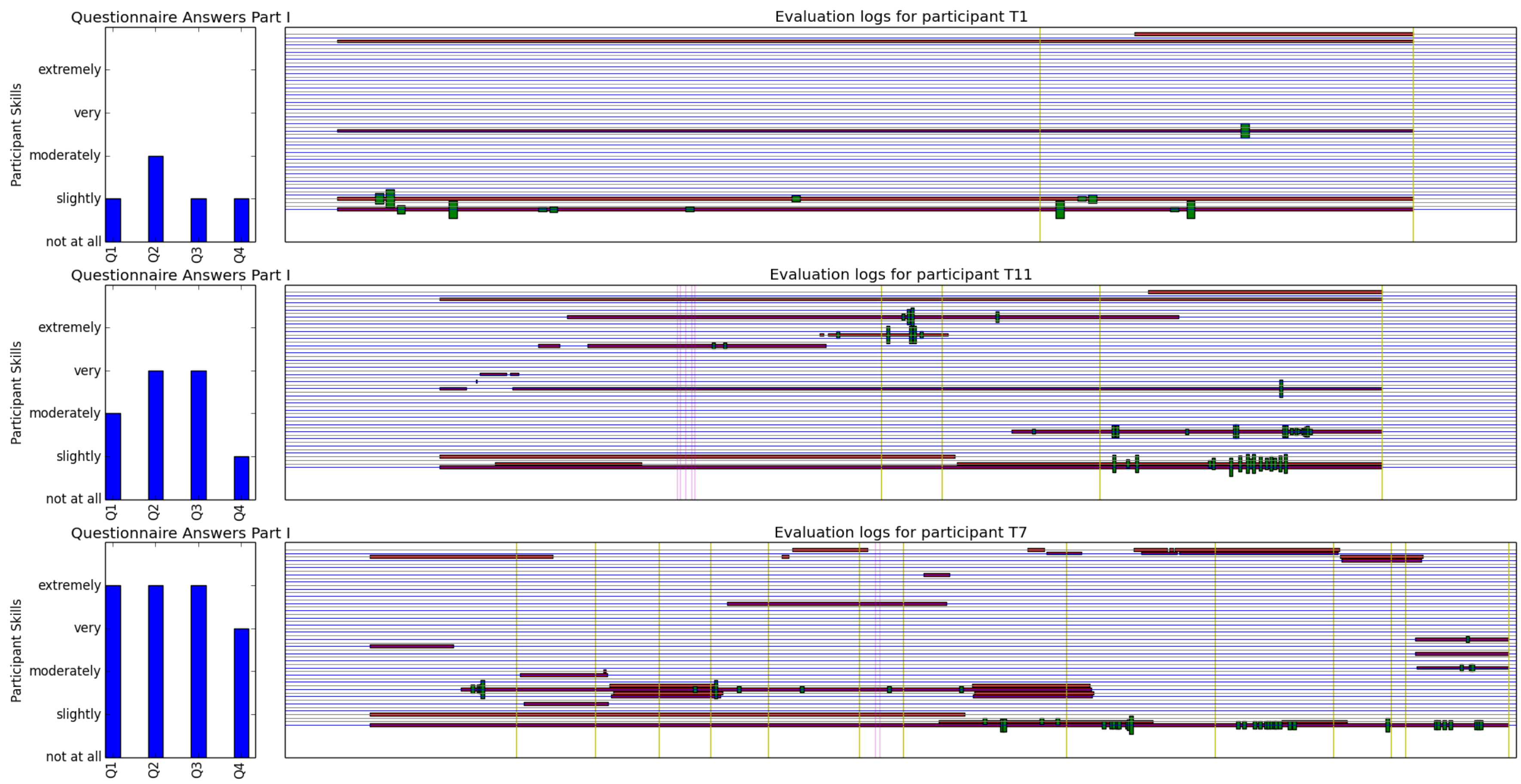

Figure 35: Comparison between participants T1, T11 and T7

7 Conclusions

7.1 Wrap up

The presented data exploration application makes use of two well known multivariate data visualization techniques, parallel coordinates and circular heat map. They have been applied to a data set from a monitored office building, located in Switzerland. Trough brush interaction, the parallel coordinates visualization can be manipulated. The other visualization, a circular heat map, is linked to the first one. A 3d model of the building provides useful dimensional information about the data variables and is used at the same time to add or remove these variables to the visualizations. Through a short questionnaire and testing, the application has been evaluated by experts in a qualitative manner.

7.2 Contributions

Current research shows a trend towards more interactive and sophisticated visualizations for building automation systems. Following this trend, two visualizations methods for multidimensional and multivariate data have been selected to provide within an application powerful visual data exploration capabilities.

The application has been evaluated by 11 experts with a building physics or engineering background and 1 visualization expert. They were able to report a multitude of observations concerning the buildings thermal comfort inside office rooms, heating and cooling behaviour, influence of outdoor variables, blinds operation and others. The experts were able to conduct detailed data investigations already during their short testing time and also their first use of the application.

The parallel coordinates visualization has been reported by the majority of experts as 'very' useful for this kind of observations. Also the use of the abstract 3d building model has been very well received. Both statements were made after short testing time. We believe that these methods are worth further investigation.

7.3 Future work

The application interaction with the building model has received very positive feedback during the evaluation. The current solution for the creation of this model is the use of a building model in .svg format, where the different room and zone locations need to be extracted manually (according to additional floor plans). An automated solution could be realized by introducing a small standard for labelling these zone/room related vectors in the .svg file. Another solution could be the use of a web viewer for CAD models, like vA3C [20]. It uses open source plugins to export JSON files from common architecture and engineering applications, and displays them in the viewer. The addition of the buildings surrounding area was also desired by an expert. This could provide valuable information in terms of shading.

Other multidimensional multivariate visualization methods are most certainly also suited for this kind of application. Tree maps were considered in the initial design phase. The hierarchical navigation used within this method could also be applied to a buildings structure. Think of dividing the building into floors, then rooms, then inhabitants. Unfortunately, the granularity of the acquired data set didn't promote this idea and was therefore discarded.

Another approach worth investigating is the visualization of the monitored data directly on the building model. The buildings facade could serve as a canvas.

The application requires some initial navigation until interesting data points can be found. As shown during the evaluation, not all experts were able to navigate successfully through the data and

[20] https://va3c.github.io/

make interesting observations. Some kind of logic (for example fault detection) that predetermines such points could be of value to speed up this process.

Various points were mentioned during in the evaluation that could be improved regarding the application usability and usefulness (section 6.2.2 and 6.2.2). The addition of a calendar could provide a more precise date selection. Also an export-function for selected data could come in handy if more in-depth data analysis is needed.

