OPTIMISING THE BUILDING MANAGEMENT SYSTEM IN SMART PASSIVE BUILDINGS

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Graduation research report
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Architecture, Urbanism and Building Sciences
Track Building Technology

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Coverpage image: MOR prototype in Hungary

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The full datasets discussed in this report can be found on the TU Delft research data repository.
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ABSTRACT

The MOR prototype is a smart passive building with a central building management system to control and optimise the operation of the active and passive building systems and therefore reduce the energy consumption of the building and improve the users comfort conditions (MOR Team, 2019b). During the competition, the systems in the prototype were set to function in the Hungarian climate (Warm-summer humid continental climate according to the Köppen climate classification) whereas the Netherlands has a temperate oceanic climate. Showing that the MOR prototype can function efficiently in both Hungarian and Dutch climates with only changing the settings of the building management system can prove that it will also be able to function efficiently when the local climate will change.

This research is aiming to extend the period in which the passive systems are used within the building management system in order to minimize the energy consumption while improving the comfort conditions. The following research questions will be used to find the important aspects to be considered: Which parameters have the biggest influence? What are the comfort conditions that the building management system has to reach? How is the building management system currently programmed? Can simulations optimise these setpoints?

The parameters that have the biggest influence on the total energy consumption of a building are space heating (16 %) and water heating (21 %). The biggest is electrical appliances (33 %) but these are not influenced by the building management system (Nuiten, et al., 2019).

For thermal comfort, the Adaptive Temperature Limits guideline suggests a range of temperatures based on a calculated average of the four preceding days (van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006). For indoor air quality, a maximum CO_2 level was found of 800 ppm above the normal outdoor level of around 400 ppm (VLA, TNO, Peutz BV en Nieman Raadgevende Ingenieurs BV., 2018). And for relative humidity, a range of 30 – 70 % was found for an indoor temperature of 18 – 24 °C (BOOM-SI, Milieukundig Onderzoek-& OntwerpBuro, 2019). For visual comfort, there are no standards for residential buildings. A recommendation for the amount of light needed in a room is based on the activities. For the average room, a minimum of around 300 lux is found. For areas with more precise work such as the workstation, kitchen counter or bathroom mirror, a minimum of 500 lux is recommended (Bodart, et al., 2011). Acoustical comfort is not controlled by the building management system

Finally, a Grasshopper model is made with Ladybug, Honeybee and Ironbug plugins to use with the modeFRONTIER optimisation software. After comparing simulations made by this model to measurements inside the MOR prototype, it turns out that this model is not able to accurately simulate the different systems. Therefore the existing DesignBuilder model is used for optimisations with the built-in optimisation engine of DesignBuilder.

The optimisations show that for the MOR prototype, an energy consumption reduction of 11 % per year could be realised if the heating setpoint is raised from 20,5 °C to 20,8 °C and the mechanical ventilation rate is reduced from 1,3 ach to 1,0 ach. An additional 2 % could be saved by not using active cooling. Because natural ventilation in the model is only considered as a cooling strategy and not as an air quality control strategy the optimisations showed that no natural ventilation is necessary.

The workflow as described in this report can be used for optimising the setpoints in other buildings using building management systems. Further research is needed to be able to optimise all setpoints mentioned in this report.

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Figure 1: Render of renovated Marconi Towers (MOR Team, 2019b)

1. INTRODUCTION

Buildings are responsible for approximately 40% of energy consumption in the EU (European Commission, 2019). Designing more efficient buildings and systems is only the first step. In order to limit the performance gap between the design and the operating building, it is important to make sure these systems are used as designed. The behaviour of the residents can impact the energy consumption of the building (Hong, Yan, D'Oca, & Chen, 2017). Implementing building management systems will help to make buildings operate more efficiently.

Energy performance of buildings directive (EPBD)

The Energy Performance of Buildings Directive (EPBD) is part of a legislative framework established by the European Union. Together with the Energy Efficiency Directive, the directive promotes policies to achieve a highly energy-efficient and decarbonised building stock by 2050. The EPBD encourages the use of smarter buildings (European Commission, 2019):

> ***"Building automation and electronic monitoring of technical building systems have proven to be an effective replacement for inspections, in particular for large systems, and hold great potential to provide cost-effective and significant energy savings for both consumers and businesses. The installation of such equipment should be considered to be the most cost-effective alternative to inspections in large non-residential and multi-apartment buildings of a sufficient size that allow a payback of less than three years, as it enables action to be taken on the information provided, thereby securing energy savings over time."***
> **- (European Commision, 2018)**

1.1 Background information

The Modular Office Renovation (MOR) team from the TU Delft developed a strategy for renovating underperforming office buildings into net positive and affordable rental housing for starters. The project aims to be net positive in five aspects: energy, air, water, biomass and materials.

The Marconi Towers in Rotterdam (Figure 2) were selected as a case study. Figure 1 shows a render of the renovated towers. At the start of this project, these towers were left empty after the municipality of Rotterdam moved to a new office building.

Figure 2: Picture of Marconi Towers (van Helleman, 2011)

Figure 3: The MOR team during the construction phase in Hungary (MOR team, 2019)

Figure 4: MOR prototype in Hungary (by author)

Solar Decathlon Europe 2019

In order to compete in the Solar Decathlon Europe 2019, the MOR team (see Figure 3) made a cut-out of the towers (prototype see Figure 4) and rebuilt it in Delft in order to transform it to a 60m² apartment with a 25m² interior garden (see Figure 5). The apartment consists of two 12m² bedrooms with each a bedroom/workstation module and a living room with a bathroom/kitchen module. These modules provide the flexibility to make numerous different combinations for different apartment sizes and functions. The interior garden provides the apartment with a buffer zone. An active green wall containing phase-changing materials (PCMs) is placed in the interior garden.

After building the prototype in Delft, the prototype was disassembled and shipped to Hungary for the competition. In Hungary, the prototype was rebuilt in two weeks and evaluated for three weeks in the ten contests: Architecture, Engineering & Construction, Energy Efficiency, Communication & Social awareness, Neighbourhood Integration & Impact, Innovation & Viability, Circularity & Sustainability, Comfort Conditions, House Functioning and Energy Balance. With this prototype, the MOR team came in overall second place at the Solar Decathlon Europe 2019 and won 8 prizes in the 10 contest.

After the competition in the prototype stayed at the exhibition in Hungary for two months. It is now rebuilt in Delft at The Green village for further research.

