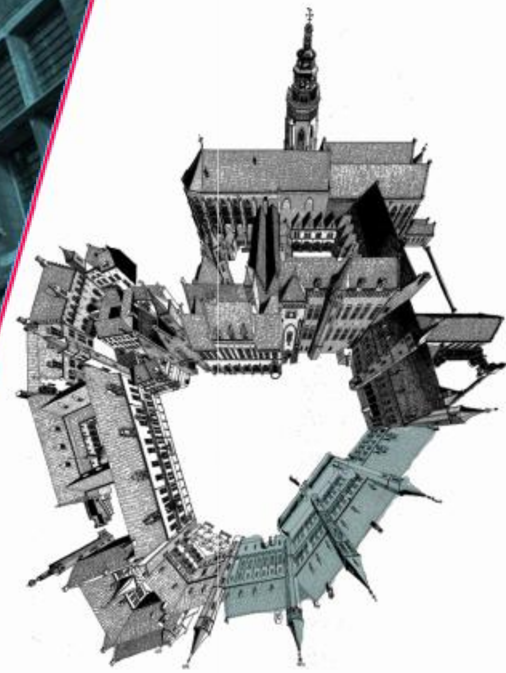
MASTER

Optimizing climate systems and control for museums
a case study for the Zeeuws Museum

Kersten, B.

Award date:
2013



Technische Universiteit
Eindhoven
University of Technology

Optimizing climate systems and control for museums

A case study for the Zeeuws Museum

Ing. B. Kersten

February 2013

Technische Universiteit
Eindhoven
University of Technology

Department of the Built Environment

Building Physics and Services

Visiting address
Den Dolech 2
5612 AZ Eindhoven
The Netherlands

Postal address
Postbus 513
5600 MB Eindhoven
The Netherlands

www.tue.nl

Where innovation starts

Eindhoven University of Technology

Graduation project:	**Optimizing climate systems and control for museums**
	A case study for the Zeeuws Museum

February 2013
Graduation project (7YY40)
Building Services

Author:
Ing. B. Kersten
Identity number 0667606
b.kersten.1@student.tue.nl

Supervisors:

Dr.ir. H.L. Schellen	Eindhoven University of Technology
Dr. ir. A.W.M. van Schijndel	Eindhoven University of Technology
Ir. E. Neuhaus	Ingenieursbureau Physitec

Eindhoven University of Technology , department of the Built Environment,
unit Building Physics and Systems.

PREFACE

With this final research project I reach the end of a beautiful and instructive period as student of the Master's degree program Building Services at Eindhoven University of Technology.
When I stepped into this field of expertise about 11 years ago, people around me (including myself), had never expected that I would study so far. At that moment, study was a necessary evil for me, and I could not wait to start working. I really did not know if this discipline would suit me, but during the study period that time the interest started growing. No problems occurred during that study, and also my teachter/mentor mentor advised me to continue with a Bachelor degree program in General Operational Technology ('Algemene Operationele Techniek) with specialization in Building Services ('Hogere Installatietechniek') at Hogeschool Utrecht.
After a period of working and this Bachelor study, I was motivated to further expand my knowledge and continued my studies with a premaster program and subsequently the Master degree program here at Eindhoven University of Technology.

Since the last period of the Bachelor's degree in Utrecht, I can get along (very) well with Marco Maas. When he decided to continue his study in Eindhoven, it took away my doubts and we put together this challenge.
We complemented each other and made a pleasant time of it. Thanks Marco, for this pleasant collaboration and hopefully we still meet each other in the 'professional life'.

I would like to thank my supervisors Henk, Jos en Edgar. In the first place for the good cooperation, but also because you provided a research subject which fits my interests. I wanted to do a graduation project wherein I gained knowledge which is useful during my professional life as building services engineer. Climate systems coupled with an ATES system had my interest, because a lot of varied knowledge is necessary to design such a system that performs well with optimal system efficiency.
An ATES system coupled with a climate system for a museum makes it even more interesting because both indoor temperature and relative humidity must be well maintained for collection preservation. Also the combination of theory and a more practice part has contributed to the motivation in this research.
Additional to this graduation project, I also want to thank Henk en Jos for the interesting courses during my study and the good cooperation during master project 2.

I want to thank Royal HaskoningDHV for providing a learning environment during this graduation project and, of course, for the provision of a challenging job after this period.

Last but not least a word of thanks to my family and girlfriend Marit for the support and interest during my study.

Bram Kersten
Egchel, December 2012

SUMMARY

The Zeeuws Museum is one of the participating museums in a PhD study which will investigate the possibilities of energy savings in Dutch museums with preservation of collections, building and comfort of visitors and staff.
In 2007 the Zeeuws Museum is equipped with an extensive climate system which does not perform as it should be. A few months after installation it became apparent that the desired indoor air conditions, as described in the HVAC design specifications, could not be achieved. High-risk conditions for preservation of the museum collections were observed during the summer season. Also a lot of energy is consumed for the climate conditioning while this climate system, with a heat pump for the supply of cooling and heating energy which is coupled with a long term energy storage system, should be fairly energy efficient. Meanwhile a (large) imbalance in the ATES system arose, which beside performance reduction, could result in financial penalties or retraction of system license.
The goal of this research is to detect the causes of the problems mentioned above, and to find out if optimizations are possible which benefit the indoor climate, energy costs and balance of the ATES system.
These research objectives are mainly achieved by the following activities:

- Problem identification;
- Analyzing of building physics and HVAC-systems;
- Monitoring of indoor climate and processes in the HVAC-systems, making use of the measurements from the building management system and additional applied measurement equipment;
- Implementation of computer simulations to gain insight in the efficiency of the cooling and dehumidification process and the impact of the relevant factors.

Various shortcomings in the HVAC system have been discovered which cause the mentioned problems at the Zeeuws Museum. The observed high indoor relative humidities are the result of deviations in the measurements of the control system, too high chilled water temperatures and a drop of the indoor air temperature during the dehumidification process. Short circuits in the capacity devices of most cooling coils were discovered, which results in small temperature differences between the supply and return chilled water flow. The combination of a low return chilled water temperature and the relative high temperature in the cold well of the ATES system ensures that the ATES system hardly contributes to the supply of ‘cold’ energy. In fact, during cold demand, both cooling power and energy, which is generated by the heat pump is partially lost to the ATES system because the groundwater temperature from the cold well is often even higher than the return chilled water temperature. The heat pump is not able to compensate this power loss, whereby too high chilled water supply temperatures to the cooling coils results in high relative humidities in the exhibition rooms and long operating times of the heat pump and ATES system.
The unusually high temperature in the cold well of the ATES system is partly caused by unwanted heat injection to the cold well during periods when the system operates in heating mode, which also increases the energy costs for heat generation. Also a large imbalance between extracted water (and energy) from the cold and warm well of the ATES system causes unwanted warming of the cold well. This imbalance is mainly a result of the extraordinary long operation times in cooling (dehumidification) mode and the unwanted energy loses to the ATES system during cooling and heating mode. In addition, by unfavorable settings in the Building Management System, the

heat pump and coupled ATES system are underused for heating the ground floor of the museum. A higher contribution of the heat pump and coupled ATES system will lead to a benefit for the energy costs and the balance in the ATES system.
Furthermore large fluctuations of air temperature and relative humidity in the active conditioned showcases were observed. This was the result of an improper system design, in which the supply air to the showcases is always equal to the (all air conditioned) exhibition rooms located on the second floor. A shutdown of the air exchange to the showcases has already led to a significant improvement of the temperature and humidity conditions in the showcases.

Computer simulations are performed to determine the efficiency of the cooling and dehumidification process by cooling coils in different setups and with varying parameters. A basic building model was used with a varying quality of envelope, in order to increase the general applicability of the simulation results. These simulation results give also an indication of the impact of several system variations and influence factors on the thermal balance in an ATES system (if applied). The simulations are carried out with the heat and moisture model 'HAMBASE' and the software package Matlab/Simulink. Based on the simulation results and actual performances one can conclude that the dehumidification process at the Zeeuws Museum is very inefficient and strongly influenced the total energy costs of the museum. The high chilled water temperature results in increasing operating hours of the cooling system and the desired relative humidity level cannot be maintained. Simulation results show that the efficiency of the dehumidification process could be significantly improved by the application of an additional coil which pre treat the ventilation airflow before it is mixed with the recirculating airflow from the exhibition zones. In the current setup, the dehumidification process takes place by supercool the total airflow after the mixing section. This mixed airflow mainly exists of recirculated air from the conditioned exhibition zones. Because during dehumidification demand the dew point of the ventilation airflow from outside is mostly higher than the dew point of the air from the conditioned exhibition zones, the dehumidification process by cooling the ventilation airflow is more efficient, and also less energy is needed to reheat the supply airflow because mostly it isn't necessary anymore to supercool the total air flow for dehumification. This additional coil in the ventilation airflow could also be used to regenerate the heat surplus in the ATES system during winter conditions by preheating the ventilation airflow with the groundwater from the warm well, and thereby reducing the energy costs for heat generation.
The simulation results demonstrate also a significant impact of the indoor air temperature, during the dehumidification process, on the energy consumption and the dehumidification capacity of the climate system. Depending on the system setup and applied indoor temperature bandwidth, considerably energy savings could be achieved when during dehumidification demand the indoor air temperature is kept high.

TABLE OF CONTENTS

CHAPTER 1

1 INTRODUCTION

This chapter describes the background of this research, the problem description, the objectives and the applied methodology to achieve them.

1.1 Background

Over the years, the focus on preservation of cultural heritage has increased. The Netherlands Court of Audit (NL: Algemene Rekenkamer) noted in 1988, that various measures have to be taken to improve the Dutch situation of preservation of museum collections. The mentioned key factors were: registration, restoration, preservation, accommodation and security. In response to this, the Delta Plan [ref.1] was started around 1990, to eliminate the arrears of conservation.
As a result of this Delta Plan, and led by (strict) national and international guidelines for preservation conditions, museums tried to improve their indoor climate especially by installing Heating, Ventilation and Air-conditioning (HVAC) systems. The museums defined their own climate specifications due to the absence of uniform (Dutch) guidelines. This absence of (uniform) guidelines led, in 1994, to the development of new guidelines [ref.2]. In this guideline, the optimal climate for the most sensitive objects of each material group was given. Although this guideline is too strict for implementation in historical buildings, many museums tried to imply these by installing HVAC-systems, subsidized by the Dutch government. This has resulted in damage to the historical buildings, high energy costs, and expensive installations that required a lot of space [ref.4].
In 1999, the American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) introduced their new climate guidelines for the museum environment in the United States of America.
These ASHRAE climate guidelines [ref.5], has become the most important design guidelines for the museum environment in the world.

Since the mid 1980's, within Eindhoven University of Technology's (TU/e) field of competence "Physics of Monuments", a lot of research has been performed on many different types of (historical) buildings. In 2003, the TU/e was contracted by the Cultural Heritage Inspectorate (CHI) for a research project from 2003 to 2006. The focus was on the actual indoor climate in three museums and the human actor on this. This study [ref.3, 6] showed that the presence of (large) climate systems and strict indoor climate specifications leads to a false feeling of safety in museums. Due to large system capacities to enhance the conditions, irregular maintenance, malfunctioning of the systems and large differences between indoor and outdoor conditions, this can lead to dramatic climate deviations.

As a result of this study, in 2007 the Netherlands Institute for Cultural Heritage (ICN) started a collaboration with other Dutch institutions: Netherlands Museum Advisors Foundation, National Service for Archaeology, CHI, Cultural Landscape and Built Heritage (nowadays the Cultural Heritage Agency of the Netherlands), the Government Buildings Agency and Eindhoven University of Technology – and formed the Dutch Climate Network (NL: Klimaatnetwerk). From this, the current Dutch climate guideline for the museum environment has been established in 2009 [ref.7], which fulfills the need for an integrated climate approach combined into a risk analysis procedure. It should be considered that for optimal preservation of specific collection objects, preservation of the historic building and for providing thermal comfort for visitors, often different climate conditions are desirable.

As an alternative or a supplement for the climate guidelines such as the ASHRAE climate guideline, Martens [ref.4] recently developed a more risk-based approach. Therefore, Martens investigated the degradation risks of four typical museum objects in relation with measured and simulated indoor temperature and relative humidity data. He concludes that the risks for collections in old buildings with a simple installation might not differ much from the risks in adjusted historic buildings where complex HVAC-systems are applied. In buildings with a poor quality envelope, climate conditions near the envelope can be different than average room conditions, introducing risks for the envelope and collection placed near the envelope.

During his PhD study, Martens also investigated the influence of set-points and applied bandwidths of temperature and relative humidity on the risks for degradation of the collection and energy consumption for Dutch weather conditions. Based on computer simulations, he concluded inter alia, that a larger bandwidth might reduce the amount of energy consumption and pointed out that this might also decrease the risks for building physical problems and large fluctuations caused by malfunctioning of HVAC systems. Previous studies of Mecklenburg [ref.8], Artigas [ref.8], Ascione et al. [ref.9] and more recent Maas [ref.10] that investigated the influence of adjusting the set-points for temperature and relative humidity and widening of short term and/or seasonal bandwidths on the energy consumption, show also possible significant energy reductions in various climate zones.

Non-optimal functioning HVAC-systems and the associated high energy consumption in many museums nowadays, is a trigger for a new PhD study [11] to be started in 2012 within the research group “Physics of Monuments” at the TU/e. The Zeeuws Museum is one of the participating museums in this PhD study and the research described in this master thesis focuses entirely on this museum. The findings in this master thesis will be the basis for the ongoing PhD study, with regards to the Zeeuws Museum.

1.2 Problem description

In 2007 the Zeeuws Museum is equipped with an expensive and complex sustainable climate system which includes a heat pump and a seasonal Thermal Energy Storage System (ATES) in the Aquifers of the soil. In practice, the energy consumption of this climate system is very high, and the desired climate conditions, as described in the HVAC design specifications, could not be maintained. Although these specifications are fairly strict, during the summer the indoor relative humidity reaches dangerous levels for the preservation of the collection.

Furthermore, a large imbalance did arise in the ATES system, both volumetric and energetic. This imbalance has a negative effect on the system efficiency and the available nominal power. As required by legislation, ATES systems must be kept in balance. Only small deviations are acceptable [ref.24]. To be able to monitor the status of the ATES system, performance data must be provided to the authorities. These authorities are able to penalize statutory overruns by financial penalties or retraction of system license. Major problems occur when the license of the system is retracted. The climate system would no longer be able to cool and dehumidify with an inoperative ATES system.

1.3 Project objective

The goal of this study is to get insight in the underlying causes of the poor indoor climate during summer conditions, the high energy consumption and the (huge) imbalance of the ATES system. When the underlying causes are known, possible optimizations can become much clearer. Depending on the findings, opportunities for improvement are considered.

To achieve the goals of this study, the following research questions were formulated:

- Why can the desired indoor air conditions not be achieved?
- What causes the high energy consumption of the climate system?
- What causes the imbalance of the ATES system?
- How can the current climate system be adjusted to decrease energy consumption, to improve the indoor climate conditions and to restore the balance in the ATES system?

1.4 Project approach

The method used to perform this research is composed of different activities and time spans. Prior to this research, a preliminary study [ref.12] was performed to get insight in the designing of building climate systems which are coupled to an ATES system. Attention was paid to efficiency optimization and identification of the main causes for the poor performance of many existing ATES systems in the Netherlands [ref.31, 32, 33].

The activities related to the case study, that is used to achieve the research goals, can be summarized as follows:

- Problem identification;
- Short-term improvements;
- Analyzing building physics and systems properties;
- Monitoring of the indoor climate;
- Monitoring of processes in the hydraulic parts of the climate system;
- Assessing the process performances of the climate system by e.g. data analysis;
- Implementation of computer simulations to gain insight in the efficiency of the cooling and dehumidification process and the impact of the main influence factors on the energy consumption, desired system capacity and the thermal balance in the ATES system.

Firstly, it is important to get a good overview of the ongoing problems. This overview is obtained by conversation with the involved people. To get insight in the actual indoor climate conditions, and to test the reliability of the already integrated measurement system, reliable measurement data is needed. The longer the measurement period, the more and better conclusions can be drawn. Therefore, almost directly at the start of the study measurement equipment was applied in the exhibition areas. Also the supply air conditions, outdoor air conditions and the conditions in the adjacent stair case are measured to gain insight in the parameters that influence the climate conditions in the exhibition areas.

Besides the monitoring of the climate conditions, it is necessary to know the real system design and its operation. Building physics and services are analyzed by visual inspections, and studying of mechanical drawings and engineering specifications. Various consultants companies and contractors have also focused on the described problems; these advisory reports are also studied.
To gain more insight into the processes of the climate systems and corresponding actual climate conditions, a VPN connection and login account is created, which makes it possible to remotely analyze and control the Building Management System.

Based on the information that is gathered by the activities written above, the focus was increased on the hydraulic parts of the climate system. To enable this, measurement equipment is placed against a large number of water-pipes in the heating and cooling part of the group, which is connected with heat pump and ATES system. By analyzing this data, the performances of the systems will be clarified, and provides insight into how certain water temperatures in the climate systems arise.

The last part of this research focuses on the modeling of different variants of: control strategies, parameters that influence the indoor climate, and the system setup of the cooling and dehumidification process by making use of cooling coils. The (computer) simulation results of these models provide insight into the effect on: energy consumption, manageability of indoor climate and required installed nominal power. With the combination with the ATES system in mind, the influence of the chilled water temperature on the dehumidification efficiency is simulated, and the effect of the variants on the balance between heat and cold consumption is made clear.

CHAPTER 2

2 THE ZEEUWS MUSEUM

In this chapter, general information is given about the Zeeuws Museum. Paragraph 2.2 and 2.3 will elaborate on the building structure and HVAC-systems of the museum. In paragraph 2.4 the problems with the indoor climate and HVAC-system are described in more detail.

2.1 General

In this paragraph, the location and history of the building, as well the Zeeuws Museum and its collection are described.

2.1.1 Location and History

Since 1972, the Zeeuws Museum is established in the abbey complex, which is located in the centre of Middelburg. Middelburg is the capital city of the province of Zeeland, in the southwest of the Netherlands.
This medieval abbey complex includes eighteen buildings, of which twelve are historical buildings with a protected status. These monuments consist of royal monuments, municipal monuments and partial monuments.
After the bombardment of Middelburg during the Second World War, the abbey complex was restored. A part of the buildings has been completely rebuilt after the war. In recent years, several measures have been performed for improving thermal comfort and energy reduction. The museum has been reopened in 2007 after a perennial thorough renovation. Other than architectural work, new climate systems were also installed during this renovation, to inter alia create favorable climatic conditions for collection preservation.

Fig. 1 Abbey complex in Middelburg which contains the Zeeuws Museum.

2.1.2 Collection

The museum stores over 30.000 treasures that recall the past of the province Zeeland. The collection includes valuable tapestries, paintings, porcelain, silver, jewelry, archaeological excavations, local traditional clothing, fossils, and contemporary art. Besides the permanent collection, the museum hosts also temporary exhibitions on a regular basis.

Fig. 2 Collection impression of the Zeeuws Museum.

2.1.3 Use of the museum

In 2011, the museum was visited by approximately 36.000 visitors. The museum is open all year round, from Tuesday to Sunday 11:00– 17:00 hours, with the exception of Christmas Day and New Years Day.

2.2 Analysis of building physical properties

This paragraph deals with the physical characteristics of the museum.

2.2.1 Orientation

The exposition rooms of the museum are located on the first to the fourth floor and have different orientations as can be seen in Fig. 3. In this pen- drawing of the abbey complex, the Zeeuws Museum is displayed with a different color tone in the upper left corner. Other buildings are, for example, the church (bottom) and the States Complex (bottom left).

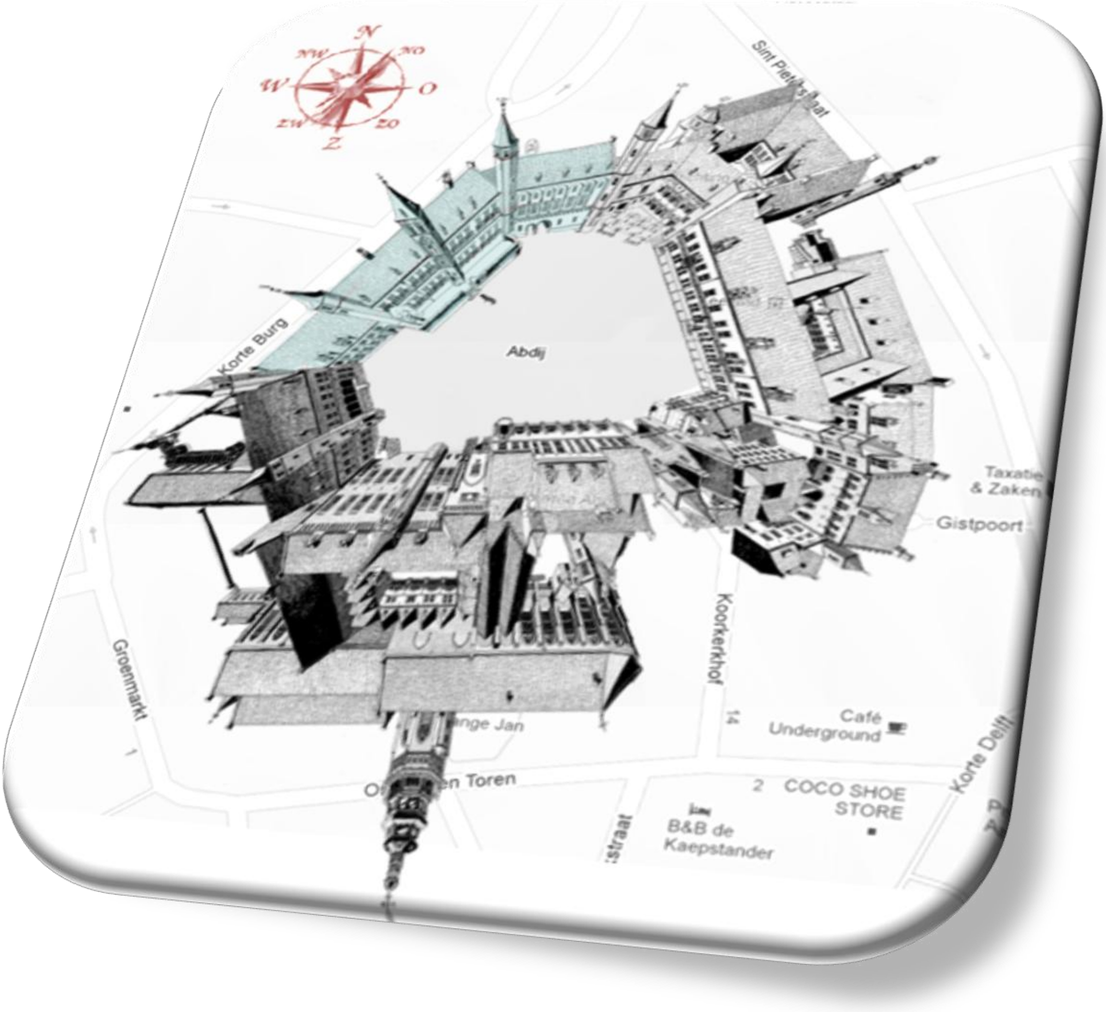


Fig. 3 Orientation of the Abbey complex (pen drawing made by Joost Heeren)

The ground floor of the museum is located partly underground**.** Appendix 1 shows the architectural plans of the museum, which contains nine exhibition spaces (highlighted with colors).

2.2.2 Floors and ceilings

The floors of the museum consist of wooden beam or concrete floors. The floors in the exposition halls however, are mainly covered with tiles or wooden flooring, as can be seen in Fig. 4.

Fig. 4 Impression of exhibition room 3.04 (left) and room 3.06 (right)

2.2.3 Walls and windows

The walls of the building consist mainly of solid masonry, with a varying thickness. The exterior consists of brickwork. The inside of the outer walls of most exhibition rooms are provided with a whitewashed plaster. The windows consist of stained-glass windows, encased in wooden frames. On the inside of the original window frame, a burglary resistant glazing in a metal frame work is placed (see Fig. 5). This extra sheet of glazing is finished with a rubber strip, but it often connects poorly, causing many cracks to be present. During last winter(s) condensation has occurred against the inner side of this glazing and its metal frame.
On the outside, at the position of the glazing, wooden shutters are partly present which are almost always open. Screens are present between the outer and inner glazing to provide sun shading. Depending on the exhibition, the screens remain opened in several rooms.

Fig. 5 View of the partial southeastern facade (left) - Picture of the outer wall in exhibition room 2.01 (middle) - Sun screen and additional window (right).

2.2.4 Roof

The roof consists of a wooden construction which is covered with slates. On the inside a wood wool slab is generally fastened between the trusses to the roof boarding on most positions.

2.3 Analysis of HVAC-systems

In this section, the climate system of the museum is described. The Zeeuws Museum features an extensive climate system for both temperature and humidity control in the exhibition rooms. The needs for cooling, heating, ventilation, and (de-)humidification are provided in these zones by use of 'all air' conditioning systems, as it is often applied in well climatised museums. According the technical specifications, the total airflow rate of these climate systems, provided to the exhibition rooms is about 5 to 7 times the room volumes per hour. A small part of this total airflow (up to 12%) is extracted from outside to fulfill the ventilation demand of the people. The exhibition rooms on the 1st and 3rd floor are conditioned by Air Handling Unit (AHU) 1 and three after treatment units: 1.1, 1.2 and 1.3.

The air treatment for the exhibition rooms on the 2nd floor and the actively conditioned showcases on the 4th floor, is provided by AHU 2. These AHU's are located in technical areas, from which the air is transported by ducts to the rooms.

In addition to these units, there are four other AHU's for ventilation and temperature control in the zones without museum collections. The large zone on the 4th floor where the showcases are located is only thermally conditioned by a fan coil unit into this zone.

The required heating energy of the museum is generated by a collective central heating system of the abbey complex and a heat pump of the museum itself. This heat pump is coupled with an 'Aquifer Thermal Energy Storage' system (ATES), which together also provides the necessary cooling demand in the museum.

2.3.1 Building management system

The mechanical equipment in the museum, such as ventilation, power systems, air treatment, fire control systems and indoor climate conditions are controlled and monitored by a 'Building Management System' (BMS).

This is a computer-based control system which consists of both hardware and software; in this case, the Siemens Desigo software system is applied. This software is configured in a hierarchical manner; Fig. 6 shows the top layer of this management software. More snapshots of several layers in this system will be displayed further in this report.

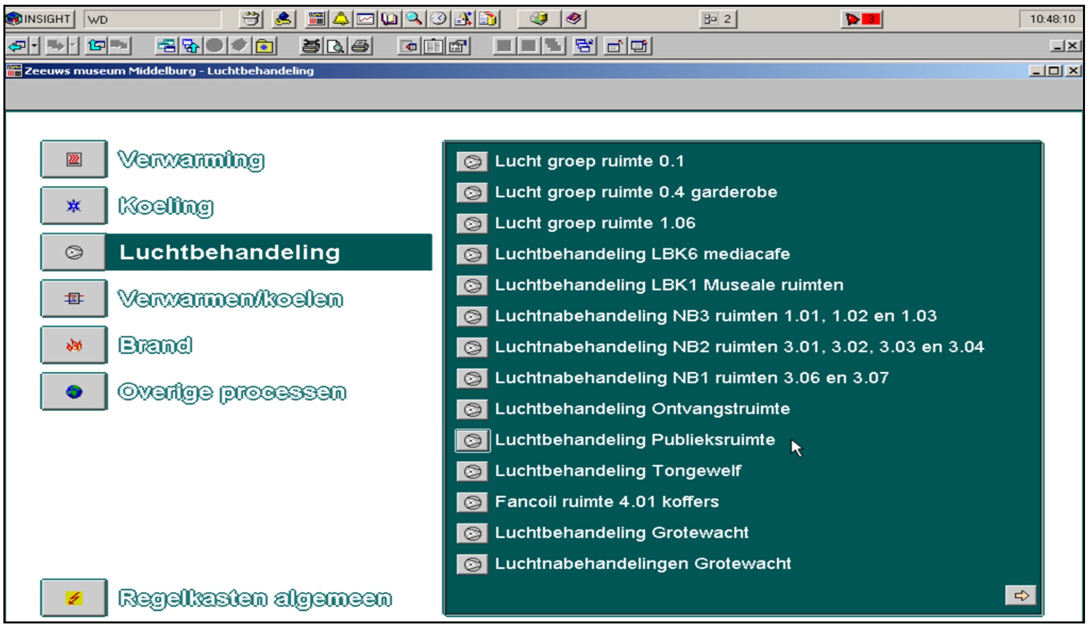


Fig. 6 Snapshot of the BMS software program (Desigo)

2.3.2 Properties of AHU 1 and aftertreatment AHU's 1.1, 1.2 and 1.3

In this section the features of the air handling units will be defined.

Air handling unit 1

AHU 1 and behind coupled AHU's 1.1, 1.2 and 1.3 are located at a large technical area on the 5th floor. The maximum volume flow through AHU 1 is 17.000 m^3/h, which mostly consists of recirculated air from corresponding exhibition rooms, and up to a maximum of 2.000 m^3/h from outside. The desired amount of outlet air can be controlled with a time program in the BMS. The difference between the supply volume flow and the return volume flow from the zones is positive and will automatically leave the building due to overpressurizaton. This small overpressure decreases the amount of unwanted air infiltration in the exhibition zones.

AHU 1 consists of a mixing section, a ventilator and filter section. The air is filtered by a fine dust filter F7 and a carbon filter. Another filter unit with a coarse dust filter G4 prefiltered the ventilation airflow from outside before it enters AHU 1. Based on the settings in the BMS, the motorized air valves control the amount of ventilation air to the zones. The ventilator in AHU 1 provides the driving force to transport the air through the three after treatment AHU's and ductwork to the zones.
Fig. 7 shows how this process is visualized in the Building Management System (BMS):

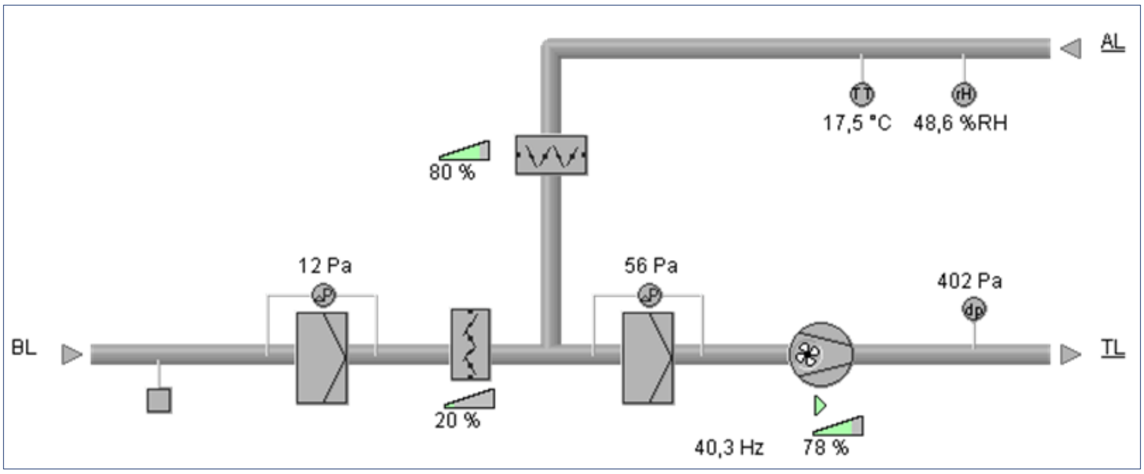


Fig. 7 Visualization of air processes in air handling unit 1

Air handling unit 1.1

By AHU 1.1 the airflow (max. 2.600 m^3/h) is conditioned according the needs of exhibition rooms 3.06 and 3.07, as is visualized in Fig. 8. Cooling and/or dehumidification are provided by a cooling coil. Behind it, a heating coil is installed to (re-)heat the airflow before it enters the last fine dust filter (F9). When the indoor air is too dry, the electrical steam humidifier will provide moisture to the airflow. The displayed rectangular blocks with a diagonal line are the fire dampers in the air ducts. The ‘variable air volume’ valves (VAV’s) in the inlet and outlet ducts regulate the amount of supply and return air to the rooms. This depends on the desired energy and humidity demand of the zones and the actual supply air condition after the AHU. The volume flow is regulated separately for almost every room. Only for room 3.06 and 3.07, the volume flow cannot be controlled separately from each other, as can be seen in Fig. 8.

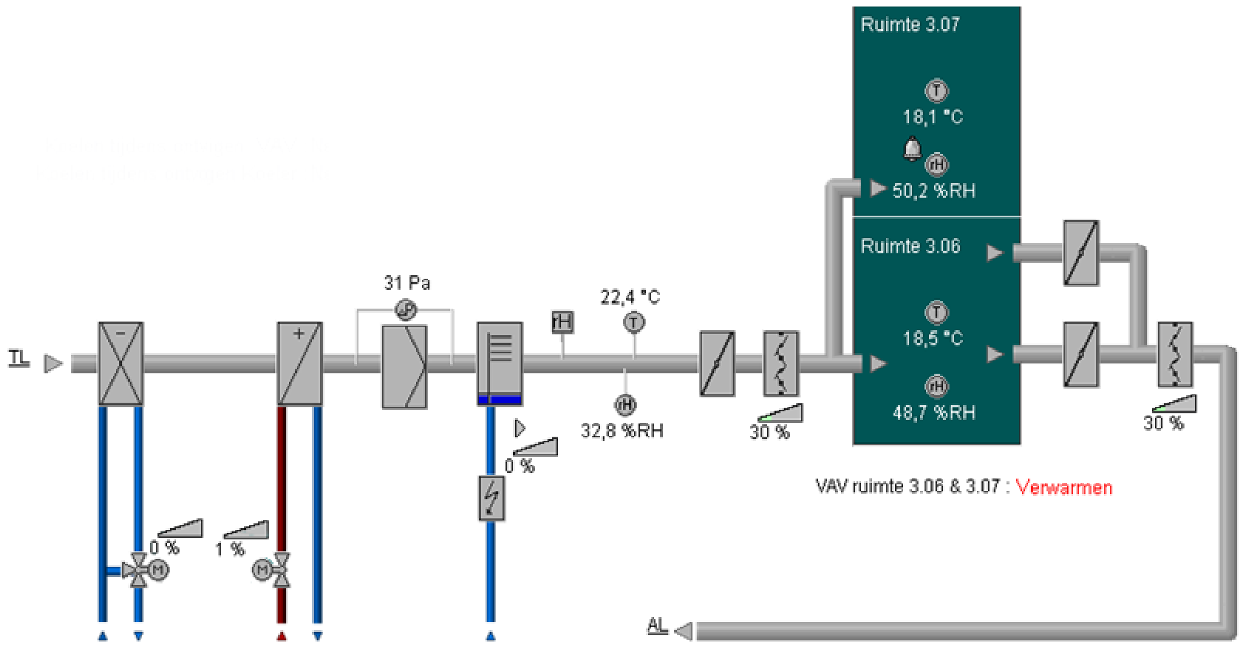


Fig. 8 Visualization of air conditioning processes in AHU1.1 and air conditions in corresponding rooms (3.06 & 3.07)

The supply air conditions of the AHU’s are controlled based on the needs of the corresponding zones. A demand is noted when the measured values of temperature and humidity in the zones exceed their set-point borders. Because the measured air conditions in the different zones are usually not the same, the AHU will provide a supply air condition based on a weighted mean condition in the corresponding rooms. Locally the VAV’s will reduce the airflow when this supply air condition is not favorable for the particular zone.