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Appendix A Building data variable list

Variable_Id	Einheit	Variable (NEU)
V005	ppm	Lueftungsanlage 01: CO2_Abluft
V022	ppm	Lueftungsanlage 02: CO2_Abluft
V037	kWh	Kaelte TABS Sued/West
V075	kWh	Kaelte TABS Nord/Ost
V034	kWh	Waerme TABS Sued/West
V074	kWh	Waerme TABS Nord/Ost
V100	%	Storen_Winkel Nord Aussen
V103	%	Storen_Winkel Nord Innen
V106	%	Storen_Winkel Ost Aussen
V109	%	Storen_Winkel Ost Innen
V112	%	Storen_Winkel Sued Aussen
V115	%	Storen_Winkel Sued Innen
V118	%	Storen_Winkel West Aussen
V121	%	Storen_Winkel West Innen
V004	% relF	Lueftungsanlage 01: Relative Feuchte Abluft
V021	% relF	Lueftungsanlage 02: Relative Feuchte Abluft
V043	% relF	Relative Feuchte Raum 1.01
V045	% relF	Relative Feuchte Raum 1.02
V076	% relF	Relative Feuchte Raum 1.03
V078	% relF	Relative Feuchte Raum 1.04
V047	% relF	Relative Feuchte Raum 2.01
V049	% relF	Relative Feuchte Raum 2.02
V080	% relF	Relative Feuchte Raum 2.03
V082	% relF	Relative Feuchte Raum 2.04
V051	% relF	Relative Feuchte Raum 3.01
V053	% relF	Relative Feuchte Raum 3.02
V084	% relF	Relative Feuchte Raum 3.03
V086	% relF	Relative Feuchte Raum 3.04
V099	%	Storen_Heohe Nord Aussen
V102	%	Storen_Heohe Nord Innen
V105	%	Storen_Heohe Ost Aussen
V108	%	Storen_Heohe Ost Innen
V111	%	Storen_Heohe Sued Aussen
V114	%	Storen_Heohe Sued Innen
V117	%	Storen_Heohe West Aussen
V120	%	Storen_Heohe West Innen
V098	0/1	Storen_Status Nord Aussen
V101	0/1	Storen_Status Nord Innen
V104	0/1	Storen_Status Ost Aussen
V107	0/1	Storen_Status Ost Innen
V110	0/1	Storen_Status Sued Aussen
V113	0/1	Storen_Status Sued Innen
V116	0/1	Storen_Status West Aussen
V119	0/1	Storen_Status West Innen
V006	°C	Lueftungsanlage 01: Temperatur Abluft
V023	°C	Lueftungsanlage 02: Temperatur Abluft

V032	°C	Aussentemperatur
V044	°C	Temperatur Raum 1.01
V046	°C	Temperatur Raum 1.02
V077	°C	Temperatur Raum 1.03
V079	°C	Temperatur Raum 1.04
V048	°C	Temperatur Raum 2.01
V050	°C	Temperatur Raum 2.02
V081	°C	Temperatur Raum 2.03
V083	°C	Temperatur Raum 2.04
V052	°C	Temperatur Raum 3.01
V054	°C	Temperatur Raum 3.02
V085	°C	Temperatur Raum 3.03
V087	°C	Temperatur Raum 3.04
V012	°C	Lueftungsanlage 01: Temperatur Zuluft
V029	°C	Lueftungsanlage 02: Temperatur Zuluft

Appendix B Questionnaire

Evaluation of an application for building data visualization

Introduction

This evaluation investigates an application developed for the exploration of building related data. Its goal is to test and improve the usefulness and usability of the application.

The data set for the application was provided by Synergy BTC AG. The monitored building is located in eastern Switzerland. The variables shown include room temperatures, window blind heights and angles, heating and cooling powers, CO^2 exhaust air and others. The data ranges from mid of 2012 until mid of 2015 with hourly measurements. The data within the application are daily averages, for performance reasons.

While performing the evaluation of the application, all actions of the participants will be recorded (button clicks, slider movement, etc.). Together with the answers from the questionnaire, the collected data will only be used to evaluate and improve the application. All of the participant's information will be anonymous, no names will be collected. The participants can interrupt or stop the evaluation or ask questions any time.

Thank you for your cooperation and your commitment.

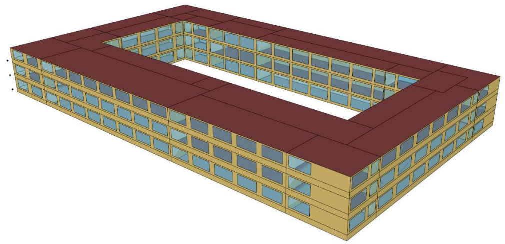
Procedure

- Introduction and Information about building use and system technology (3')
- Part I: Questions about testers background (2')
- Part II: Application Evaluation (15')
- Part III: Questions about Interface and Application Performance (2')

1

Information on building use and system technology

- Gross floor area: 9‘560 m²
- Number of floors: 3
- Location: Eastern Switzerland, industrial area
- Use: Office and administrative building



Building Shell:

- Outside Walls: U = 0.24 W/m²K, massive
- Glazing: Uf = 1.1 W/m²K, Ug = 0.65, g = 0.40
- Interior walls: U = 2.0 W/m²K, lightweight

Space (zoning) per floor:

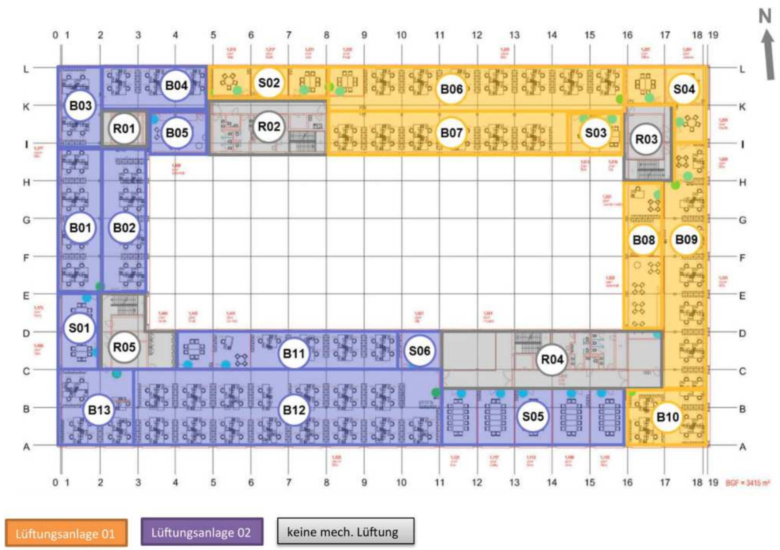
- 13 office areas (mostly open space)
- 6 meeting rooms
- 5 border zones (traffic area, toilet, stairs)

Mechanical Ventilation System:

- 2 central ventilation systems (yellow and blue)
- One ventilation system supplies all floors of the corresponding building side

Heating and Cooling

- Heating and Cooling take place through thermally-activated building system (TABS)
- 2 TABS zones
- One TABS zone supplies all floor



Part I (BEFORE Application Testing)

1. How comfortable are you using a new software or computer? (cross one)

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

2. How familiar are you with Building Physics?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

3. How familiar are you with Building Monitoring Systems?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

4. How familiar are you with Data Visualization?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

PART II Application Testing

Play around with the application and discover its functionality. Report the observations you make in the building data.

Use the three significance buttons (1,2 or 3) to report an observation, depending on how you value its interest.

Part III (AFTER Application Testing)

5. How would you rate the usefulness of the parallel coordinates visualization?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

6. How would you rate the usefulness of the circular heat map visualization?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

7. Did you find the linking between the two visualizations above useful?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