1st prize in the communications and social awareness contest
1st prize in the energy efficiency contest
1st prize in the innovation and feasibility contest
2nd prize in the sustainability and circularity contest
2nd prize in the neighbourhood integration and impact contest
2nd prize in the engineering and construction contest
2nd prize in the house functioning contest
3rd prize in the comfort conditions contest
Special prize for most contest awards

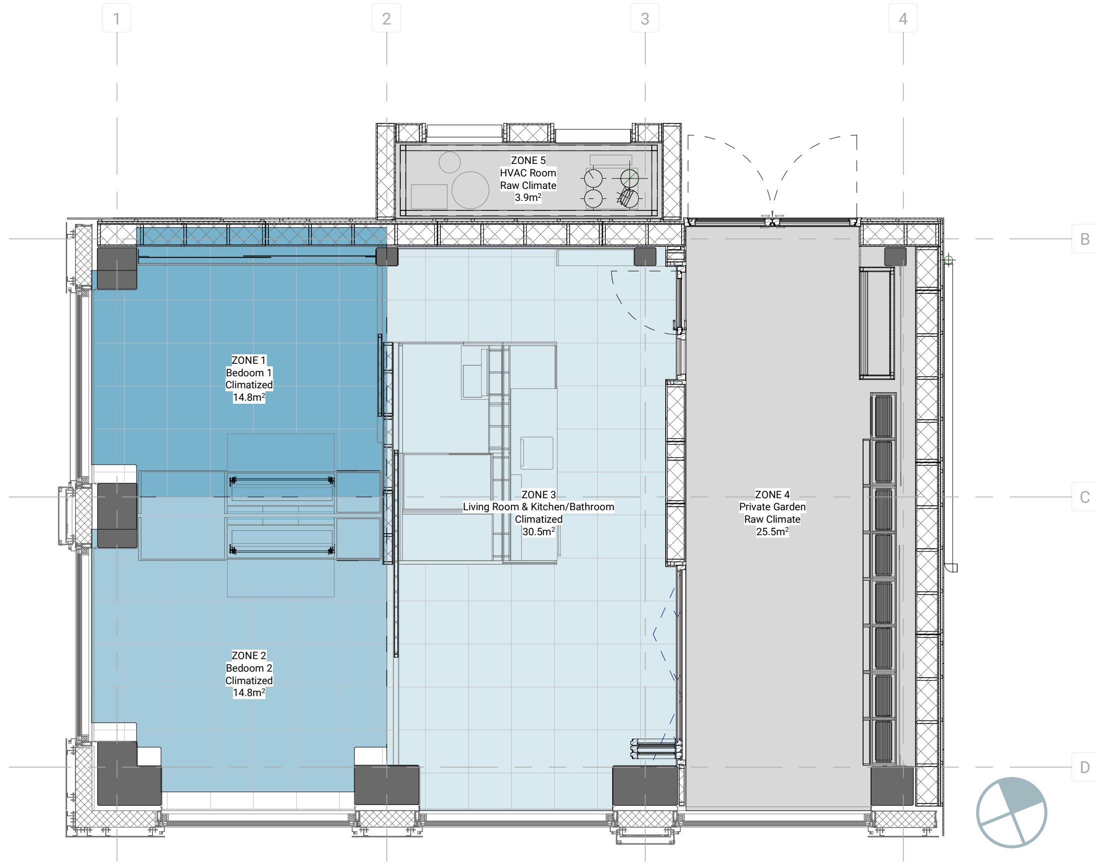


Figure 5: Floorplan prototype (MOR Team, 2019a)

1.2 Relevance of graduation research

During the competition, the systems in the prototype were set to function in the Hungarian climate (Warm-summer humid continental climate according to the Köppen climate classification) whereas the Netherlands has a temperate oceanic climate (MOR Team, 2019a). Showing that the MOR prototype can function efficiently in both Hungarian and Dutch climates with only changing the settings of the building management system can prove that it will also be able to function efficiently when the local climate will change.

Another part of the MOR project is to show the adaptability of buildings. The prototype is based on a section of the Marconi towers, which are three office towers located in Rotterdam. The prototype shows how these towers can be transformed into apartments with the possibility to transform back to offices if the demand from the market changes. Because the building management system can be used in residential buildings as well as offices or other functions (Priva, 2019), this can also show that the building could change its function and still perform at the most efficient level for that function.

1.3 Research questions

How can the building management system be optimised to extend the passive period of having a positive impact on the energy efficiency for MOR and more?

- Which parameters have the biggest influence?
- What are the comfort conditions that the building management system has to reach?
- How is the building management system currently programmed?
- Can simulations optimise these setpoints?

2. LITERATURE REVIEW

The EPBD gives the following definition for a building management system:

> ***"Building Automation and Control System, means a system comprising all products, software and engineering services that can support energy-efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems."***
> **- (European Commision, 2018)**

A building management system has three main functions: energy efficiency, comfort conditions, heat and cold generation. Another optional function is safety and security. Energy efficiency consists of energy production, conversion, storage and usage. ¬Energy is used to reach the comfort conditions and for heat and cold production. Comfort conditions have to be reached in order for the system to work successfully. The function for safety/security mainly consists of checking the system for malfunctions or preventive maintenance. But also the fire protection system or burglar alarm could be part of this (Bali, Half, Polle, & Spitz, 2018).

2.1 Energy usage (Efficiency)

Buildings are responsible for approximately 40% of all energy consumption in the European Union (European Commission, 2019). A lot of measures are already taken in order to reduce the total energy demand of all buildings. In Figure 6 the average energy usage by end-use for residential buildings in the European Union is shown. In this figure, the most energy is used for space heating. This figure is not representative of the MOR pavilion because it shows the average of all residential buildings in the European Union, and the MOR pavilion is an energy-efficient building.

Figure 7 shows the energy demand for nearly zero-energy buildings (nZEBs in the Netherlands. In this figure, space heating is still one of the biggest consumers of energy but this figure shows that water heating is also very important. Next to that, the energy demand for cooling has also become a bigger share. It is important to note that due to the overall energy going down the numbers look distorted. From these figures, you can only see the difference in contribution of the different types of end-use to the total energy demand.

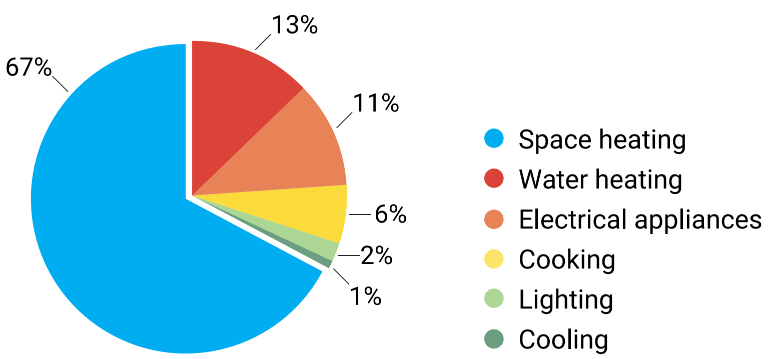


Figure 6: Energy usage by end-use in the European Union (Csiba, 2016)

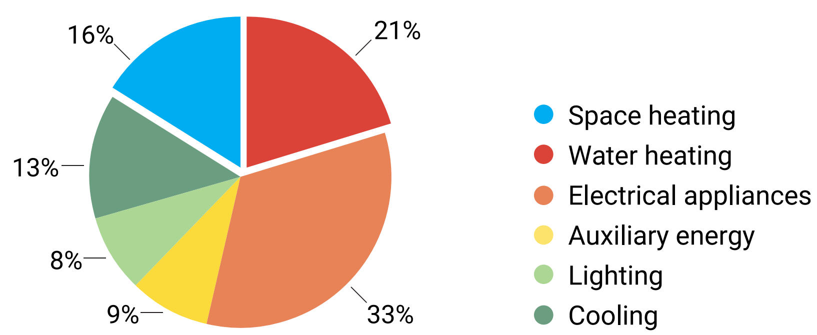


Figure 7: Energy usage by end-use nZEBs in the Netherlands (Nuiten, et al., 2019)