Air handling unit 1.2

AHU 1.2 exists of the same components as AHU 1.1 and takes care of the climate in the exhibition rooms 3.01, 3.02, 3.03 and 3.04. According the HVAC specifications, the maximum volume flow through this AHU is 8.650 m^3/h. Due to the large floor of room 3.04, this room is equipped with two measuring devices in order to obtain a more accurate indication of the average air condition, as can be seen in the BMS visualization (Fig. 9).

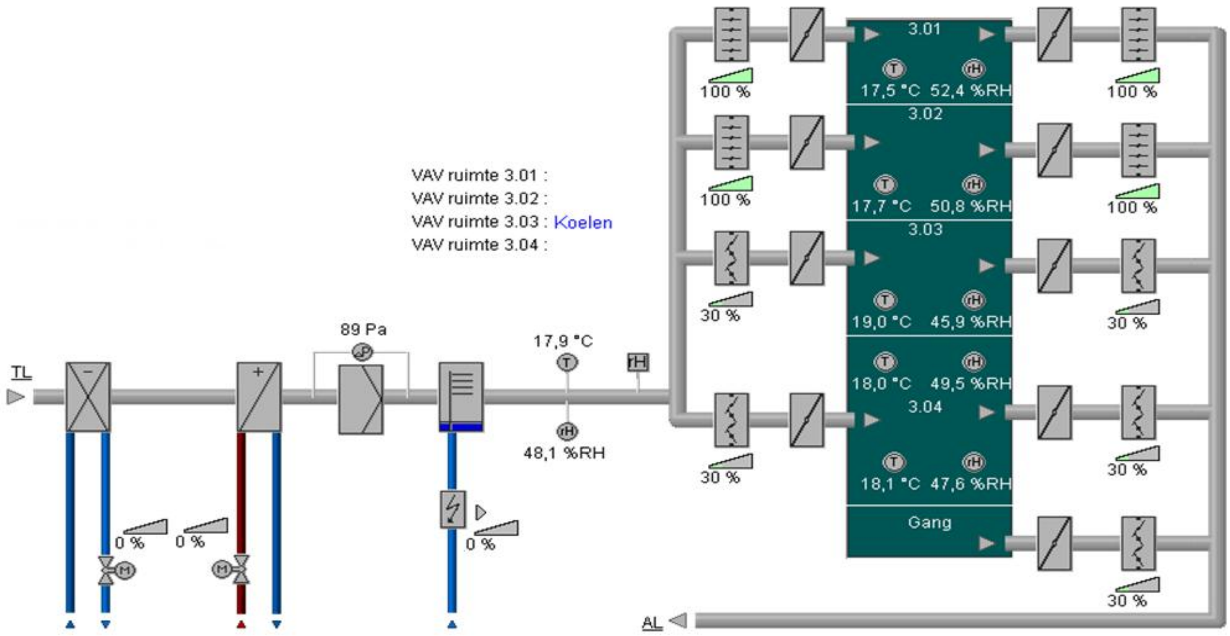


Fig. 9 Visualization of air conditioning processes in AHU1.2 and air conditions in corresponding rooms.

Air handling unit 1.3

The exhibition rooms on the 1st floor are conditioned on the same way by AHU 1.3 (max. 5.650 m^3/h):

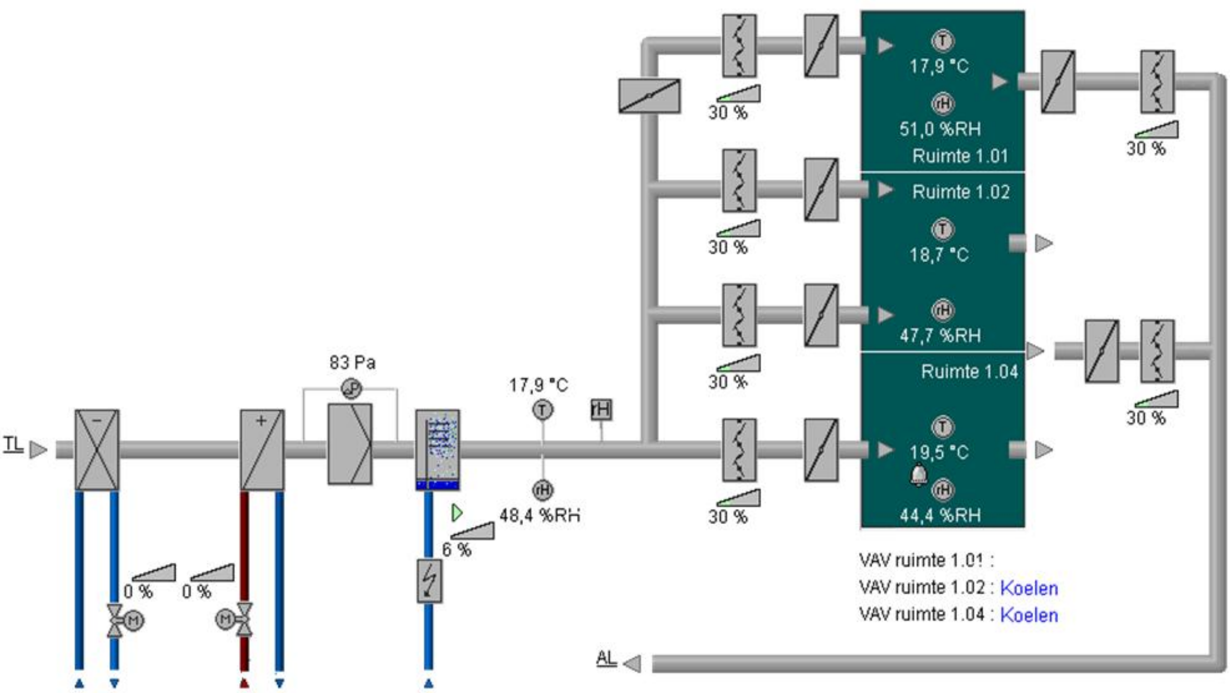


Fig. 10 Visualization of air conditioning processes in AHU1.3 and air conditions in corresponding rooms.

2.3.3 Properties of air handling unit 2

The rooms on the north side of the stairwell are conditioned by AHU 2, which is located in the technical area on the ground floor. In contrast to the above appointed AHU's, the heating coil of this AHU is not in connection with the system wherein the heat pump releases its generated heat. The required energy for heating is derived from the collective central heating system of the abbey complex. Cooling energy, however, is provided by the heat pump and coupled ATES system. AHU 2 takes care of the climate in the exhibition rooms 2.01, 2.03, 2.04 and the show cases on the 4th floor. Fig. 11 shows the visualization of this air conditioning process in the BMS. It can be seen that the air dampers belonging to the showcases are closed in an overruled status. The raison for this is mentioned in paragraph 3.2.4.

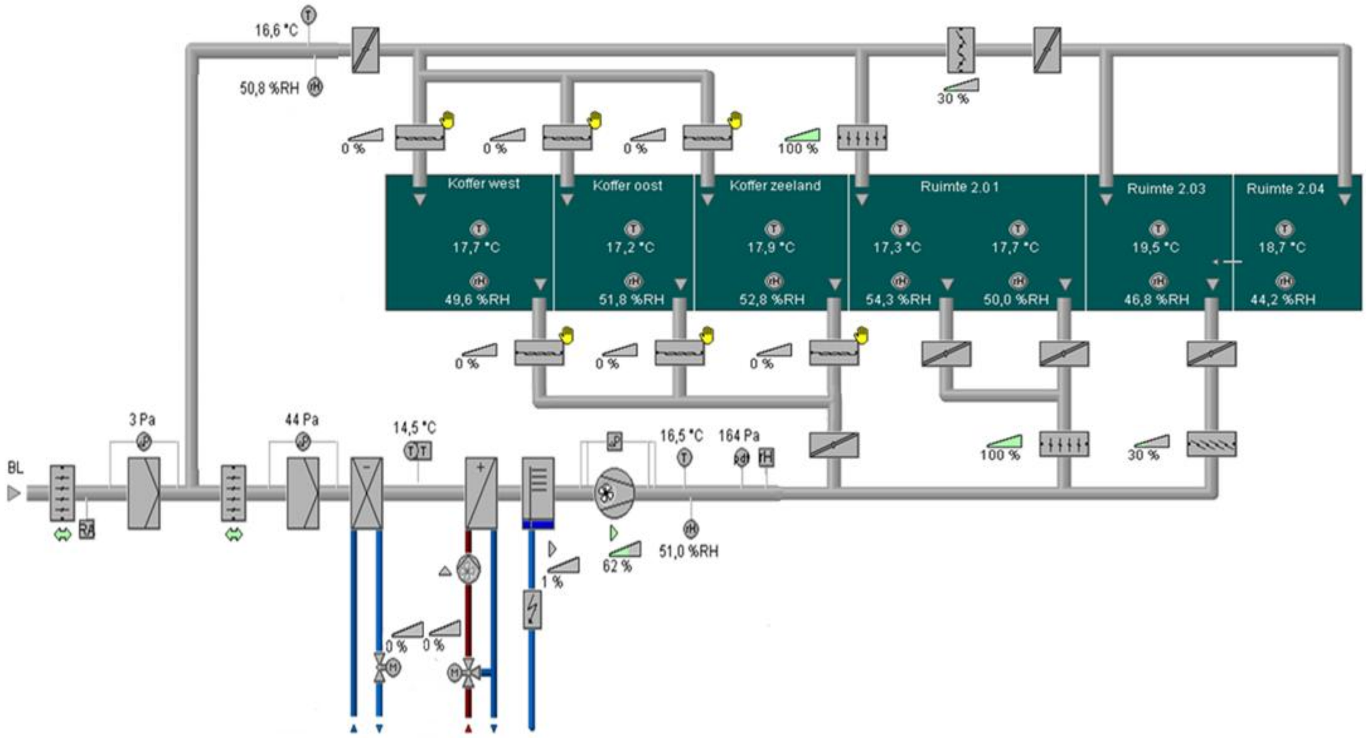


Fig. 11 Visualization of air conditioning processes in AHU 2 and air conditions in corresponding rooms.

2.3.4 Hydraulic parts of the climate system

The hydraulic parts of the climate system are described with reference to the schematic drawing shown in Fig. 12 and magnified in appendix 2. In the blue frame the cold consuming groups of the museum are visualized. These are the cooling coils in the air handling units. This 'cold energy' is generated by the ATES system and the heat pump presented in the green frame. The two rectangles at the bottom of this green frame indicate the cold (left) and warm well (right) of the ATES in the ground. The return flow from the cold consumers is first cooled by the ATES system, by means of energy transfer in the left counter flow heat exchanger (TSA1). Subsequently this water flow is more deeply cooled by the evaporator of the heat pump, which is visualized top left of the green frame. After that, the chilled water is pumped back to the distributor and connected cold consuming groups.

During cooling energy generation by the heat pump, the released heat of the condenser (upper side of the heat pump) must be disposed of. When there is no heating demand in the building, this heat is issued to the warm well of the ATES system by energy transfer in the right counter flow heat exchanger (TSA2). When there is a need for

heating in the building, the energy is transported to the heat consumers which are visualized in the orange frame. These are in particular the heating coils in the AHU's which take care of the climate in the exhibition zones. If the heat production is higher than the heating demand, this difference is stored in the buffer vessel indicated at the bottom of the red frame. When also the buffer vessel is loaded, the heat pump can be switched off, unless the system operates in cooling mode. In that case the superfluous heat has to be stored in the ATES system. Also in the opposite case, when there is demand for heating, but the resulting cooling energy at the evaporator side of the heat pump cannot be used in the building, this will be stored in the ATES system using the left heat exchanger (TSA 1). When during cold winter days the heat pump cannot supply sufficient heat or is in malfunction, the (extra) heat will be delivered by the collective heating system of the abbey complex. This energy exchange takes place through the heat exchanger presented at the bottom left of the red frame.
The heat consuming groups at the North side of the staircase are not connected with the heat pump, so this heating energy is provided by the collective system, as can be seen at the bottom right of the red frame.

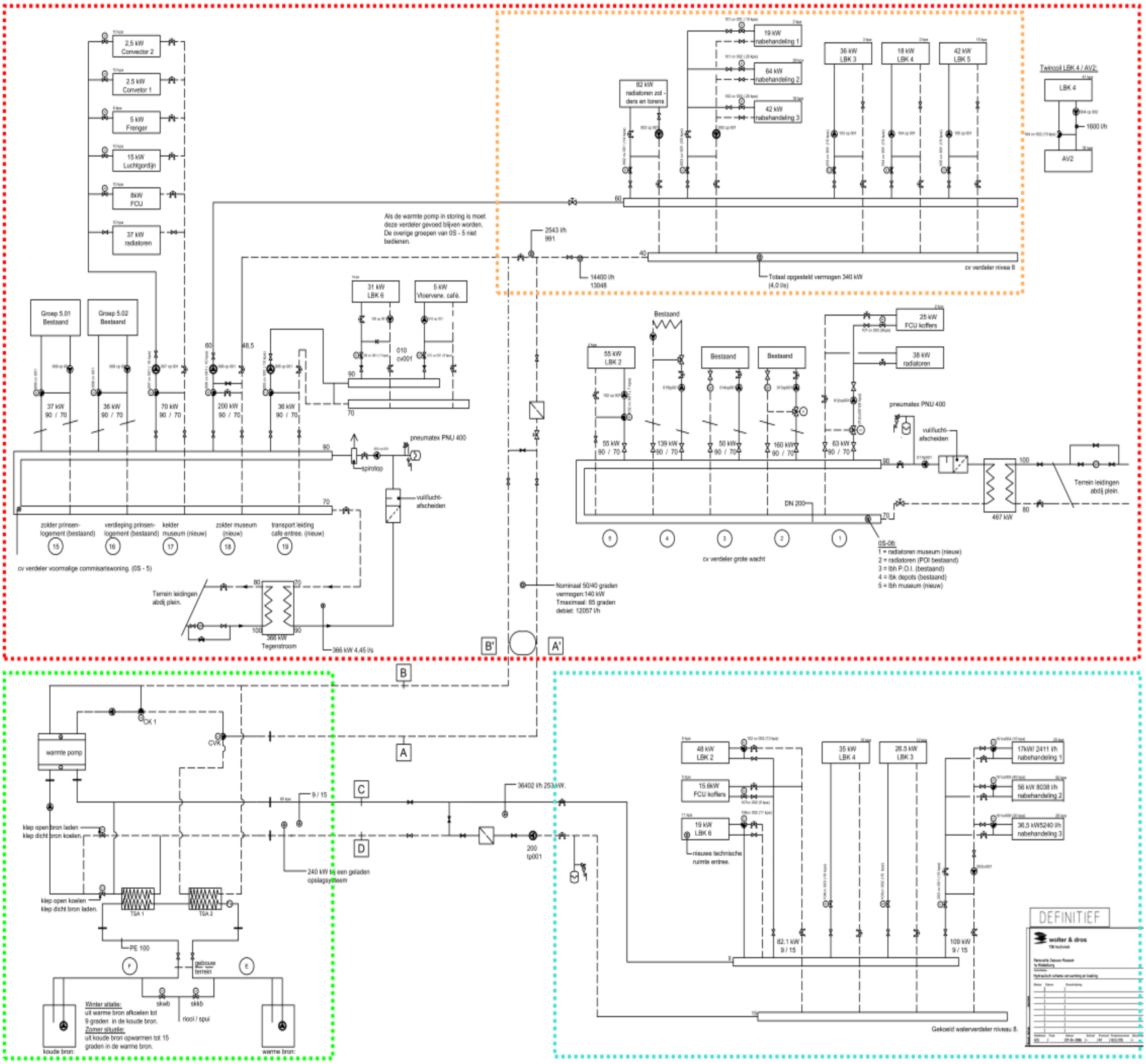


Fig. 12 Schematic drawing of hydraulic parts of the climate system

2.4 Problem identification and taken short term measures

This section further explained the problems with the indoor climate and unbalanced ATES system at the Zeeuws Museum. Also the measures taken in short term are discussed here.

To get an impression of the indoor climate problems, conversations were started with the people involved. The research at the Zeeuws Museum started during the summer season of 2012. In order to achieve an optimized indoor climate for preservation of the collection during upcoming summer, the people of the Zeeuws Museum asked to implement optimizations as fast as possible, even when the study was not finished.

2.4.1 Poor control of relative humidity

From the conversations mentioned in the introduction of this chapter, it became clear that during the summer seasons the relative humidity in the exhibition rooms largely exceeds the desired maximum levels. This has been the case since this new climate system has been installed in 2007.
According the HVAC design specifications [ref.25], the climate system was designed to keep the indoor climate conditions during the summer season at 22^{o}C ± 1.5^{o}C and 53% ± 1.5% with absolute upper limits of 25^{o}C and 55%. That these conditions are not met in reality, is confirmed by the hard copies of measurement data obtained by the BMS in the past. For several weeks, the indoor relative humidity values reached dangerously high levels concerning conservation of the museum collection. Fig. 13 shows the measured temperature (red) and relative humidity values (blue) in two exhibition rooms during a week in August of 2011. It can be seen that the relative humidity values even exceed the applied range of y-axis, which was set at 65%.

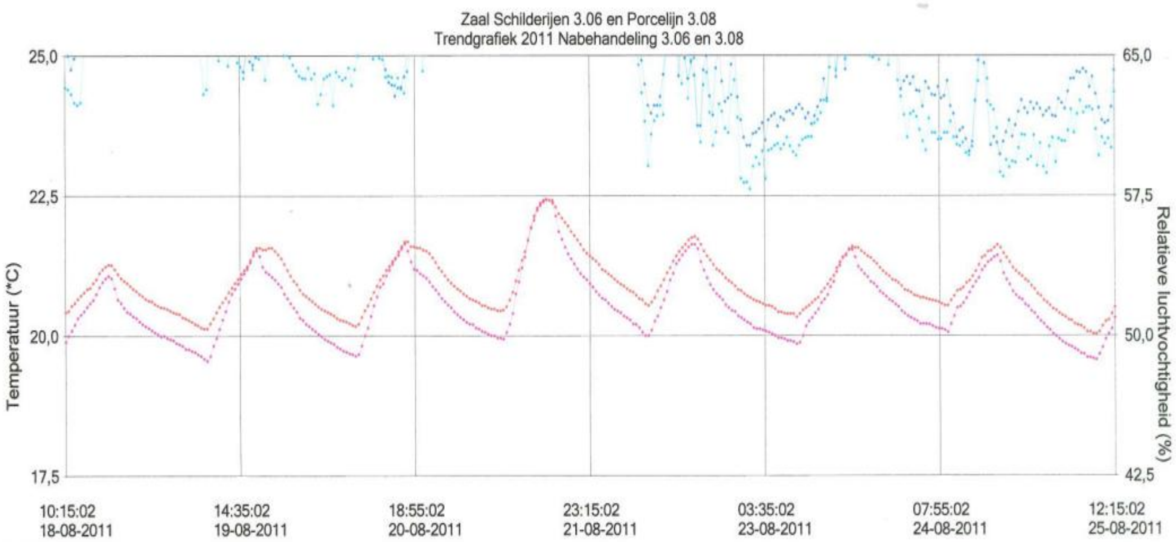


Fig. 13 Measured air conditions in room 3.05 and 3.08 during a week in the summer of 2011; temperatures (red), R.H. (blue)

2.4.2 Imbalanced ATES system

It also became clear that a large imbalance arose in the long term aquifer thermal energy storage system. To gain insight into this imbalance, the energy data of the ATES system (since the commissioning in 2007) was collected by the BMS and is visualized in a time-dependent trend presented in Fig. 14 and Fig. 15. These figures indicate respectively the energetic and volumetric status of the ATES system. When both trends decrease, it means that groundwater is extracted from the cold well of the ATES system and after energy transfer injected in the warm well. When the lines go up, the opposite has happened; groundwater is extracted from the warm well and, after heat extraction, injected back into the cold well. Due to the type of energy demand in the Zeeuws Museum, the seasons are visible in these trend graphs of the ATES system. An ATES system is in balance when the sinusoidal lines fluctuate around the baseline (x-axis). This is clearly not the case; much more 'cold' than 'heat' was extracted from the ATES system, representing by the downward trend in these two graphs.

Based on the available data of the ATES system, one can also conclude that the injection temperature in both warm and cold well are not favorable. The graph in Fig. 16 shows that there is only a small difference between the monthly mean injection temperature into the hot and the cold well. This temperature difference is an important indicator of the efficiency of the ATES system. This efficiency is determined by the ratio of energy consumption of the groundwater pumps in the wells, and the amount of thermal energy that is exchanged between the groundwater from the wells and the building. Favorable injection temperatures are typically between the 5 and 8ºC to the cold well, and around 18 to 25ºC to the hot well. This would lead to more favorable temperatures in the wells which results in more capacity and system efficiency for heat and cold energy supply.
Related to the peak injection temperature in 2008, it must be noticed that an injection temperature above 25ºC is not allowed by legislation. The reason of these high injection temperatures is unclear; probably it has to do with a misalignment between the water volume flows on both sides of TSA2.

Royal HaskoningDHV TU/e

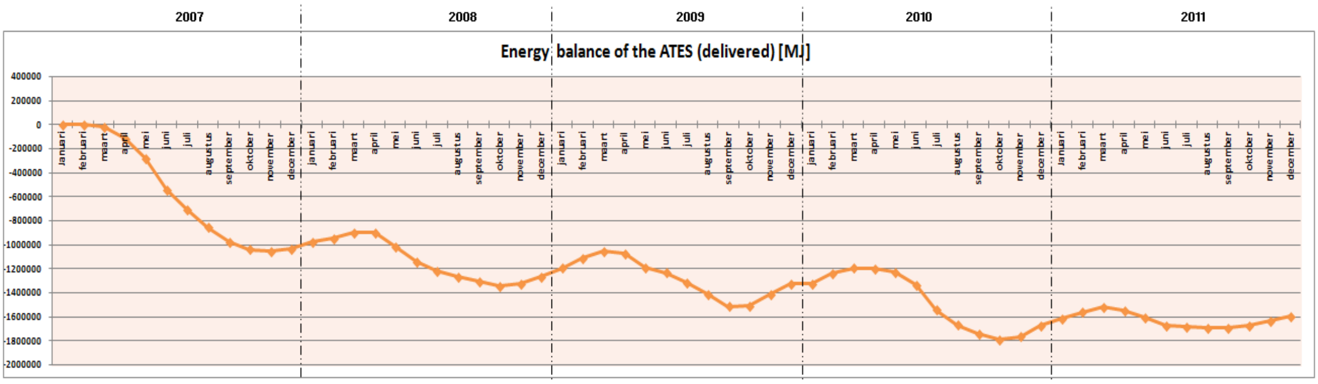


Fig. 14 Thermal energy balance in the ATES system

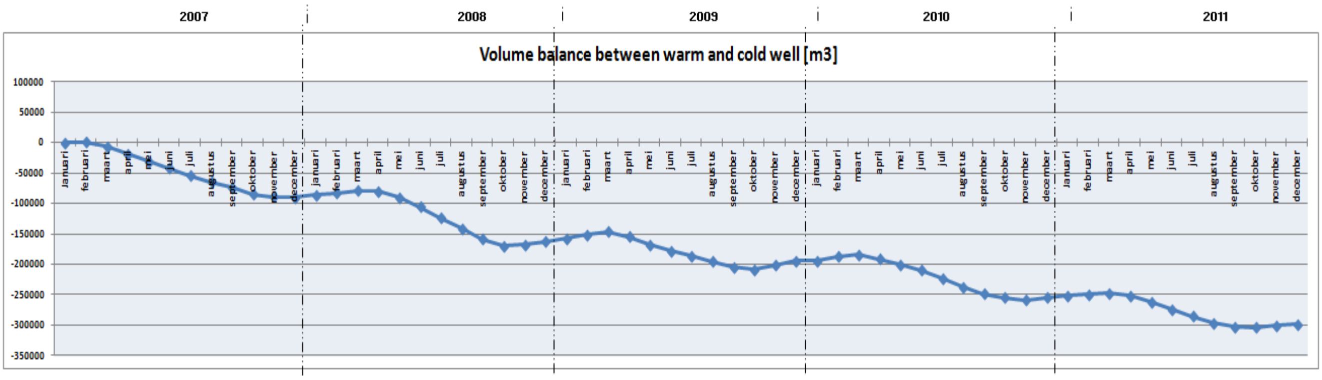


Fig. 15 Volumetric balance in the ATES system

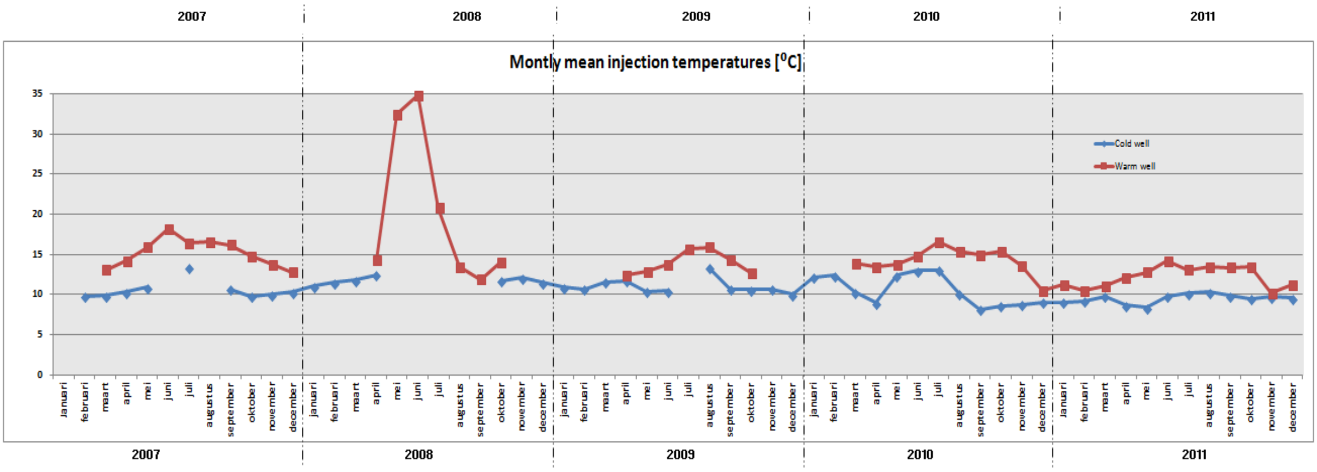


Fig. 16 Monthly mean injection temperatures in warm well (red) and in the cold well (blue) of the ATES system

2.4.3 Previous studies

Before this research was started, various consulting companies and HVAC-contractors already tried to find the causes of the described problems. From these resulting research reports [ref.*27*, 30, 28], it can be observed that they, in general, all designate the same cause: they concluded that the imbalance in the ATES system is caused by a much greater cooling demand than heating demand of the museum.
One company indicated, with recalculations of the expected cooling and heating demand, that the original calculations and corresponding assumptions in the design process represent a non-real ratio between the expected cooling and heating demand. Due to this imbalance, the soil should slowly warm up with the consequence that the nominal cooling capacity of the ATES system decreases. This was designated as the main reason for the reduced dehumidification capacity of the climate system, which results in the higher indoor relative humidities.

As a result of these investigations, the system has been customized (2009-2010) in such a way that the ATES system and heat pump are able to produce more heat during the heating season, which should positively influence the balance in the ATES system. This adjustment implies that the heat pump must be able to contribute to the heat generation for the collective heating system of the abbey complex. This contribution is only possible when the water temperature at the primary site (collective heating system) of the heat exchanger, is a number of degrees beneath the outlet water temperature of the heat pump. According to the people involved, this adjustment did not yield the desired effect, as is also confirmed by the two graphs in Fig. 14 and Fig. 15. The most likely reason for the lack of effect is the fact that the temperature in the collective heating system is seldom low enough for contribution to the heat supply by the heat pump of the Zeeuws Museum. Because the collective heating system is a traditional 'high temperature system', it is not possible to decrease this temperature. This should result in too less heating power in the coupled buildings.
A next proposed adjustment was the purchase of a dry-cooler. This should allow excess heat to be transferred to the outdoor environment, instead of injected it into the ATES system. During winter days, also cold energy could be extracted from the outdoor air to load the cold well of the ATES system. In consultation with the stakeholders it was decided to postpone the purchase of the dry cooler in anticipation of the outcome of this investigation.
In this TU/e research, a broad approach of the project was chosen. The focus was not too quickly on a specific area, but the previous findings were kept in mind.

2.4.4 Short term measures

In order to achieve a less risky climate for the preservation of the museum collection during the summer of 2012, it was decided to change the used set-points of temperature and relative humidity for the exhibition spaces.
The existing temperature set-points were about 19 to 20°C, and were changed to 22-24°C for the summer season. This allows the air to contain more moisture at the same relative humidity levels, so extremely high relative humidity levels should occur less often, and the demand for sensible and latent cooling will be less. The relative humidity set-points are also increased from around 49-53% to 50-60%, mainly due to the fact that the upper limit of the relative humidity could hardly be maintained. The idea behind this adjustment is that less cooling is consumed, so that more cooling energy is available at the moments when it is more necessary. The cold well of the ATES system will discharge less quickly which also benefits the balance in the ATES.
In addition, it was suspected that the dehumidification capacity of the cooling coils would increase with these new set-points, because the corresponding air dew point theoretically increases by about 6°C, as is indicated by Fig. 17.

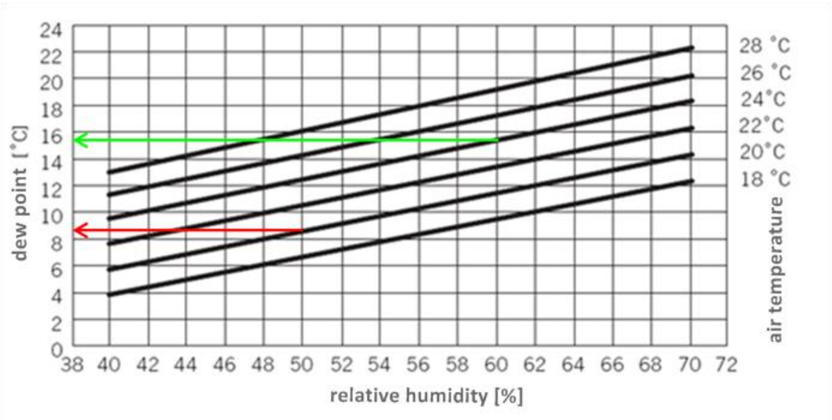


Fig. 17 Dew point corresponding to the air temperature and specific humidity

Another short term measure was to reduce the cooling demand by decreasing the heat load to the building. The advice was to make more use of the sun blinds during warm and sunny days, and closing of an opening in a chimney in exhibition room 3.07. This has been accidentally left open after proceedings and was found during a site inspection.
The glass vestibule at the entrance is also a large unwanted heat source during warm and sunny days (ground plans in Appendix 1). When both automatic sliding doors are closed, the heated air by incoming solar radiation mainly enters the building through an opening to the café, and when the inside door opens. If the automatic sliding door at the outside is kept open during warm and sunny days, this heated air can partially leave the building. The automatic sliding door at the inside of the glass vestibule can continue to function, to separate the climate of the entrance from the outdoor climate.

CHAPTER 3

3 ANALYSIS OF CLIMATE AND THE FUNCTIONING OF HVAC SYSTEMS

This chapter deals with the research into the causes of the appointed problems at the Zeeuws Museum. Paragraph 3.1 discusses the manner in which necessary information has been obtained. Subsequently in paragraph 3.2 this obtained information will be analyzed, with the focus on the prescribed problems.

3.1 Monitoring of indoor climate and HVAC systems

To gain more insight into the indoor climate and processes in the climate systems, additional measuring devices are placed in the museum. This measurement data can be viewed on the internet and automatically alarm messages by email are sent when the indoor temperatures or relative humidities exceeds the desired set values.

3.1.1 Method of measuring

The applied telemetric measurement system of the TU/e consists of a wireless measurement set. This measurement set is able to measure both relative humidity and temperature. The sensors send their data to a centrally placed data logger in the museum, which stores this data (with sample time of 10 minutes) and provides the ability to readout the data. Fig. 18 shows the applied measurement instruments, the specifications of this equipment can be found in appendix 3.

Fig. 18 Applied measurement equipment

The starting point of the air measurement period is 11-06-2012. The locations of the sensors are visualized by the red dots in Fig. 19, and are described in Table 1.
The exhibition rooms are accentuated by colors. Rooms which are indicated with the same color are conditioned by the same AHU.

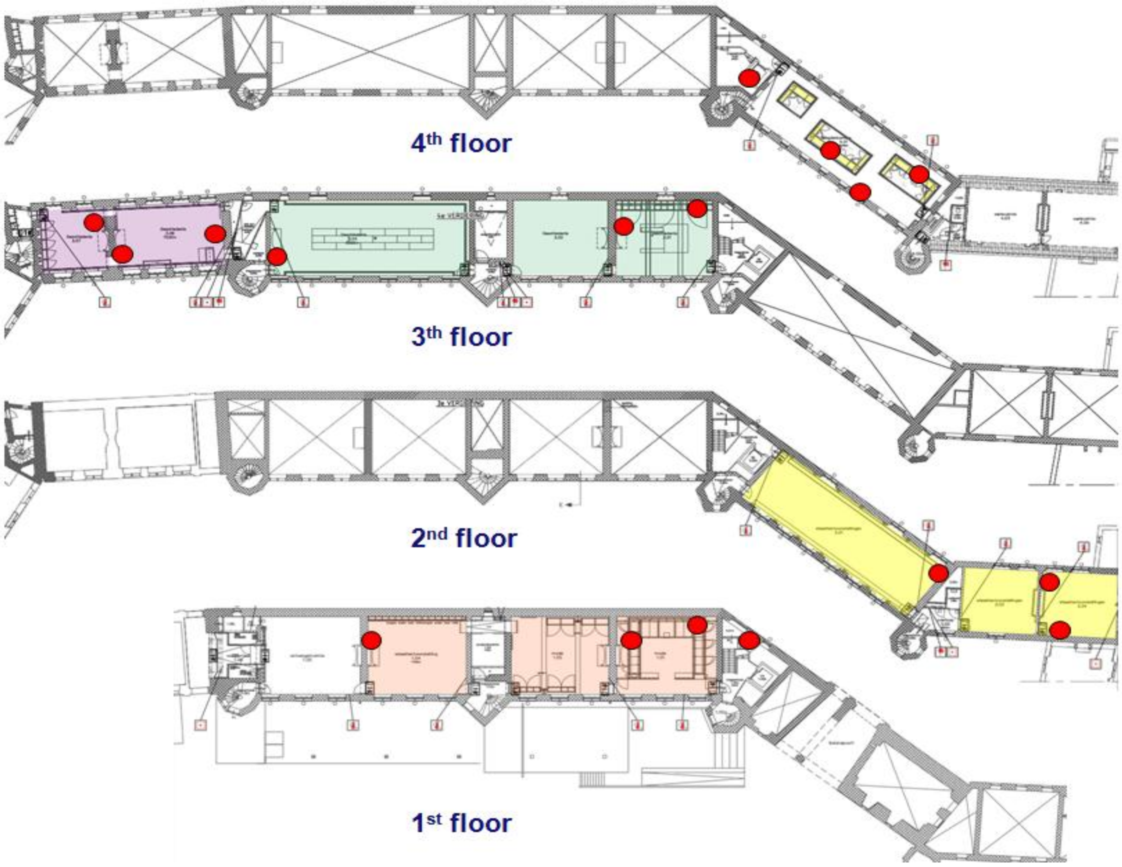


Fig. 19 Floor plans of the Zeeuws Museum [ref.29] and measurement locations indicated by the red dots.