8. How good is the interaction with the application?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

9. Did you find the interaction with the 3D-building model useful?

Not at all	Slightly	Moderately	Very	Extremely
☐	☐	☐	☐	☐

General Comments

Appendix C Evaluation Results

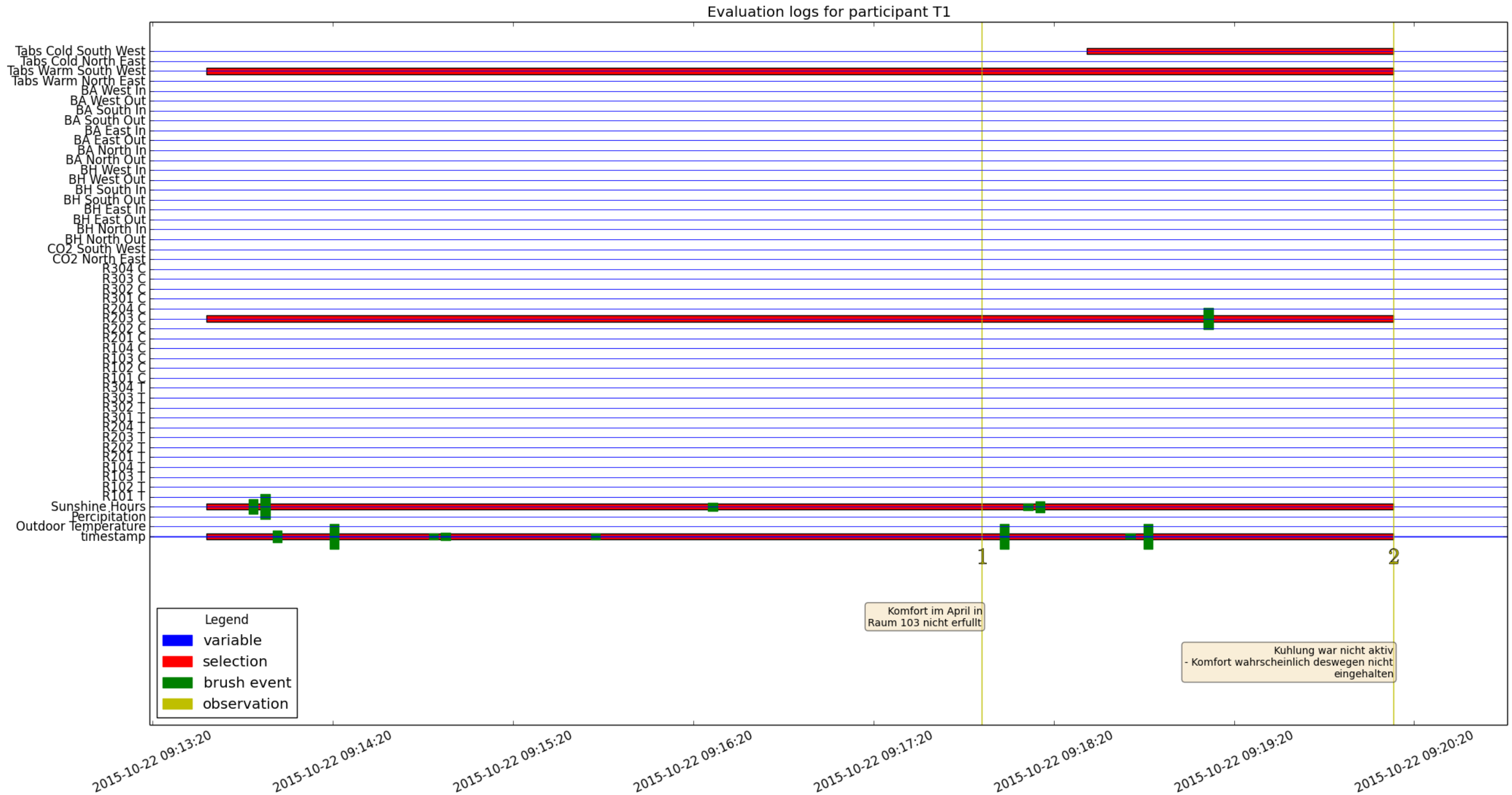


Figure 36: Log file visualised for participant T1

Figure 37: Log file visualised for participant T2

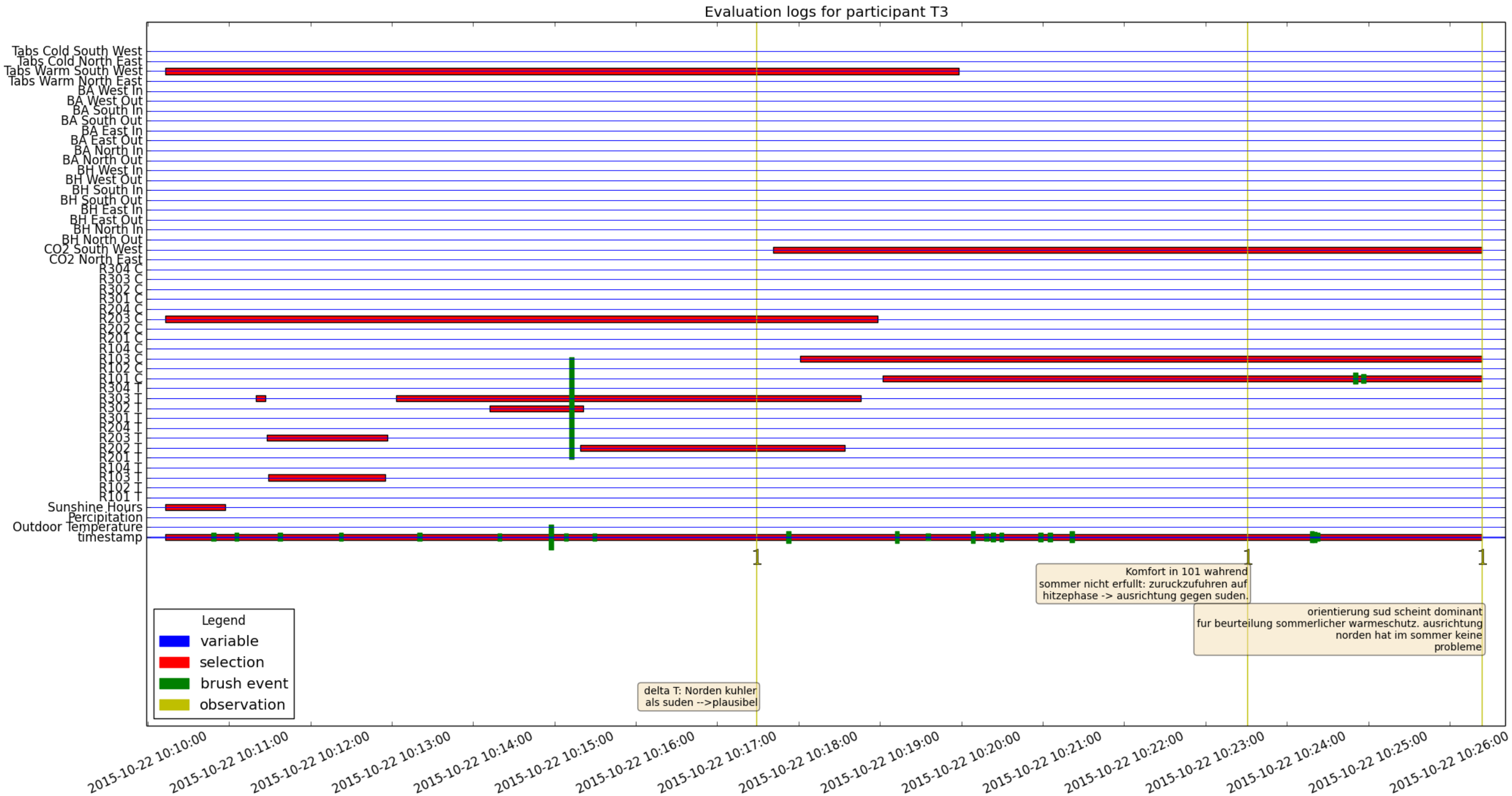


Figure 38: Log file visualised for participant T3

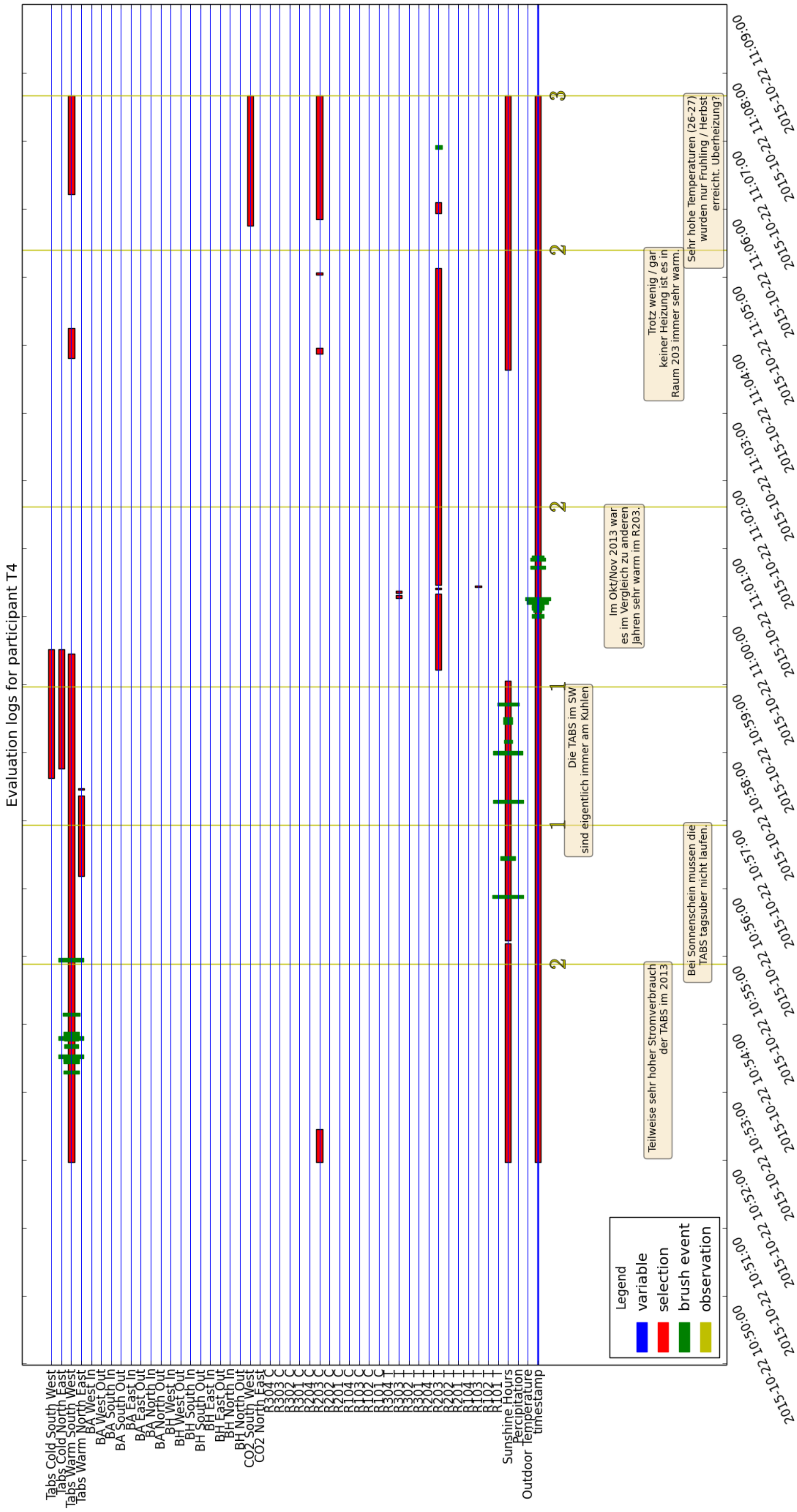


Figure 39: Log file visualised for participant T4

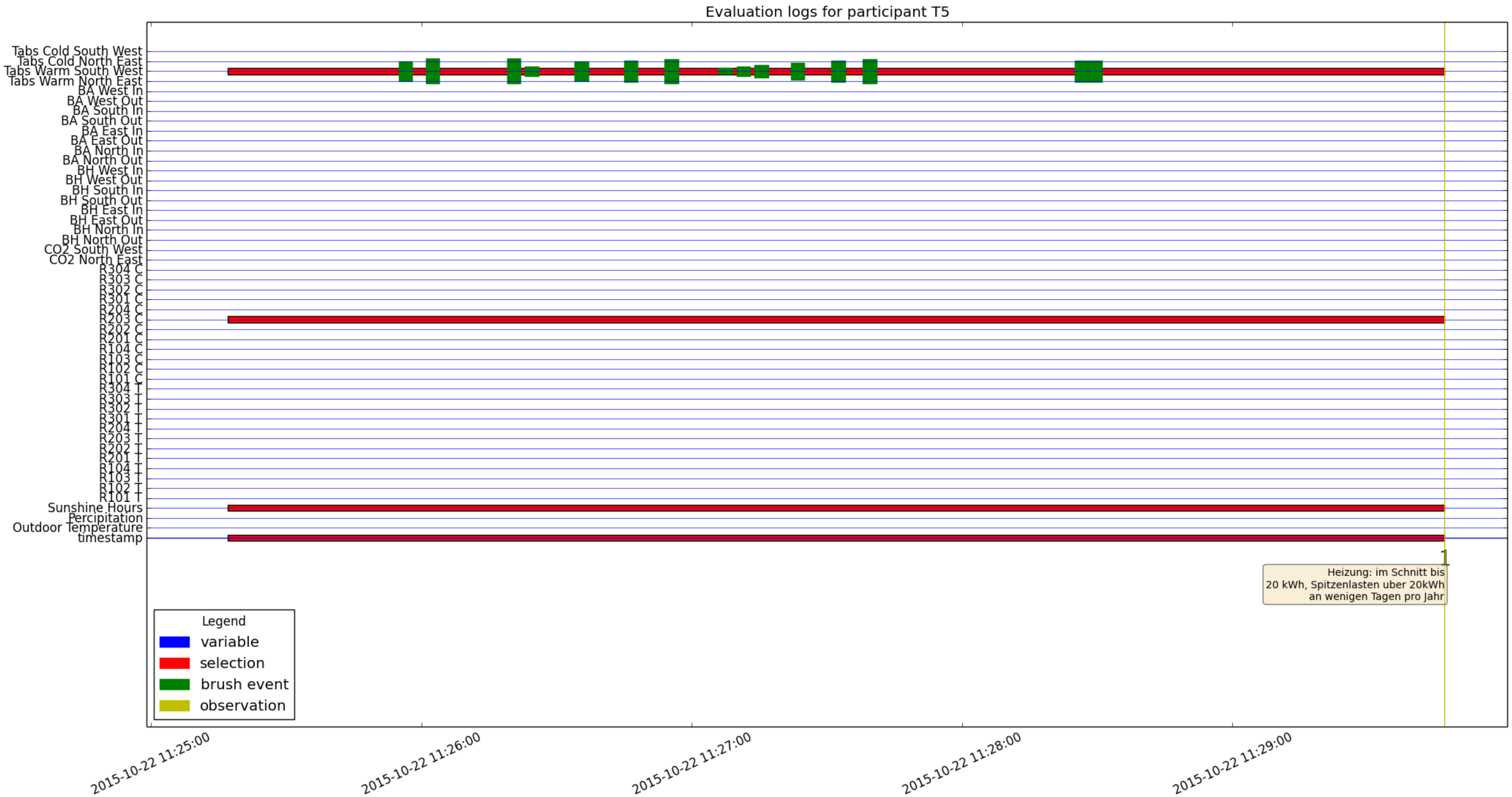


Figure 40: Log file visualised for participant T5

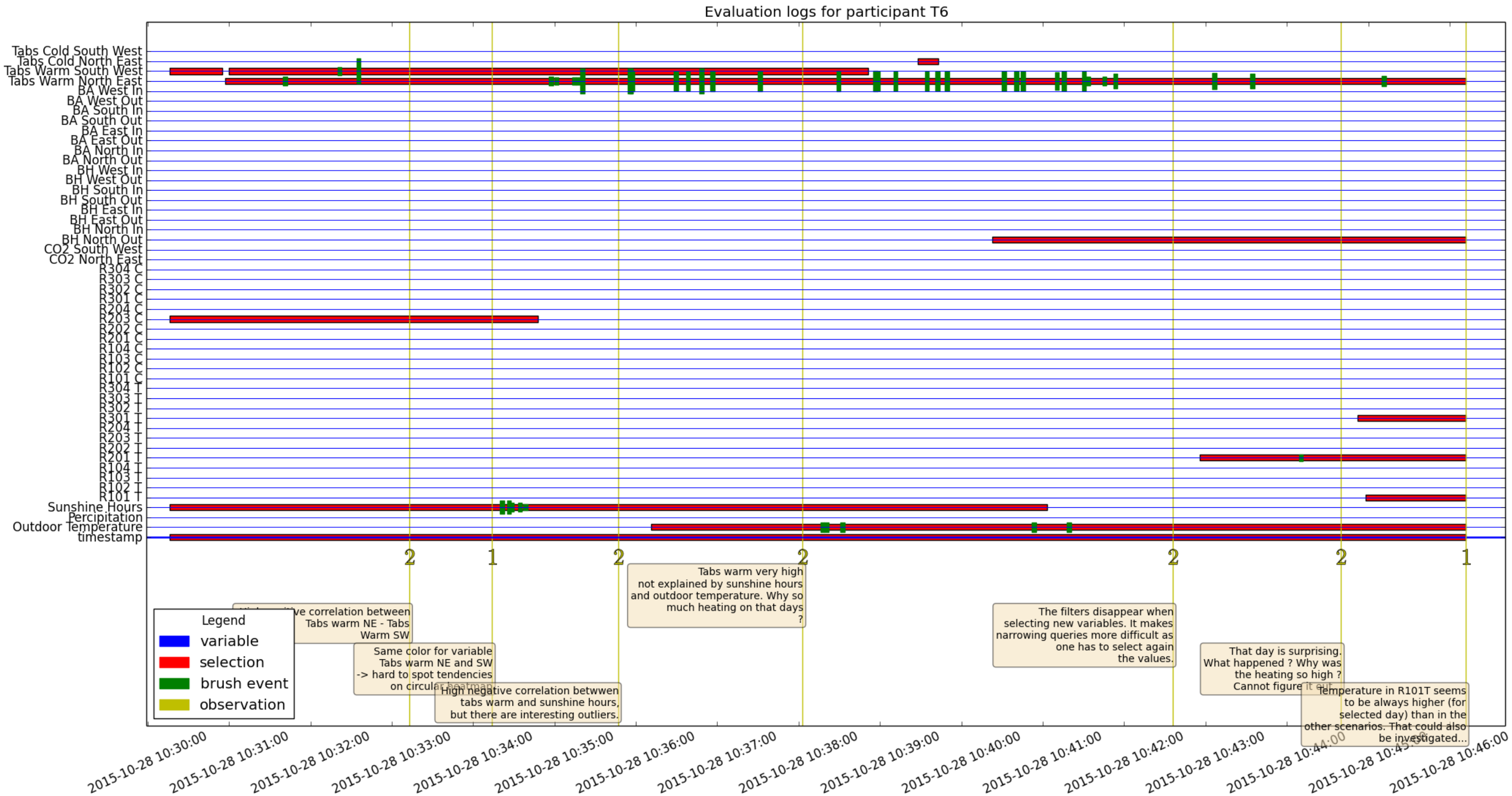


Figure 41: Log file visualised for participant T6

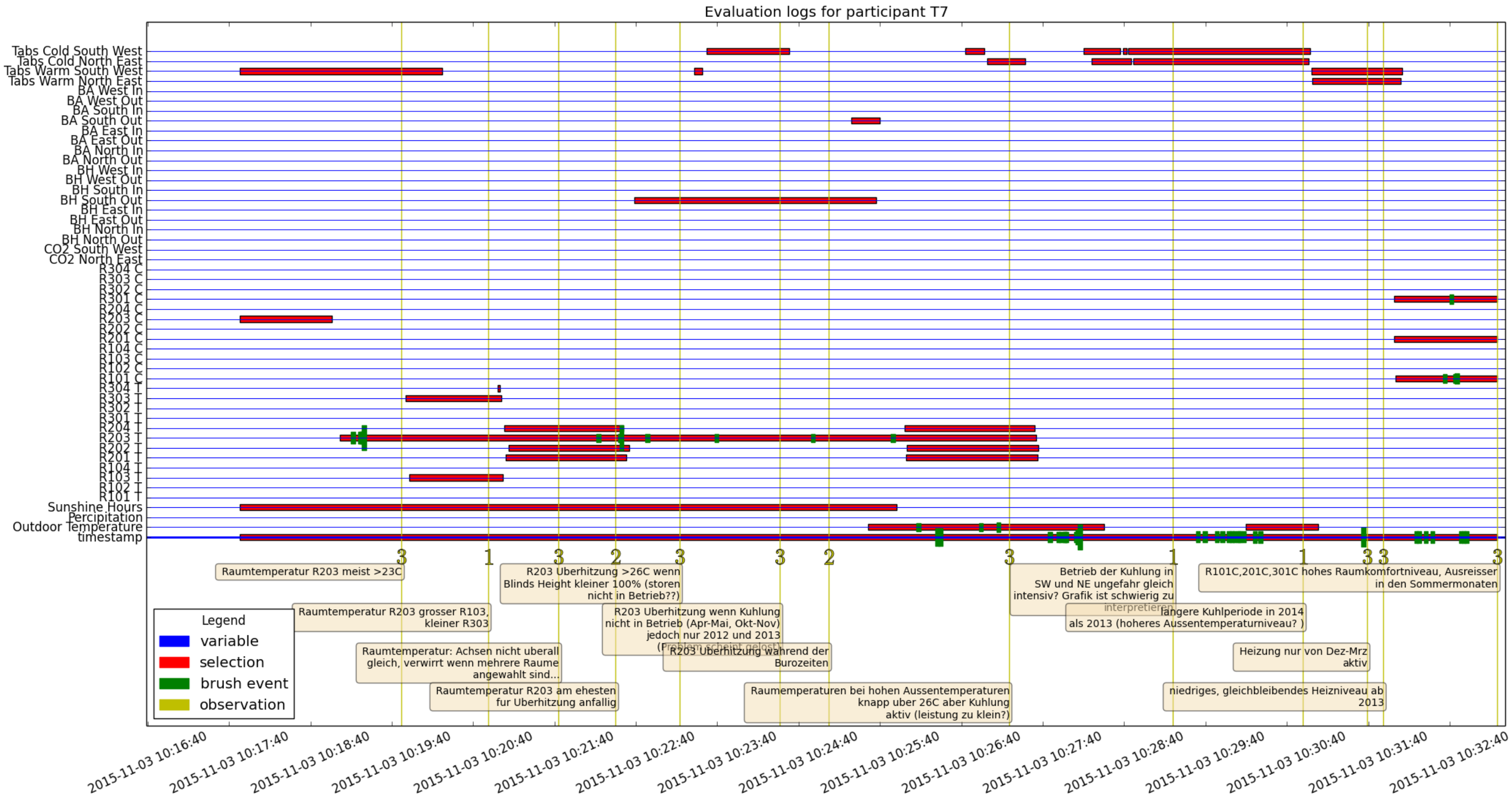


Figure 42: Log file visualised for participant T7

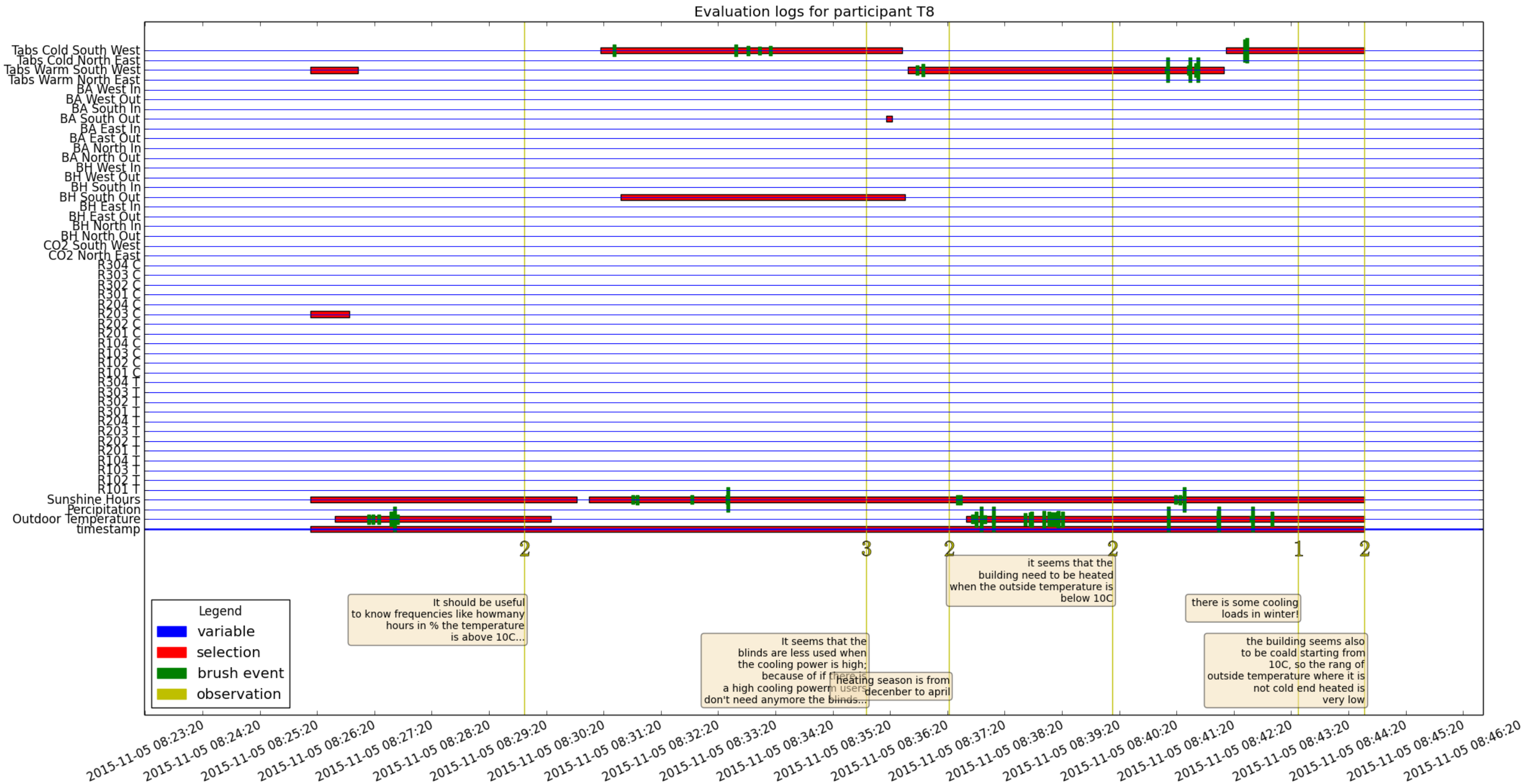


Figure 43: Log file visualised for participant T8