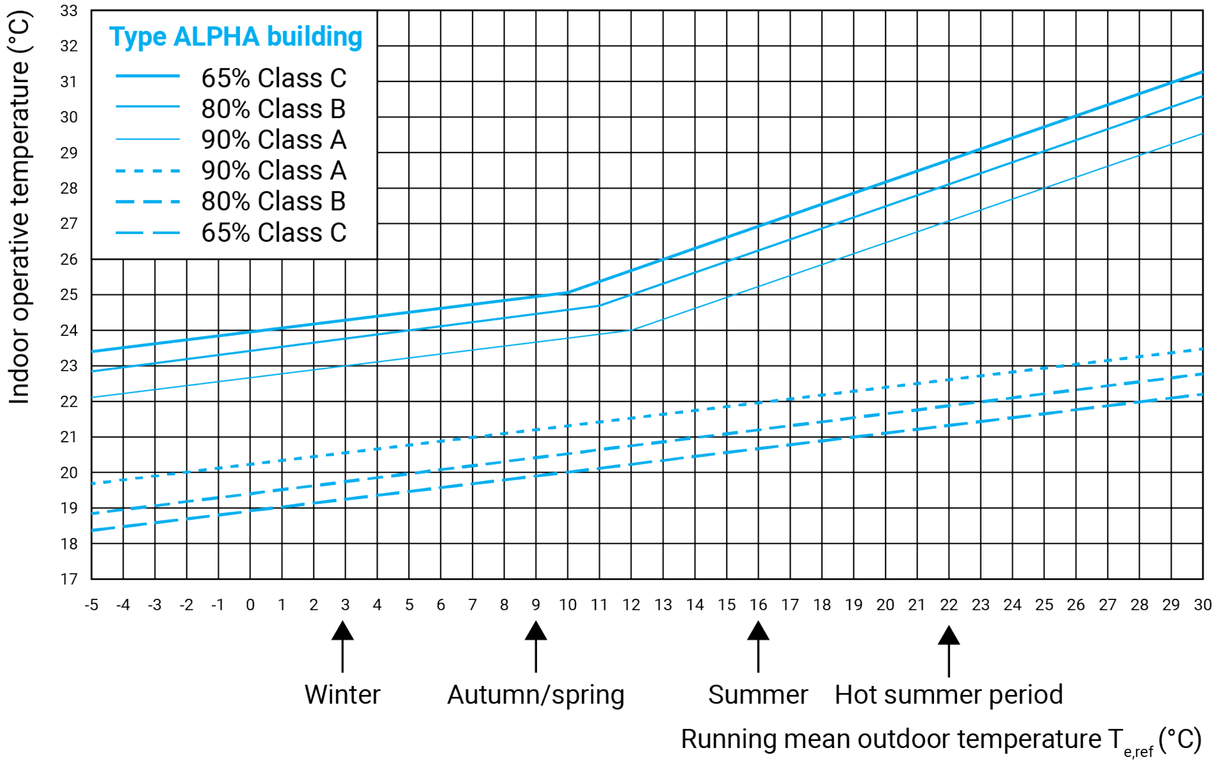


Figure 8: Maximally allowed operative indoor temperature for a specified acceptance level, as a function of the outdoor temperature $T_{e,ref.}$ (van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006)

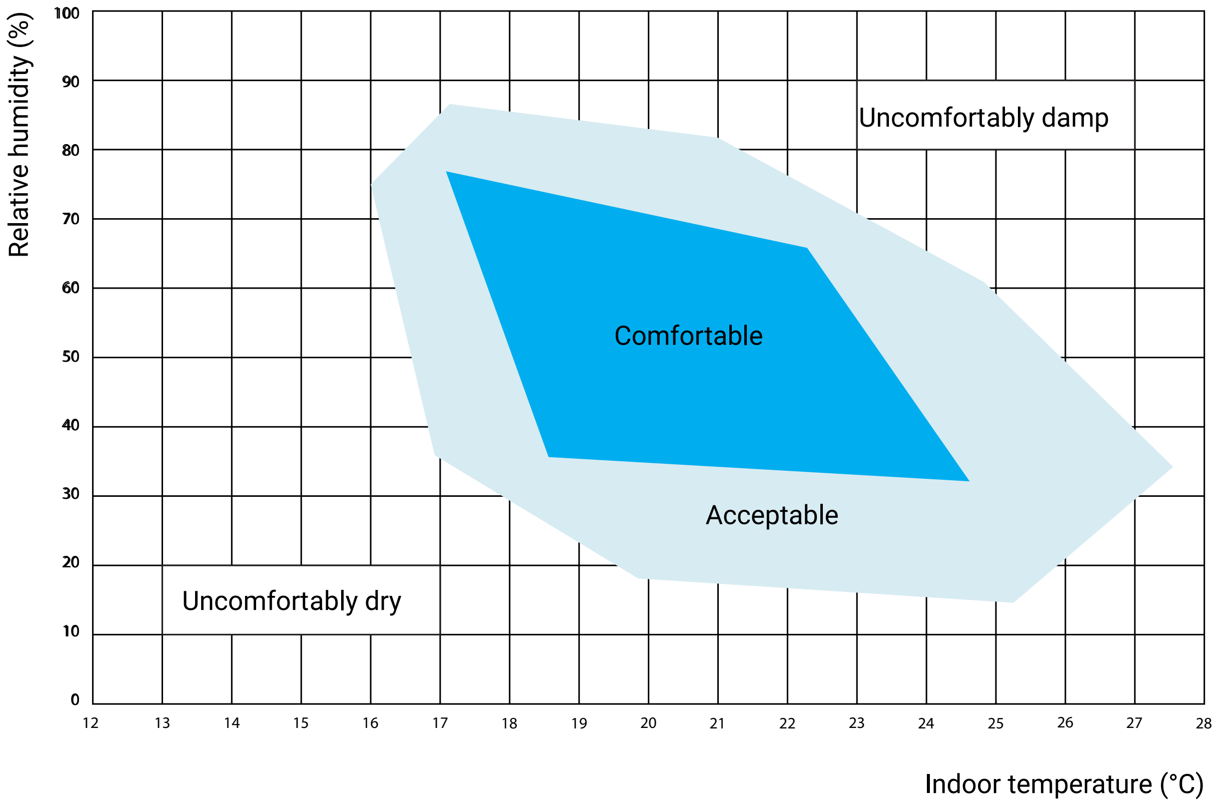


Figure 9: Comfort diagram (BOOM-SI, Milieukundig Onderzoek-& OntwerpBuro, 2019)

2.2 Comfort conditions

In order reach a high energy efficiency level we have to make sure that the systems have a positive impact on the residents' comfort, otherwise the residents will manually override the system in order to restore their comfort (Hong, Yan, D'Oca, & Chen, 2017). Therefore the setpoints for the system have to be defined. By looking at thermal comfort, indoor air quality and visual comfort the limits for the levels of comfort can be defined. Acoustical comfort is not controlled by the building management system but by the constructions, materials and sound insulation and is therefore not included.

Thermal comfort

Thermal comfort inside a building is dependent on a lot of factors. Since the amount of clothes and level of activity (state of metabolism) are not controllable by the system these are not taken into consideration. Relative humidity will be discussed in the paragraph about indoor air quality (van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006).