Measuring location	Sensor-ID	Above floor [m]
Room 1.01 & *air supply condition*	1546+*1589*	2,8
Room 1.04	1544	2,3
Room 2.01	1560	2,8
Room 2.04 & *air supply condition*	1577+*1602*	2,3
Room 3.01 & *air supply condition*	1603+*1557*	2,3
Room 3.04	1610	2,4
Room 3.06 & *air supply condition*	1790+*978*	2,7
Room 3.06	1590	5
Room 4.01	974	2,8
Room 4.01 Showcase 'Oost'	1591	± 1,5
Room 4.01 Showcase 'Zeeland'	1803	± 1,5
Staircase low	1545	1,8
Staircase high	1588	12
Outdoor	1457	± 13

Table 1 Measurement locations

3.1.2 *Measurements at hydraulic parts of the climate system*

At the beginning of July (2012), the measurements at the hydraulic parts of the system were started. Also here, additional measurement equipment is placed because the Building Management System (BMS) gives only limited insight into these processes. The same type of equipment is used, where the temperature is measured with flat sensors against the water pipes (Fig. 20). Because these sensors are placed underneath the insulation layer, it is expected that the measured temperatures will give a fairly good approximation of the water conditions into the pipes.

Fig. 20 Temperature measurement devices

In totally twenty temperature sensors are placed at the hydraulic system, at the locations that are indicated with the red dots in Fig. 21. In appendix 2, this scheme is displayed enlarged. The focus is on the processes where the heat pump and ATES system are included (green), and energy is exchanged with the thermal buffer and the cold/heat consuming groups in the building which are highlighted with the blue and orange frames in Fig. 21. These include the AHU's which take care of the climate conditioning in the exhibition spaces. Later on in this research (august 2012), the sensors in the return pipes of the cold consuming groups separately were placed. These sensors are indicated with the four red dots in the blue rectangle in Fig. 21.

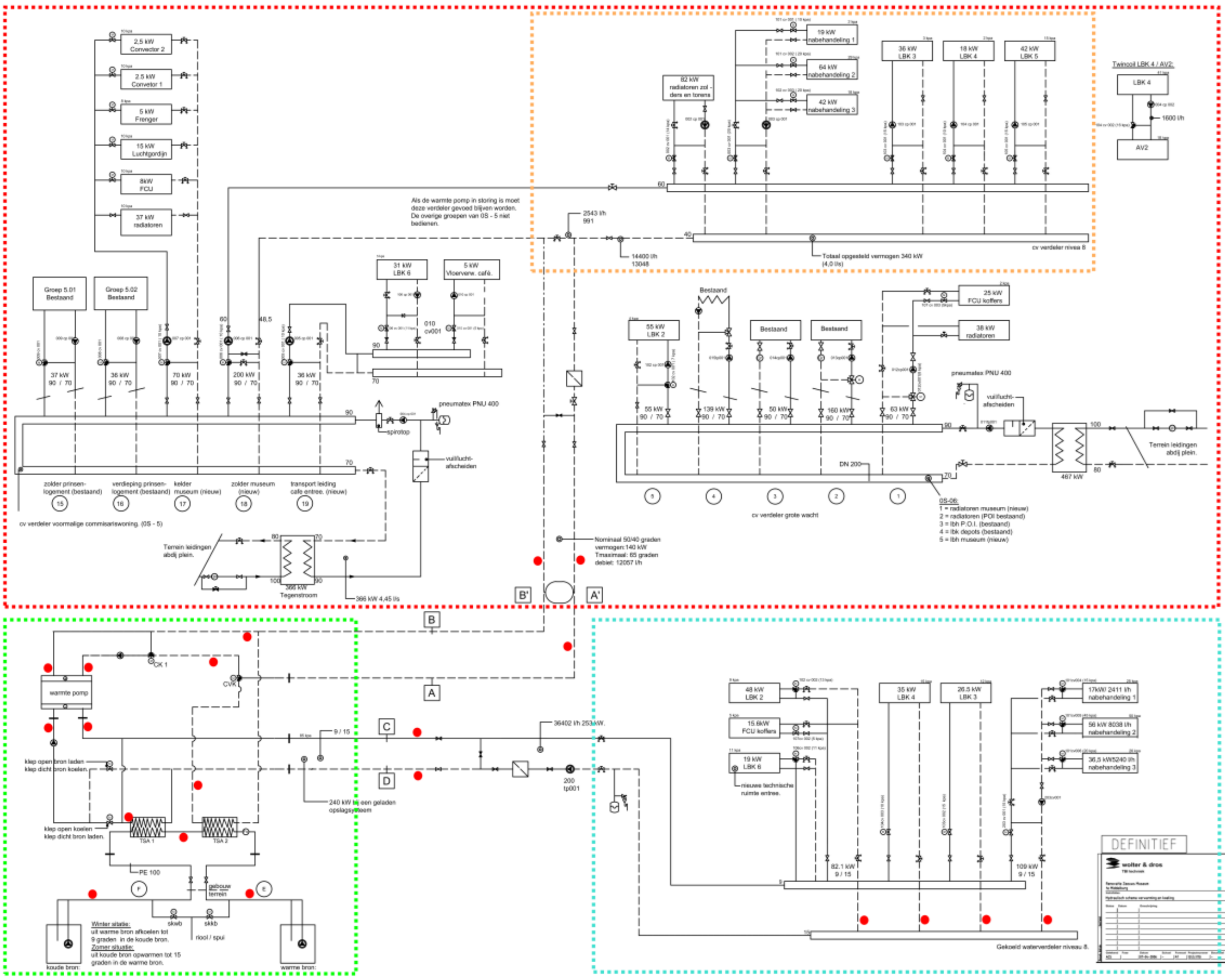


Fig. 21 Schematic drawing of the hydraulic climate system with applied measurement locations indicated with the red dots

3.1.3 *Data obtained from the BMS*

A lot of measurement data of the BMS is automatically stored in a database. However, only measurement data up to one month ago is stored. Here, this data is also used for examination and comparison with the data from the additional measurement system. A VPN-connection is made with the BMS to obtain data from previous months and for real time monitoring of the climate conditions and the status of the climate systems.

3.2 *Analysis of the obtained information*

In this paragraph the obtained information from will be analyzed. The identified causes of indoor climate problems and imbalanced ATES system are discussed.

3.2.1 *The effect of the previously executed set-point adjustment*

As mentioned before, the temperature set-points for the summer season were increased by approximately 3°C to a value of 22°C (for heating demand) and an upper level of 24°C (for cooling demand), in order to achieve less risky relative humidities for the preservation of the collection during the summer season.

Indoor climate

In spite of this measure, high indoor relative humidity values were still observed during humid weather conditions. Remarkable is that during periods of dehumidification by the cooling coils, the indoor temperature dropped a couple degrees. These periods of dehumidification are highlighted in Fig. 22. Even the lowest temperature set-point of 22°C was amply exceeded. If the indoor temperatures would be kept at 22°C, the indoor relative humidity should hardly exceed a relative humidity level of 60%, which corresponds with a specific humidity of 10 g/kg.

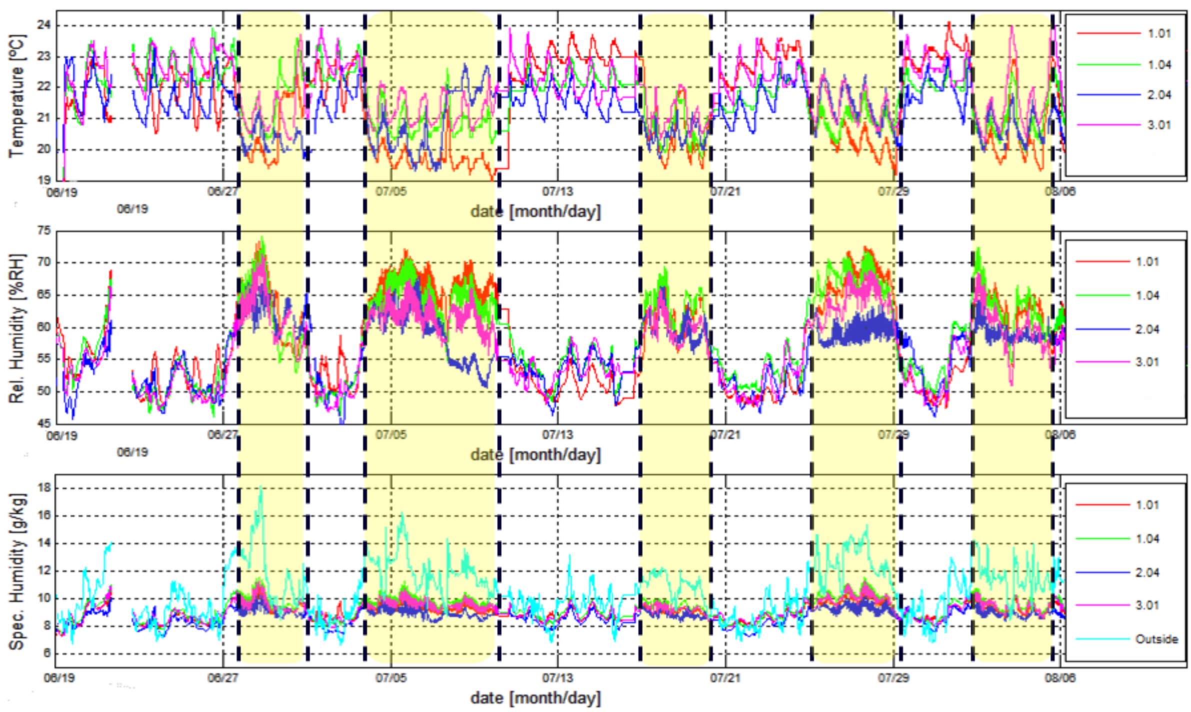


Fig. 22 Measurements in exhibition rooms 1.01, 1.04, 2.04 and 3.01 which show the indoor temperature drop during periods of dehumidification caused by the climate system; air temperatures (upper graph); relative humidities (middle graph) and specific humidities (lower graph).

Energy consumption

The effect of the set-point changes on the energy consumption is obvious. This is not only beneficial for the energy costs, but also for the balance in the ATES system, because less energy for cooling is extracted.

In the graphs shown in Fig. 23, the electricity consumption of the Zeeuws Museum during the summer season is compared to the electricity consumption of the same month (June, July and August) in previous years.

The differences in weather conditions are indicated with the amount of heating and cooling 'degree days', during these corresponding months. A 'degree day' is an expression which signifies that the mean daily temperature is below or above 18°C. For example, when the mean temperature of a particular day is 22°C, four cooling degree days would be listed because also the size of the deviation (4°C) is taken into account.

Electricity is the driving force of the heat pump, which generates heating and cooling energy in combination with the ATES system of which pumps are also driven by electricity. However the climate system is not the only electricity consumer of the Zeeuws Museum, it can be assumed that it is definitely one of the largest. The comparisons shown in Fig. 23 demonstrate that the energy consumption of last summer is by far the lowest since the commissioning of the climate system, and this is not caused by the weather conditions.

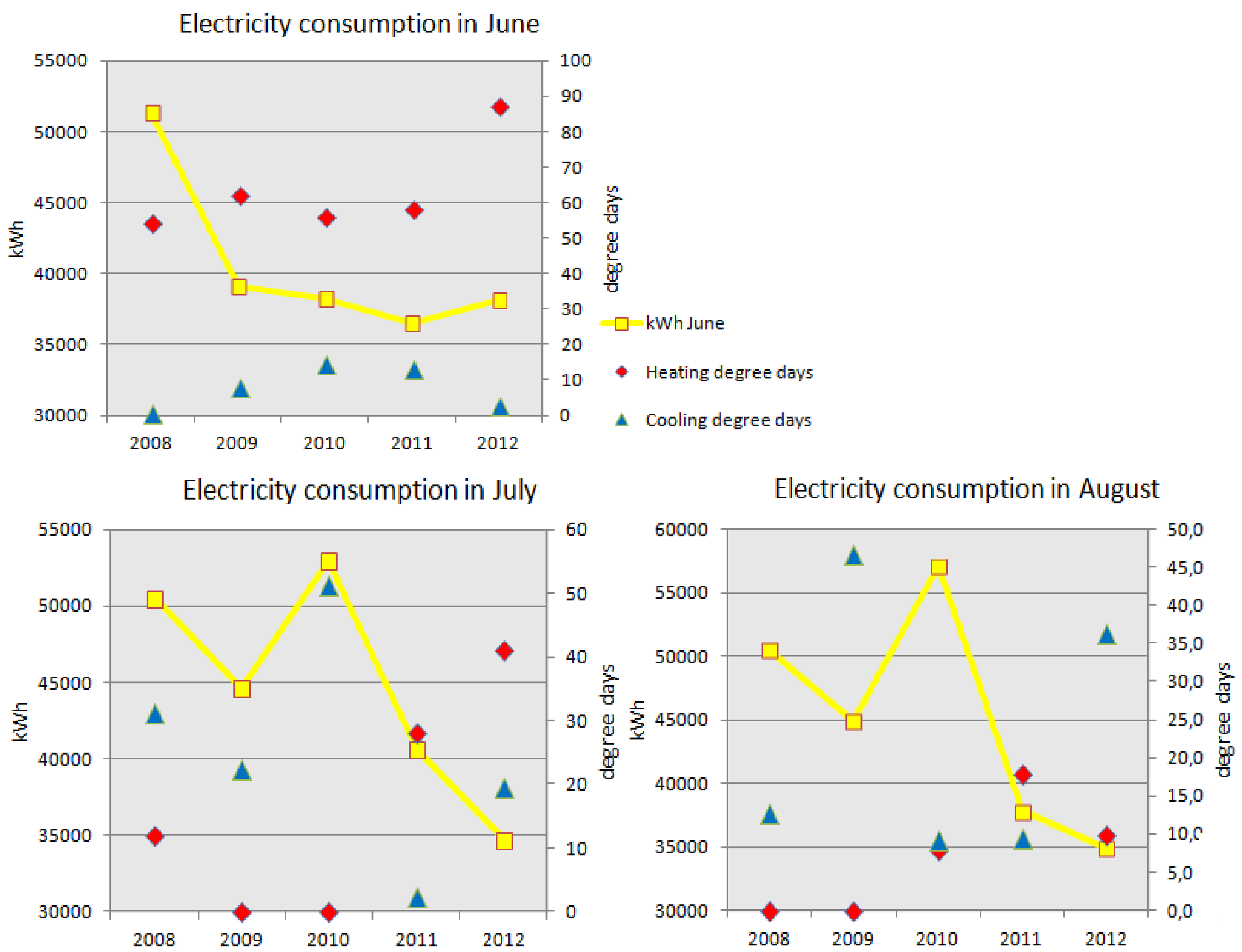


Fig. 23 Comparison of the electricity consumption during the summer months of last 5 years, with indication of outdoor climate; Month June (above); Month July (left); Month August (right).

3.2.2 *Comparison of BMS and TU/e measurements*

In order to check the reliability of the temperature and relative humidity observations by the building management system, these measurements are compared with those of the additional sensors of the TU/e. To exclude the influence of inhomogeneous conditions in the zones, the additional TU/e sensors are placed against the BMS sensors.

During this comparison it became clear that the temperature measurements of the BMS in the exhibition rooms are about 1 to 2^{o}C higher than the measurement data obtained with the TU/e sensors. The observed values of the relative humidities show a better correspondence. As an indication, in Fig. 24 both measurements of temperature and relative humidity in exhibition room 2.01 are visualized.

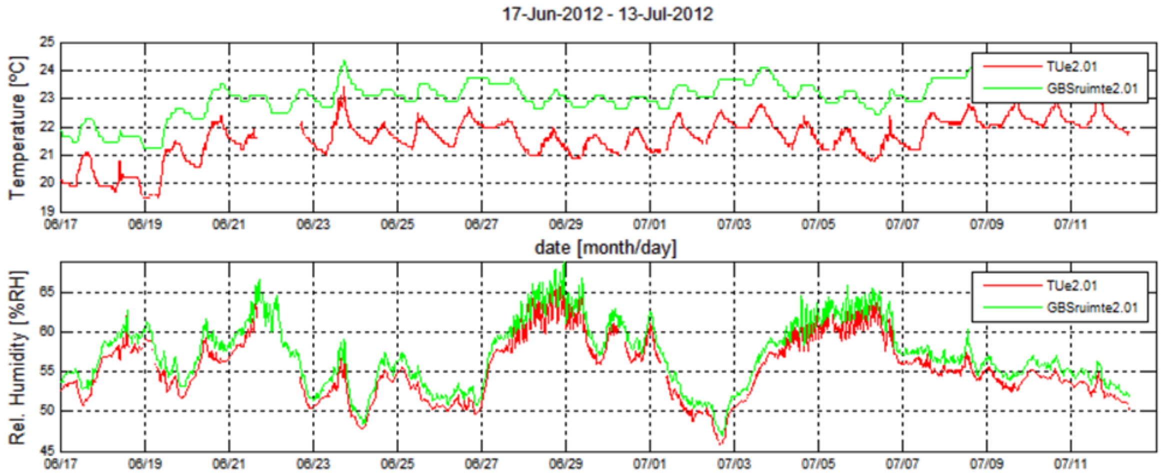


Fig. 24 Comparison of BMS (green) and TU/e (red) measurement equipment in exhibition room 2.01; Measured temperature (upper graph) and relative humidity (lower graph).

Moreover, the measured temperature values by the BMS in the exhibition rooms 1.01, 1.02, 3.01, 3.02, and 3.03 show a step-shaped graph which has a lower and upper temperature limit of rounded values, as can be seen in Fig. 25 (room 1.01). These values are also mostly 1 to 2°C higher than the additional TU/e measurements. The measurement comparisons of the other exhibition zones are presented in appendix 4.

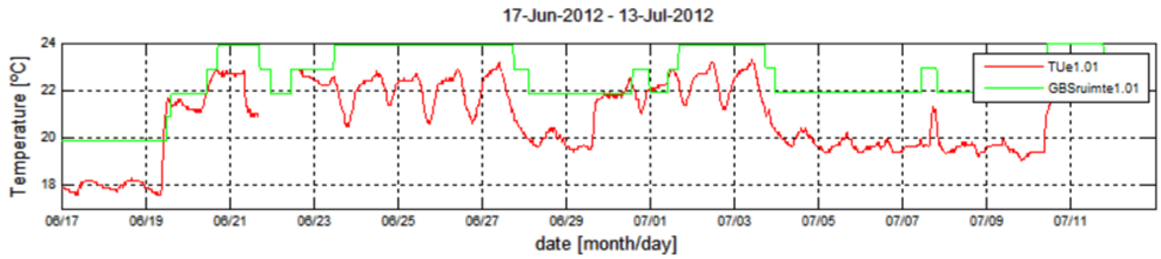


Fig. 25 Measured air temperature in exhibition room 2.01 by BMS measurement equipment (green) and TU/e measurement equipment (red).

Because all the measured temperature values of the BMS are higher than the additional measurement, an extra measurement took place with a 'Rotronic Hygropalm' in room 2.04, with an expected accuracy greater than 0,2ºC. In Fig. 26, it can be seen that these measurements are close to the measured values of the TU/e equipment.

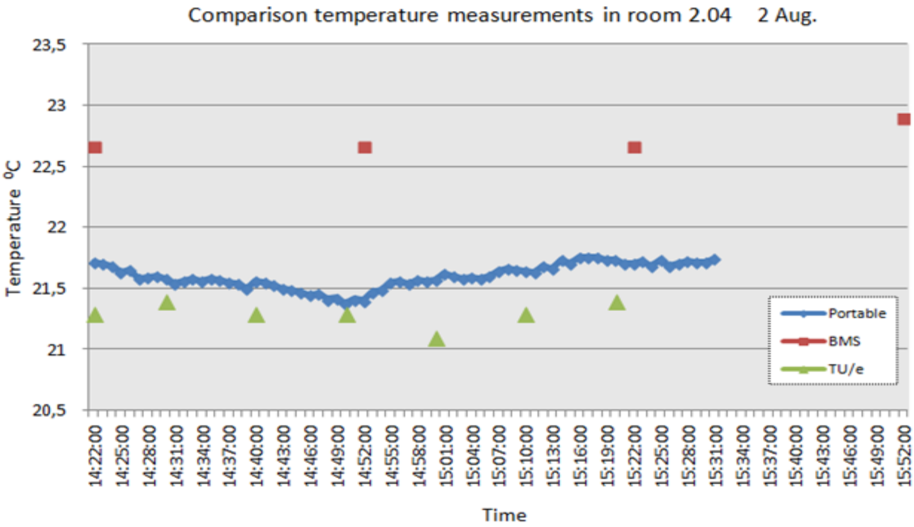


Fig. 26 Additional temperature measurement check with a Rotronic Hygropalm beside BMS and TU/e temperature sensors in exhibition room 2.04.

Since the BMS controls the HVAC systems based on the indoor temperature and relative humidity measurements, the climate will be negatively affected when the measurements are not accurate.

3.2.3 Weighting factors

The favorable supply air conditions from the AHU's to the zones are determined on the basis of the weighted mean measured air condition in the zones which are conditioned by this AHU, and the set desirable air conditions in these rooms. From analysis of the BMS appears that there are large deviations between the set weighting factors, as can be seen in Table 2.

The involved people of the Zeeuws Museum did not know what the actual weighting factors were, but could remember that these are realized after experiments in the past. With these values, the observed overall indoor climate seemed to be least poorly at that time. Distinctions are not made on the basis of different priorities between exhibits.

It is noticeable that there is a correlation between the BMS zone measurements which seems to deviate most from the real temperature, and the low set weighting factors for these rooms (except 3.01).

When the BMS measurement equipment is optimized, it is advisable to revise and fine-tune these weighting factors to achieve a better indoor climate.

AHU's	Rooms	Weighting factor for temperature	Weighting factor for R.H.
AHU 1.1	3.06	50 %	50 %
	3.07	50 %	50 %
AHU 1.2	3.01	40 %	40 %
	3.02	15 %	15 %
	3.03	15 %	15 %
	3.04	30 %	30 %
AHU 1.3	1.01	10 %	10 %
	1.02	10 %	10 %
	1.04	80 %	80 %
AHU 2	2.01	28 %	28 %
	2.03	14 %	14 %
	2.04	14 %	14 %
	Showcase 1	14 %	14 %
	Showcase 2	14 %	14 %
	Showcase 3	14 %	14 %

Table 2 Weighting factors for measured temperature and relative humidity values in each exhibition room.

3.2.4 Climate in the showcases

On the 4th floor of the museum, three actively conditioned showcases are located, called: showcase 'Oost', 'Zeeland' and 'West'. These showcases include small and sensitive museum objects. From interviews taken with the staff it was clear that the climate in these showcases was very unstable. This is also made clear by the hard copies in the logbook and the additional TU/e measurements that were performed in one of the showcases ("Oost"). Fig. 27 shows the measured climate conditions in the showcases by the BMS during the first week in June (2012). Dangerously high relative humidity levels and fluctuations are observed. It can be seen that the relative humidity values even exceed the applied range of y-axis.

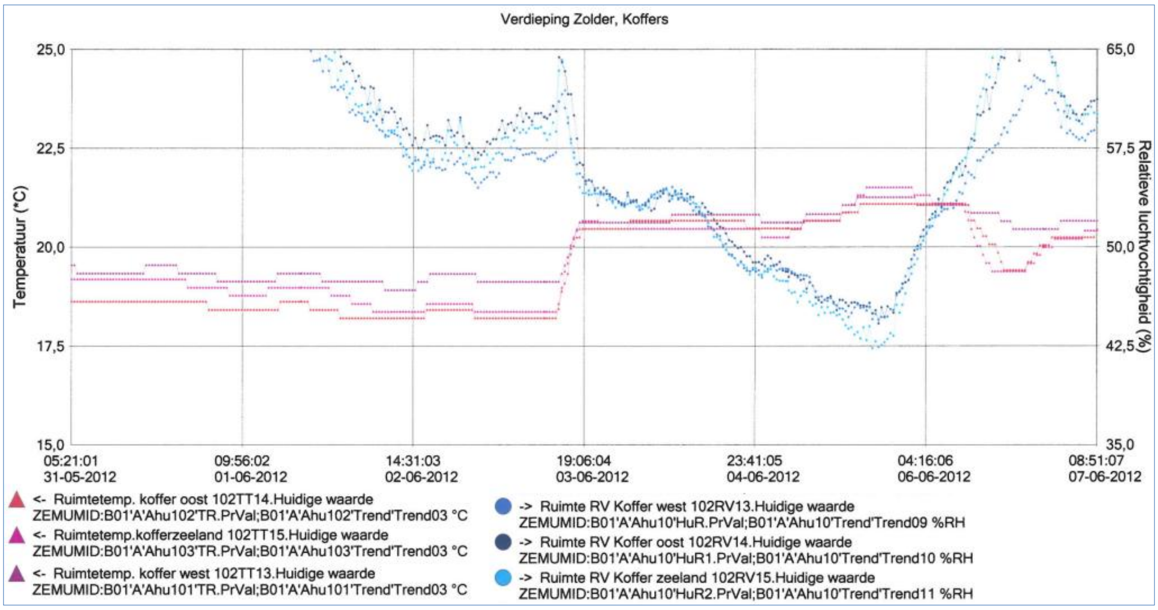


Fig. 27 BMS measurements of temperature and relative humidity in the showcases during first week of June 2012.

To find out how the climate in the showcases is achieved, the indoor climate conditions of the room in which the showcases are placed, and the supply air conditions in the showcases are compared with each other. The showcases are placed in walk-in boxes, so solar radiation cannot enter the showcases. In Fig. 29, the climate conditions in two show cases are shown which are measured by the additional TU/e equipment. Also the climate conditions in the adjacent room (4.01) and the air supply conditions to room 2.04 on the second floor are presented.

There is no measurement equipment in the air supply ducts to the showcases, but it can be assumed that the conditions of this supply air are almost the same as the air supply condition to room 2.04, because they are both conditioned by the same air handling unit (2), and no after treatment takes place. In paragraph 2.3.3, the design of this all-air system is described and a schematic drawing is shown.

Cause of instable climate in the showcases

The show cases on the 4th floor are conditioned by AHU2, as described and visualized in paragraph 2.3.3. This air handling unit is also responsible for the climate in the exhibition halls of floor 2. Because the internal and external influences to the climate in the showcases differ considerably in contradiction to the influences on the rooms on the 2nd floor, also the favorable supply air condition differs mostly. Because the air system is coupled, it is not possible to achieve a desirable air supply condition which satisfies the needs of the showcases, as well as the needs of the rooms on the 2nd floor (Fig. 28).

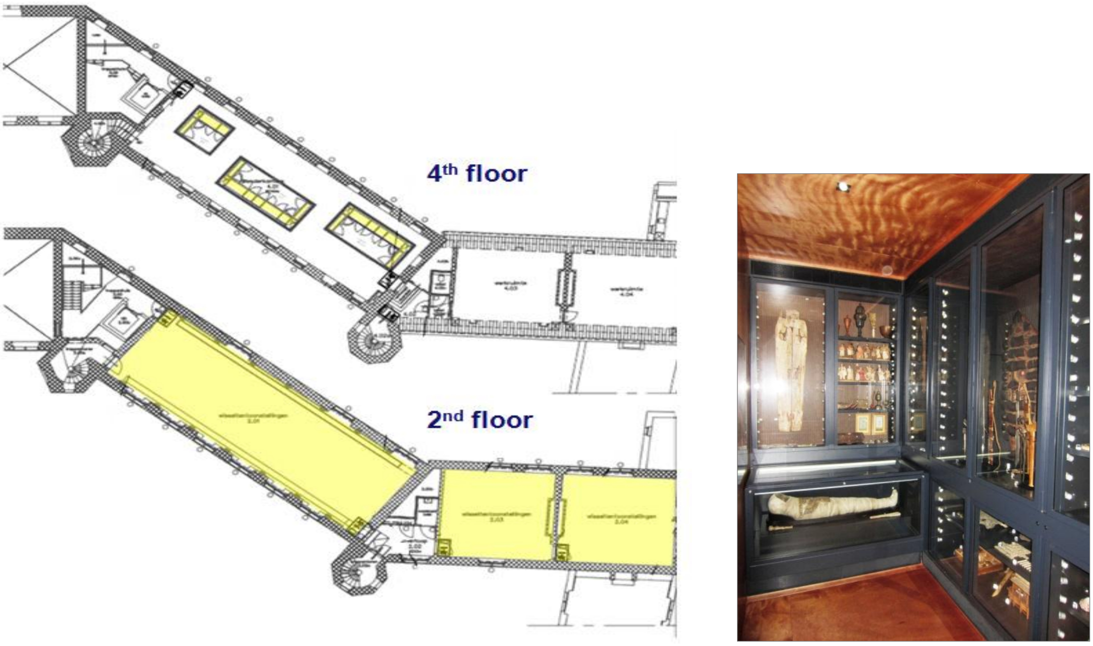


Fig. 28 Left: visualisation of climatized rooms on the second floor and showcases on the fourth floor by AHU 2; Right: picture of a showcase on the 4th floor

Based on the weighted mean air conditions of all concerning rooms and showcases, a certain supply condition is produced by AHU 2. Because the volume of the showcases is small in relation to the supply airflow (up to 425 m^3/h on a total volume of about 15 m^3 in showcase “Oost’ [ref.26]), the condition of the air in the showcases will almost be the same as the supply condition, as can be seen in Fig. 29. The differences in air supply conditions are that high, because it has to compensate disturbances in the exhibition halls on the 2nd floor.

Increasing the weighting factor for a particular space has a negative effect on the climate in the other zones, so this is not a good solution.

Temporary measure

When the measurement data until 5 July is investigated, it can be concluded that the climate in showcase “Oost” is mainly driven by the condition of the supplied airflow delivered by the climate system.

To improve the climate in the showcases, it was recommended to close the VAV-valves in the supply air and return air ducts of the showcases, which are presented in Fig. 11. This seemed the only quick solution with the present technique and control possibilities. The valves were closed at the 5th of July, with the expectation that the climate in the showcases would adopt about the same air conditions as the air in the adjacent room. This expectation is confirmed by the measurements which are performed after this action (Fig. 29). From that day, also a measurement sensor is placed in showcase “Zeeland” (green trend line). Fig. 30 shows only the measurement data in both showcases, it can be seen that both conditions are nearly the same and that they are more stable and beneficial for preservation of the collection than the older indoor climate conditions.

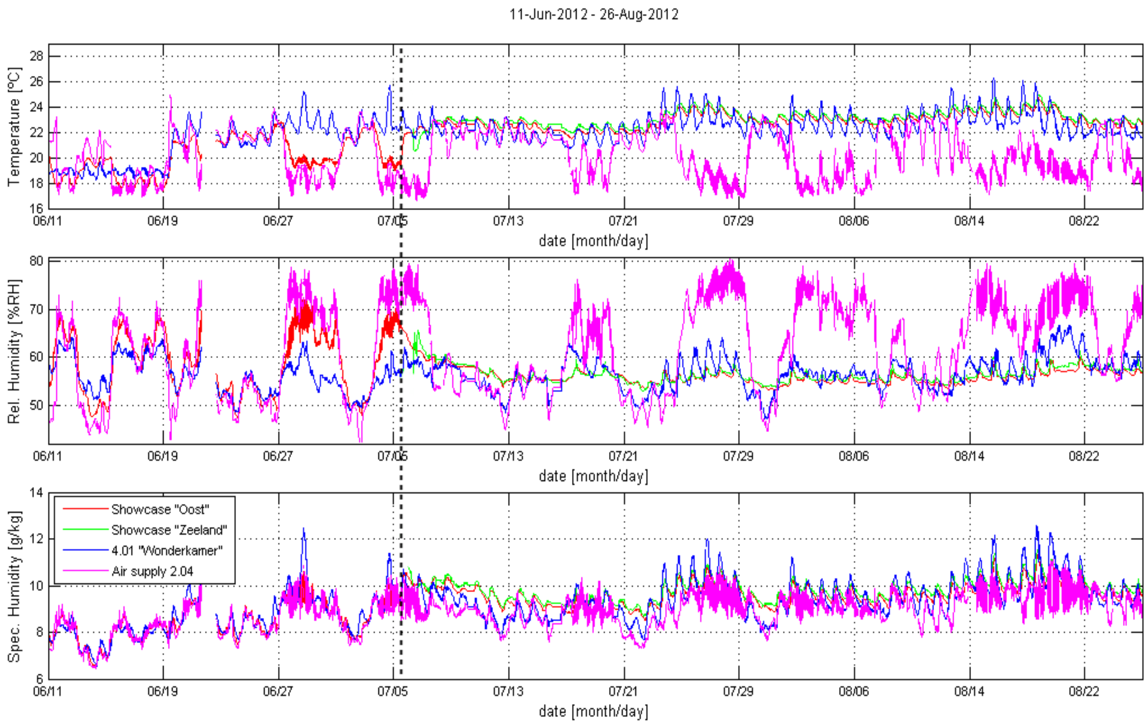


Fig. 29 TU/e measurements of air temperatures (upper graph), relative humidities (middle graph), and specific air humidities (lower graph) concerning the showcases.

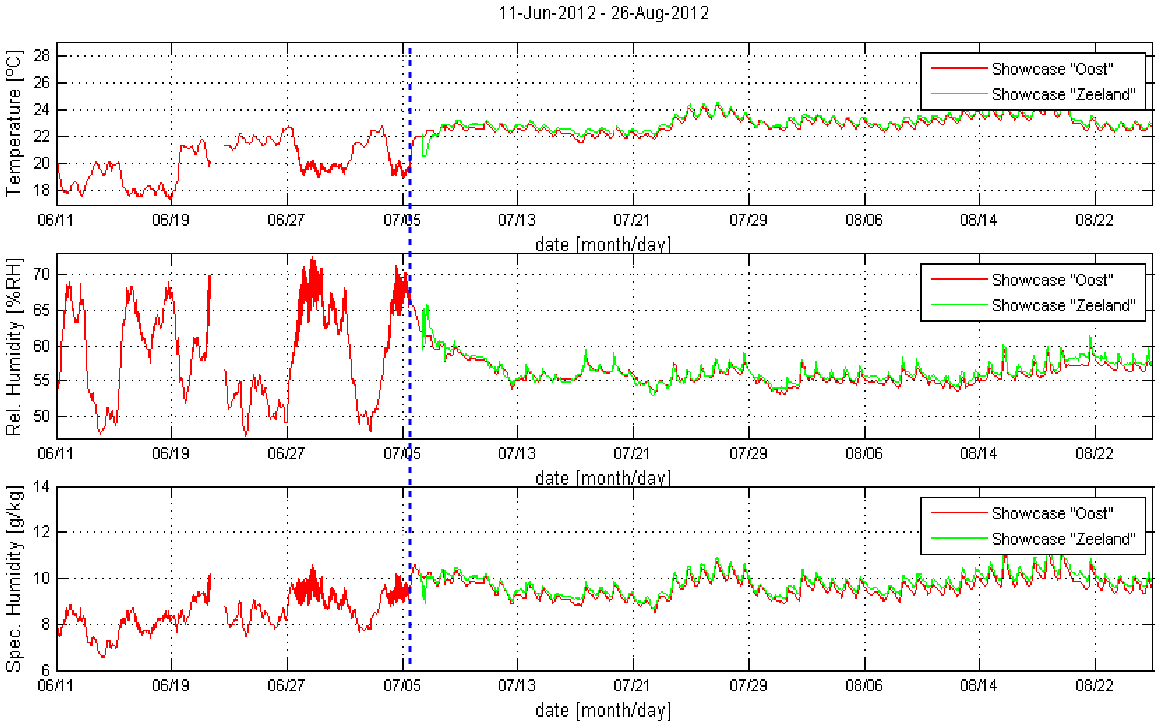


Fig. 30 Measured air conditions in showcases 'Oost 'and 'Zeeland' before and after the closing of the airducts at 5 July; Temperatures (upper graph), relative humidities (middle graph) and specific humidities (lower graph).