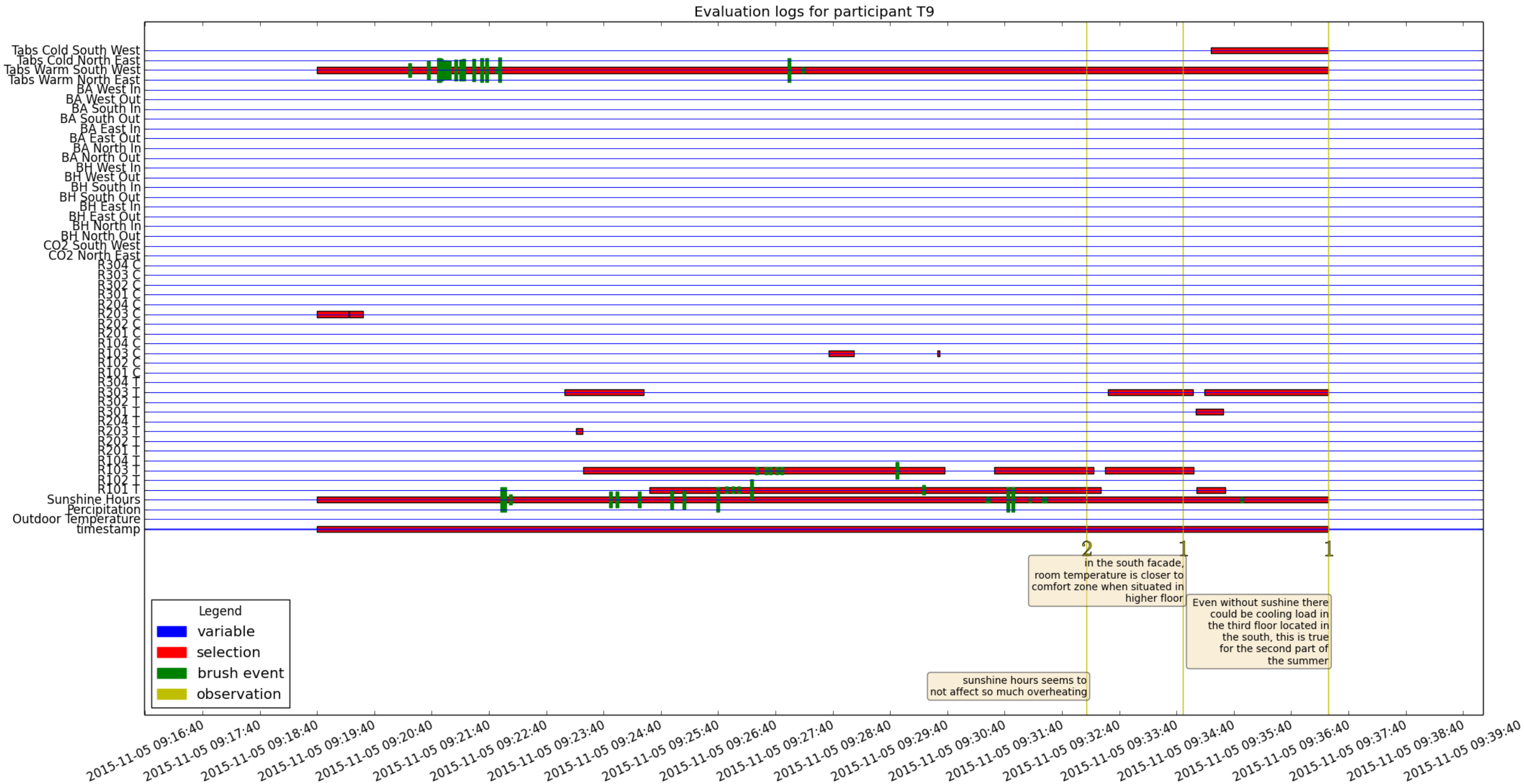


Figure 44: Log file visualised for participant T9

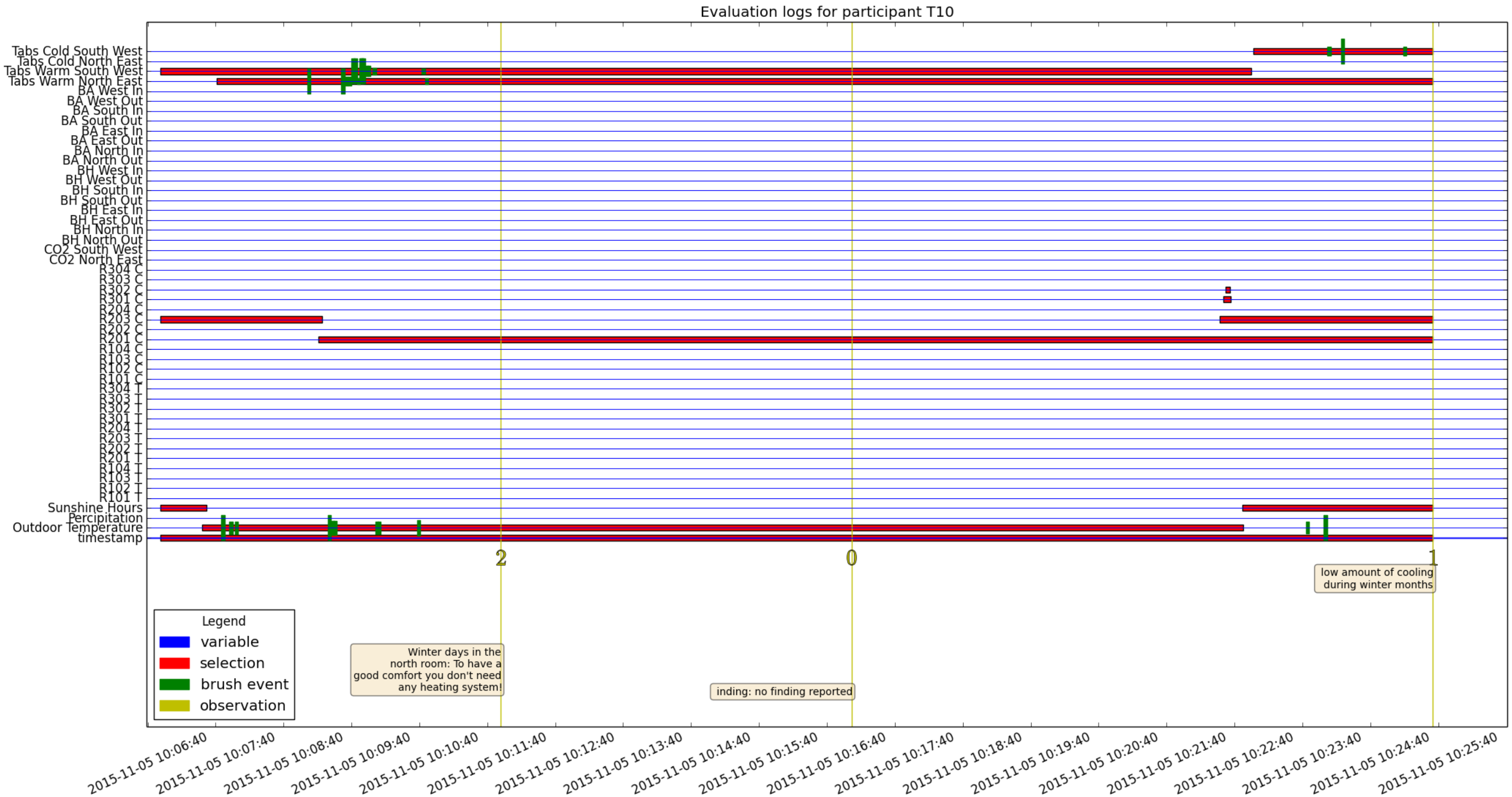


Figure 45: Log file visualised for participant T10

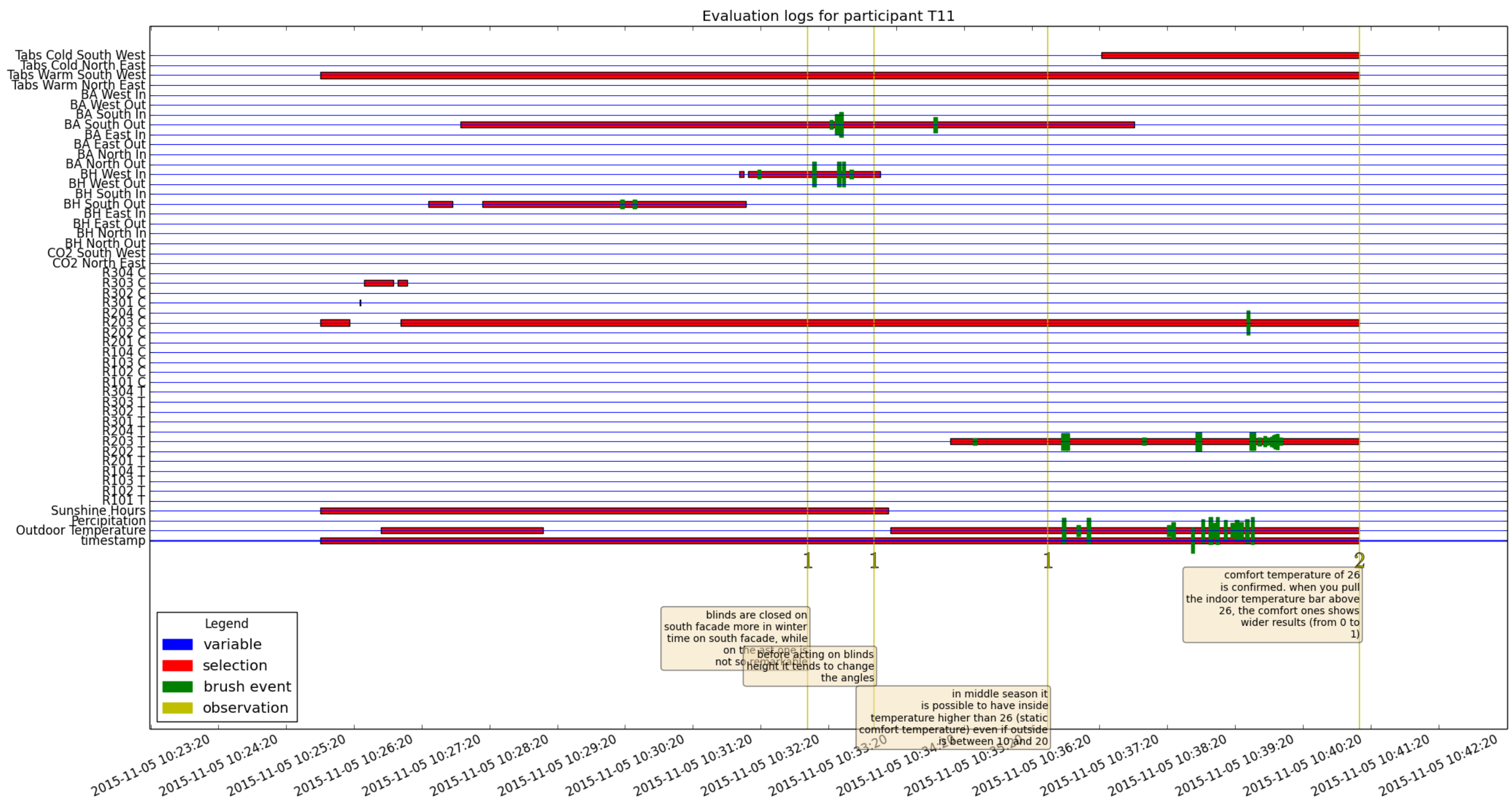


Figure 46: Log file visualised for participant T11

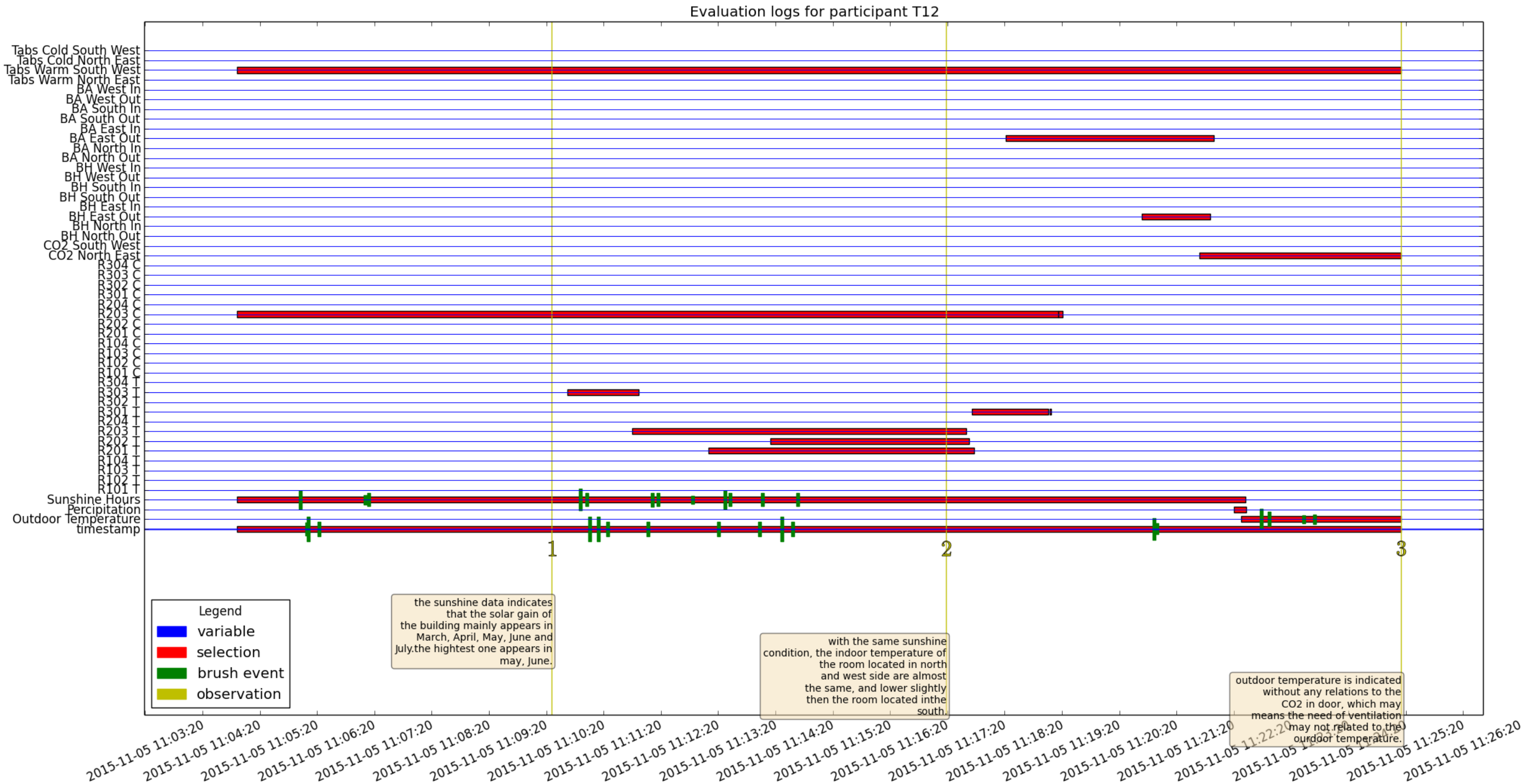


Figure 47: Log file visualised for participant T12

Appendix D Evaluation observations by the participants

Expert Group	Observation	Significance rating
1	Thermal comfort not satisfied at different dates	1
1	Cooling was not active - thermal comfort not satisfied because of this	2
1	Room temperature depended on high sunshine hours values in summer	2
1	Less dependency in winter, because of heating	2
1	Low amount of sunshine hours leads to average room temperatures and therefore pleasant room comfort	3
1	December/January: Blinds completely closed. assumption: blinds closed during Christmas	2
1	North room temperatures cooler than south	1