The Dutch Adaptive Temperature Limits guideline (ATG) is used to describe thermal comfort at different outdoor temperatures. $T_{e,ref}$ is calculated from the averages of the maximum and minimum outdoor air temperature of today and the three proceeding days (van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006):

$$T_{e,ref} = \frac{(1T_{today} + 0{,}8T_{yesterday} + 0{,}4T_{day\ before\ yesterday} + 0{,}2T_{day\ before\ day\ before\ yesterday})}{2{,}4}$$

Two different graphs are made for two different climate types: Alpha and Beta. The MOR prototype is considered to be a type Alpha building because of its operable windows. Figure 8 shows the adaptive temperature limits. It shows six lines, three for the upper limit and three for the lower limit. They represent the three classes (A, B and C). Class B is generally considered to be 'good'. Class A is used for extra high-quality buildings and considered to be 'very good'. Class C is used for older existing buildings or temporary buildings. Going below the limit of Class C is considered to be inadequate (van der Linden, Boerstra, Raue, Kurvers, & de Dear, 2006).

Indoor air quality

The indoor air quality is defined by multiple different factors. A building management system can measure and control CO_2 levels and relative humidity.

VLA (Vereniging Leveranciers Luchttechnische Apparaten) assumes a limit of a maximum CO_2 level of 800 ppm above the normal outdoor level of around 400 ppm (VLA, TNO, Peutz BV en Nieman Raadgevende Ingenieurs BV., 2018).

The relative humidity is dependent on the temperature. In Figure 9 the comfortable and acceptable levels of relative humidity and indoor temperature are stated. Within a temperature of 18 to 24 °C the relative humidity can vary between 30 – 70 % (BOOM-SI, Milieukundig Onderzoek-& OntwerpBuro, 2019).

Visual comfort

Visual comfort can be evaluated for different parameters: illuminance levels, glare, controllability and view outside (Giarma, Tsikaloudaki, & Aravantinos, 2017).

For visual comfort, there are no standards for residential buildings. A recommendation for the amount of light needed in a room is based on the activities as can be found in Table 1 on the next page (Bodart, et al., 2011).

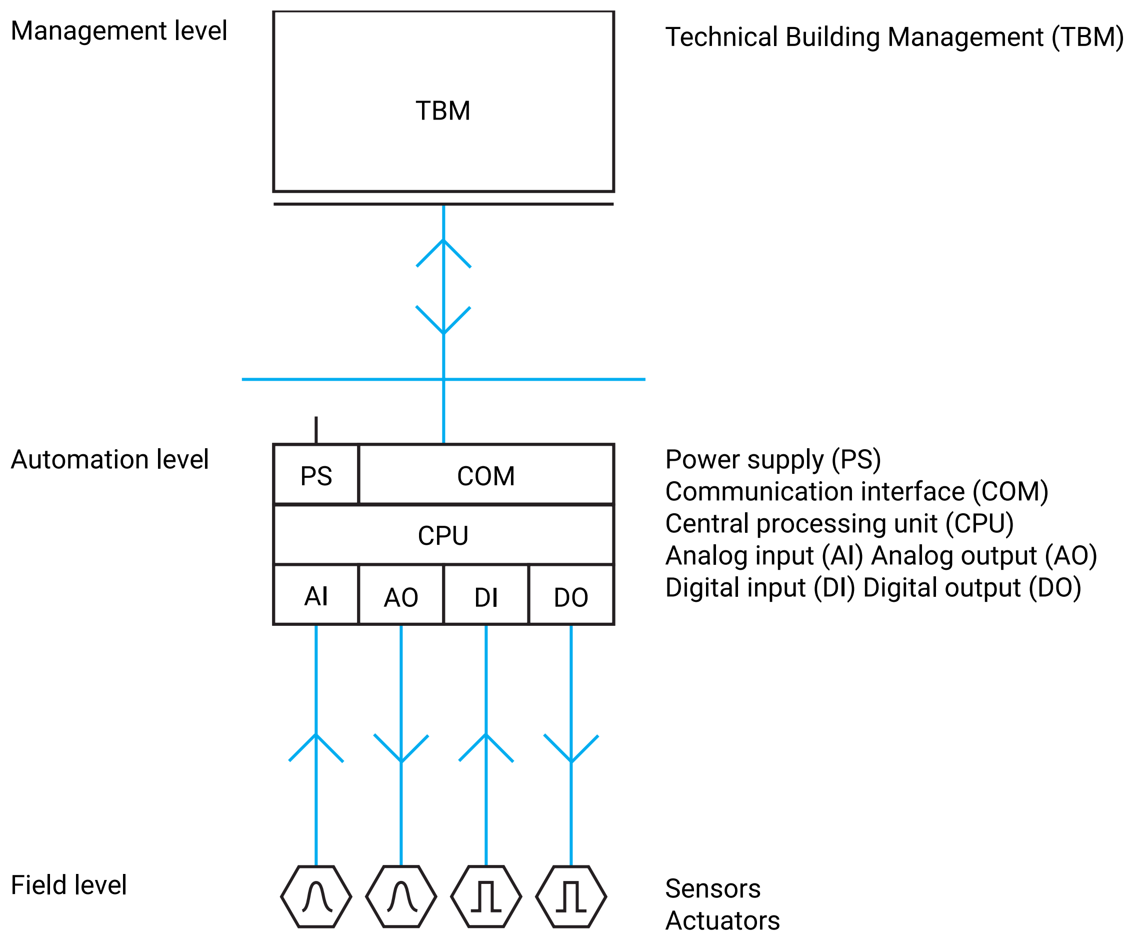


Figure 10: Levels of a building management system

For glare, multiple guidelines are established. The International Commission on Illumination (CIE) recommends the Unified Glare Rating (UGR). The UGR-value expresses the value of discomfort and is dependent on multiple factors: shape and size of the room, reflection factors of walls, ceiling, floor and other large surfaces, type of fixture, the distribution of fixtures over the room, and the position and viewing direction of the observer in the room (Normcommissie 351005 "Verlichting", 2011). The NEN-EN 12464-1 standard describes the maximum UGR-value for different rooms. Again, there are no standards for residential buildings.

Room	Specific area	lux
Bathroom	Sink and mirror Ambient lighting Toilet	300 – 500 200 100
Living room	Resting area Reading area	50 – 200 300
Bedroom	Ambient lighting Reading area	100 – 200 300
Workstation		500
Kitchen	Ambient lighting Kitchen counter	200 – 300 300 - 500
Hallway		50 - 100

Table 1: Recommended illuminance for residences (Bodart, et al., 2011)

2.3 Building management system

The building management system automates systems to optimise the operation of the three main functions: energy efficiency, comfort conditions, heat and cold generation.

A building management system has different levels (see Figure 10). The management level is the software which is used to gain insight into the gathered data. It provides information about operation, maintenance, services and management of buildings, especially for energy management – measurement, recording trending and alarming capabilities and diagnosis of unnecessary energy use (Normcommissie 351074 "Klimaatbeheersing in gebouwen", 2017).

The automation level is the controller of the system. This equipment is responsible for processing functions (monitoring, controlling, regulating and optimising). This system is responsible for two parts, room automation and plant automation. Room automation controls the different building systems such as lighting, sun-shading and air-conditioning. Plant automation controls the primary systems, for example, the ventilation system (Bali, Half, Polle, & Spitz, 2018).