The measured climate of the showcase "Oost", before and after the 5th of July, is evaluated based on the ASHRAE climate guidelines [ref.5]. As can be seen in Fig. 31, the climate of the period between 7 July and 7 October fits much better between the bandwidths of the ASHRAE climate classes than that of the period before the air valves were closed. The given percentages demonstrate the part of the time in which the climate satisfy the concerning ASHRAE class. On the left side of the percentage the measured temperatures and desired bandwidths of the ASHRAE class are given, and on the right side the same is presents for the relative humidity. It has to be noted that a high fit of ASHRAE climate class AA not automatically mean that damage to collection is excluded, because a poor climate for collection preservation during the short period of exeedance may be sufficient to cause damage.

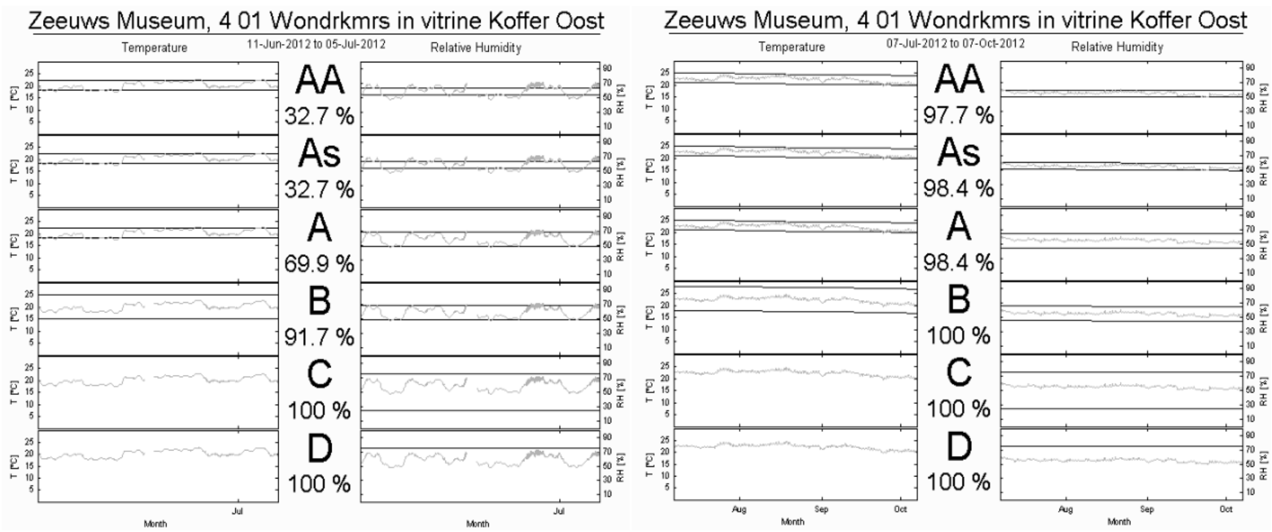


Fig. 31 Comparison of measured climate conditions in showcase 'Oost' with ASHRAE climate classes; Left: before closure of the airvalves, Right: period after closure of the airvalves.

Because the zone which is surrounding the showcases is only thermally conditioned, additional measures will be necessary to prevent too low relative humidity values during the winter period, and provide further R.H. stabilization during the whole year.

Possibilities are:

- The application of moisture buffering materials (e.g. silica gel) in the showcases [ref.21], combined with an improvement of the air tightness.
- Disconnecting air ducts of showcases from AHU2, and extract some air with a small fan from the return air ducts of other exhibition zones for supply to the showcases (after filtering). In that case, without after treatment, the climate in the showcases would not be better than the climate in the exhibition room(s) where the air comes from.
- Expand the climate system of the large surrounding zone with the possibility to (de-)humidify the air in this room. Probably this adjustment will lead to the highest initial and operating costs, and may be detrimental to the protection of the building.

Without the adjustments to the climate control system and/or showcases, it is not possible to achieve the climate conditions As (ASHRAE) as described in the building specifications (48,5-54,5%) in the showcases.

3.2.5 Power and energy loss in the hydraulic part of the climate system

Some notable observations were made in the processes of the hydraulic part of the climate system which probably form the basis of the main problems at the Zeeuws Museum. These findings are discussed in this section.

High supply chilled water temperature to the cooling coils

The high indoor relative humidities are the result of the poor dehumidification capacity of the cooling coils in the AHU's. This is not due to the dimensions of the cooling coils, but due to the high supply chilled water temperature. The cooling coils should have the capacity to cool and dehumidify the total airflow (return flow and ventilation flow) from 23,5°C/57% to 10,5°C/99% with a corresponding chilled water temperature regime of 9°C (in) and 15°C (out), according to the HVAC specifications.

In Fig. 32 it can be seen that the supply chilled water temperature (red) during the summer is often far above the desired 9°C. As an indication, when the cooling coil temperature is 12°C, condensation only occurs when the specific humidity of the airflow is above 8,5g/kg (e.g. 20°C/60%).

The system is in cooling mode during the periods when a dark red band is visible, and the green line is approximately constant. The green line indicates the meacements on the pipe which transports the groundwater from the cold well of the ATES stystem to the HVAC system. This temperature is too high to contribute directly to the cooling proces, and is even higher than the natural soil temperature (about 11°C). This is the consequence of the volumetric and energetic imbalance in the ATES system, and the high infiltration temperature in the cold well during the heating season.

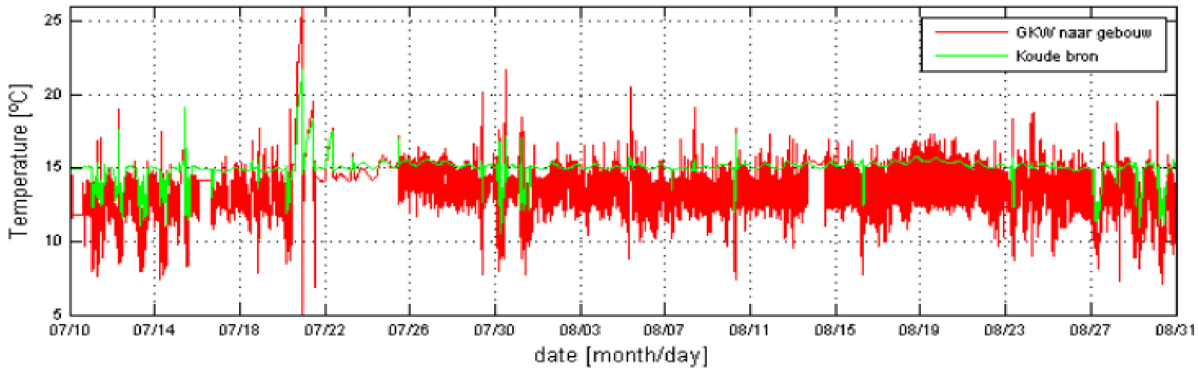


Fig. 32 Temperature measurements of supplied chilled water flow to the building (red), and extracted groundwater from the cold well of the ATES (green).

Another disadvantage of the higher chilled water supply temperature is that the HVAC system operates much longer in cooling mode due to the fact that the periods wherein the relative humidity values are above the desired levels are longer. The simulation results in paragraph 4.6 shall give more insight in the consequences of this effect.

Short circuits in chilled water system

The measurements also show that during the cooling mode, energy and power is lost to the ATES system. Because the temperature of the return chilled water flow from the consumers during cooling mode is often lower than the temperature of the ground water which is extracted from the cold well, it will lose energy and power in the heat exchanger (TSA 1), instead of vice versa. Fig. 33 shows the measurements of both groundwater and return chilled water flows during the summer months. The higher return chilled water temperatures (red) towards 18° are mainly cause by frequent switching (on/off) of the heat pump and the periods when there is no demand for cooling/dehumidification.

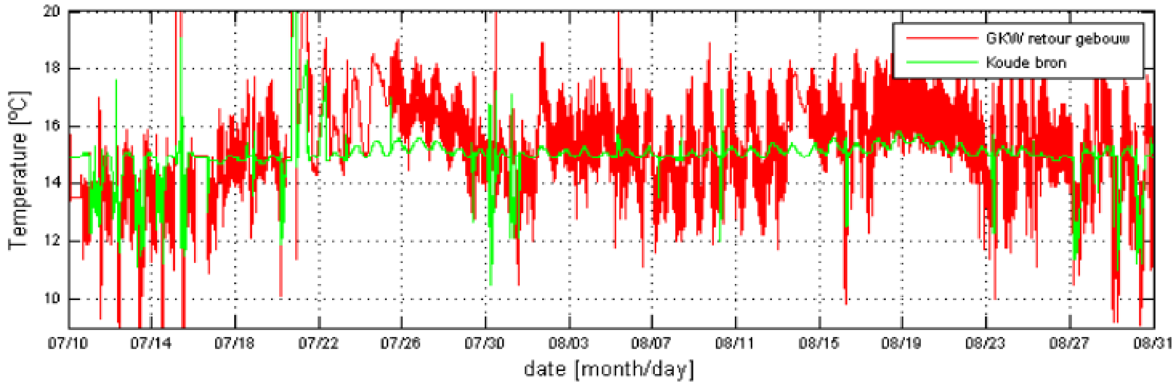


Fig. 33 Temperature measurements of retour chilled water flow from the building (red), and extracted groundwater from the cold well of the ATES (green).

Due to the loss of cooling power to the groundwater, the heat pump is not able to further reduce the chilled water temperature to the desired supply water temperature. The lower the supply chilled water temperature, the lower the return chilled water temperature and the higher the amount of cooling energy loss to the ATES system. Also the imbalance of the ATES will further increase when the contribution of the heat pump to the generation of cooling energy rises, because the residual heat is mostly supplied to the ATES system.

The graph in Fig. 34 shows the measurements of both the supply water temperature (red) and the return water temperature (green) of the chilled water circuit during the same period. The difference between them is extremely small, mostly about 2°C, as can be seen in Fig. 35. Because the system efficiency and power supply of an ATES system in cooling mode mainly depends on this parameter (ΔT), the design guidelines emphasize the need to design ground coupled HVAC systems in such a way that this temperature difference would be high (about 8-12°C) [ref. 13, 14, 15].

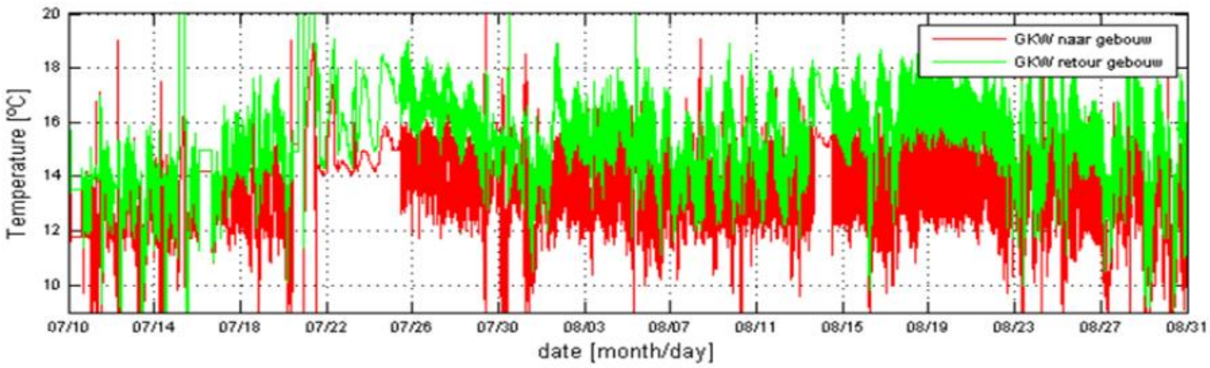


Fig. 34 Temperature measurements of supply (red) and retour (green) chilled water flow.

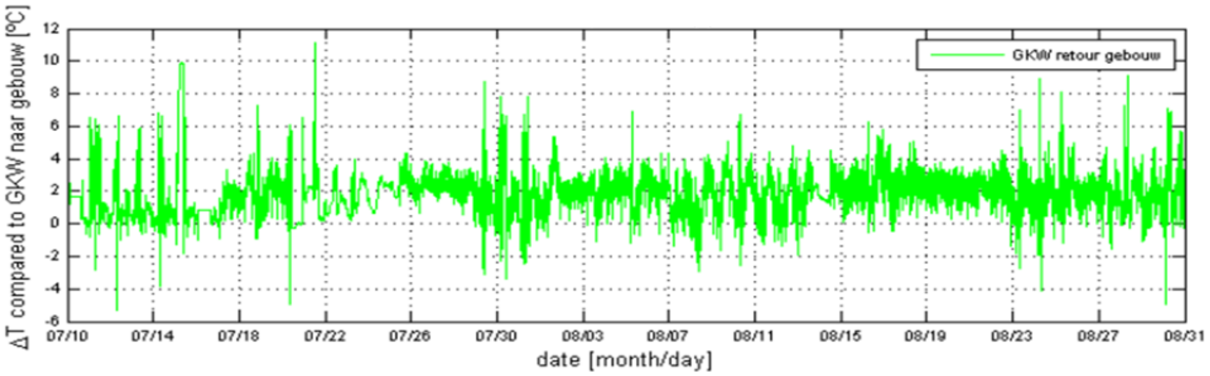


Fig. 35 Temperature difference between measured supply and retour chilled water flows.

The main cause of the small temperature difference between supply and return chilled water flow is the wrong selection of the control valve and piping device at the cooling coils, which regulates the power of the coils.
Depending on the type of control, the control valves reduce the energy transfer to the cooling coils during part load demand by: increasing the supply chilled water temperature or, by reducing the water flow through the coils. The principle of increasing water temperature is applied by the collective hydraulic control device belonging to the connected group of AHU1.1, AHU1.2 and AHU1.3. This hydraulic cooling power control system is highlighted by the big orange ellipse 'A' at the bottom right of the schematic drawing in Fig. 36.
During part load conditions, this 2-way valve reduce the cold water flow, so the supply water temperature to the cooling coils will rise because outlet water blends with the supply flow since the secondary mass flows remain constant. This is not the desired type of hydraulic control when the cooling coils should be able to dehumidify in part load conditions, because this ability strongly reduced when the supply chilled water temperature rises.
In order to circumvent this problem at the Zeeuws Museum, this control valve is taken out of operation by setting the valve at 100% open in the BMS.

The other (3-way) control valves, which are highlighted with the orange ellipses 'B', are types of load-controllers which are able to reduce the mass flow through the coil. The downside of these power controllers in this case is that the amount of mass flow reduction through the coil will be directly deposited in the return side of the chilled water system (bypassing the cooling coil). These short-circuits are the main cause of the low return chilled water temperatures.

The load controllers which are circled with the green ellipses 'C' have the right characteristics for this application, and should have been installed at all these cooling coils. The supply temperature to the coil remains low in part load conditions, while the return chilled water temperature further increase [ref.16]. New insights from a recent study of v. d. Brink [ref.17] show that the temperature difference between the supply and return chilled water flow is also quit dependent on the design conditions of the cooling coil.

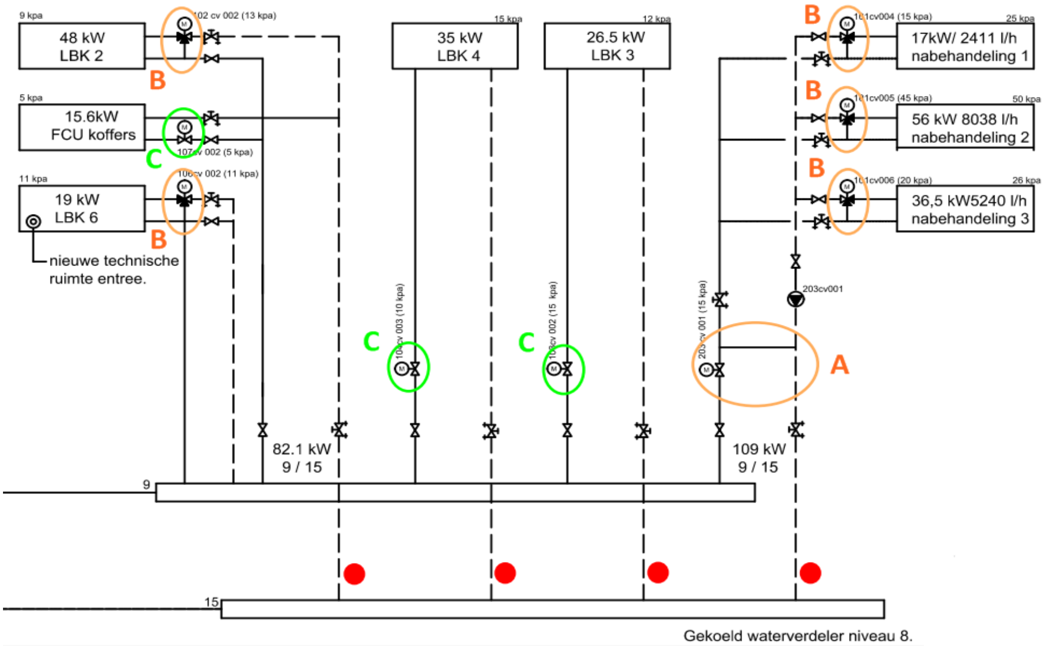


Fig. 36 Schematic visualization of the cooling coils and hydraulic connection to the chilled water circuit.

Temperature sensors are placed to measure the return chilled water temperature at the locations which are indicated with the red dots in the schematic drawing (Fig. 37). Not that in reality AHU 6 (bottom left) is not individually connected to the main collectors, but coupled together with AHU 2 and the FCU to the left group of the collector.

In Fig. 37, the influence of the different hydraulic power controllers on the return chilled water temperature is clearly visible.

Due to the relatively small volume flow from the cooling coils in AHU 3, AHU 4, and FCU, in relation to the other coils (with bypasses), is the total return water temperature mainly influenced by the groups with the wrong hydraulic control device.

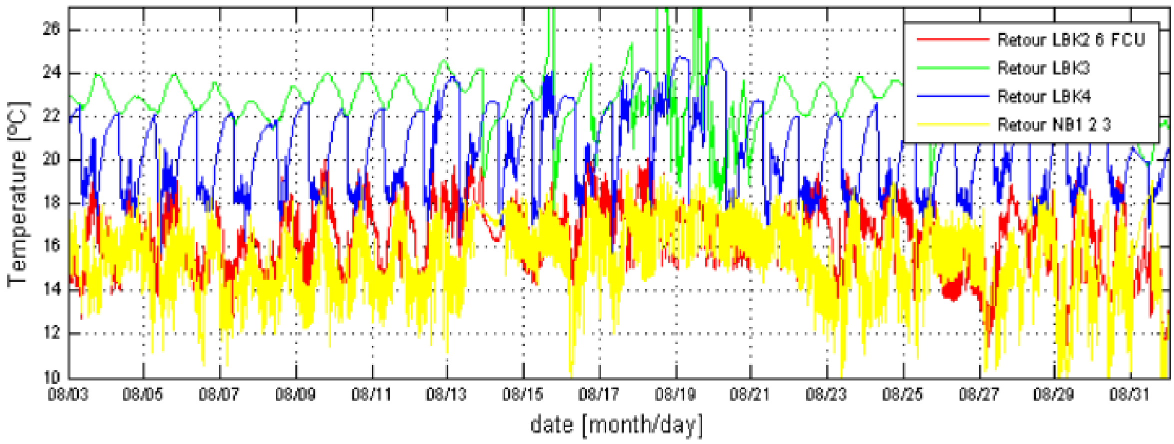


Fig. 37 Measured return chilled water temperatures from the cooling coils separately

Temporary measure

The arrows in Fig. 38 indicate the flow directions of the heating and chilled water circuit between the heat pump, heat exchangers and the distribution to the energy consumers (right side).

In order to prevent further energy and power loss to the ATES system (TSA1) during cooling mode, the 2-way valve circled in Fig. 38 is taken out of operation (constantly open). Now the return chilled water flow bypasses the left heat exchanger (TSA1) and is (only) cooled by the heat pump. Normally this 2way valve is close during cooling demand and only open when there is no demand for cooling but rather superfluous cold energy (during heating mode) which has to be transported to the ATES by TSA 1. In this case, the other 2way valve projected left of TSA 1 will close.

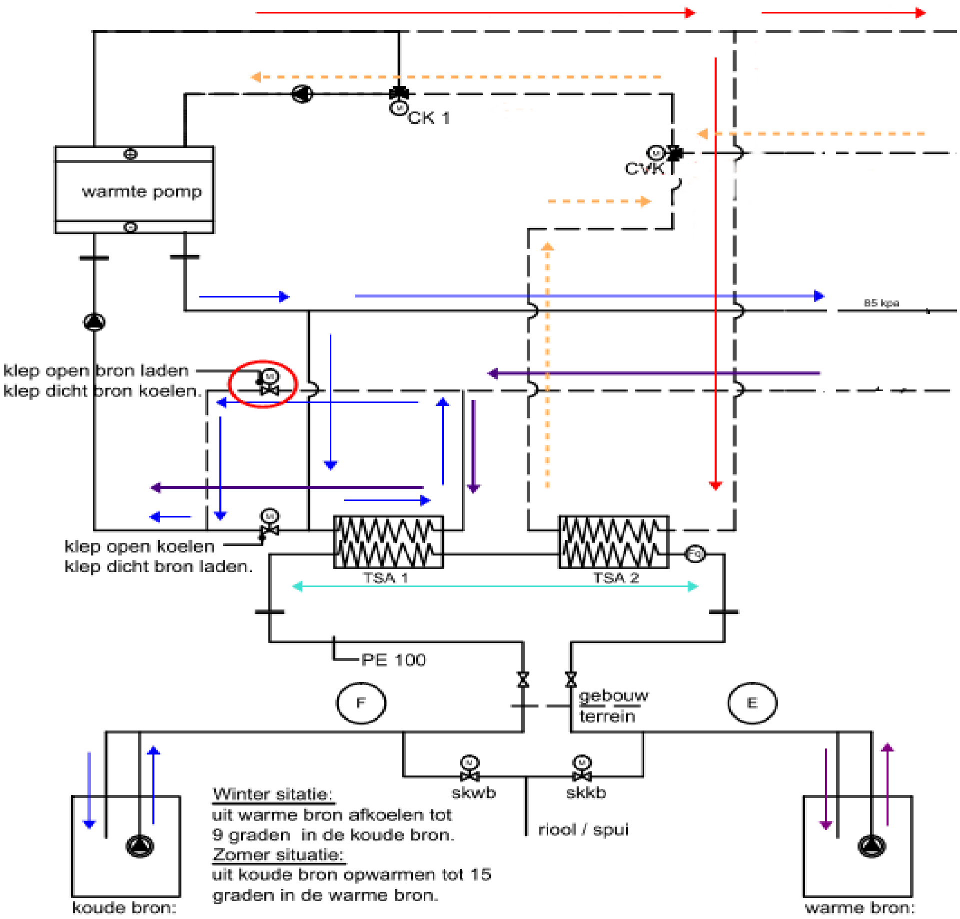


Fig. 38 Concerning 2-way valve in the chilled water circuit which bypasses the return chilled water flow along TSA1

Unfortunately this ‘temporary’ measure took place at the end of the summer season (10/9), so the effect on the balance of the ATES system and energy costs is not visible yet. The influence on the chilled water temperature was immediately apparent. This temperature decreased to the set value of 7.5^{o}C.

However, the heat pump switches of immediately when this set value is reached, causing instable system behavior. The reason for this will be described in the next section.

Misalignment between energy production and demand

It can be observed in the measurements of the hydraulic climate system and that of the indoor air conditions that the climate system acts very restless during cooling mode. This is the result of a misalignment between the energy production of the heat pump, and the amount of heat/cold consumption in the building. Due to the relatively high capacity of the heat pump (about 140 kW cooling and 155 kW heating), the actual demand is often much lower. This is partly compensated by the heat pump to operate in part load condition, but also this part load capacity is usually still too high. The heat pump and ATES system cannot get rid of the heat or cold energy, and need to switch off. Frequent switching is detrimental for the system efficiency and the lifespan of the heat pump [ref.13, 15]. It should be noted that the heat pump is one of the most expensive components of the HVAC system.

In addition to this, when the heat pump and ATES system switch off, they cannot turn on within 10 to 30 minutes for system protection, so due to the misalignment, this switching cycles will influence the indoor air condition, in particular during cooling/dehumidification mode, as can be seen in Fig. 23.

A layered buffer vessel is able to equalize the differences between energy generation and consumption. When the vessel is discharged and there is a need for energy, the system starts to generate till the energy consumption is too low and the thermal vessel is loaded. During the time that the system is switched off, some energy is still available in the buffer vessel. In the chilled water circuit of the Zeeuws Museum there’s actually no buffer vessel installed.

However, in the hot circuit of the heat pump there is a (small) buffer vessel installed, but also in this circuit the energy alignment could be optimized. The 3-way valve which is responsible for the distribution of heat to the building/buffer, or to the hot well of the ATES system (during cooling mode) does not function optimally. This 3-way valve is highlighted in Fig. 40 of the next paragraph. During cooling mode, the heat pump should get rid of the heat, otherwise it switched off. The measurements showed that the superfluous heat during cooling mode was insufficient ceded to the ATES system. This results in a too high return heating water temperature to the heat pump making it turned off. In Fig. 39 this observation is visualized by the measurements during two random days in august. Herein the switching cycles of the heat pump are clearly visible. Because the chilled water temperature (orange line) doesn’t reach the desired set temperature of 8^{o}C, this will not be the reason that the heat pump switched off. It can also be seen that the return heating water temperatures (dark blue line) to the heat pump are almost as high as the heating outlet temperature (light blue line) of the heat pump, which is probably the raison for the frequent switches. The measurements on the groundwater flow indicate that during cooling mode little superfluous heat is ceded to the ATES system. The water flow to the hot well (purple line) is just a couple degrees higher than the groundwater flow (red line) before this particular heat exchanger TSA2.
The green line indicates the return heating water flow from TSA 2, back to the heat pump. The mass flow of this heating water flow determined the amount of heat injection to the ATES, and is controlled by the automatic 3-way valve described above. The control of this mass flow should be optimized during cooling mode, in order to prevent frequently switching of the heat pump and increase the system performance (COP) of the heat pump. It can be observed from the measurements on 8 august in the early morning that the chilled water temperature reached the level of 10 degrees Celsius. During this period, the system operates in heating mode, and the groundwater flows from the hot well to the cold well. Remarkable is that during heating mode the heat injection to the ATES system increased, as can be seen from the green en red line during this period. This is actually not desirable when the system operates in heating mode to satisfy the heating demand in the building. In addition, the heating loss to the ATES system is injected into the cold well, which adversely affected the temperature in this well. The next section focuses on this issue.

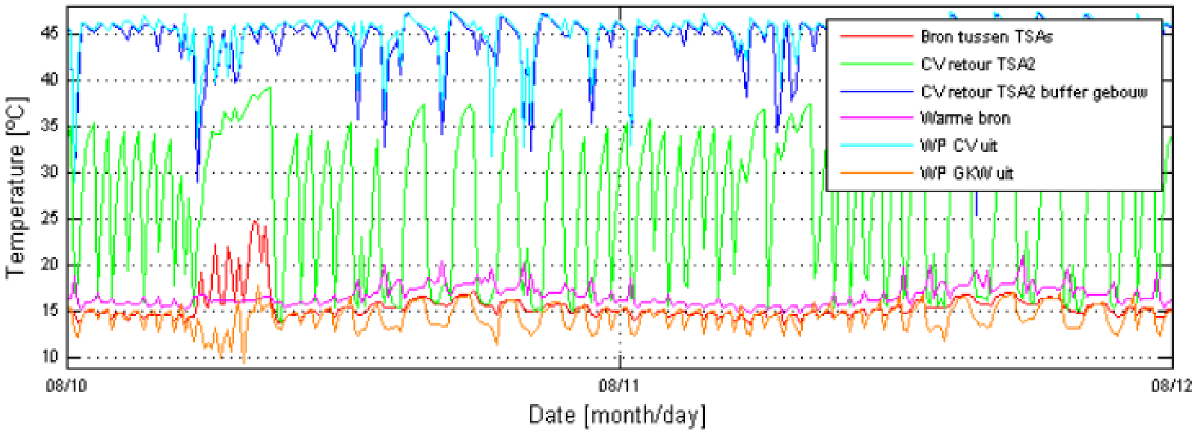


Fig. 39 Temperature measurements of supplied heating water from the heat pump (light blue), total return heating water from building and TSA2 (dark blue), and return heating water of only TSA 2 before it mixes (green). The supply chilled water temperature (orange) and the groundwater temperature on the left side (red) and right side (purple) of TSA 2.

Unwanted heat dissipation to the cold well

The measurement data revealed that a lot of heat was lost and injected in the cold well of the ATES system when it operates in heating mode. During periods that there is more heating than cooling demand, the heat pump and ATES operates in the heating mode and the residual cold from the heat pump is stored in the cold well.

The 3-way valve which controls the distribution of heat to the building or the ATES system does not function optimally. The particular 3-way valve and the heat flow directions are highlighted in Fig. 40. The four horizontal pipes on the right side indicates the distribution pipes of heating (above) and chilled water (below) to the building.

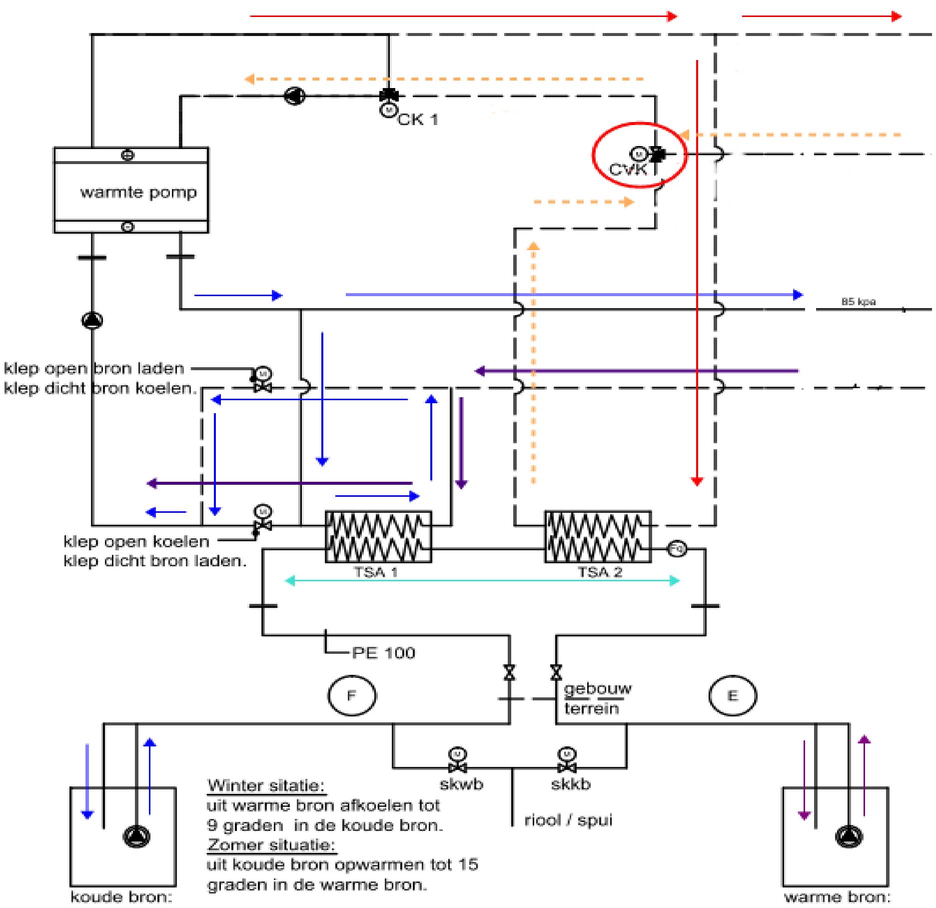


Fig. 40 Concerning 3-way valve which regulate the heating water distribution to the building, or in case the heat is superfluous to TSA2 (ATES)

In Fig. 41 and Fig. 42 it can be seen that lot of heating energy is lost to the groundwater flow when the system operates in heating mode. The green, red and blue lines indicate the temperature of the groundwater flow, measured respectively left, between and to the right of the two heat exchangers. When the system is in heating mode, the groundwater is pumped from the warm well (right) through both heat exchangers and infiltrates in the cold well of the ATES system. The measurements indicate from which well the groundwater is extracted at a certain moment, because the temperature values of the extracted groundwater are more constant than those of the groundwater to the injection well after the energy transfer in the building.

The temperature difference between the hot well and the groundwater flow between the heat exchangers (red line) indicates the heat loss by the right heat exchanger (TSA 2) to the groundwater, when the system is in heating mode. Because the heat pump releases the residual cold to the ATES system through the left heat exchanger, this groundwater flow cools down again (green line) and enters the cold well of the ATES system. The building management system of the ATES system only monitors the extracted and injected groundwater temperatures, so this heating loss is not observed before.

The undesirable consequences of this unwanted heat loss are high energy costs, and a less favorable (too high) injection temperature in the cold well. The colder this well, the more power and cooling energy it can supply during the summer season.

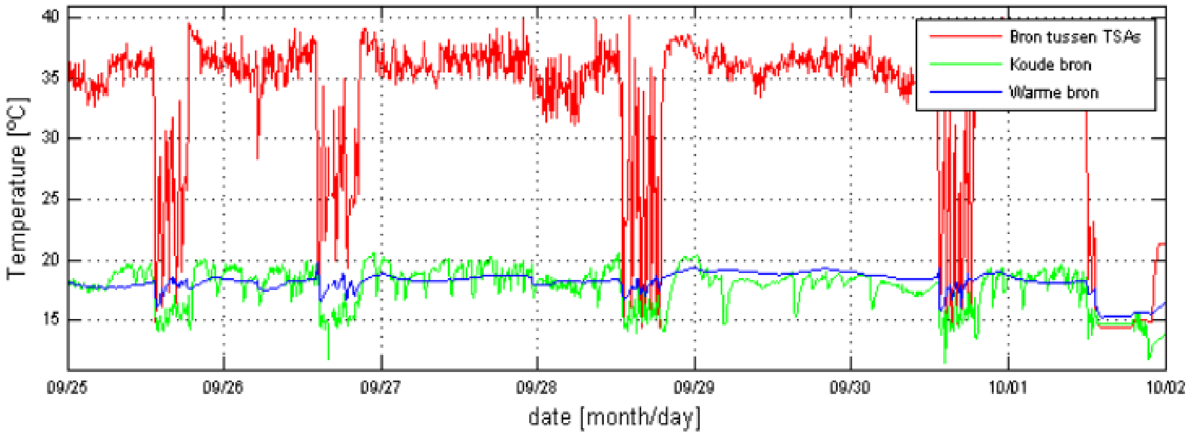


Fig. 41 Measured temperatures in ground water circuit; between TSA 1 and TSA 2 (red); left side of TSA 1 (green); right side of TSA 2 (blue).

Pertaining to the previous figure, in Fig. 42 another three temperature measurements are added.
The dark blue line indicates the heating water flow from the right heat exchanger back to the heat pump (before the 3-way valve). The green line shows the temperature of the return heating water flow from the heat consumers (e.g. heating coils) and the buffer vessel. The yellow line indicates the temperature after the 3-way valve where both return heating water flows are mixed and returns to the heat pump.
Despite the fact that volume flow measurements are not taken, one can conclude that the volume flow for heat dissipation to the ATES by TSA2 is usually dominant to the volume flow to/from the heat consumers (during heating mode).