1	Comfort not satisfied during heatwave in summer	1
1	South orientation seems dominant for judgement of mechanical blinds system during summer	1
1	High power usage of TABS system during 2013	2
1	During high sunshine hours days, the TABS don't need to be running	1
1	TABS in south west are almost constantly running	1
1	Its was extraordinary warm in room 203 during October/November compared to the other rooms	2
1	Even with low/no heating in room 203, the room temperature is always high	2
1	High temperatures (26-27) have been recorded in spring and autumn. Overheating?	3
1	Heating: on average 20 kWh, peek loads on a few days per year	1
4	High positive correlation between Tabs warm NE - Tabs Warm SW	2
4	High negative correlation between tabs warm and sunshine hours, but there are interesting outliers	2
4	Tabs warm very high not explained by sunshine hours and outdoor temperature. Why so much heating on that days?	2
4	That day is surprising. What happened ? Why was the heating so high ? Cannot figure it out...	2
4	Temperature in R101T seems to be always higher (for selected day) than in the other scenarios. That could also be investigated...	1
3	Room temperature 203 mostly more than 23°C	3
3	Room temperature 203 higher than 103, lower than 303	1
3	Room 203 is most likely to overheat	2
3	Room 203 overheats (>26C) if blinds height smaller 100% (blinds not working?)	3
3	Room 203 overheats if cooling is not active (April - May, Oct-Nov). But only in 2012, 2013	3
3	Room 203 overheats during working hours	2
3	Room temperatures over 26C by high outdoor temperatur. But cooling is active, to less power?	3
3	Operation of cooling in SW and NE approximately the same	1
3	Longer cooling period in 2014 then 2013 (higher outdoor temperatures?)	1
3	Heating only active from December till Mars.	3
3	low, steady heating level from 2013	3

3	Room 101, 201, 301 high room comfort, outliners in summer months	3