On the field level, you can find the sensors and actuators. The system uses sensors in order to measure the indoor and outdoor environment. The controller, the central brain of the system will collect these data points and make decisions on whether to change settings or not. Actuators are then used in order to adapt settings in building systems to the environmental needs. These sensors and actuators perform the five basic functions of building automation: switching, positioning, indicating, counting and measuring (Bali, Half, Polle, & Spitz, 2018).

Standardisation – NEN-EN 15232-1

The standard NEN-EN 15232-1: Energy performance of buildings – impact of building automation, controls and building management, contains a specification of methods assessing the influence of building automation on the energy efficiency of buildings. The standard contains a list of functions of building automation that influence the energy efficiency of buildings. Next to that, it provides a simplified and detailed method of assessing the influence of these functions on the energy efficiency of a building (Bali, Half, Polle, & Spitz, 2018). Finally the standard contains a list of minimum BAC function type requirements to be implemented for a project.

Method 1 contains the detailed calculation procedure of the BAC contribution to the energy performance of the building. This method knows five approaches that can be used to calculate the impact of building management functions on energy performance (Normcommissie 351074 “Klimaatbeheersing in gebouwen”, 2017):

- The direct approach (using a detailed simulation method)
- The operating mode approach (calculating the energy consumption for each operating mode)
- The time approach (used when the control system has a direct impact on the operating time of a device)
- The setpoint approach (used when the control system has a direct impact on the control accuracy)
- The correction coefficient approach (used when the control system has a more complex impact)

Method 2 contains the factor-based calculation procedure of the BAC impact on the energy performance of buildings. This method gives the opportunity to simply evaluate the impact of building management functions on the buildings’ energy performance by using BAC efficiency factors. These factors are related to the annual energy use of a building including (Normcommissie 351074 “Klimaatbeheersing in gebouwen”, 2017):

- Thermal and auxiliary energy input to the space heating system
- Thermal and auxiliary energy input to the cooling system
- Thermal energy input to the domestic hot water system
- Electric energy input to the lighting system
- Electric energy input to the ventilation system

With this standard, it is possible to categorise building management systems into BAC efficiency classes, see Table 2. For residential buildings, the reduction in thermal and electrical energy consumption of class A compared to class C can reach up to 27% (eu.bac, 2015).

Class	
A	High-energy performance BAC and technical building management functions
B	Advanced BAC and some specific technical building management functions
C	Standard BAC functions (reference case)
D	Non-energy-efficient BAC functions. Building with such systems shall be retrofitted. New buildings shall not be built with such systems.

Table 2: Building automation efficiency classes in accordance with EN 15232 (Normcommissie 351074 “Klimaatbeheersing in gebouwen”, 2017)

Certification/Labelling - eu.bac

The European building automation controls association (eu.bac) provides certification based on EN 15232. The eu.bac system is used for individual rooms and zones instead of the whole building at once. In the eu.bac system, the classes range from AA to E. Currently the system is mostly based on theoretical calculation evaluated on a scale from 0 to 100 points (Bali, Half, Polle, & Spitz, 2018).

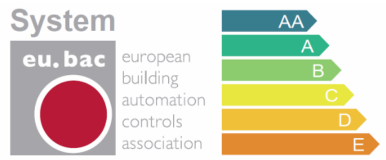


Figure 11: eu.bac System Certification levels (eu.bac, 2017)

2.4 Conclusion

Since the building management system has not been used in the prototype yet, it is still unknown if it functions properly. It is not certain yet what uses the most energy in the prototype. But looking at the average energy consumption of nZEBs in the Netherlands it is most likely that space heating and water heating consume the most energy. Coincidently those are two of the main functions of a building management system.

The following limits for comfort conditions were found. For thermal comfort, according to the Adaptive Temperature Limits guideline, the indoor air temperature is dependent on the calculated average of the outdoor temperature of the five preceding days. Class B of type Alpha buildings should be considered for buildings with operable windows (see Figure 8 on page 16). For indoor air quality, a maximum CO_2 level of 1200 ppm was found. The relative humidity is dependent on the temperature. Within a temperature of 18 to 24 °C the relative humidity can vary between 30 – 70 %. For visual comfort, a minimum of 300 lux is recommended for most rooms, 500 lux is recommended for more precise work.

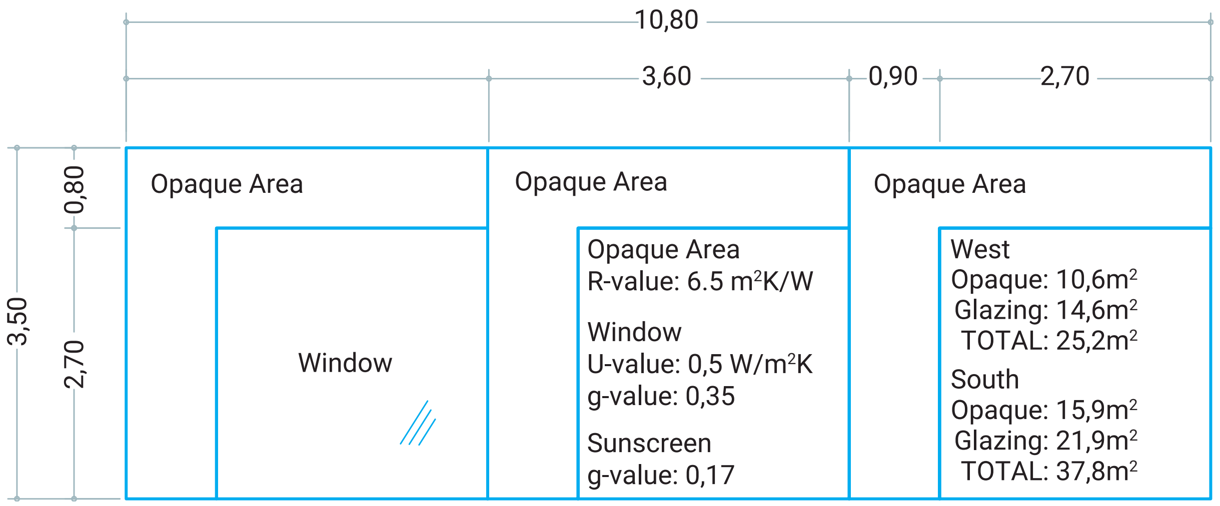


Figure 12: Facade properties (MOR Team, 2019b)