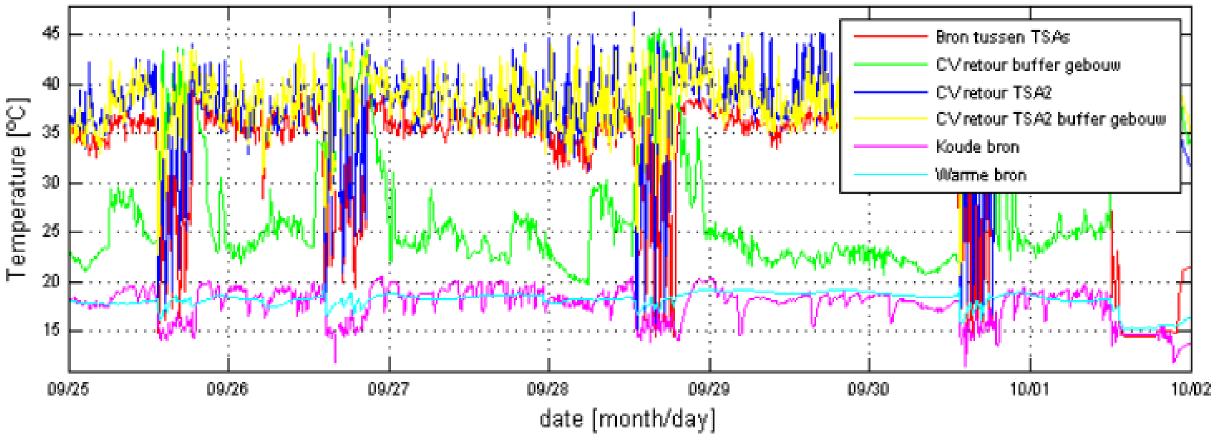


Fig. 42 Measured temperatures in hydraulic water circuit which indicates the heat energy loss to the cold well when the climate system operates in heating mode.

Temporary measure

As temporary measure to prevent heat injection to the cold well during heating mode, the concerned 3-way valve is taken out of operation by closing the way to the right heat exchanger (TSA 2).
However this measure works fine during the heating season, it is not a definitive solution because during cooling mode the heat pump cannot transfer the residual heat to the ATES system anymore. The control software of this 3-way valve needs to be optimized in order to obtain a permanent solution.

3.2.6 Utilization of heat pump with ATES system

From the settings in the Building Management System it appears that the contribution of heat pump and ATES system to the heat supply is underused. Here is a possibility to reduce the energy costs and contribute to the recovering of the imbalance in the ATES system. The ground floor of the museum exists of the entrance, toilets, a café, a wardrobe and a kitchen (Fig. 43).

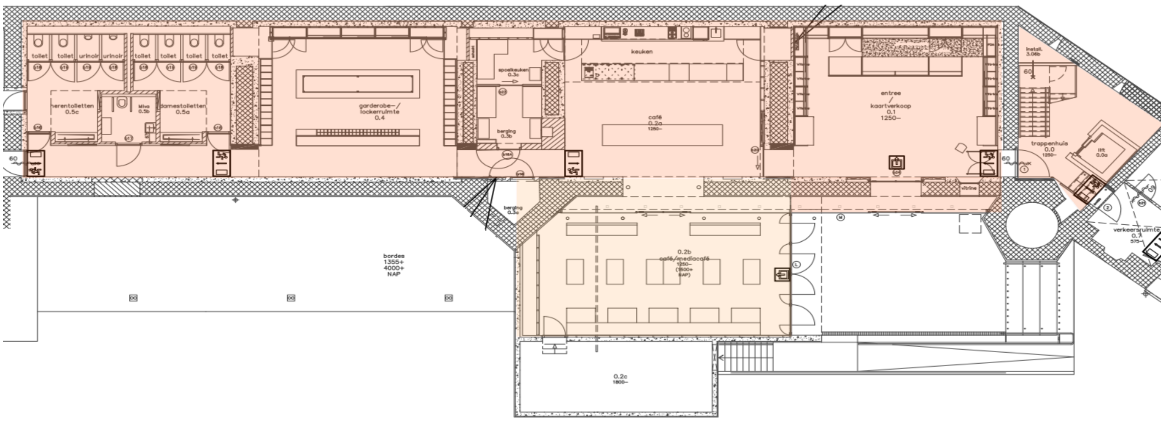


Fig. 43 Floor plan of the area's on the ground floor which are partly conditioned by AHU 4.

Several heat delivery systems contribute to the thermal climate on this floor. These systems and corresponding nominal power are listed in Table 3. Except for AHU 4, the heating energy for these systems is delivered by the central heating system of the Abbey complex.

The heating energy demand of AHU 4 is generated by the heat pump (with ATES) and partly recovered from the exhaust air flow from the zones of the ground floor. This AHU 4 provides conditioned ventilation airflow of 3.450 m^3/h to the zones on the ground floor. Concerning the energy cost and imbalance in the ATES, it would is advisable to provide the heating energy as most as possible by the airflow from AHU 4. According to the current settings in the BMS, this contribution was limited in the past. The total heating capacity of AHU 4 can be utilized by adjusting the set-points in the BMS for the heating systems listed in Table 3.

Heat supply system	Power
AHU 4	19,5 kW + Heat recovery (60%)
Air curtain (entrance)	15 kW
Radiators	37 kW
Convectors	5 kW
Fan coil unit	8 KW
Floor heating (café)	5 KW
AHU 6 (café)	31 kW

Table 3 Heating power supply systems for the area's on the ground floor

3.2.7 Fault in control system of air handling unit 4

As mentioned before, air handling unit 4 contributes to the conditioning of the public spaces on the ground floor. By analyzing the BMS system, it appears that there is a flaw in the software for the control of AHU 4. Two desired temperature set-points can be entered for this AHU, one for the periods of cooling demand and the other one for the moments when there is a demand for heating (Fig. 44).

The software actually, does not properly interpret these entered values, because this AHU is controlled to satisfy the highest entered temperature set-point all the time. Even when the set-point for cooling is higher than that for heating mode, the AHU is controlled to heat the air to satisfy this higher set-point for cooling mode.

Consequences of this fault in the control software are higher energy consumption and less comfort in the corresponding rooms. This is probably the reason why the staff in the kitchen complained about too warm indoor temperatures.

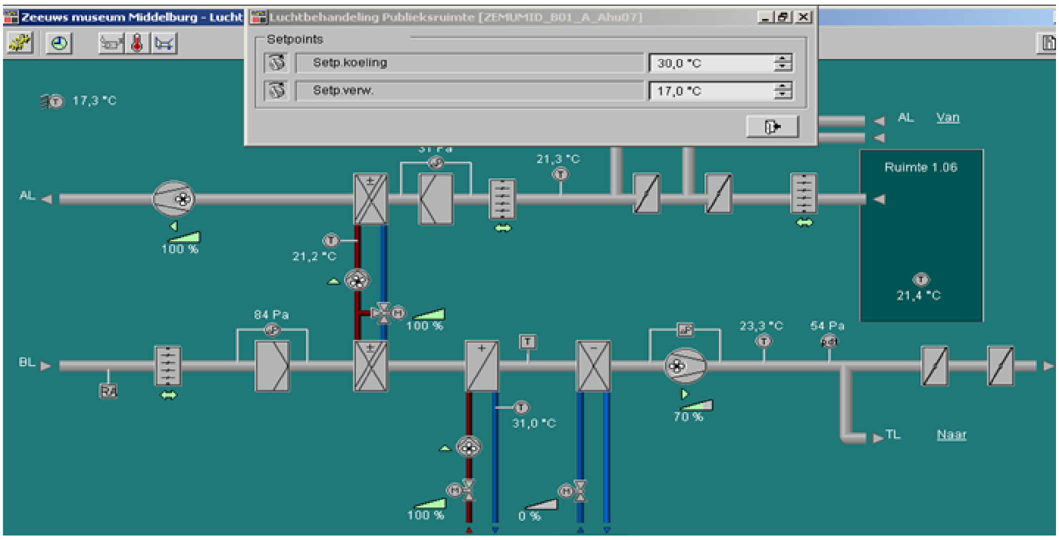


Fig. 44 Visualization of air conditioning processes in AHU 4 and input window for desired air supply temperature set-points.

CHAPTER 4

4 MODELING

This chapter addresses the modeling part of this study. Computer simulations are performed to determine the efficiency of the cooling and dehumidification process by cooling coils in different setups and with varying parameters. The aim of this study will be explained in paragraph 4.1. The software package and the built models used for this study are described in respectively paragraph 4.2 and 4.3. Section 4.4 and 4.5 describes the applied simulation variants and climate file. In paragraph 4.6 the result obtained from this simulation study are present en discussed.

4.1 Aim of the simulation study

Recently Marco Martens completed a Phd-study at the Eindhoven University of Technology with the thesis ‘Climate risk assessment in museums’ [ref.4]. As a part of his study he investigates the influence of temperature and set-points adjustments on the energy consumption and indoor climate risks for preservation of four specific collection objects in museums by computer simulations.

The simulated energy consumptions of these variants are the primary needs for cooling, heating, humidification of dehumidification in the building. The way of generating these needs and associated system efficiency were not taken into account. The advantage of this fact is that these results are generally interpretable and only depending on building type, internal heat/moisture sources, outdoor climate and required indoor climate. Disadvantage is that these simulated results give no insight into the effect of set-point adaptations to the overall energy consumption, including system efficiency etc. In general, reasonable assumptions can be made about the system efficiency concerning the generation of heating, cooling and humidification. When the relative humidity level have to be controlled by dehumidification in cooling coils, the system efficiency for this coupled latent and sensible cooling generation system is more complex to define. The addition of the simulation study described in this chapter, is getting more insight in the efficiency of cooling and dehumidification by use of cooling coils in various system setups. Also the observed shortcomings in the dehumidification process at the Zeeuws Museum will be simulated, in order to obtain more insight in the consequences for example energy consumption and climate manageability.

Just as in the Zeeuws Museum, mostly cooling coils are used to provide the required cooling and dehumidification demands in museums. However, this simulation study is based on the situation at the Zeeuws Museum; the intention is to produce more general interpretable simulation results, to be useful in the ongoing PhD-study.

The goals of the simulation study are further defined in the following paragraph.

4.1.1 Effects of cooling/dehumidification with the aid of cooling coils

The principle of the condensing dehumidification method is as follows: dehumidification is done by cooling the airflow through the coil below its dew point, so condensation will occur. This implies that as a by-product of the dehumidification process, also sensible cooling will be provided. This may apply vice versa. When the air temperature drops below its dew point during cooling demand, also latent cooling (dehumidification) occurs.
In situations when only dehumidification or cooling is desirable, the residual is in essentially wasted energy. When during dehumidification the residual sensible cooling is even undesirable, it has to be compensated by reheating the air, which results in additional energy consumption.

To gain more insight into the effect of the main parameters concerning cooling/dehumidification with cooling coil(s) on the energy consumption, with respect to the primary demand in the building, several variants of system setup and parameters will be analyzed. The simulation results should demonstrate which variants perform best on energy consumption and realizing the required indoor climate. In order to make the results applicable to a wider range of buildings, several qualities of building envelopes and usage are taken into account, just as in Martens Phd-study.

Influence of desired indoor condition and control of the climate system

Besides the design of the cooling/dehumidification system by cooling coils, the effect of the required indoor climate on the system performance will be simulated. The dehumidification efficiency will be dependent on the desired climate conditions. For example, when the dew point of the desired indoor condition is high, it is easier to dehumidify this air.
There is more, when during the dehumidification process the indoor air temperature drops, it is assumed that this has the undesirable affect that more/longer dehumidification (energy) is required due to the corresponding rise of the relative humidity. This effect is also observed in the Zeeuws Museum. When the amount of reheating is controlled in such a way that the lowest desired indoor temperature was not exceeded, the indoor temperature can drop during dehumidification till this temperature.
By simulating only the primary thermal and (de-)humidification needs of the building with for example HAMBASE [ref.19], the model does not assume that the air temperature will be influenced by the dehumidification process.
The impact of this phenomenon should be demonstrated by the computer simulations of this study which include a model of the cooling coil(s) with associated parameters like air flows, fluid temperatures and a control system.

Effect on thermal balance in the ATES system

Beside the energy consumption of the HVAC system, it is very important by use of an ATES system to know the ratio between yearly cold and heating demand in the building [ref.13, 14]. In Dutch it is required by law to keep an energetic and volumetric balance in the ATES system. This usually also improves the system efficiency. Climate systems which make use of an ATES system, mostly also include one or more heat pumps, to upgrade the extracted energy out of the groundwater to a higher temperature for heating use, and often reduce the temperature for cooling/dehumidification application.
When the heat pump is in operation, it always produces both heat and cold energy. Depending on the actual demand of the moment in the building, the superfluous heat or cold has to be carried away. By use of an ATES system it is the intent to store the excess heat or cold into the ground, which is suitable for use later in the season. With the viewpoint on system efficiency and thermal energy balance in the ATES, it is useful to know which part of the consumed energy for heating is used for regular heating, and which part is used for reheating during the

dehumidification process, because this last part of heating energy is available as 'residual' by using a heat pump to generate the desired cold energy. The simulations results should provide insight in the influence of the various variants on the thermal balance in the ATES system.

Efficiency increase by pre-treatment of ventilation airflow

In case of the Zeeuws Museum (and many other museums), a climate system is installed which realizes a desirable indoor climate by supplying a relative large conditioned airflow to the zones. These 'all-air' systems are suited, because they are quite easy and fast to control, they also enable a well distributed indoor climate and makes water distributed pipes/systems in the zones for unnecessary. These are risky because the danger of leakage. In case of the Zeeuws Museum, the amount of airflow to the exhibition zones is between 5-7 times the total room volume per hour (according the system specifications). These are common numbers for such all-air systems in museums. In view of energy saving and required capacity of the HVAC systems, the greatest part of the total treated supply airflow is extracted out the conditioned room, instead of outdoor. Some air is extracted from outside, to fulfill the ventilation requirements for visitors and staff.

Usually, as also in the Zeeuws Museum, the thermal and humidity treatment of the airflow will happen after both airflows (ventilation and recirculation portion) are mixed with each other, as is visualized in Fig. 45.

During dehumidification demand, the plausible air-conditions before and after the cooling coil and mixing section are present in a psychometric chart (Fig. 47). The mixed air condition (m) is almost equal to the recirculation airflow condition (i) from indoor, because the recirculation flow is usually much greater than the fresh part of air (e) from outside. During the periods of dehumidification demand, the dew point of outdoor air is usually higher than that of the conditioned air in the museum.

Because the efficiency of the dehumidification process by a cooling coil is strongly dependent on the dew point of the incoming airflow and the chilled water temperature, it should be more efficient to (pre-) dehumidify the outdoor air before it mixed with the recirculation airflow, as is visualizes in Fig. 46.

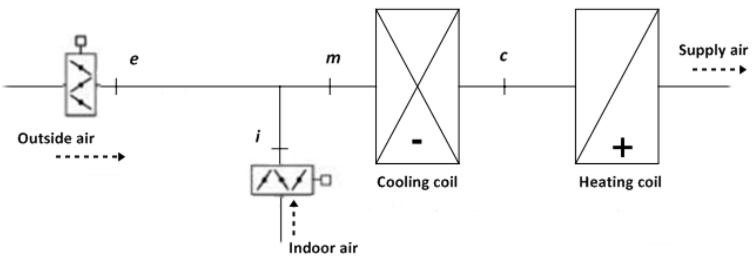


Fig. 45 Schematic visualisation of air handling without pretreatment

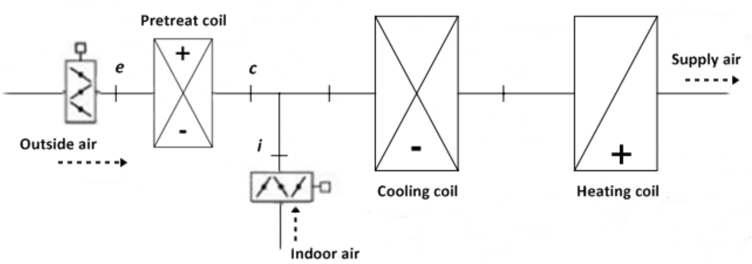


Fig. 46 Schematic visualisation of air handling with pretreatment of the ventilation air flow from outside

The right psychrometric chart in Fig. 47 indicates that the dehumidification process of the outdoor air-condition (e) is much more efficient than that of the mixed air condition (m), if we assume that sensible cooling energy is not required. The green lines indicates the latent enthalpy reduction of both processes, and the red lines the corresponding sensible enthalpy reduction.

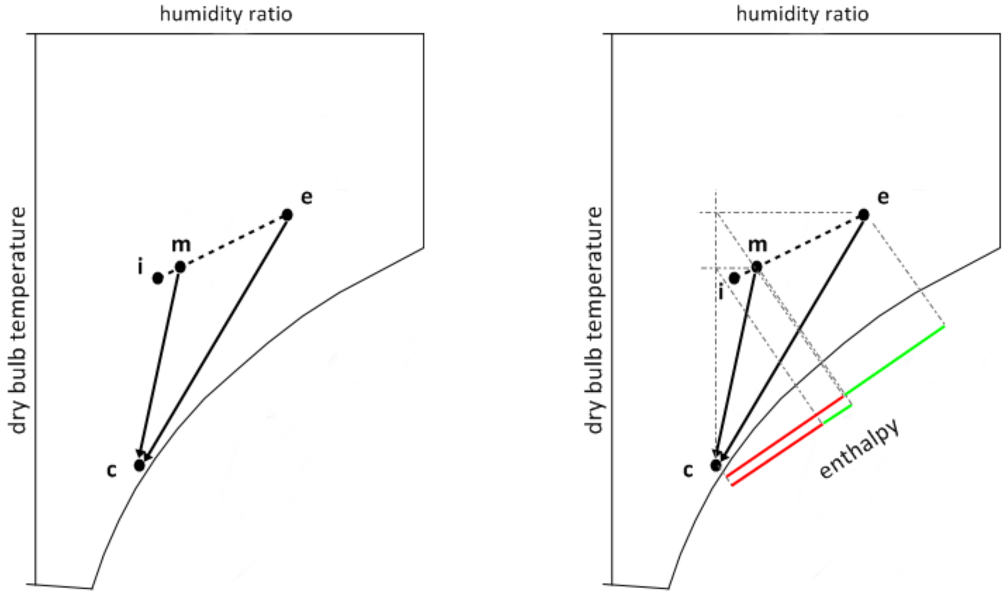


Fig. 47 Visualization of the cooling/dehumidification process in a psychometric chart of the combined airflow (m) and pretreatment of ventilation air flow (e).

When the sensible cooling isn't required, this is, in essence lost energy. In addition, an excess of sensible cooling must be corrected by reheating to prevent an undershoot of the indoor temperature. This is often the case during dehumidification at the Zeeuws Museum. This additional energy consumption for reheating should be less when the climate system is able to pretreat the ventilation airflow, because it is less often necessary to cool the total airflow to achieve the desired dehumidification demand.

From Fig. 48 it can be observed that the period of 'higher' outdoor humidity levels is much longer than that of 'higher' outdoor temperatures, compared to general applied climate conditions in museums. This implies that the latent cooling component is dominating cooling load from ventilation and infiltration during summer season. As indication, an air condition of 20^{o}C and 55% R.H. has a specific humidity of approximately 8 g/kg.
The added value of pretreatment of the ventilation airflow on energy consumption and dehumidification performance should be obtained from the computer simulations.

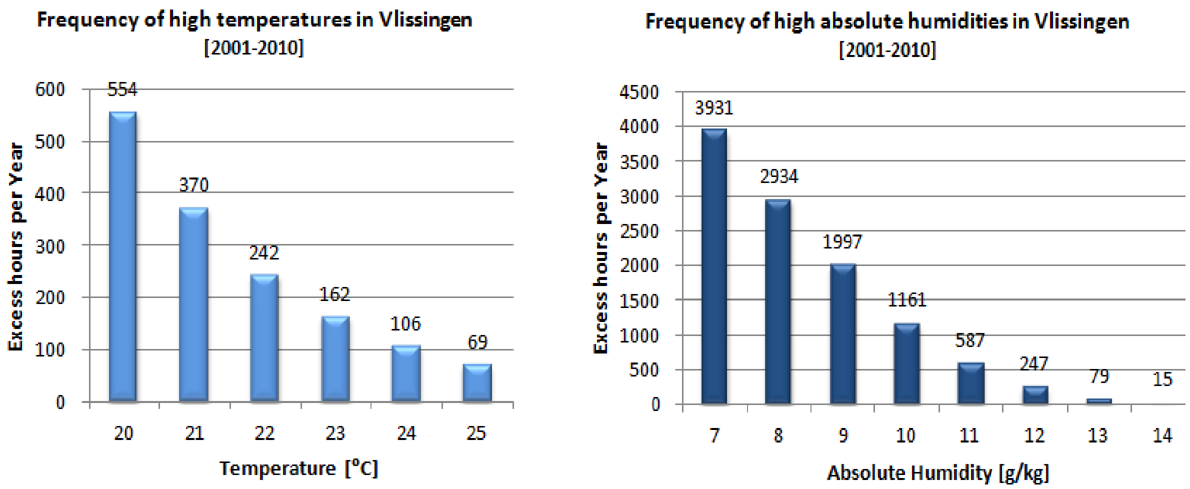


Fig. 48 Frequency of high temperatures (left) and high specific humidities in Vlissingen (right) [ref.18].

When using an ATES system, as in the Zeeuws Museum, a pre- cooling coil may offer more benefits. This has to do with the applied chilled water temperature, as will be explained later, and the possibility to restore a thermal imbalance in the ATES system. A (pre-) cooling coil in the ventilation airflow can also be used to load extra cold energy in the ATES system during winter conditions. This cold energy is extracted out of the cold outdoor ventilation air by this coil, and exchanged with the groundwater of the ATES system.
This is a very energy efficient method to recover a shortage of cold in the ATES system, because the stored warmth in the ATES is also efficiently used in this case by pre-heating of the ventilation airflow to about 8-12^{o}C, so less heating energy is needed from the boiler or heat pump.
In other systems which are used to recover a cold shortage in the ATES, like dry coolers and cooling towers; the heat out of the ATES is unutilized emitted to outdoor air during cold loading, and therefore less sustainable.
Another disadvantage of a dry cooler in the case of the Zeeuws Museum is the need of a long pipeline route, because in connection with the protected building status it is impossible to locate it nearby on the roof. In addition to the extra investment it also causes energy loss. Because of the severe shortage of cold in the ATES of the Zeeuws Museum, preparations for the purchase of a dry cooler were ongoing, at the beginning of this study.
This research has shown that the imbalance in the ATES of the Zeeuws Museum is mainly not the cause of an imbalance between the cold and heat requirements of the building, but caused by shortcomings in the hydraulic system (paragraaf 36), therefore a dry cooler will be no good solution to the real problem.
It will be investigated by the simulations how much cold could be approximately loaded in the ATES by a coil in the ventilation airflow during the winter, and also the corresponding savings on heating energy generation.

Impact of applied chilled water temperature

The temperature range in the chilled water circuit is an important factor on the system performance of an ATES system. By use of higher chilled water temperatures for cooling processes with the aid of ATES systems, normally the system performance benefits, due to the dependency of the groundwater temperature.
In contradiction to this; when also dehumidification is required, a higher chilled water temperature through the coil makes it harder to dehumidify the air, which can result in a worse indoor climate, a longer period of cooling use, and a corresponding higher energy consumption. This impact should be obtained from the simulation study.

Required system capacity

Beside influences on energy consumption and maintainability of the indoor climate, the simulation results should also demonstrate the differences between the required full load capacities of the variants. This maximum required power is an important factor of the investments costs of the HVAC systems, and often also the required installation space.

4.2 Simulation software

Modeling and simulating the indoor climate and energy demand is done by using HAMBASE [ref.19]. HAMBASE is a simulation model for heat and moisture flows in a building, which is developed at the Eindhoven University of Technology (TU/e) from 1987 until now. The program(-code) of HAMBASE works in the MatLab environment, so also the software package MatLab/Simulink [ref.35] is used for these simulations. Matlab is a high-level program language and interactive environment for numerical computation, visualization, and programming. With the HAMBASE model the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building can be simulated. HAMBASE was validated using the ASHRAE test [ref.20, 34] with satisfactory results. Over the past 25 years a lot of experience is gathered in developing and using HAMBASE.

Simulink, which is part of the Matlab package, is an environment for the simulation of dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that makes it possible to design, simulate, implement, and test a variety of time-varying systems. It has a large degree of flexibility, modular structure and transparency of the models.
Simulink can be coupled to HAMBASE [ref.36], which enables the coupling of models with different time constants. In this research Simulink is used for modeling of the climate control systems and the cooling/dehumidification section of the climate system.

4.3 Simulation model

In this paragraph the applied models of the building and climate system are explained.

4.3.1 Building model

For this simulation study, the same building models were applied as Martens has used in his Phd-study. The model shows a typical exhibition room layout (Fig. 49), which is applied four times with different qualities of the building envelope. Because of this, the effect of the building envelope on indoor climate and energy use will be obtained, and results will be interpretable for a greater range of buildings.

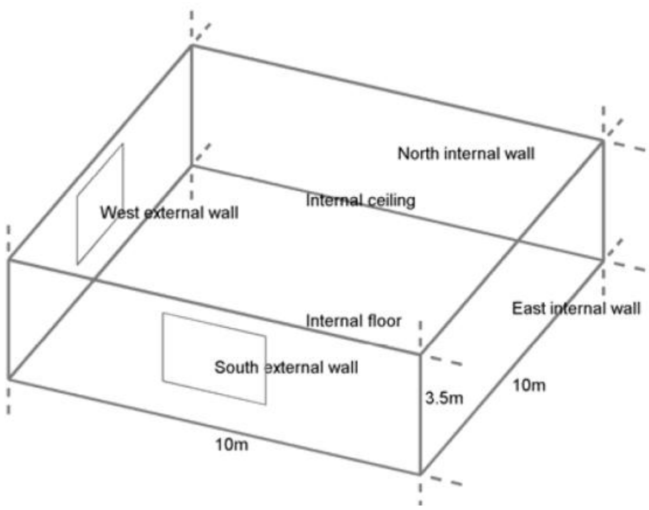


Fig. 49 Dimensions of the applied building model.

The model consists of a single zone, 10m long, 10m wide and with a height of 3.5m. The ceiling, floor and the north and east wall are adiabatic, which means that these are connected to other zones, which are identical in behavior, but are not part of the simulation. The south and west wall are external walls and have a window of $5m^2$ each. Martens used four types of quality of envelop and also four levels of climate conditioning systems. In this simulation study, only the fourth level of climate conditioning systems will be applied, which means that the simulated HVAC system is able to cool, heat, humidify and dehumidify. The building model with the lowest quality of building envelope (QoE1) will be limited applied, because a building with such envelope is not a usual combination with an extensive climate system and tight climate conditions [ref.4].

The differences in quality of the envelope are determined by variations in infiltration rate (caused by leakages in the envelope), walls and glazing properties (Table 4). In appendix 5, a full description of the input parameters for the building model is provided.

Table 4 Influence of Quality of Envelope on input parameters:

	QoE 1	QoE 2	QoE 3	QoE 4
Exterior wall	Solid brick wall 400mm, plastered	Solid brick wall 400mm, plastered	Solid brick wall 400mm, insulation on the inside 100mm, plastered	Brick wall 100mm, cavity, insulation 150mm, brick 100mm, plastered
Glazing type	Single	Double	Double low-e	Double low-e
Infiltration rate	$1\ h^{-1}$	$0{,}4\ h^{-1}$	$0{,}2\ h^{-1}$	$0{,}1\ h^{-1}$

4.3.2 Model of the climate system

The models dispose of an 'all air' climate system to satisfy the ventilation demand and desired temperature en humidity set-points by heating, cooling, dehumidification and humidification. Because in this study the focus is on the cooling and dehumidification process, the heating and humidification processes are simulated very basic in the models. For the heating and moisture supply, ideal system models were used that has the power and response time to fulfill exactly the needs in the zone to maintain the desired set-points. The energy consumption of the air conditioning processes will be monitored, whereby a distinction is made between normal heating during the heating season and reheating during the dehumidification process.

Because the focus is on the process of cooling and dehumidification by use of cooling coils, this part of the climate system is more extensively translated in a model which imitates the main characteristics of this process.

All the simulation variants has the ability to cool and dehumidify the air after the mixing section by a cooling coil, but a part of the variants does also have the ability to pretreat the ventilation airflow before the mixing section by use of an extra cooling coil.

Model of the cooling and dehumidification section

In fact the performance of an air-water heat exchanger like heating and cooling coils is depending on many parameters [ref.37], like mass flows, fluid velocities, flow patterns, heat transfer resistance, heat exchange surface and ratio, fluid conditions, etc. Beside thermal energy exchange, also moisture removal and latent energy exchange takes place when the airflow passes a cooling coil in which condensation occurs.

When condensation arises, the energy transfer characteristics will change due to the thin water layer locally on the air-side heat exchanger.

Because setting up a cooling coil model with heat and mass equations is therefore not easy, and very dependent on specific coil characteristics and applied fluid conditions, the choice is made to create a more generally applicable model which can imitate the cooling and dehumidification process as a kind of black box model.

The goal with this coil model is not to reproduce the performance of a specific existing cooling coil, but to obtain performance differences caused by variations in the system design. For this coil model is needed that imitates the air cooling and dehumidification process by a cooling coil in general. In a general way, a cooling and dehumidification process by a counter flow cooling coil can be visualized as shown in Fig. 50.

This psychometric chart contains a curve which represents the air condition from the beginning (1 inlet condition) to the end (2 outlet condition) of the cooling process by a cooling coil. The air condition is expressed in temperature and humidity. When the cooling coil operates in full load, the outlet air-condition will approach the inlet cooling water temperature, depending on the coil capacity. The specific properties of a cooling coil and fluid flow characteristics determine the degree of curvature between point 1 and point 2.

This line will be straighter in case of a tube heat exchanger, in comparison with a finned tube heat exchanger. This is because the temperature of the fins is higher than the temperature of the pipe wall and chilled water.

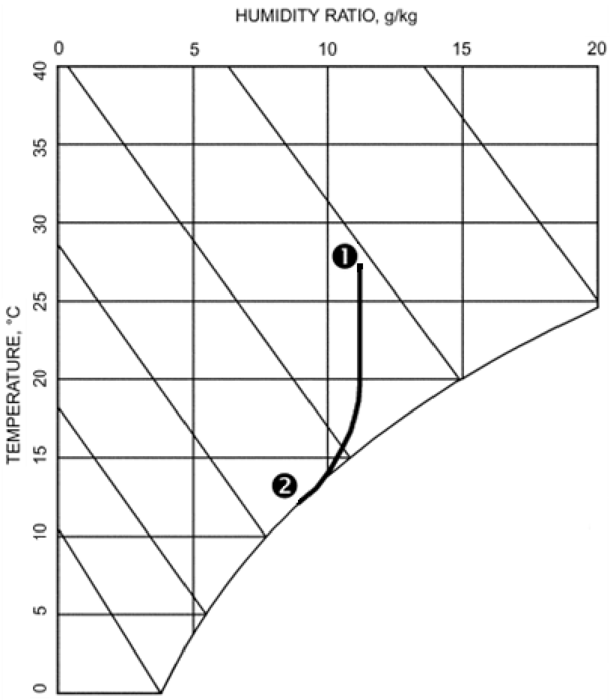


Fig. 50 Visualization of a general air cooling/dehumidifcation process by a cooling coil [ref.37]

Practical implementation

This general cooling/dehumidification process by a cooling coil is translated into a Matlab-programming code and integrated in a Simulink function block. This Simulink model decides, depending on the actually need for cooling and/or dehumidification, the inlet air condition and the lowest possible outlet air condition by full load condition (with associated power), what the required air outlet condition will be at a certain moment. When the demand for cooling and or dehumidification is below the maximum capacity of the cooling coil, the applied coil model is able to function in part load condition between 0 and 100%. The outlet air condition will be somewhere on the cooling curve between inlet air condition and lowest outlet air condition, depending on the level of partial load (Fig. 51). If the required part load level for sensible cooling need is lower than the required load level for dehumidification demand at a certain moment, the highest desired load level determines the state of the cooling coil, so in this case for satisfying the dehumidification demand.

When the need of cooling or dehumidification becomes higher than the coil can provide, the coil just operates in full load condition. The coldest outlet air-condition (in full load condition) is depending on the applied inlet chilled water temperature and the minimum given offset. This offset is an input parameter of the coil model, in the simulations a value of 1°C is used, which means that the lowest outlet air condition is 1°C above the inlet chilled water temperature. The maximum cooling and dehumidification capacity of the coil model is depending on the inlet air condition, the air mass flow through the coil, the chilled water temperature and the minimum offset.

In Fig. 51, the simulated air outlet conditions of the coil model are visualized in a psychrometric chart by the green and purple dots. The presented outlet air conditions belong to an inlet air condition of about 23°C and a specific humidity of about 10 g/kg (during the year 2005). The differences in outlet air conditions are the result of various needs for cooling/dehumidification in the building model at those certain moments.

The applied curve of the cooling process model is essentially a 1/4 parabola of which vertical and horizontal radius depends on the maximum temperature and humidity reduction of the airflow which enters the cooling coil. This cooling curve will be overruled by the 100% RH-curve (saturated condition), when the simulated air conditions threaten to exceed this saturation line.

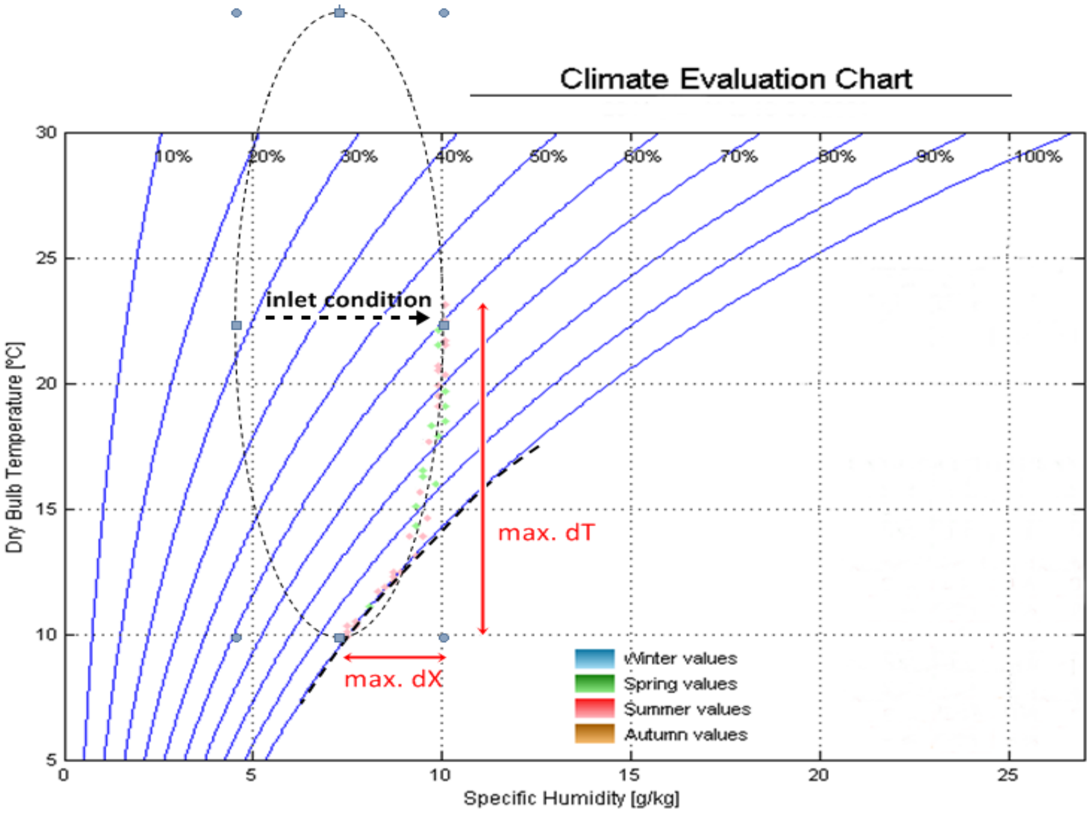


Fig. 51 Simulink cooling coil model with curved cooling process; visualization of simulated outlet air conditions after the cooling coil which belong to approximately the same inlet air condition.