2	It seems like the blinds are less used when the cooling power is high; because if there is a high cooling power, users don't need the blinds any more.	3
2	heating season is from decenber to april	2
2	it seems that the building need to be heated when the outside temperature is below 10°C	3
2	there is some cooling loads in winter!	1
2	the building seems also to be cold starting from 10C, so the range of outside temperature where it is not cold end heated is very low	2
2	sunshine hours seems to not affect so much overheating	2
2	in the south facade, room temperature is closer to comfort zone when situated in higher floor	1
2	Even without sunshine there could be cooling load in the third floor located in the south, this is true for the second part of the summer	1
2	Winter days in the north room: To have a good comfort you don't need any heating system!	2
2	low amount of cooling during winter months	1
2	blinds are closed on south facade more in winter time on south facade, while on the east one is not so remarkable	1
2	before acting on blinds height it tends to change the angles	1
2	in middle season it is possible to have inside temperature higher than 26 (static comfort temperature) even if outside is between 10 and 20	1
2	comfort temperature of 26 is confirmed. when you pull the indoor temperature bar above 26, the comfort ones shows wider results (from 0 to 1)	2
2	the sunshine data indicates that the solar gain of the building mainly appears in March, April, May, June and July.the highest one appears in may, June.	1
2	with the same sunshine condition, the indoor temperature of the room located in north and west side are almost the same, and lower slightly then the room located in the south.	2
2	outdoor temperature is indicated without any relations to the CO^2 in door, which may means the need of ventilation may not related to the ourdoor temperature.	3

Table 5: Table of interesting observations made by the participants