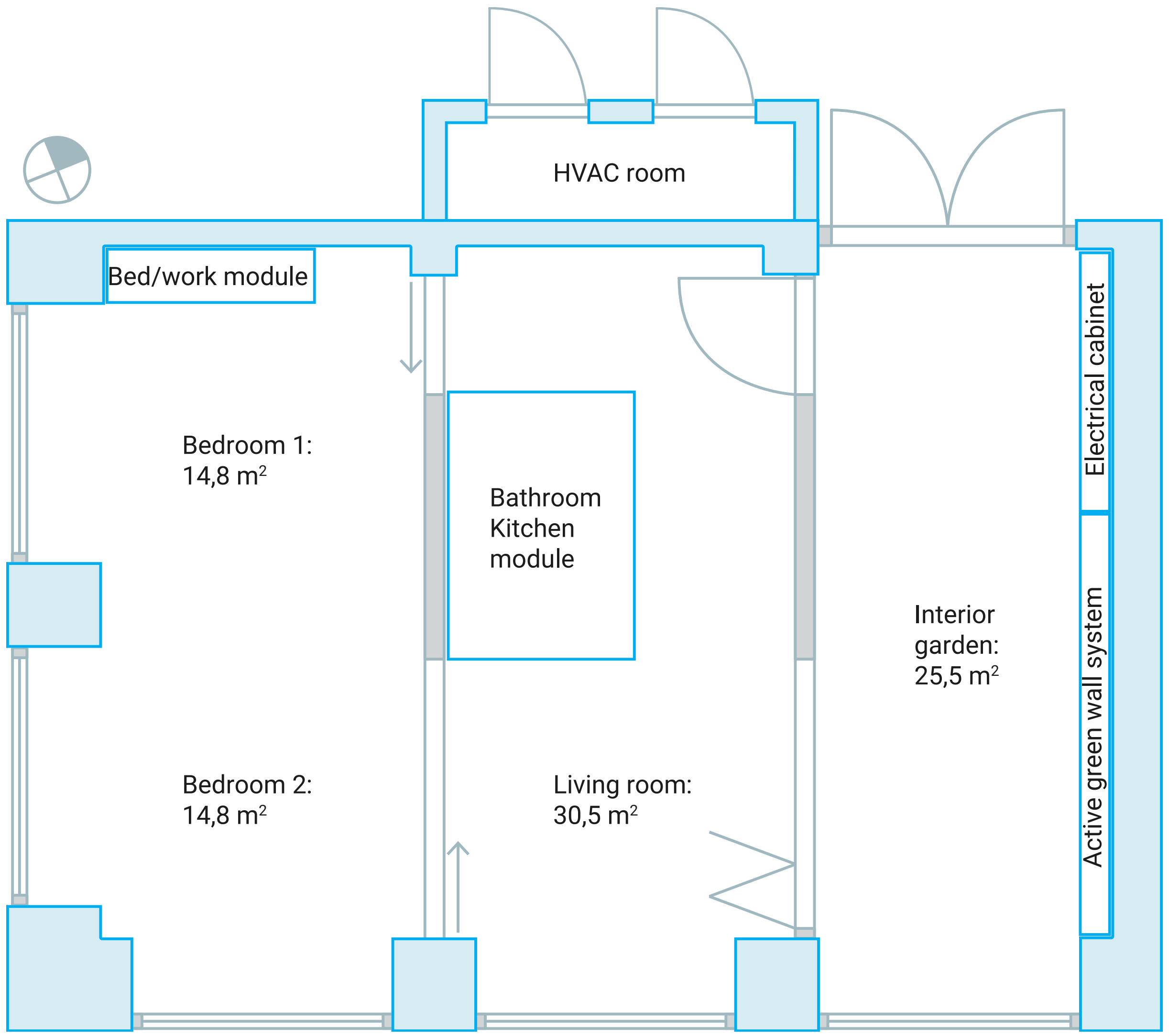


Figure 13: Space plan properties

3. CASE STUDY

For this research, the MOR prototype is used as a case study. The MOR prototype consists of a building management system that controls all passive and active systems. The building management system will first use passive systems in order to restore the comfort conditions. In case the passive systems do not suffice in order to reach the desired indoor climate conditions the semi-passive systems will start operating. If this too is not sufficient, active systems will start operating as well. In this chapter, all systems will be discussed.

3.1 Passive systems

The passive period is the timespan that the building functions solely on passive systems, such as the use of solar heat gain, heat recovery, solar shading, natural ventilation (Yannovshtchinsky, Huijbers, & van den Dobbelsteen, 2012).

Facade

For the simulations, some properties are fixed and cannot be changed. An example of such properties can be found in Figure 12. The used materials in the façade can be found in Appendix A.

Shading

The exterior shading is made of a grey-black weaved glass and PVC cloth screen from Helioscreen which is rolled up with a Somfy motor. The shading has a g-value of 0,17 and the distance to the glass is 0,20 m (MOR Team, 2020).

Windows

The windows are build up with triple glazing with krypton and an aluminium frame from Metaglas. A vertical sliding window will allow for a free area of 3,2 m². The windows are powered by an electric tubular motor (MOR Team, 2019a).

Space plan

The heavy concrete columns, floor and roof act as thermal mass to store thermal energy. The ceiling height is 3,4 m. Since the prototype is back in the Netherlands, the space plan has changed a little. In order to use the prototype as an office, the bedrooms are merged (see Figure 13).

Buffer zone

During the semi-passive period, mechanical ventilation is running but is not actively cooling or heating. Instead, it will make use of outdoor air to distribute. This air enters the prototype via the internal garden. The internal garden acts as a buffer zone and will pre-heat or pre-cool the air before entering the prototype. Additionally, it could transport the air past the phase-changing materials inside the active green wall to pre-cool or pre-heat the air (see Figure 14 on the next page) (MOR Team, 2019b).

These phase-changing materials act as a thermal mass. The phase changing is used to store or release heat. When the air is warm, it will liquefy the mixture inside the panels, absorbing the heat from the air and storing it inside. When the air is cold, the phase of the material will change from liquid to solid releasing the heat that was stored to the air (Yannovshtchinsky, Huijbers, & van den Dobbelsteen, 2012). The phase-changing materials used in the prototype are salt hydrates with a mixture of 23 and 26 °C. When the air temperature falls below this temperature the panel will start to pre-heat the air. When the temperature exceeds this temperature the panel will start to pre-cool the air. This mixture of temperatures was designed for Hungary, new PCMs with a lower temperature of around 20 °C are needed for the Dutch climate (MOR Team, 2019b).