To determine the influence of the degree of curvature on the final simulation results, another coil model is built with a cooling process whereby the air outlet conditions during part load operation are somewhere on a straight line between the inlet air condition, and lowest outlet air condition at full load operation. Fig. 52 shows a number of simulated air outlet conditions, which belongs to the same inlet air condition and coldest outlet air condition (10ºC) at full load condition. This coil model is used in one simulation variant to demonstrate the effect of the applied cooling process curvature on the simulation results.

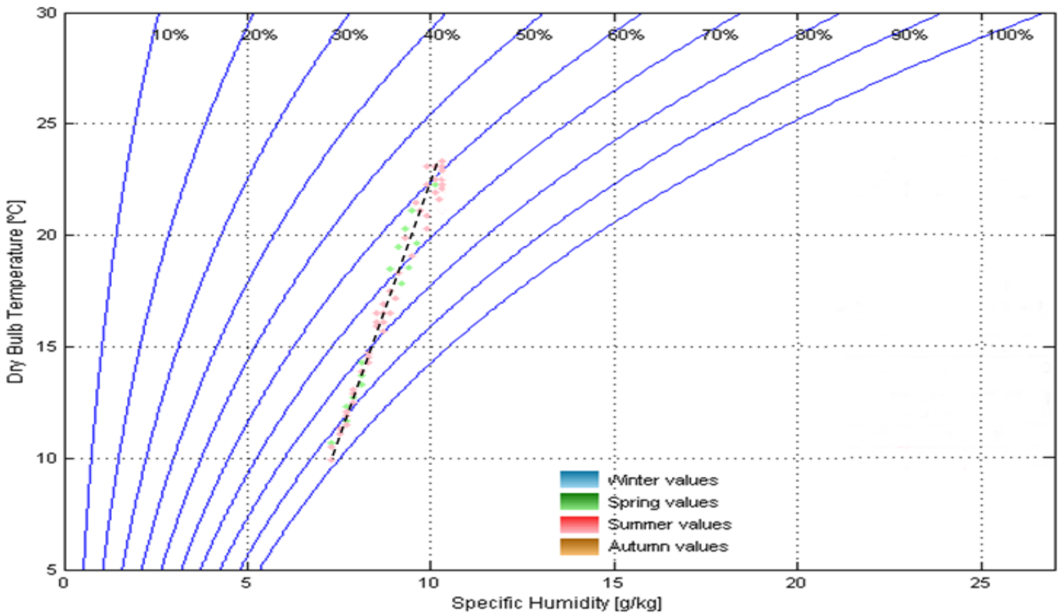


Fig. 52 Simulink cooling coil model with straight line cooling process; visualization of simulated outlet air conditions after the cooling coil which belong to approximately the same inlet air condition

Simulink model of the cooling/dehumidification section

The Matlab script of these cooling coil models is implemented in the Simulink environment by a Matlab function block. This function block with input and output ports is displayed in Fig. 53. The Matlab code itself can be viewed in appendix 8.

The Simulink model actually consists of a combination of two cooling coils and an air mixing section in between. One pretreat cooling coil is placed in the ventilation airflow before the mixing section, and the other one is located in the total airflow which is a mixture of the ventilation and recirculation airflow. The simulation variants which does not have the ability to pretreat the ventilation airflow, the pretreat coil of the model is taken out of function.

The input parameters of the Simulink model block are listed below:

- Mass flows of both ventilation airflow and total airflow [kg/s].
- Both incoming air conditions which fluctuate over time, by temperature [^{o}C] and specific humidity [kg/kg].
- Inlet chilled water temperature for each cooling coil in [^{o}C].
- Offset temperature that determines the minimum difference between inlet chilled water temperature and the lowest outlet air temperature when the coil operates in full load condition [^{o}C].
- Desired amount of dehumidification [kg/s] and/or sensible cooling [^{o}C].

The output parameters of this Simulink block are:

- Both outlet air conditions after each cooling coil in temperature [^{o}C] and specific humidity [kg/s].
- The amount of dehumidification by each coil [kg/s].
- The amount of sensible cooling of each coil [^{o}C].
- Signal whether the cooling/dehumidification section is in function or not.

Just for analysis, the generated sensible cooling of each coil is divided in two outputs. One cooling power output for situations when the dehumidification demand is leading and determines the load level of the coil. The other output gives the sensible cooling power in case that the cooling demand is leading.

The generated total amount of cold and dehumidification by the cooling coils are subsequently inputs of the building model.

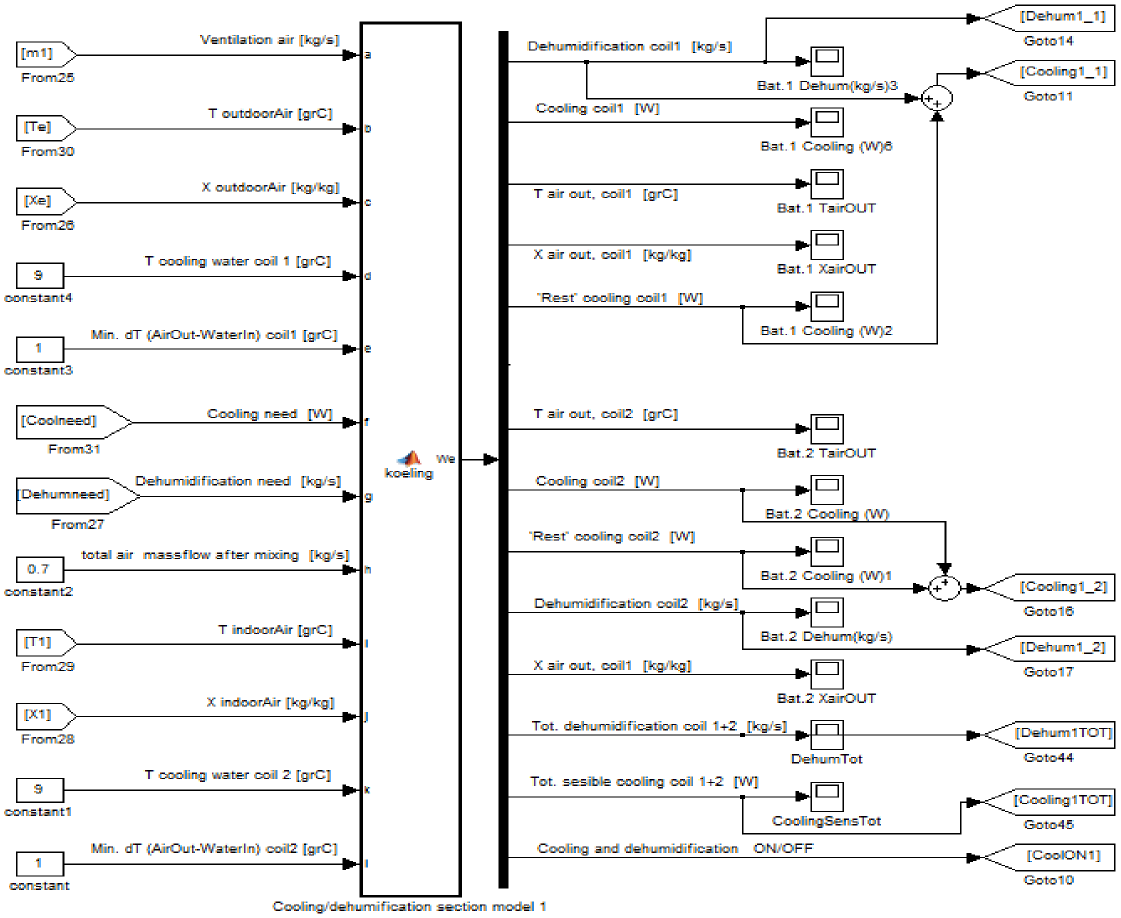


Fig. 53 Simulink model of the cooling/dehumidification climate system

Model verification

Appendix 7 presents the successful verification of this Simulink cooling/dehumidification model. Verification is done by comparing static manual calculation results with the simulation outputs obtained from the Simulink model, both based on the same input parameters. This is carried out at four random circumstances with different input parameters.

Complete Simulink model

The complete Simulink model is shown in Fig. 54, and in a larger size in appendix 6. The building model with inputs (left) and outputs (right) is highlighted by the green frame. The inputs consist of: the amount of ventilation airflow, heating and cooling energy and quantity of (de)humidification. The amount of air infiltration through the building envelope is dictated in the underlying building code.

The outputs of the building model include the indoor air conditions and the outdoor air conditions arising from the applied climate file. The simulations are done with three independent building zones, which differ in quality of building envelope. Each of these zones has its own inputs and outputs.

On the basis of the indoor air conditions is determined what the desired amount of (de-)humidification, cooling and heating energy supply should be to maintain the set-points. These provisions are done by the function blocks into the frames A1, A2, B and C (Fig. 54). The required sensible cooling and dehumidification were determined in the frames A1 and A2 respectively. These desired capacities were sent to the corresponding cooling/dehumidification models, which are highlighted by the yellow frame.

In frame B, the desired heating energy is calculated for each zone. These desired values are also the final input values for (re)heating energy, because an ideal (re-)heating process is assumed. This input port of the building model is combined with the sensible cooling supply, generated by the cooling coils.

Within the purple frame C, the same has happens for humidification and dehumidification. The humidification is assumed as an ideal process, so the supplied moisture to the building model is just the same as the calculated humidity needs to satisfy the set-point. The amount of dehumidification which is generated by the cooling coils, enters the building model through the same input port as the supplied amount of humidification.

The energy consumption of each building zone is calculated by the blocks in the red frame above. These are from left to right: humidification, reheating, total heating energy, sensible cooling and latent cooling (dehumidification).

The total generated latent and sensible cooling for each zone is separately calculated for both cooling coils. The coil that pretreats the ventilation airflow, and the second coil which is located after the air mixing section.

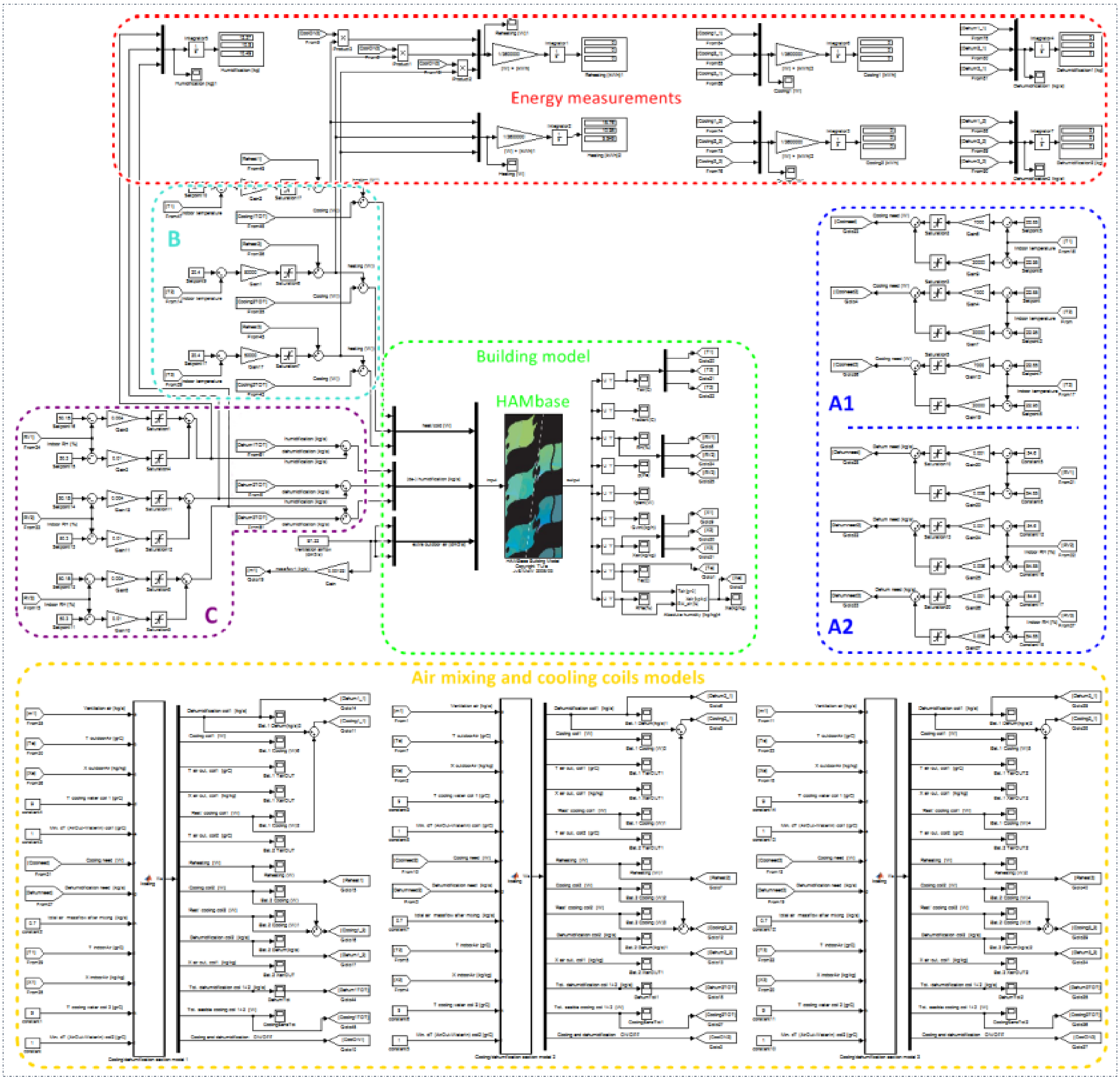


Fig. 54 Complete Simulink model

4.4 Simulation variants

This section presents the applied simulation variants which are used to obtain the desired knowledge. Table 5 listed all the 69 applied variants of this simulation study. For clarification, in this section the changing parameters of these variants are briefly explained.

Building model

Al the variants are simulated with 4 different qualities of building envelop, as mentioned in paragraph 4.3.1.
The quality of the envelopes is determined by differences in thermal capacity and resistance of walls and windows, and by the degree of infiltration air rate.
The impact of this infiltration air rate will be investigated separately by an additional simulation variant. In this variant the infiltration rate of the three building models will be the same as the zone with the best quality of envelope.

With or without pretreatment of ventilation airflow

The impact of an extra 'cooling' coil that pretreats the ventilation airflow before it is mixes with the large recirculation airflow from inside, should be demonstrated by a number of simulation variants in which some variants have this possibility, and other that do not make use of pre-treatment. The pretreat coil will be leading to satisfy the demand for cooling/dehumidification. When the pretreat coil is not able to completely provide the needs, the second cooling coil after the mixing section will assist.

Separated from this group of simulation variants, another model is used to investigate the possible amount of cold energy load in the ATES system during winter conditions and the corresponding saving on heating energy due to the preheating of the ventilation airflow by the groundwater.
For this, another (basic) Simulink model is build in which is assumed that the groundwater from the warm well (normally around 15^{o}C) is able to preheat the ventilation airflow till 9^{o}C after the preconditioning coil.
The visualization of this Simulink model is present in appendix 11.

Variations in chilled water temperature

As mentioned before, the chilled water temperature affects the dehumidification capacity and efficiency. This effect should be clearly by simulating the variants with different chilled water temperatures. Chilled water temperatures are applied of 6, 9 and 12 ^{o}C.

Humidistatic heating during dehumidification need, within the desired temperature bandwidth.

To gain insight into the effect of applying humidistatic heating between the allowable indoor temperature bandwidth, some simulation variants including this control strategy. In the Simulink model this principle is practical converted as follows:
Imagine a desired indoor relative humidity bandwidth between 50 and 55% and for temperature between 20 and 23^{o}C. The cooling coil for dehumidification will still start dehumidifying when the indoor relative humidity exceeds the highest level of 55%. The 'humidistatic heating modus' takes place when the measured relative humidity exceeds 54% (1% lower). The lowest desired indoor temperature is increased linearly to the measured relative

humidity condition between 54 and 55%, to a maximum of lowest desired temperature condition of half a degree lower than the highest desired temperature. This means that the desired indoor temperature bandwidth by a measured indoor relative humidity of 55% is changed to 22,5-23°C, as can be seen in Fig. 55.

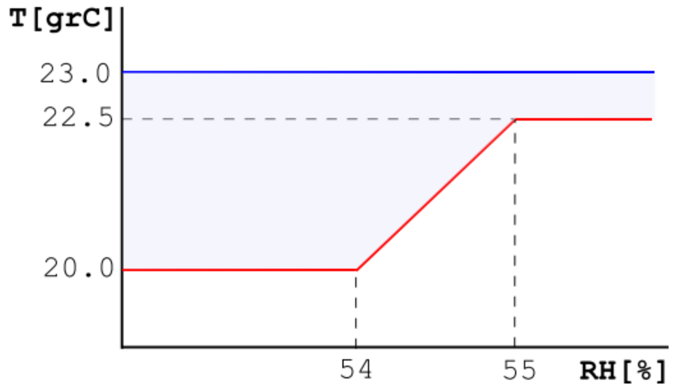


Fig. 55 Implementation of RH dependent temperature set-points for humidistatic heating during high indoor relative humidities.

Two different coil models

As mentioned before (paragraph 4.3.2), the influence of the applied coil model on the results would be somewhat understandable when also another coil model is implemented.

The difference between these two models is the cooling process when the coil is in part load. In the main model, the outlet air condition will be somewhere on a curve between inlet condition and lowest outlet condition by full load, seen in a psychrometric chart. The outlet condition by the other coil model in part load will be somewhere on a straight line between these inlet and full load outlet conditions. So proportionately, more latent cooling occurs during part load conditions.

Variations in amount of ventilation air

Although the total process airflow (recirculation & ventilation) will be the same in all simulation variants (6 h^{-1}), variants are simulated with different amounts of ventilation airflows. The applied variations in ventilation rates are 0.5, 1 and 1.5 times the total zone volume per hour. A deviant variant with only the building model in HAMBASE, without Simulink is done without a ventilation airflow. This variant simulates the primary building needs without ventilation, but includes the infiltration airflow through the building envelope.

Variations in desired temperature and humidity set-points

The simulation variants are carried out with desired indoor set-points for temperature and relative humidity which are commonly used in museums. These applied temperature borders are 20 to 23°C, and for the relative humidity 50 to 55%. In addition to these simulation variants, one variant is simulated with a lower desired relative humidity bandwidth between 45 to 50%, and another variant with a wider temperature bandwidth, namely 19 to 23°C.

Differences in capacity utilization

The used building zone model has a floor area of 100 m^2 (10x10 m). In the simulation variants, the assumption is made that during opening hours (10-17 h each day) 2 people are into this room continuously.

Also some simulation variants are done with a higher occupancy, namely 5 people. For each person, a sensible heat load of 100 W and a moisture production of 30 mg/s are applied. For the other internal heat loads (e.g. lights), 15 W/m^2 is used.

Table 5 gives a total overview of all the simulation variants and their adjusted parameters. To quickly find the differences between these variants, only the changed parameters with respect to variant A are shown.
Also a short description of the changing parameters is present on the left side of the table.

Al these variants are applied on three building models, which have the same dimensions but differences in the quality of building envelope, as mentioned earlier.

Table 5 Overview of the applied simulation variants:

Parameters: **Simulation variants** ***(All applied on 3 types of building envelopes):***	With pre-treatment	Humidistatic heating	C oil model type (Straight/curve)	Cooling water temp. [°C]	Temperature set-points [°C]	R.H. set-points [%]	Ventilation rate [h^{-1}]	Visitors
A: Base case (Pre-treatment)	**Yes**	**No**	**Curve**	**9°C**	**20-23°C**	**50-55%**	**1 h^{-1}**	**2**
B: No pre-treatment	No							
C: Humidistatic heating; no pre-treatment	No	Yes						
D: Humidistatic heating		Yes						
E: Humidistatic heating; ↑ T.water 12°C		Yes		12°C				
F: ↑ T.water 12°C				12°C				
G:↓ T.water 6°C				6°C				
H: ↓ T.water 6°C; no pre-treatment	No			12°C				
I: ↑ Ventilation 1.5h^{-1}; no pre-treatment	No						1,5h^{-1}	
J: ↑ Ventilation 1.5h^{-1}							1,5h^{-1}	
K: ↓ Ventilation 0.5h^{-1}							0,5h^{-1}	
L:↑ Visitors 5								5
M:↑ Vis. 5; ↓Vent. 0.5h^{-1};							0,5h^{-1}	5
N:↑ Vis. 5; ↓Vent. 0.5h^{-1}; no pre-treat	No						0,5h^{-1}	5
O:↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C				6°C			0,5h^{-1}	5
P:↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C; no pre-treat	No			6°C			0,5h^{-1}	5
Q:↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C; Hygro		Yes		6°C			0,5h^{-1}	5
R: T.indoor (19-23°C)					19-23°C			
S: T.indoor (19-23°C), : No pre-treatment	No				19-23°C			
T: ↓ R.H. (45-50%)						45-50%		
U: ↓ R.H. (45-50%); ↓Tw6°C; Hygro		Yes		6°C		45-50%		
V: Primary energy demand (HAMBASE)	No	No	-	-				
W: Primary demand (HAMBASE); no ventilation	No	No	-	-			0h^{-1}	
X: Coil model2 (straight line)			Straight					
Y: Low infiltration rate (0,1 h^{-1} same as QoE4)								
The variants A, G, H, X and Y are also simulated in combination with the building model with the lowest quality of envelope (QoE1)								

4.5 Climate data

A Dutch weather data file of the year 2005 is used for the input of the simulation models. These weather conditions are measured in De Bilt, by the Royal Netherlands Meteorological Institute (KNMI), and are visualized in Fig. 56. In the Netherlands, the year 2005 is regarded as a quite warm and sunny year, with an average amount of precipitation (785 mm in total). As expected in future climate scenarios, the global (and therefore also the Dutch) climate will possibly be warmer and more extreme, while precipitation will decrease in summer and increase in winter [ref.38]. The year 2005 matches this expectation, and is therefore chosen as reference year for these simulations.

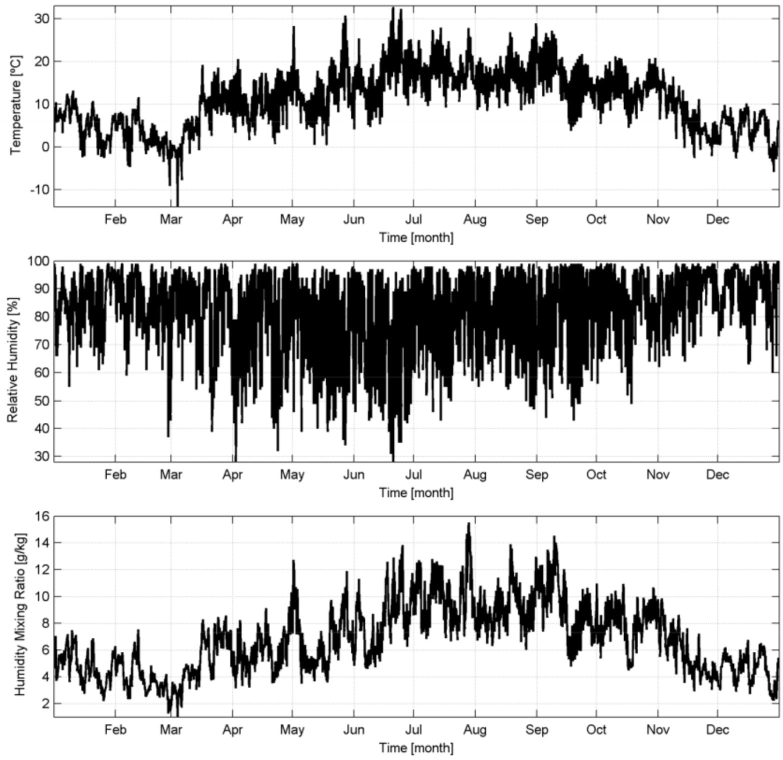


Fig. 56 Outdoor climate used for simulation: De Bilt (NL), 2005 [ref. 18].

The minimum and maximum temperatures during this year were -14.0^{o}C and 32.7^{o}C. In Table 6 the annual mean temperature, relative humidity and unweighted degree days are given of the year 2005, in comparison with the mean values of the period from 1901 to 2011.

Table 6 Comparison of the climate year 2005 with average climate values [ref.18]:

Dutch weather during:	2005	1901-2011
Annual mean temperature [ºC]	10.7	9.5
Annual mean relative humidity [%]	82.0	81.6
Unweighted degree days “heating”	2765	3020
Unweighted degree days “cooling”	95	79

4.6 Simulation results

In this section, the results of the simulation study are presented. For each variant the simulated energy consumption and it's manageability of the desired indoor conditions are shown. The simulated indoor air conditions and load duration curves of all the variants are visualized in respectively appendix 9 and appendix 10
The simulation results will be discussed in paragraph 4.6.7.

In paragraph 0, the simulated energy demand (belonging to the building models with qualities of envelop 2, 3 and 4) for humidification is presented. The energy consumptions for (re-)heating, cooling and dehumidification are split up according to the type of building model. Results of the building models with the qualities of envelope 2, 3 and 4 are presented in respectively paragraph 4.6.3, 0 and 0. In these sections, also the manageability of the desired relative humidity conditions are shown. The desired indoor temperature levels can be achieved in all the simulation variants. This is not the case for the indoor relative humidities.

The presented energy consumption for cooling and dehumidification is divided in a sensible part and a part which is ceded by latent cooling.
In the simulation variants V and W, only the primary energy need for cooling and dehumidification in the zone is simulated with HAMBASE. The presented cooling energy consumption of the other simulation variants (Simulink models) shows the energy consumption of the cooling coil(s) to satisfy the primary energy needs for cooling and dehumidification. This energy consumption will be higher, because latent and sensible cooling is not generated independently of each other.

The simulation results of the few variants, in which also the building model with the lowest quality of envelope (QoE1) is incorporated, are shown in paragraph 0.
In this section, also the results of variant (X) with the other cooling coil model (straight line) and variant (Y) in which all the building models have the same low infiltration rate (0,1h-1) as the building model with the best quality of envelop (QoE4) are given.

But first, the simulated potency of additional cold energy storage in the ATES system during winter conditions is presented in the section below.

4.6.1 Cold storage and preheating of ventilation airflow during the heating season

The simulated amount of cooling energy, generated by the pretreat cooling coil out of the ventilation airflow during winter conditions, is shown in Table 7. The amount of energy that is exchanged between the groundwater and the ventilation airflow depends on the mass flow of the ventilation airstream.
The ventilation rates according to the building volume are given, corresponding to the presented air mass flows.
The assumption is made in the model that the ventilation airflow is preheated to 9^{o}C after the preconditioning coil.

Table 7 Simulated thermal energy exchange between ventilation air flow and ground water:

Ventilation rate/mass flow	kWh/a
1 kg/h	3,86
0,5 h^{-1} ~ 214 kg/h	811
1,0 h^{-1} ~ 427 kg/h	1.623
1,5 h^{-1} ~ 641 kg/h	2.434

4.6.2 Energy consumption for humidification

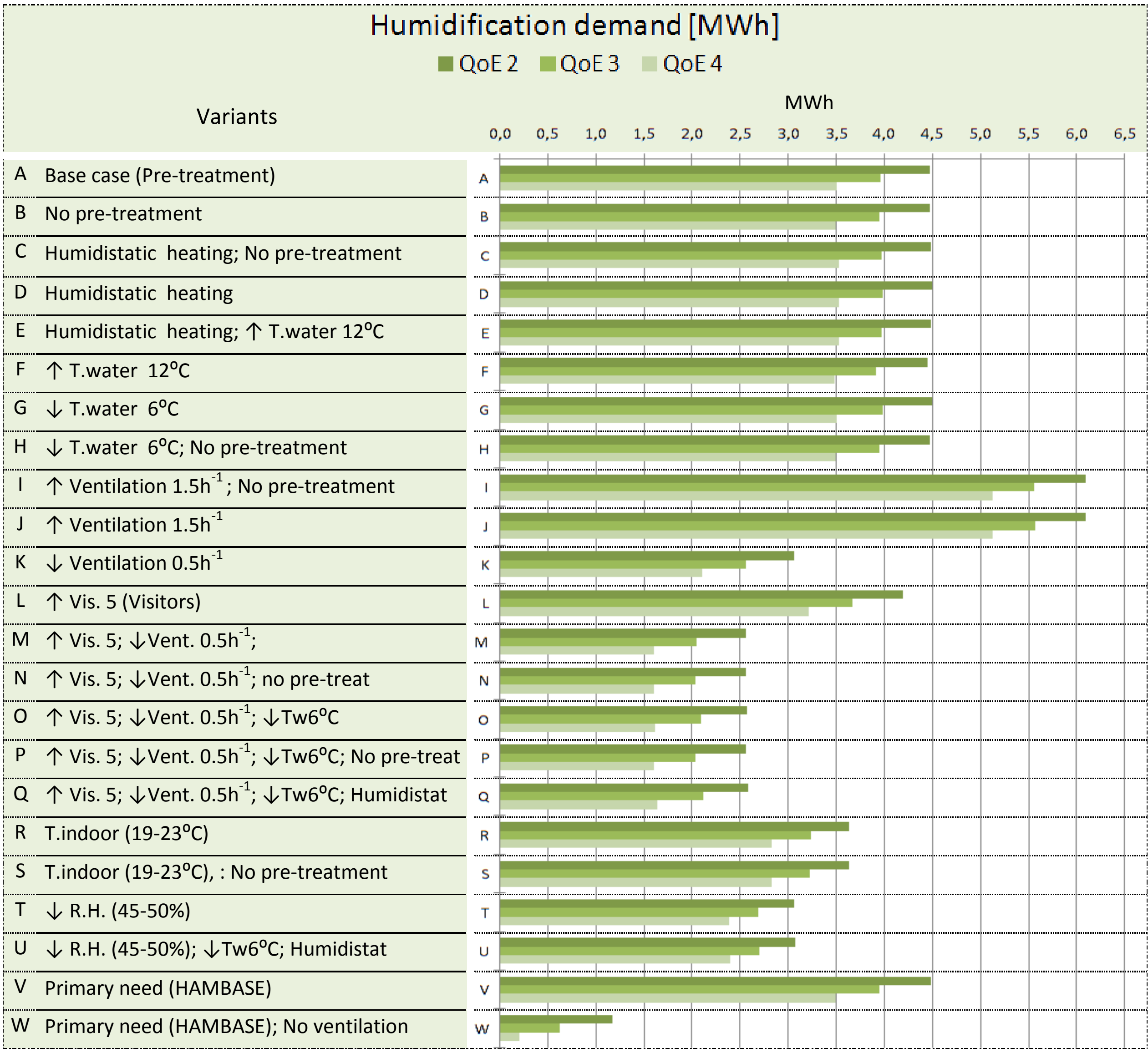


Table 8 Simulated energy demand for humidification

4.6.3 *Energy consumption associated with Quality of Envelope 2*

Energy consumption for cooling and dehumidification

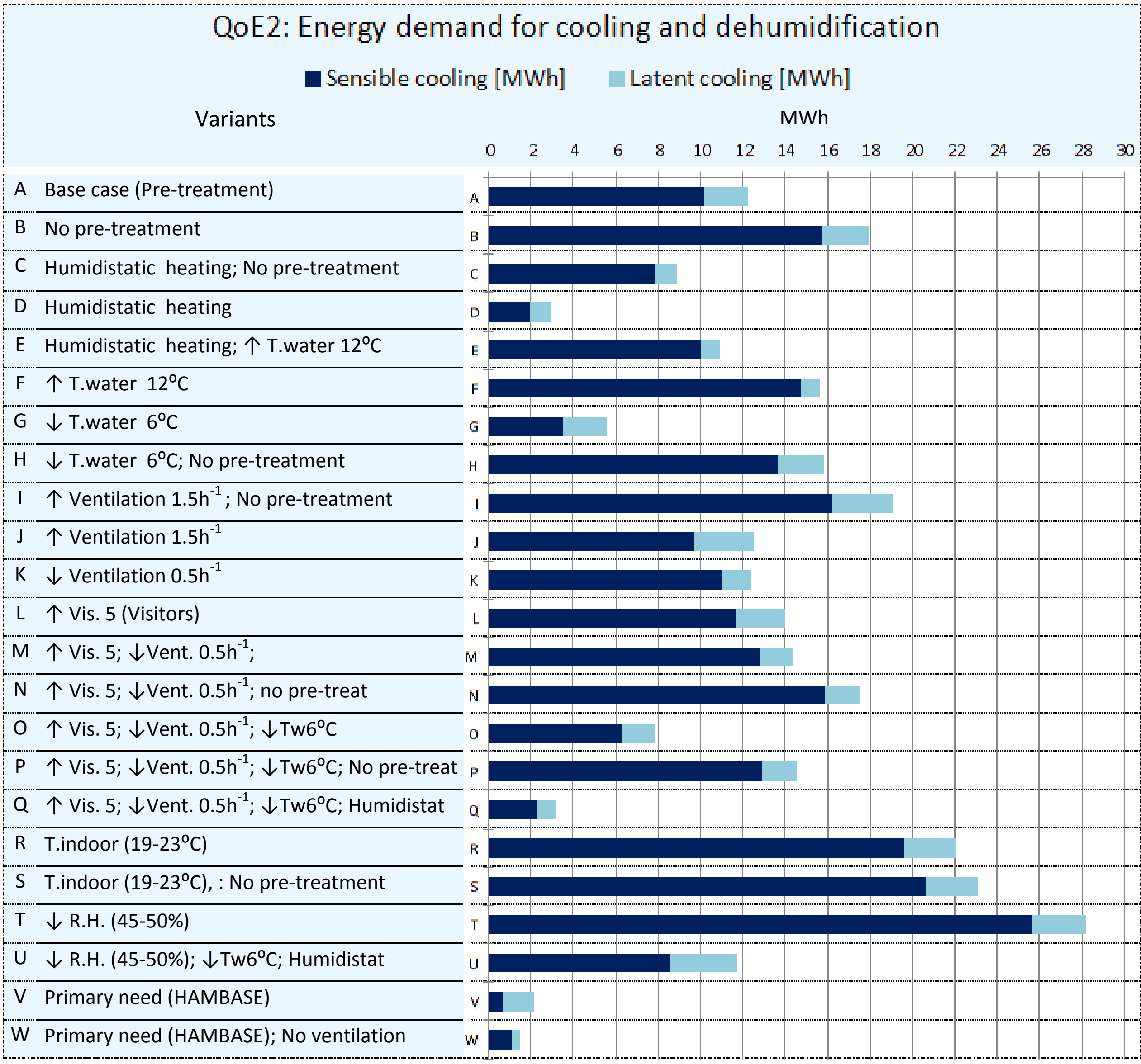


Table 9 Simulated energy consumption for cooling and dehumidification (QoE 2).

Energy demand for heating and reheating

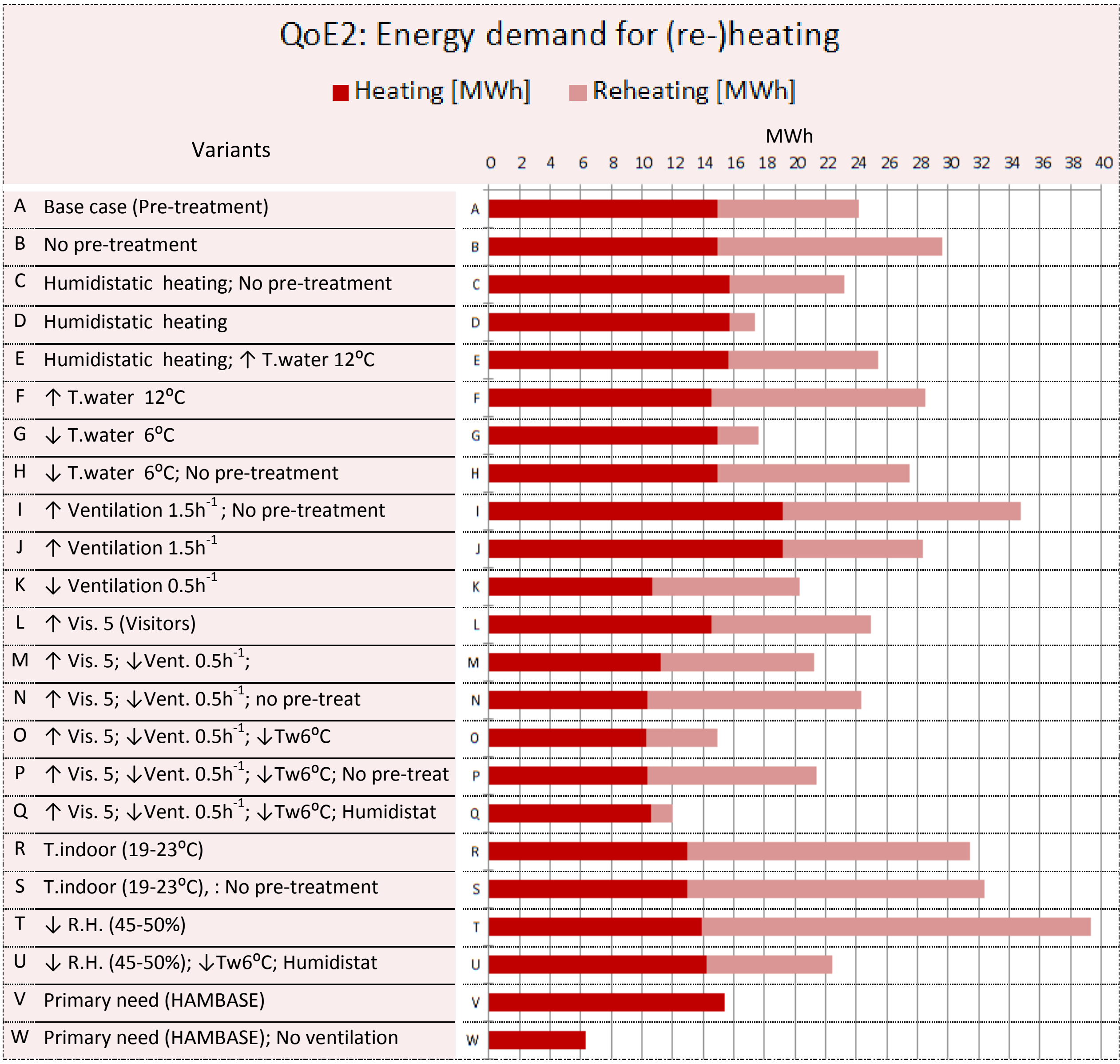
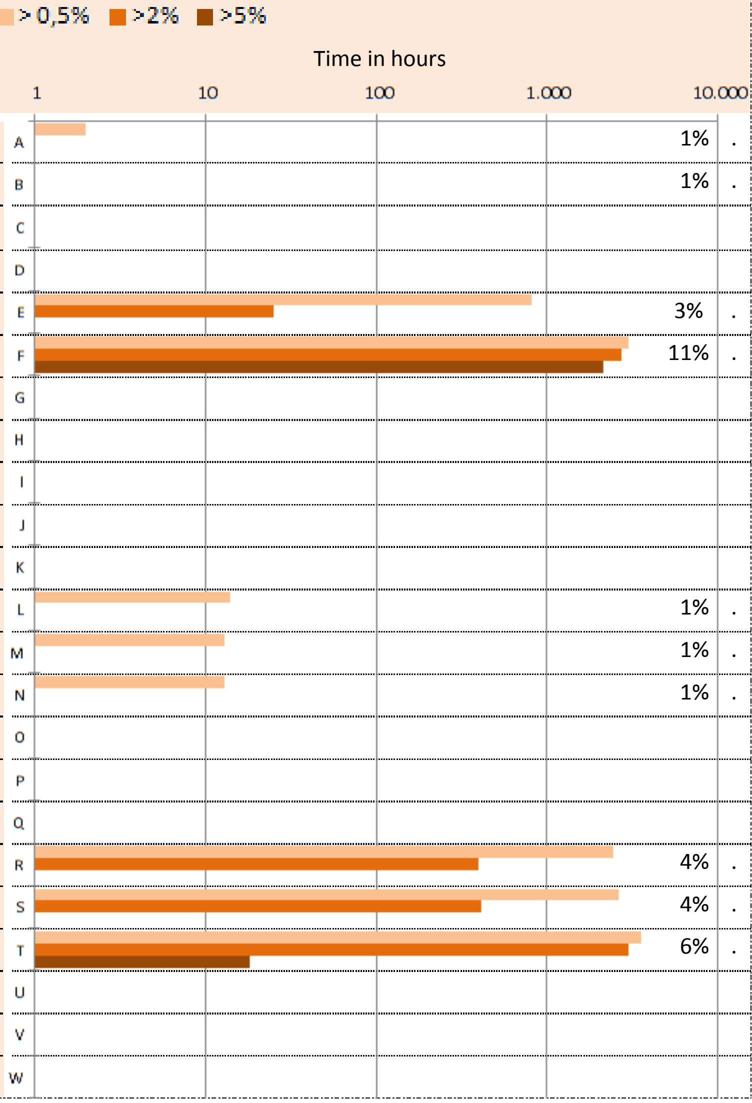


Table 10 Simulated energy demand for heating and reheating (QoE 2).

Maintaining of desired set-point levels

QoE2: Excess hours of desired relative humidity level



	Variants	
A	Base case (Pre-treatment)	1%
B	No pre-treatment	1%
C	Humidistatic heating; No pre-treatment	
D	Humidistatic heating	
E	Humidistatic heating; ↑ T.water 12°C	3%
F	↑ T.water 12°C	11%
G	↓ T.water 6°C	
H	↓ T.water 6°C; No pre-treatment	
I	↑ Ventilation 1.5h^{-1}; No pre-treatment	
J	↑ Ventilation 1.5h^{-1}	
K	↓ Ventilation 0.5h^{-1}	
L	↑ Vis. 5 (Visitors)	1%
M	↑ Vis. 5; ↓Vent. 0.5h^{-1};	1%
N	↑ Vis. 5; ↓Vent. 0.5h^{-1}; no pre-treat	1%
O	↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C	
P	↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C; No pre-treat	
Q	↑ Vis. 5; ↓Vent. 0.5h^{-1}; ↓Tw6°C; Humidistat	
R	T.indoor (19-23°C)	4%
S	T.indoor (19-23°C), : No pre-treatment	4%
T	↓ R.H. (45-50%)	6%
U	↓ R.H. (45-50%); ↓Tw6°C; Humidistat	
V	Primary need (HAMBASE)	
W	Primary need (HAMBASE); No ventilation	

Table 11 Simulated exceedances of desired relative humidity level (QoE2)

Note that the presented percentages on the right side of the graphic bars indicate the maximum exceedance of the highest desired RH level.

4.6.4 *Energy consumption associated with Quality of Envelope 3*

Energy consumption for cooling and dehumidification

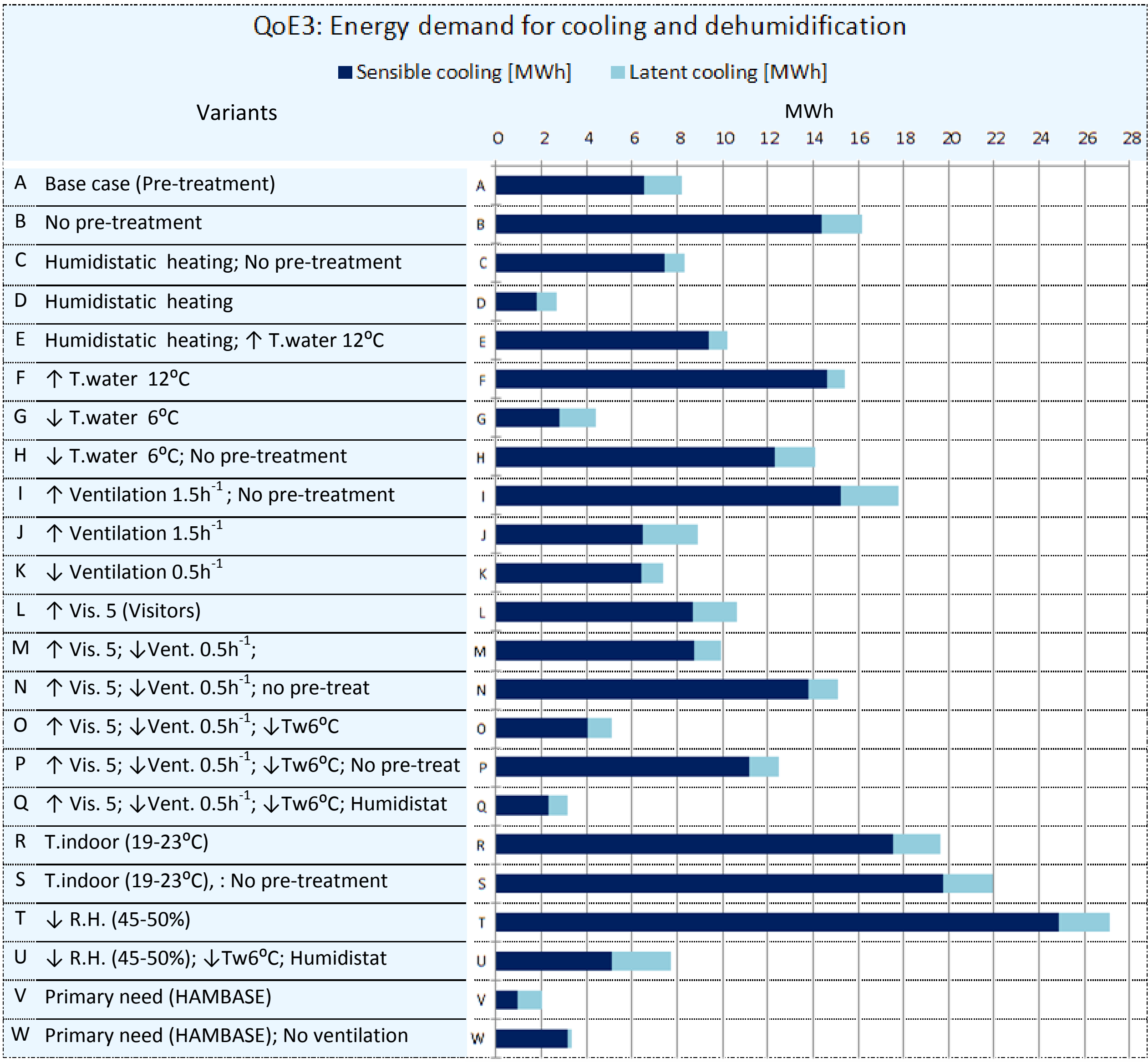


Table 12 Simulated energy consumption for cooling and dehumidification (QoE 3)

Energy demand for heating and reheating

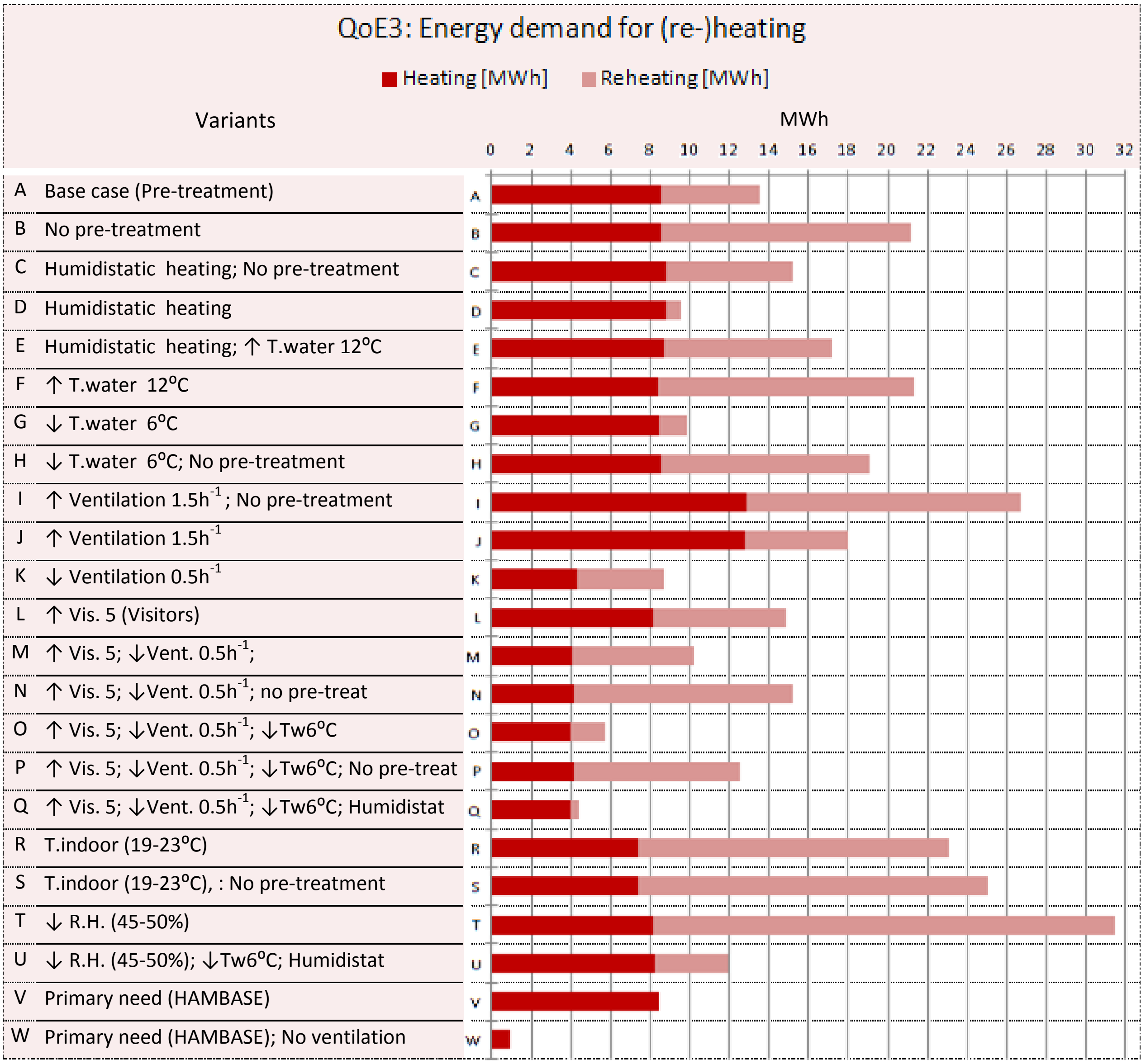


Table 13 Simulated energy demand for heating and reheating (QoE 3).

Maintaining of desired set-point levels

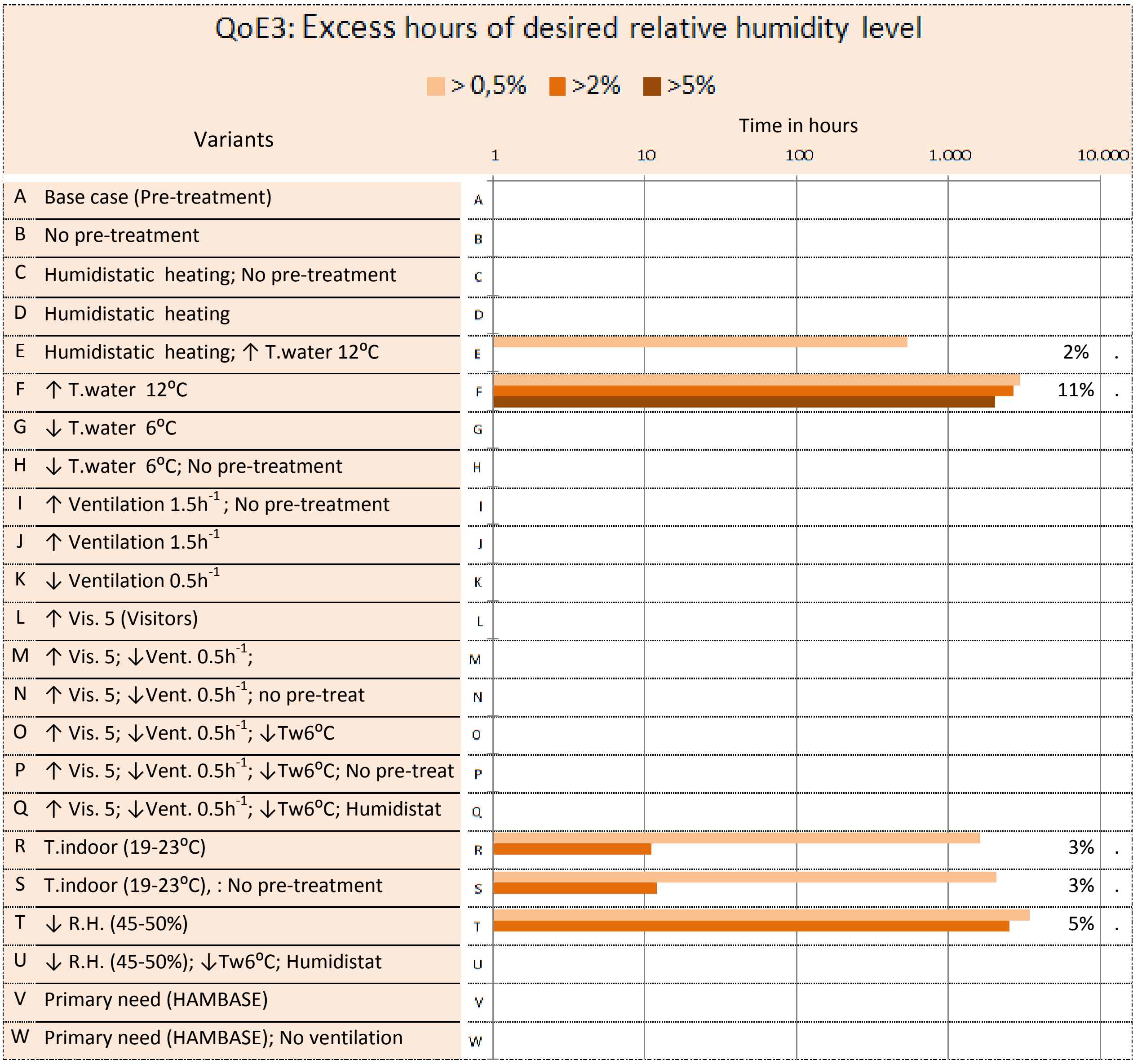


Table 14 Simulated exceedances of desired relative humidity level (QoE3)

4.6.5 Energy consumption associated with Quality of Envelope 4

Energy consumption for cooling and dehumidification

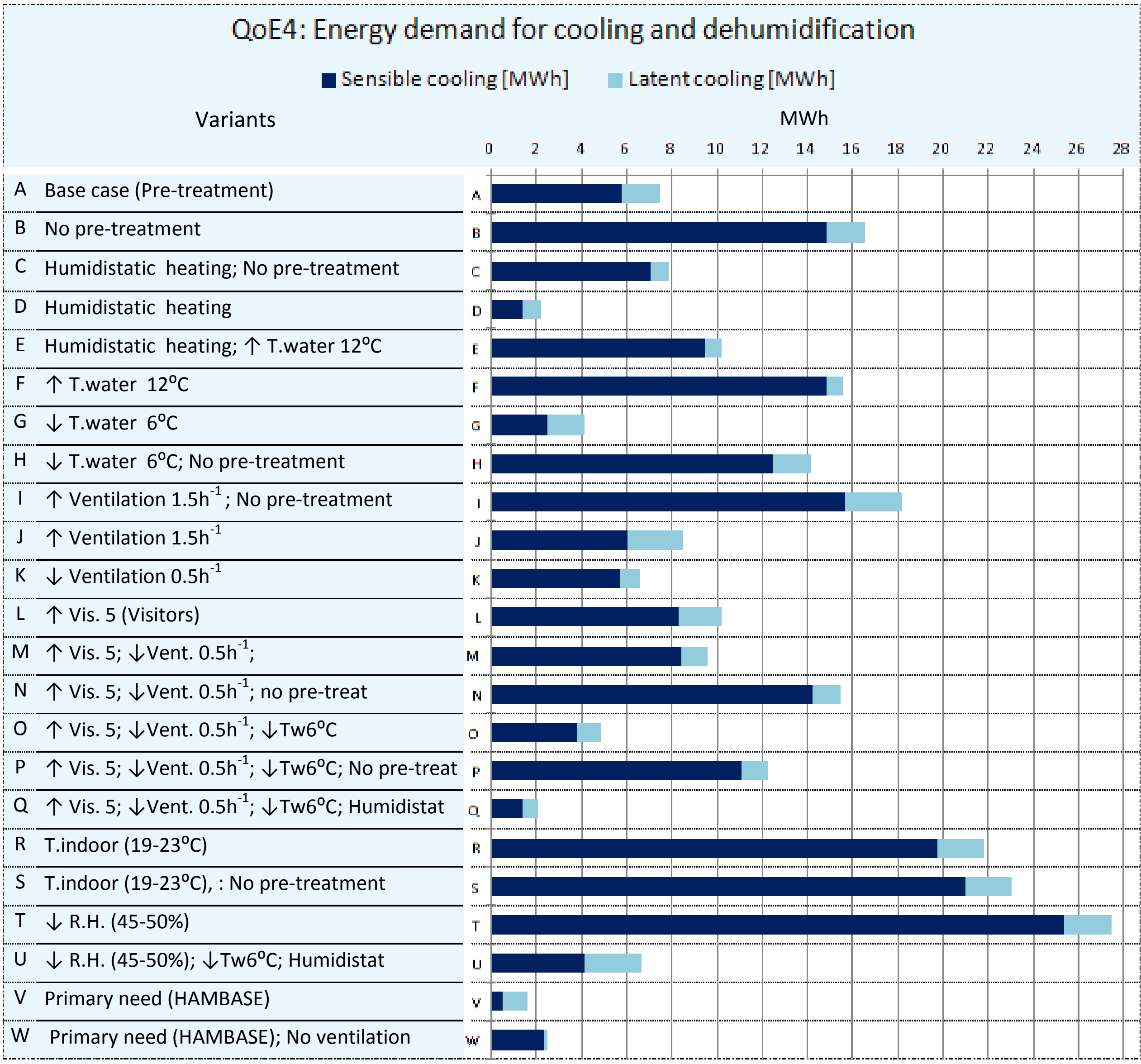


Table 15 Simulated energy consumption for cooling and dehumidification (QoE 4).

Energy demand for heating and reheating

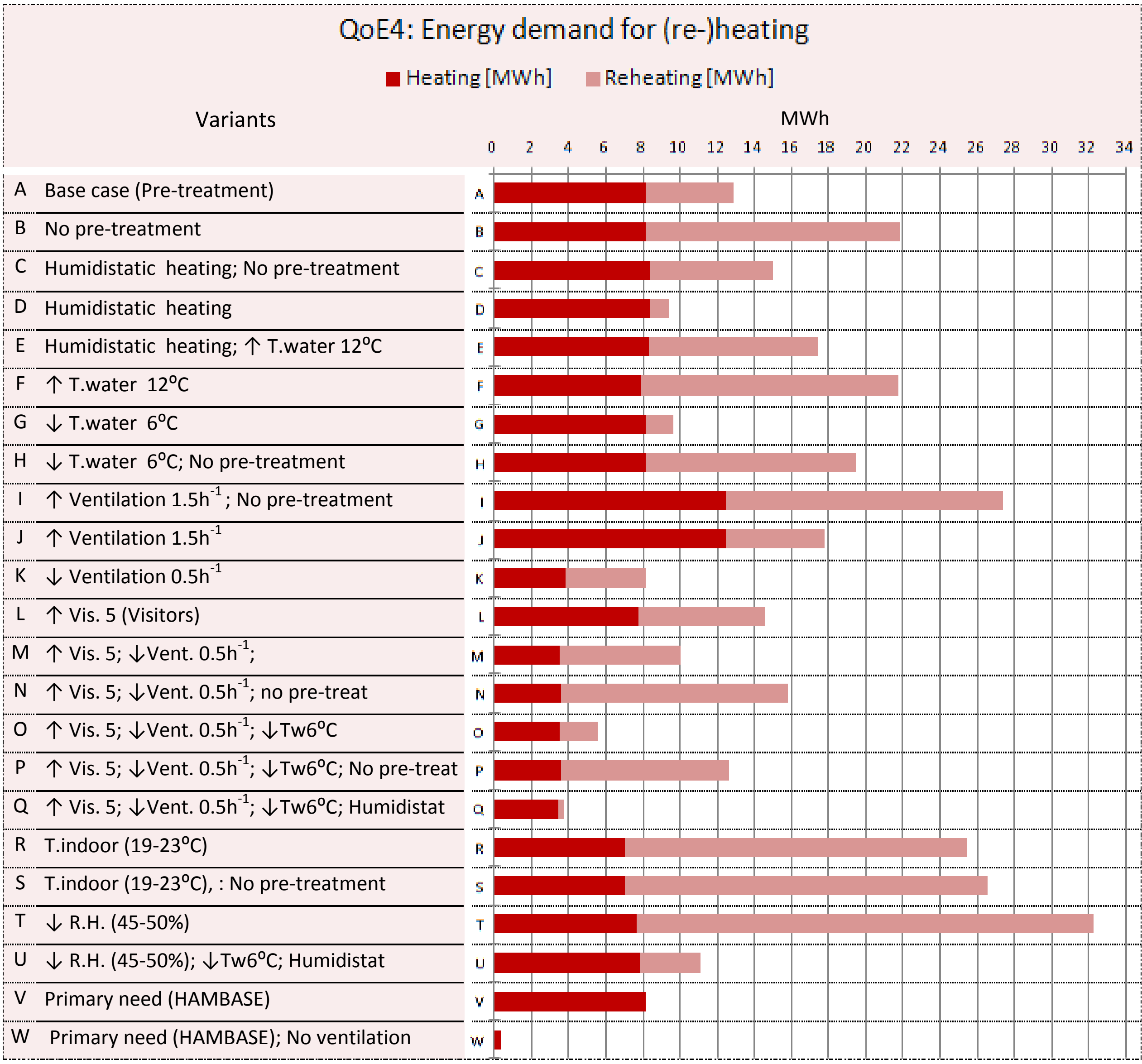


Table 16 Simulated energy demand for heating and reheating (QoE 4).

Maintaining of desired set-point levels

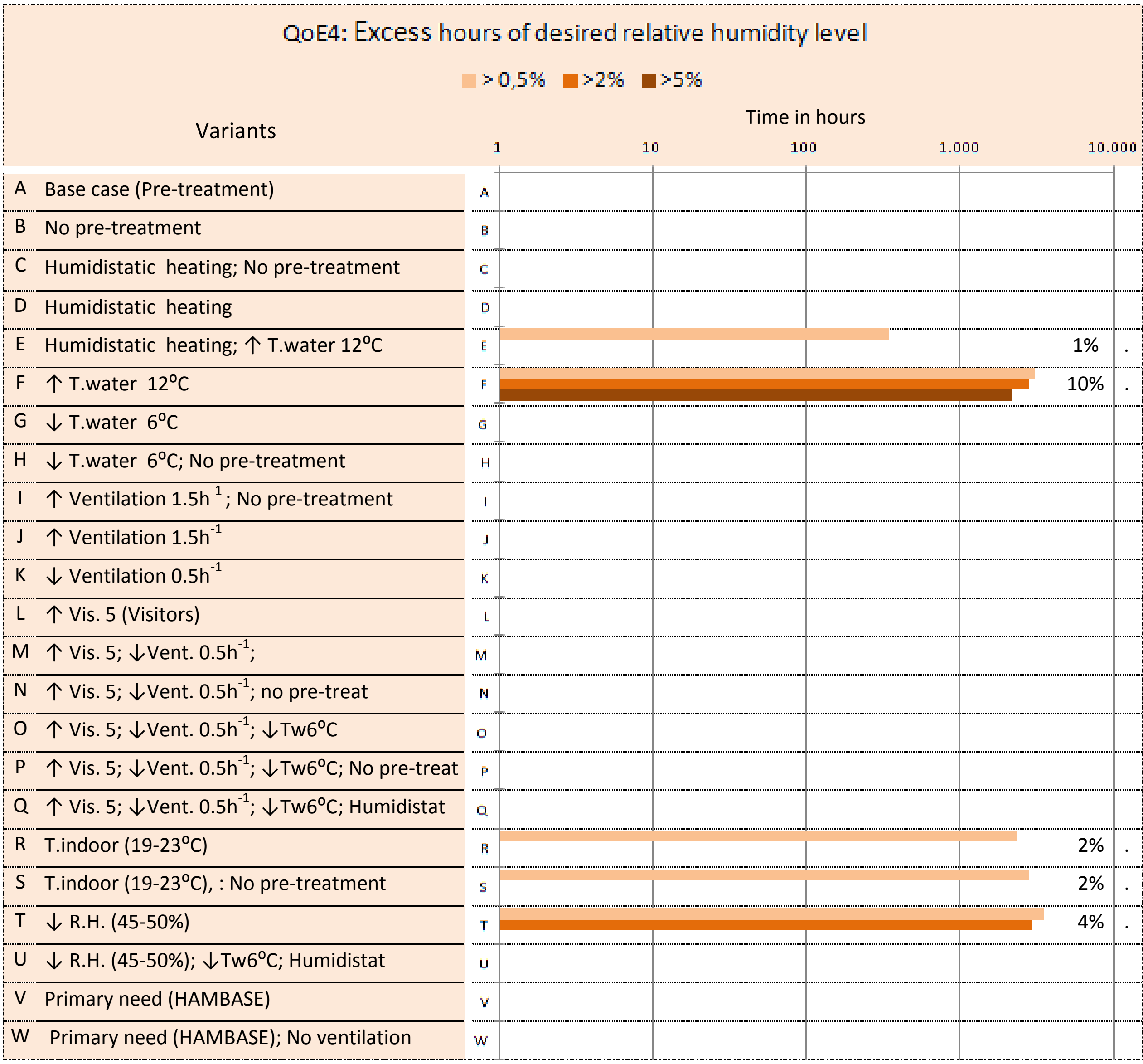


Table 17 Simulated exceedances of desired relative humidity level (QoE4)

4.6.6 *Divergent simulation variants*

Below the simulation variants are present which include the building model with the lowest quality of envelope (QoE1). Also results of the variant with the other cooling coil model (X; straight line) and the variant (Y) were all the building models have the same low infiltration rate ($0{,}1h^{-1}$) are shown in this section.

Energy demand for humidification

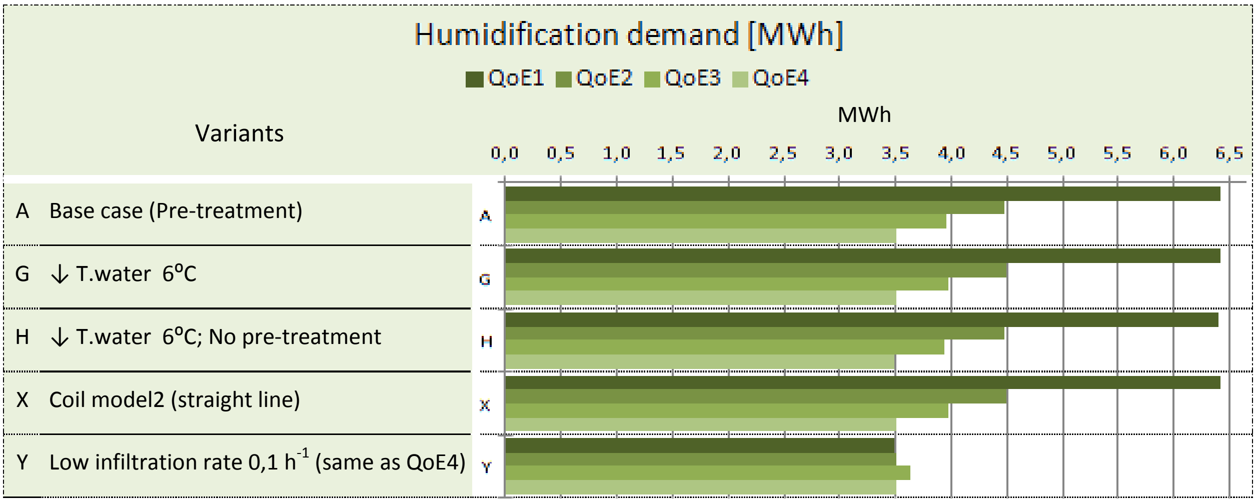


Table 18 Simulated energy demand for humidification

Energy demand for heating

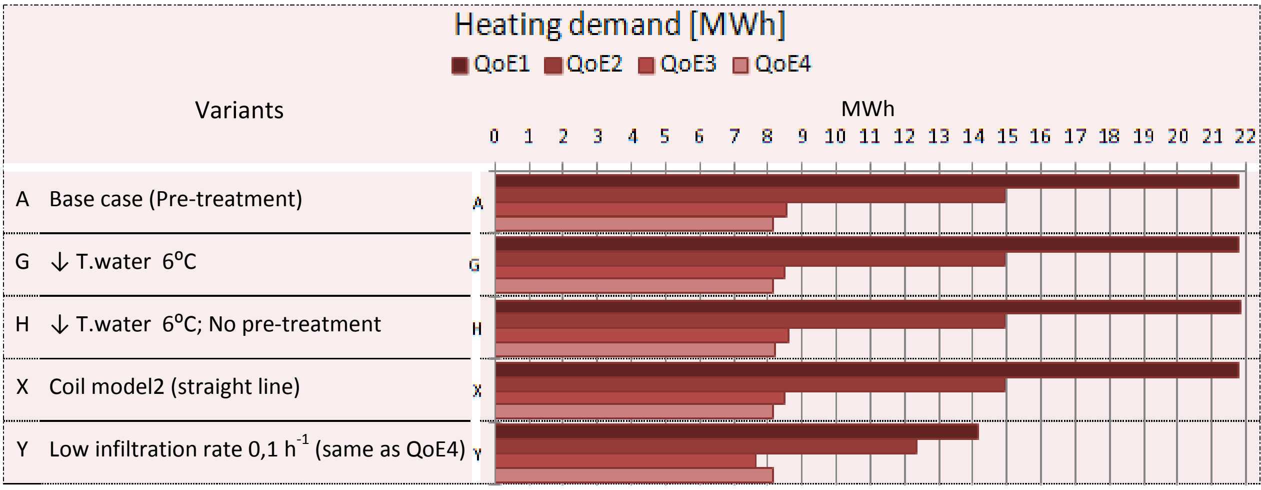


Table 19 Simulated energy demand for heating.