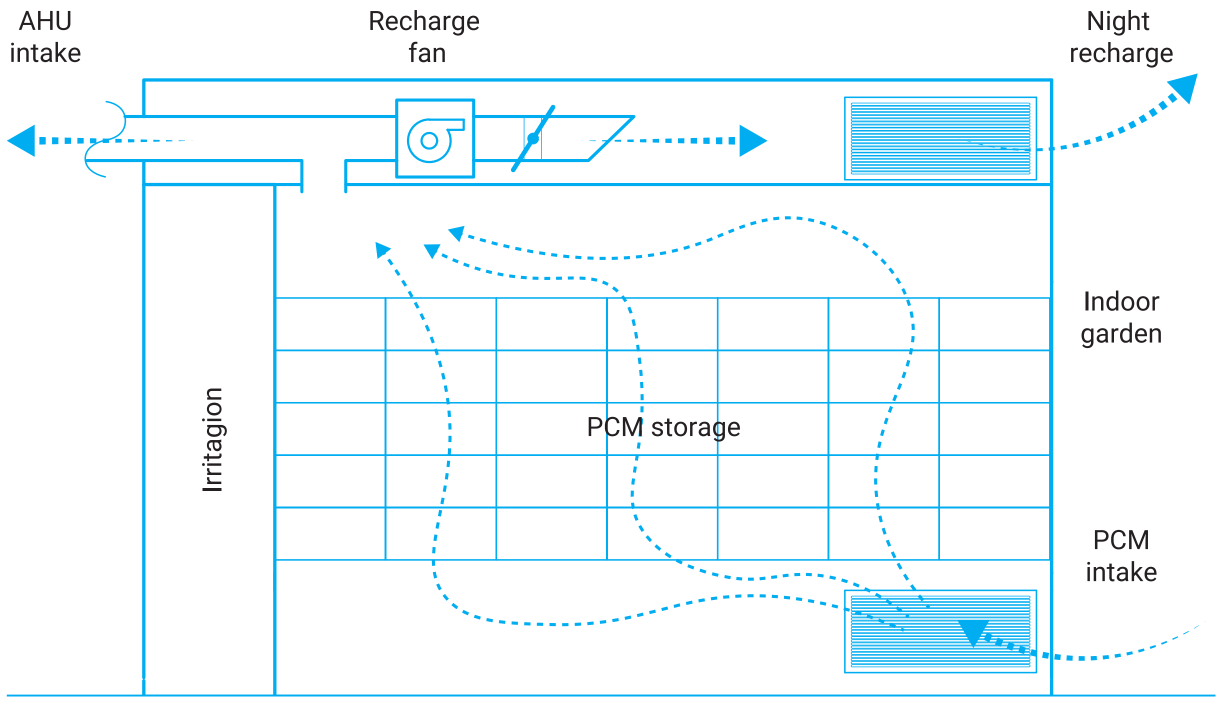


Figure 14: Diagram of active green wall with PCM storage (MOR Team, 2020)

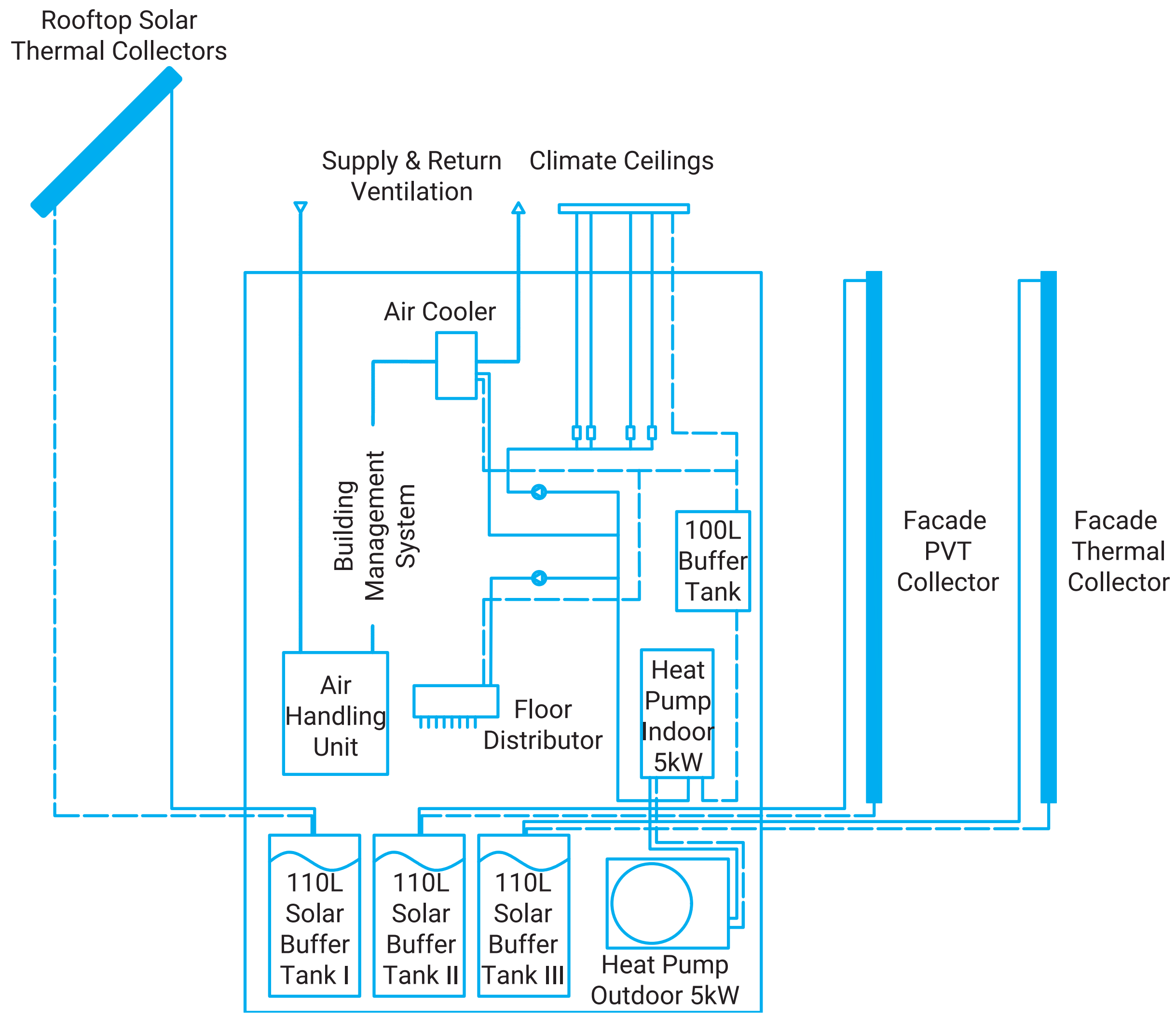


Figure 15: Diagram of HVAC room (MOR Team, 2020)

3.2 Active systems

When the passive systems are insufficient in restoring the comfort conditions the building management system will switch to using active systems. During the active period, the building functions with the use of active systems that draw power for these processes from electricity. See Figure 15 or Appendix B and C for the schematic overview.

Floor heating

The prototype is equipped with floor heating and cooling from manufacturer WTH. This is a slow-reacting system to provide base heating and cooling. The system consists of PE piping inside aluminium heat diffuser plates laid into the wood fibreboard of the floor buildup. The piping is divided into 7 groups, two in each bedroom and three in the living room (See Appendix E). These groups are not individually controllable (MOR Team, 2019b).

Climate ceilings

The climate ceilings are the MecuRo system from manufacturer Inteco. This is a fast-reacting system to provide instant heating and cooling. This system consists of copper piping inside an aluminium extrusion profile which is glued to the metal ceiling panel. Each ceiling island consists of four panels of 1200 x 600 mm. The four islands can be controlled individually (MOR Team, 2019b).

Active air cooler

The system also contains an active air duct cooler from Orcon which operates at a maximum of 450 m^3/h (MOR Team, 2019b).

Heat pump

The water for these systems comes directly from the air source heat pump, a 5 kW Panasonic Aquarea Bi-block. This system pumps 2500 m^3/h of airflow over its external unit and leads the air back outside from underneath the prototypes basement. The water loop also contains a 100 L buffer tank (MOR Team, 2020).

Heat exchanger

The air handling unit is a Zehnder ComfoAir. This unit contains an air-to-air plate heat exchanger which operates at a maximum of 450 m^3/h. The low-pressure system supplies a maximum of 125 m^3/h air to the four inlets directly above the ceiling islands (MOR Team, 2020).

Each type of system connected to the heat pump or heat exchanger is individually controlled by adjusting the control valves and pumps by the building management system (MOR Team, 2020).

Lighting

The lighting inside the prototype consists of an Arcano modular 48V DC system from manufacturer nuudo. The lights are clicked into a pendulum track hanging from the ceiling. Because of the multiple different lights, the system can be composed for each room and the different lighting needs. Each track can be controlled wireless, separately or together with a track connecter (MOR Team, 2019b).