Energy demand for reheating

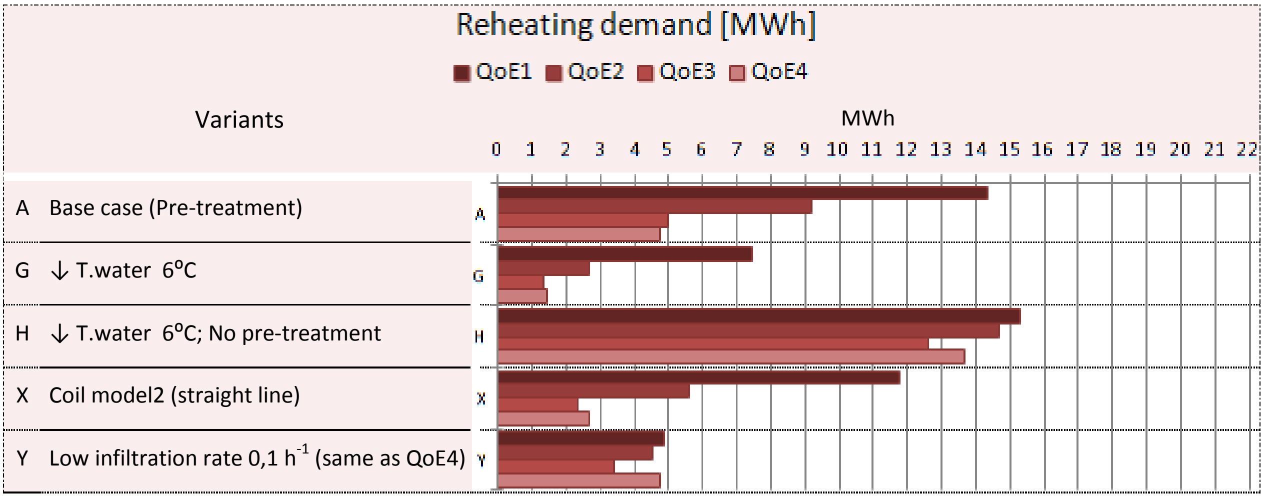


Table 20 Simulated energy demand for reheating

Energy consumption for cooling and dehumidification (Sensible ceded)

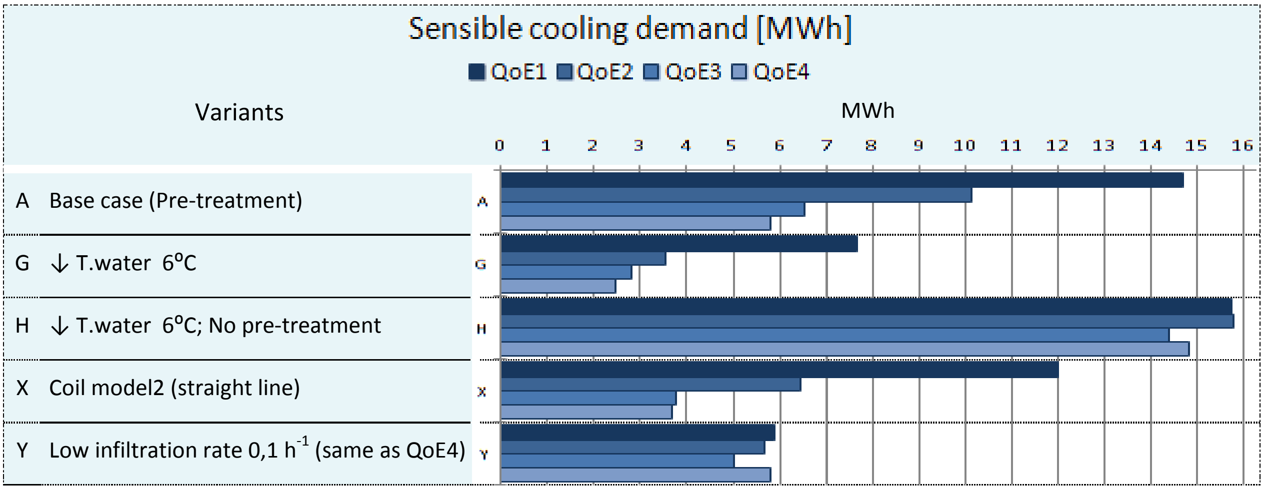


Table 21 Delivered sensible cooling energy by the cooling coils

Energy consumption for cooling and dehumidification (Latent ceded)

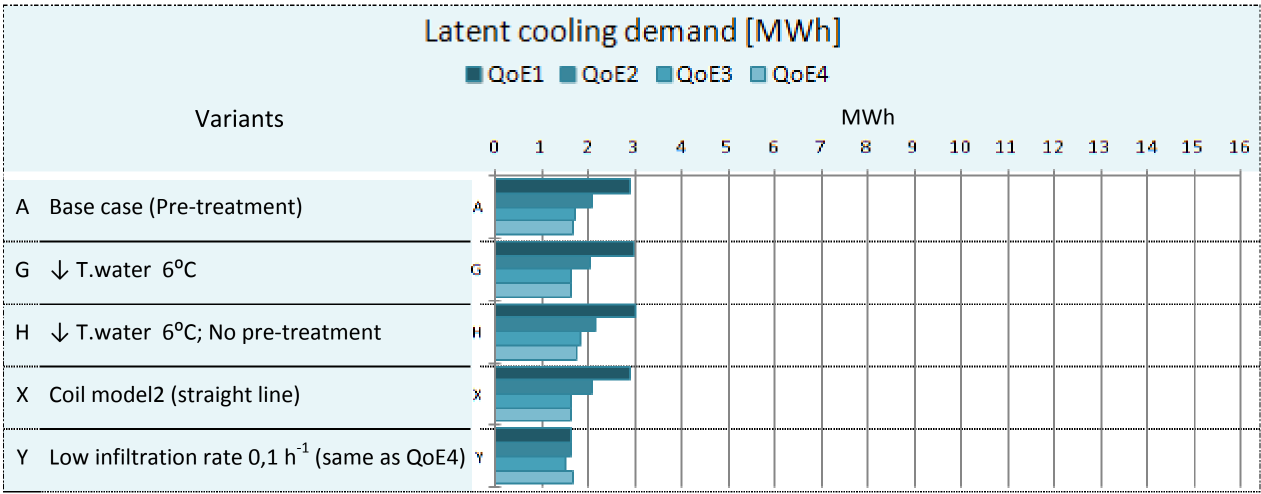


Table 22 Delivered latent cooling energy by the cooling coils

Maintaining of desired set-point levels

Of the five simulation variants above, relative humidity exceedance of more than 2% occurs only in variant A-QoE1 (86hours) and variant X-QoE1 (85 hours), with a maximum exceedance of 4% in both cases.

4.6.7 Analysis of simulation results

In this section, the effects of the changing parameters on the simulation results will be discussed.

Energy demand for humidification

As mentioned before, the focus of this simulation study is not on the energy consumption for humidification. In the simulation models, just the amount of moisture which is necessary to prevent undershooting of the lowest desired value for relative humidity, is supplied to the building model. This amount of moisture is simulated and converted into the amount of (latent) energy which is needed to evaporate this amount water.

From the results in section 0 one can see that only the models with variations in amount of ventilation/infiltration airflow, or the models with variations in the lowest set-points for temperature and relative humidity, have different humidity needs (

Table 8). Also the amount of visitors has some influence on this need.

The simulation variant without ventilation airflow (only infiltration airflow) has by far the least need for humidification.

Preheating of ventilation airflow during winter conditions

An extra coil for pretreatment of the ventilation airflow can be used for loading cooling energy in the ATES system during the winter. In that case, water from the warm well (±15ºC) warms the ventilation airflow and returns to the cold well. The amount of energy that is exchanged between the airflow and the groundwater is calculated by a basic simulation model. This model assumes that the ventilation airflow is preheated by the groundwater to a temperature of 9ºC. The average amount of energy that is exchanged, belonging to the weather conditions in Vlissingen (NL) from 2001 till 2010, is 3.86 kWh/a, according to a ventilation mass flow of 1 kg/h. When this ventilation mass flow is converted into a ventilation rate in the building model of $0.5h^{-1}$, $1h^{-1}$ and $1,5h^{-1}$, this results in an energy exchange of respectively 811 kWh, 1.623 kWh and 2.434 kWh. Besides recovering the imbalance in the ATES system, it also reduces the desired heat energy generation by almost the same amount. According to the simulated heating energy demand (without taking the energy consumption for reheating during dehumidification into account), this reduction would be between 7-21% of the heat consumption during the heating season, depending on the quality of the envelope and the ventilation rate. The recovery of the heat surplus in the ATES system depends on the resulting difference of extracted energy from the ATES system.

Precooling and predehumidification of ventilation airflow

Besides the winter conditions, the simulation results show that there is a large energy reduction possible when the ventilation airflow can be pretreated by an extra cooling coil. This energy reduction is possible because the ratio of latent and sensible cooling of the ventilation air, by making use of a cooling coil, is more favorable than that of the airflow after the mixing section. Thereby, this smaller cooling coil operates more in full load condition (when the temperature of the cooling coil is as low as possible), which is a benefit for the cooling ratio.

Due to a better ratio between sensible and latent cooling by making use of pretreatment, the amount of required reheating energy is also considerably reduced.

The simulation results show that the energy consumption for cooling and reheating is reduced by approximately 50 to 80 %. The results of variants M and R show that the energy reduction is less when the operating time of the second cooling coil after the mixing section is increased. The ventilation rate in variant M is halved, so the pretreat coil is less able to compensate the indoor moisture load by dehumidifying the ventilation airflow.

In variant R, were the temperature set-point for heating is lowered from 20 to 19^{o}C, the application of a pretreat coil results in a very low energy reduction for cooling and reheating. This is caused by the fact that during the dehumidification process the indoor temperature may drop to 19^{o}C instead of 20^{o}C, so the dehumidification demand increases, the dehumidification efficiency drops and thus the operating time of the second coil after the mixing section rises.
From the load duration curves (appendix 10) one can conclude that the cooling coils in the variants without pretreatment operates relatively short time in low part load conditions. This is because relatively less condensation occurs in the cooling coil (after mixing section) when they operate in part load conditions, caused by the higher surface temperature of the coil, and the relative low specific humidity of the mixed airflow.
Also the cooling coils in the variants with a lower dehumidification capacity, caused by a higher chilled water temperature or a lower indoor air dew point; operate less time in low part load conditions.

Little humidistatic heating during dehumidification demand

By increasing the heating temperature set-point during periods of dehumidification demand, a significant reduction of the energy consumption for cooling and reheating can be achieved. The potential savings are about the same as by making use of a pretreat cooling coil. It was questioned whether the reduction in cooling energy consumption for dehumidification, should outweigh the possible extra energy consumption for heating, which is necessary for the increase of the indoor air temperature. However, the results show that even the total energy consumption for heating is greatly reduced, due to the reduction of ceded sensible cooling energy during the dehumidification process.
The energy saving that is achieved by making use of humidistatic heating in variant E, is less than in the other variants, because the chilled water temperature is higher (12^{o}C) and the dehumidification capacity drops, which results in much more operation hours of both cooling coils. However, the exceedance of the desired relative humidity level (55%) in variant E is strongly reduced with respect to variant F, by making use of this control measure for temperature set-point adaption (humidistatic heating).

Variations in chilled water temperature

As also was observed at the Zeeuws Museum, the simulation results show that the chilled water temperature strongly affects the dehumidification capacity and efficiency of the cooling coils. When the chilled water temperature is increased to 12^{o}C, the energy consumption for cooling and reheating may increase by approximately a factor of 4 (variant E). This energy consumption in variant F is only increased by a half, but the exceedance of the desired relative humidity level (55%) is strongly increased. Despite of the higher chilled water temperature, the indoor humidity conditions can be maintained reasonably in variant E, due to the humidistatic heating control.
The simulation variants in which the chilled water temperature is decreased to 6^{o}C, consume less energy for both cooling and reheating. In particular the variants which make use of a pretreat cooling coil, whereby in combination with the lower chilled water temperature, the operating time of the second cooling coil after the air mixing section is strongly reduced.

Combinations of measures

The simulation results of variants O, D, Q, U and Q show that with a combination of the discussed improvements a further reduction of the energy consumption, and also the maintainability of a lower desired humidity level (variant U), can be achieved. Pretreatment, in combination with humidistatic heating control and/or a low chilled water temperature, affects the ratio between sensible and latent ceded cenergy by the cooling coils in such a way that superfluous energy consumption is limited. Note that the highest possible efficiency occurs when both ceded latent and sensible cooling energy are desired in the building. In appendix 10 can be seen that these combinations of improvements also significantly reduce the required nominal power for dehumidification and reheating during full load conditions, which results in less initial costs and necessary technical area.

Set-point changes of desired indoor temperature and relative humidity

In variant R and S, where the temperature set-point for heating is lowered from 20 to 19^oC, the energy consumption for heating during the winter season slightly reduced. However, this reduction is negligible compared to the increase of energy use for the dehumidification process, due to the further indoor temperature drop during dehumidification to 19^oC. Also the maintainability of the desired humidity levels is deteriorated, caused by the reduction of the dehumidification capacity of the cooling coil in the airstream with a lower dew point temperature. This indoor temperature drop and consequences on the relative humidity are also observed in practice at the Zeeuws Museum.

A lower desired relative humidity level (45-50%) in variant T, cannot be achieved and also a large amount of energy is consumed. In variant U, these indoor conditions can be maintained with much less energy consumption than in variant T, because besides the possibility of pretreatment of the air also a lower chilled water temperature (6^oC) and humidistatic heating during dehumidification demand is applied.

Influence of the quality of envelope and applied ventilation rate

The quality of envelope of the applied building models is defined by differences in the thermal characteristics and the air tightness of the envelope. The results of simulation variant Y, show that the differences in energy consumption for the humidification and dehumidification/cooling demand (including reheating) are mainly caused by the differences in air tightness, while the thermal characteristics have minor influence on this. Only the heating demand during the winter season is reasonable influenced by the thermal characteristics. Due to the large amount of provided sensible cooling (residual) during the dehumidification process, the thermal properties of the envelope hardly affect the energy consumption by the cooling coils during the summer season. One can expect that this influence will increase when there is less dehumidification demand and/or when the dehumidification process will be more efficient.

Just like the infiltration rate, also the amount of ventilation has a large influence on the energy consumption. However, when the air handling system contains a preconditioning cooling coil, the influence of infiltration air to the room has more impact than the air which enters the building by the ventilation system, because this airflow can be dehumidified more efficiently.

Influence characteristics of the cooling coil

Beside the air system design and the chilled water temperature, also the construction of the cooling coil has some influence on the ratio between ceded latent and sensible cooling energy by the coil. The depth of the coil, fin density and air speed through the coil are the main key factors which affect this ratio [ref.393939].

The simulation results show that less energy is needed when during the cooling process relative more condensation (dehumidification) occurs in relation to the amount of ceded sensible cooling. In simulation variant X, this is accomplished by using another cooling coil model (straight line cool process). These results demonstrate that in all the applied building models energy can be saved when cooling coils were selected which enhance the latent cooling load.

5 CONCLUSIONS

This research has revealed that the predefined problems, about the poor indoor climate conditions for the preservation of the art in the museum and the imbalance of the ATES system, can be confirmed.
Below the research questions of this study are cited, which are formulated in chapter 1:

1 Why can the desired indoor air conditions not be achieved?
2 What causes the high energy consumption of the climate system?
3 What causes the imbalance of the ATES system?
4 How can the current climate system be adjusted to decrease energy consumption, improve the indoor climate conditions and restore the balance in the ATES system?

One can conclude that the identified design flaws form a basis for the poor indoor climate, the high energy consumption and the imbalance of the ATES system. Besides these design flaws, also deviations in the measurement and control equipment of the climate system are discovered, which also contributes to the bad indoor climate.
A simulation study is performed to investigate possible measures to correct these shortcomings and/or improve the performance of HVAC system. The results of the simulation study show that some adaptations to the control system and/or the air handling systems can lead to a significant reduction of energy consumption, recovering of the imbalance in the ATES system and increase of the maintainability of the indoor relative humidity.

Shortcomings in the hydraulic part of the climate system

The wrong selection of power control valves and piping arrangements for the cooling coils induce short circuits between the supply and return chilled water system, which result in low return water temperatures. Often these return water temperatures are even lower than the groundwater temperature from the cold well, so cooling power and energy is lost to the ATES system. Due to this power loss, the desirable supply chilled water temperature cannot be reached by the heat pump, which greatly reduces the dehumidification capacity of the cooling coils.

Also the misalignment between energy production by the heat pump and the energy consumption in the building ensure that the heat pump frequently switches off and on. This is adversely for the dehumidification capacity, but also results in higher energy costs and wear on the system.
The abnormal high groundwater temperature in the cold well of the ATES system also contributes to the high chilled water supply temperature. The temperature in the 'cold' well is strongly influenced by the water injection temperature to this well during heating mode. Measurements have shown that this injection temperature is indeed often too high (approximately 10°C).
This is caused by the misalignment as mentioned above, unwanted heat loss to the cold well during heating mode, and the great amount of extracted groundwater from the cold well in relation to the warm well.
The consequence of a large imbalance in the ATES system is a short circuit underground, which means that water from the warm well flows to the cold well and is mixed with each other.
The large amount of extracted groundwater from the cold well in the summer is mainly the cause of the poor dehumidification capacity, whereby the system operates much longer in cooling mode and consumes much more energy. This is also demonstrated with the simulation variants in which higher chilled water temperatures were applied. One can conclude that the problems reinforce each other. The discovered shortcomings (dashed lines), with the consequences and interdependency, are visualized in

Fig. 57.

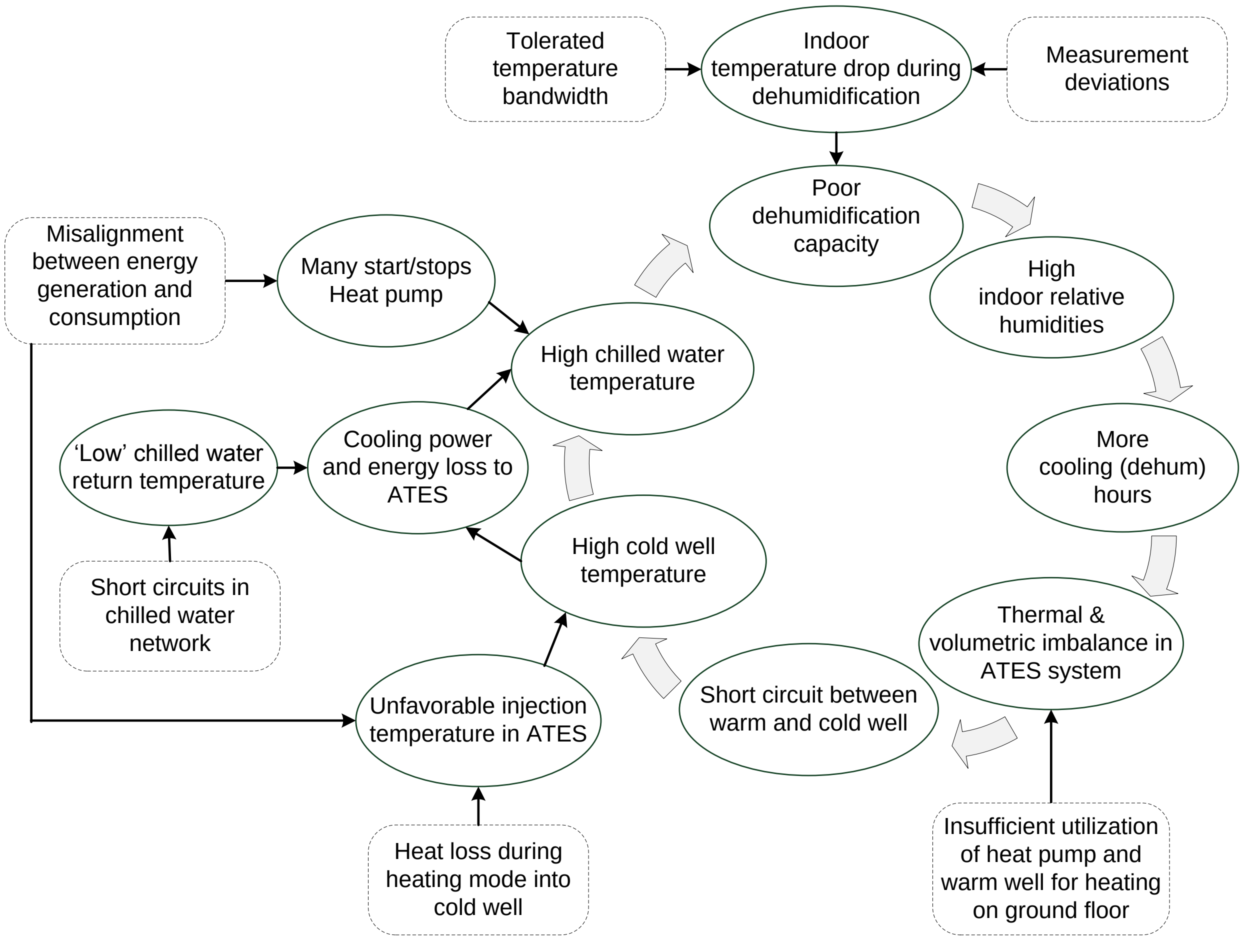


Fig. 57 Visualization of the discovered shortcomings with consequences and interdependence.

Causes of poor indoor climate conditions

The deteriorated dehumidification capacity, as described above, is the main cause of the relative humidity exceedance in the exhibition zones during the summer season. In addition to this, due to the indoor temperature drop during the dehumidification process, the need for dehumidification increases while the dehumidification capacity drops, if the desired relative humidity stays the same. The large influence of the indoor temperature during the dehumidification process on the energy consumption and the dehumidification capacity is confirmed by the simulation results. The increase of cooling consumption for dehumidification results in a further imbalance of the ATES system.

It was discovered that the climate observations (in particular, the temperature) by the Building Management System deviates from the real conditions, causing less favorable supply and indoor air conditions. Once this has been corrected, also the weighting factors for each room have to be adjusted.

The poor climate and large fluctuations in the active conditioned show cases are the consequence of an illogical system design. Together with the zones on the second floor they where conditioned by the same air supply condition from AHU 2. It is impossible to maintain the desired temperature and relative humidity in the showcases and the rooms on the second floor with the same supply air conditions. Due to the relatively small volume of the show cases, the indoor climate quickly adapts to the supply air condition.

A fault in the control system of air handling unit 4, in the interpretation of the entered set points for cooling and heating, results in unnecessary energy consumption and less thermal comfort in the area's on the ground floor.

Conclusions from the simulation results

The simulation study indicates the efficiency of the dehumidification process by making use of cooling coils in different setups. Insight has been obtained about how the dehumidification efficiency is affected by each individual main influence factor. This knowledge is useful for the engineering of such climate systems, but can also be used to optimize existing inefficient air conditioning systems. When the climate system is coupled to an ATES system, there are still some other important aspects. The application of an ATES system is less profitable when the yearly demand of cooling and heating energy from the ATES system is not in balance, because artificially recovering the imbalance is costly, but required by the legislation. Therefore, a good estimation of the desired cooling and heating energy is important during the feasibility study of an ATES system. In practice, it is hard to make a good estimation of the future cooling and heating consumption in a (new) building, but this becomes even more difficult when the climate system should also maintain prescribed relative humidity levels. The simulation results show that the amount of cold and heat consumption during the dehumidification process strongly depends on the setup of the dehumidification system, the actual indoor air conditions (during dehumidification) and the chilled water supply temperature. The results also demonstrate that this energy consumption for dehumidification could be a major part of the total energy consumption for climate conditioning. With regard to the chilled water temperature, there is a contradiction: the efficiency of the dehumidification process deteriorated significantly when the chilled water supply temperature to the cooling coils increased. On the other side, making use of a higher chilled water temperature benefits the cooling power and efficiency of an ATES system. Therefore, the challenge is to increase the return chilled water temperature while the supply chilled water temperature to the cooling coils for dehumidification stays low. A possible way to do this is by reusing the outlet chilled water from the cooling coils for sensible cooling elsewhere in the building, before it returns to the heat exchanger of the ATES system. On the other side should be tried to lower the cold well temperature of the ATES system by favorable injection temperatures of the surplus 'cold' energy from the heat pump into the cold well.

In addition to the chilled water temperature, the efficiency of the dehumidification process by cooling coils significantly increases when the dew point of the airflow through the coils rises. This is the main reason why the simulation variants which make use of an extra coil for preconditioning of the humid ventilation airflow show considerable energy savings. In all-air systems (like at the Zeeuws Museum) mostly a great part of the process airflow is extracted out of the conditioned areas, of which the dew point is relative low. Also less energy is needed for reheating when, during dehumidification process, less sensible energy is extracted from the process airflow.
From the simulation results one can also conclude that a small indoor temperature drop during the dehumidification process could have major consequences on the energy consumption and maintainability of desired indoor humidity levels. This fact can be used in a positive way when during dehumidification demand the possibility exists to increase the indoor air temperature, in order to raise the dew point temperature and decrease the dehumidification demand. In particular when the permitted temperature bandwidth becomes wider, the possibility of humiditatic temperature set point adaption could result in high energy savings and indoor climate improvement. In general, the applied temperature and humidity bandwidths in museums became broader in the past years.
Besides the energy reduction, the simulation results show also that the required nominal cooling and reheating power during full load conditions can be reduced when the dehumidification efficiency increase. This is beneficial for the initial costs of the climate system and the necessary installation area. In particular in historical buildings this last aspect can be important, because often little space is available for climate systems.

The simulation results show that the amount of ventilation and infiltration air to the building effects the total energy consumption for air conditioning enormously. When the climate system has the possibility to 'efficiently' dehumidify the ventilation airflow separately from the return airflow, the infiltrated air through the building envelope has more impact on the energy consumption than the air which enters the building by the ventilation system.
By making use of an ATES system, the pretreat coil in the ventilation airflow can also be used to preheat the air with groundwater during winter conditions. This can reduce the energy costs and the desired nominal power of the heating system. The cold that is extracted from the ventilation airflow can be extra desirable when there is a cold shortage in the ATES system, as in the case of the Zeeuws Museum.

CHAPTER 6

6 DISCUSSION AND RECOMMENDATIONS

Now the main causes of the poor indoor climate, high energy consumptions and (large) imbalance in the ATES system at the Zeeuws Museum are known, it is recommended to recover the discovered system failures.
Below, these system failures are summarized:

- The measurement deviations of the climate measurement system;
- The wrong air-system setup for conditioning of the showcases;
- The power control valve and piping arrangements for the cooling coils which cause the short circuits;
- The poor control of the 3-way valve which regulates the superfluous heat release to the ATES system;
- The fault in the control system of AHU 4.

In addition to the recovering of these shortcomings in the system, there are more opportunities to optimize the air-conditioning system of the museum. The simulation results show a great potential for energy savings and indoor humidity maintainability when, during dehumidification demand, the indoor air temperature can be increased within the tolerated bandwidth. The measurements during last summer indicate substantial air temperature drops when the climate system operates in dehumidification mode. This adaption will also benefit the imbalance in the ATES system, because less cooling energy will be needed and also less residual heat of the heat pump has to be injected in the ATES system, because more reheating of the process air will take place.
By increasing the desired indoor air temperature during the dehumidification process, also the outlet chilled water temperature of the coil will slightly rise during dehumidification of this indoor air, which benefits the cooling power of the ATES system, and the injection temperature to the warm well.
To increase the cooling power and efficiency of the ATES system, it is also important to decrease the temperature in the cold well of the ATES system. Mainly due to the design faults as mentioned in this report, the cold well temperature is extraordinarily high at the Zeeuws Museum. It is also possible the reduce the injection temperature of residual cold during periods when the system operates in heating mode, by optimizing the outlet chilled water temperature of the heat pump and alignment of volume flows on both sides of the heat exchanger.

The absence of a buffer vessel in the chilled water circuit also results in less favorable injection temperatures, but perhaps even worse, a lower system efficiency and agitated operation of the heat pump, to the detriment of the indoor climate and the lifetime of the heat pump.

From analysis of the BMS system it appears that the heat pump (and ATES system) has barely contributed to the heat generation for the zones on the ground floor of the Zeeuws Museum. It is recommended to optimize these settings in the BMS system in such way that the heat pump is the main supplier of the heating energy on the ground floor, and when necessary is supported by the collective heating system of the abbey complex. This measure will benefit the energy costs and the balance in the ATES system.

The discussed improvements could have such an impact on the balance in the ATES system that it is wise to monitor this effect during the next summer and winter season, before new investments are done in additional systems for recovering of this imbalance. When eventually still a cold shortage in the ATES system remains, the implementation of an extra pretreat coil in the ventilation system is probably the best solution. Besides the possibility of loading extra cold in the ATES system during the winter, also the energy costs reduce by preheating of the ventilation airflow during winter conditions. During the summer season, a lot of energy can be saved with the pretreat coil due to a more efficient dehumidification process, which is also favorable for the imbalance and injection temperature in the ATES system. In case of the Zeeuws museum, the ventilation airflow to AHU 1.1, 1.2 and 1.3 is together extracted from outside, which makes it possible to pretreat this total airflow by only one additional coil.

The simulation results also demonstrate the significant effect of infiltration and ventilation air flow to the building on the total energy demand for air conditioning. The infiltration rate to the exhibition rooms of the Zeeuws museum could be reduced by sealing the metal frames of the additional windows which are placed on the inside of the original windows. This will also reduce the risk of condensation on the original window constructions.
Another energy optimization would be to regulate the amount of air ventilation based on indoor CO_2 levels, which could be measured in the return airflow to AHU 1 and AHU 2 or in each room individually. The air system has the possibility to automatic adjust the ventilation airflow but at the moment this is done by a time clock program. The possible energy savings of this measure depends on the feasible ventilation reduction at the Zeeuws Museum, which is not investigated in this study.

Recommendations for further research

The simulation results of this study demonstrate that there could be large differences between the primary energy need in the building, and the consumed amount of energy to fulfill this primary need. This deviation is highly dependent on the efficiency of the dehumidification process. At the Zeeuws Museum there is a great potential for energy savings by optimization of the dehumidification process, and this will be no exception in comparison with other climate systems in museums. Therefore, it is recommended to incorporate the dehumidification efficiency of the climate system and its influence on the indoor air temperature in future building simulation studies. The effect of dehumidification by making use of cooling coils on the indoor air temperature could have significant influences on the maintainability of the relative humidity and also the energy consumption. This is the raison why the simulation variants ‘R’ and ‘S’ with a broader tolerated temperature bandwidth during the dehumidification process finally consume much more energy than the variants in which the indoor temperature may be kept at higher levels.

7 REFERENCES

1 d'Ancona, H. 1990. *Deltaplan Cultuurbehoud in Nederland,* Ministry of Welbeing, Health and Culture, The Hague.

2 Jütte, B.A.H.G. 1994. *Passieve conservering; klimaat en licht.* Centraal Laboratorium voor Onderzoek van Voorwerpen, Amsterdam.

3 Meul, V.L.B.M. 2007. *Luchtspiegelingen, de mens en het museale binnenklimaat,* Erfgoedinspectie, The Hague.

4 Martens, M.H.J. 2012. *Climate risk assessment in museums: degradation risks determined from temperature and relative humidity data,* PhD thesis, Eindhoven University of Technology, Eindhoven.

5 ASHRAE, 2011. *Museums, libraries and archives (chapter 23),* in 2011 ASHRAE handbook: Heating, ventilation and air-conditioning applications, SI edition, American Society of Heating, Refrigerating and Air-conditioning Engineers.

6 Martens, M.H.J., Schellen, H.L., Schijndel, A.W.M. van & Aarle, M.A.P. van. 2007. *Project Klimaatonderzoek Rijksmusea,* Eindhoven University of Technology.

7 Ankersmit, H.A. 2009. *Klimaatwerk; richtlijnen voor het museale binnenklimaat,* Amsterdam University Press, Amsterdam.

8 Artigas, D.J. Thesis 2007. *A comparison of the efficacy and costs of different approaches to climate management in historic buildings and museums,* Historic preservation, University of Pennsylvania.

9 Ascione, F., Bellia, L., Capozzoli, A. & Minichiello, F. 2009. *Energy saving strategies in air-conditioning for museums,* Applied Thermal Engineering 29.

10 Maas, M.P.E., 2012. *Optimizing climate control systems for museums; A case study for the Hermitage Amsterdam.*

11 Schellen, H.L., Schijndel, A.W.M. van & Ankersmit, B., 2011. *Toelichting promotieonderzoek naar optimalisering klimaatinstallaties voor musea en monumentale gebouwen: een beter klimaat met minder energie en minder impact op het gebouw.* Eindhoven University of Technology.

12 Kersten, B., 2012. *Aandachtspunten in het bovengrondse installatiegedeelte van WKO-installaties*, Eindhoven University of Technology.

13 ISSO 81, 2007. *Handboek integraal ontwerpen van warmtepompinstallaties voor utiliteitsgebouwen.*

14 ISSO 39, 1997. *Langetermijnkoudeopslag in de bodem.*

15 NVOE, 2011. *Cursusboek 'Integraal ontwerp van installaties met warmte/koude-opslag.*

16 ISSO 47, 2005. *Ontwerp van hydraulische schakelingen voor koelen.*

17 Brink, A. van den, 2012. *Waterzijdige prestaties van een koelbatterij in niet-ontwerpcondities; Het verhogen van het waterzijdig temperatuurverschil in deellast.* Eindhoven University of Technology.

18 Royal Netherlands Meteorological Institute, KNMI 2012. *Klimatologie- Uurgegevens van het weer in NL.*

19 Wit, M.H. de. 2006. HAMBASE, *Heat, air and moisture model for building and systems evaluation,* Bouwstenen 100, Eindhoven University of Technology.

20 ASHRAE, 2001. *Standard method of test for the evaluation of building energy analysis computer programs,* standard 140-2001.

21 Neuhaus, E. Thesis 2006. *Onderzoek naar methoden voor beperkte RV-beheersing in monumentale gebouwen aan de hand van casussen.* Eindhoven University of Technology.

22 ASHRAE, 2008. *Air handling and distribution (chapter 4),* in 2008 ASHRAE handbook: Heating, ventilation and air-conditioning systems and Equipment, SI edition, American Society of Heating, Refrigerating and Air-conditioning Engineers.

23 Luxton, p., Marshallsay, 1998 *Optimal design of air conditioning systems,* Bulletin I.I.R.

24 Provincie Zeeland, 2005. *Vergunning involgde de Grondwaterwet,* Bisschikkingsnummer RMW0512402, Zeeland.

25 Grontmij, 2005. Bestek werktuigkundige installaties, verbouwing en inrichting Zeeuws Museum, Grontmij Nederland bv, projectnummer 132231.

26 Ingenieursbureau Wolter & Dros bv, 2007. *Luchtbehandeling installaties niveau 7, Renovatie Zeeuws Museum te Middelburg,* tekeningnummer LK72, revisie 29 juni 2007.

27 Hiensch, 2011. *Notitie warmtebalans WKO-systeem,* Hiensch Engineering bv, project 3383, notitie d.d. 19 september 2011.

28 ETP, 2012. *Aanbieding inpassing droge koeler,* Energie Totaal Projecten bv, doc.nr.100-063ETPAA010, d.d. 8 juni 2012.

29 Raadgevend Ingenieursburo F. Koch bv, 2006. *Bouwkundige plattegronden t.b.v. gebruiksvergunning*, tekeningnummer T-002 t/m T-004 d.d. 18-12-2006.

30 Grontmij, 2009. Werkomschrijving aanpassingen warmtepompinstallatie Zeeuws Museum te Middelburg.

31 IF Technology, 2007*. Koude/warmteopslag in de praktijk.*

32 IF Technology, 2009. *Besparingskentallen warmte- en koudeopslag.*

33 De Ingenieur, 2012. *70% van de warmte-/koudeopslagsystemen functioneert slecht,* 11-2012.

34 Schijndel, A.W.M. van. 2007a. *Introduction of a HAMBase sensitivity analysis tool applied to Case 600 (BESTest),* Eindhoven University of Technology.

35 The MathWorks, Inc. 2012. *MATLAB: Data Analysis. Natick, MA, United States of America.*

36 Schijndel, A.W.M. van. 2007b. *Integrated heat air and moisture modeling and simulation,* Eindhoven University of Technology.

37 ASHRAE, 2008. *Air-cooling and dehumidifying coils (chapter 22),* in 2008 ASHRAE handbook: Heating, ventilation and air-conditioning systems and Equipment, SI edition, American Society of Heating, Refrigerating and Air-conditioning Engineers.

38 Hurk, van den, B., Klein Tank, A., Lenderink, G., Van Ulden, A., Van Oldenborgh, G.J., Katsman, C., Van den Brink, H., Keller, F., Bessembinder, J., Burgers, G., Komen, G., Hazeleger, W. & Drijfhout, S. 2006 *KNMI Climate Change Scenarios 2006 for the Netherlands,* KNMI Scientific Report WR 2006-01, De Bilt, The Netherlands.

39 Mazzei, P. Minichiello F., Palma D., 2004. *HVAC dehumidification systems for thermal comfort: a critical review.* University of Naples, Italy.