Energy production

On the roof of the prototype 12 Panasonic photovoltaic (PV) panels are placed to produce electricity. Two additional photovoltaic thermal (PVT) flat-plate panels are placed on the roof to produce domestic hot water. The PVT panels are connected to the 110 L solar buffer tank and an additional 18 kW post-heater (see Figure 15 and Appendix D) (MOR Team, 2020).

Building-integrated photovoltaic (BIPV) panels are placed on the façade. These are Colorblast panels in two shades of grey and three shades of green from manufacturer Kameleon solar.

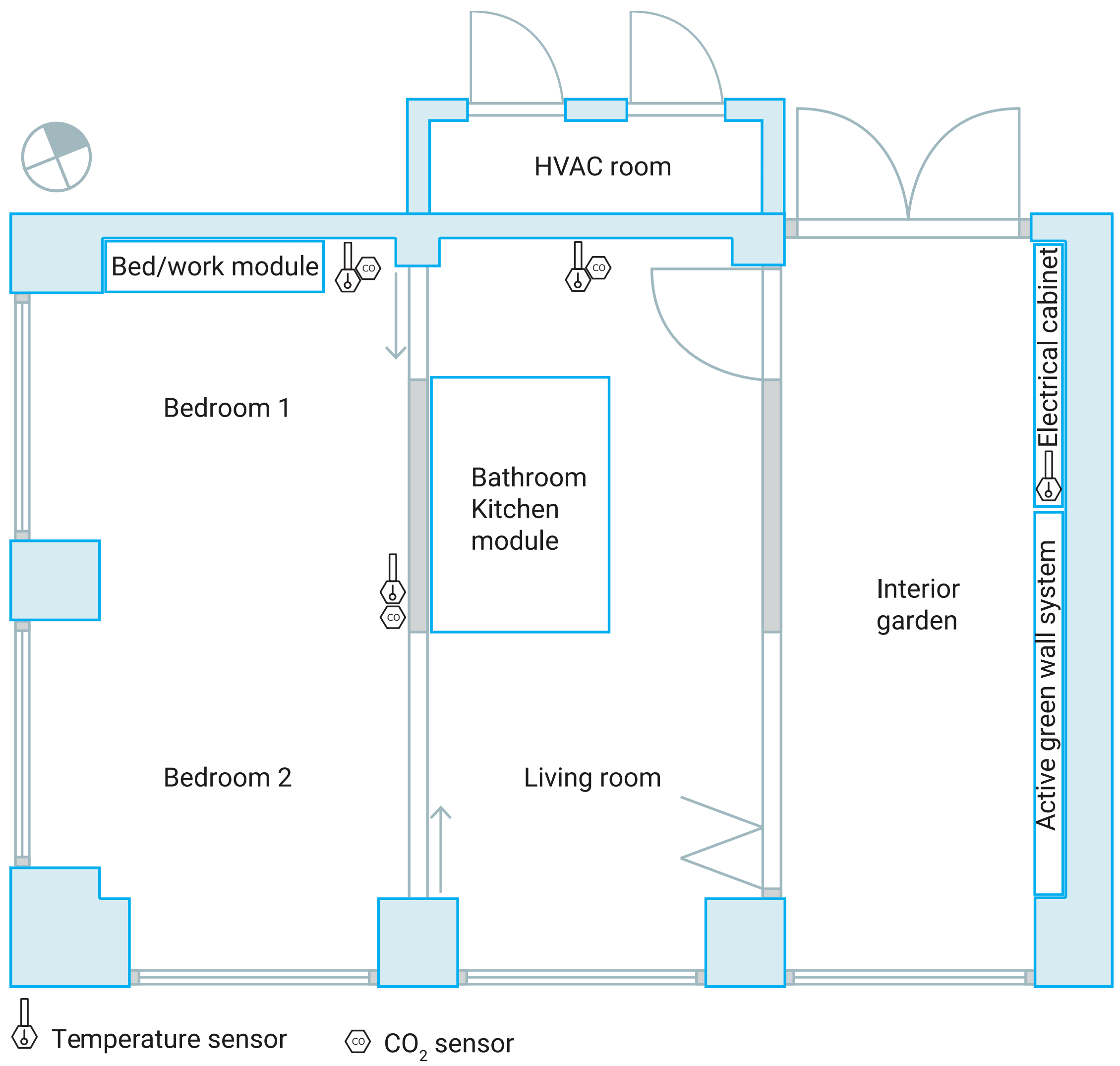


Figure 16: Location of sensors

Three panels on the west façade and seven panels on the south façade are active. All panels can be made active, but for the competition, this was the maximum amount allowed (MOR Team, 2019b).

The façade also includes two solar chimneys. These provide hot water and electricity. Currently, the hot water of each chimney is connected to a separate 110 L buffer tank for testing purposes (see Figure 15 on the previous page). Inside the glass of the solar chimneys, black BIPV panels are placed. Copper tubes run behind these panels. The south solar chimney contains functioning panels (MOR Team, 2019b).

3.3 Building management system

The MOR project is a smart passive building with a central building management system to control and optimise the operation of the active and passive building systems and therefore reduce the energy consumption of the building and improve the users comfort conditions (MOR Team, 2019b).

Sensors

The prototype is equipped with indoor sensors (Table 3) (see Figure 16 for the location of the sensors):

- 3x combined temperature and CO_2 sensor
- 1x temperature sensor
- Light intensity sensor (not implemented)
- Relative humidity sensor (not implemented)
- Motion sensor (not implemented)

A couple of sensors are located inside the HVAC room. These measure the water and air temperature inside pipes and ducts (Table 4 on the next page):

- 11x water temperature sensor
- 2x duct temperature sensor

	
Combined temperature and CO_2 sensor nr. 111242	Temperature sensor nr. 111260
Bedrooms and living room	Interior garden
-20 ... +60 °C	-40 ... +70 °C

Table 3: Indoor sensors (Priva, 2018)

	
Strap-on water temperature sensor nr. 111231	Duct temperature sensors nr. 111270
3x Climate ceilings 3x Floor heating/cooling 2x Active air cooler 1x PVT 1x Supply cold water central heating 1x Return cold water central heating	1x Interior garden 1x HVAC room
-40 ... +110 °C	-30 ... +70 °C

Table 4: Sensors inside the HVAC room (Priva, 2018)

Clima sensor USM nr. C9200.00.001	
Wind velocity Wind direction Temperature Relative air humidity Air pressure Light intensity Precipitation	0 ... 60 m/s 0 ... 360 ° -30 ... +70 °C 0 ... 100 % 300 ... 1100 hPa 0 ... 150 kLux 0 ... 10 mm/min

Table 5: Weather station

For outdoor sensors a weather station is located on the roof (Table 5 on the next page):

- Wind speed and direction
- Temperature
- Relative humidity
- Air pressure
- Light intensity
- Rain detection

Actuators

The following actuators are present in the prototype (see Figure 17 or Appendix F and 7 for the locations of the actuators):

- 5x window motor
- 5x exterior shading motor
- 4x mechanical ventilation exhaust vent
- 4x mechanical ventilation supply vent with volume control (located above the climate ceilings)
- 1x mechanical recirculation vent for the active green wall

The following actuators are located inside the HVAC room:

- 4x control valve for climate ceilings
- 1x control valve for floor heating/cooling
- 1x exhaust
- 1x circulation pump climate ceilings
- 1x circulation pump floor heating/cooling

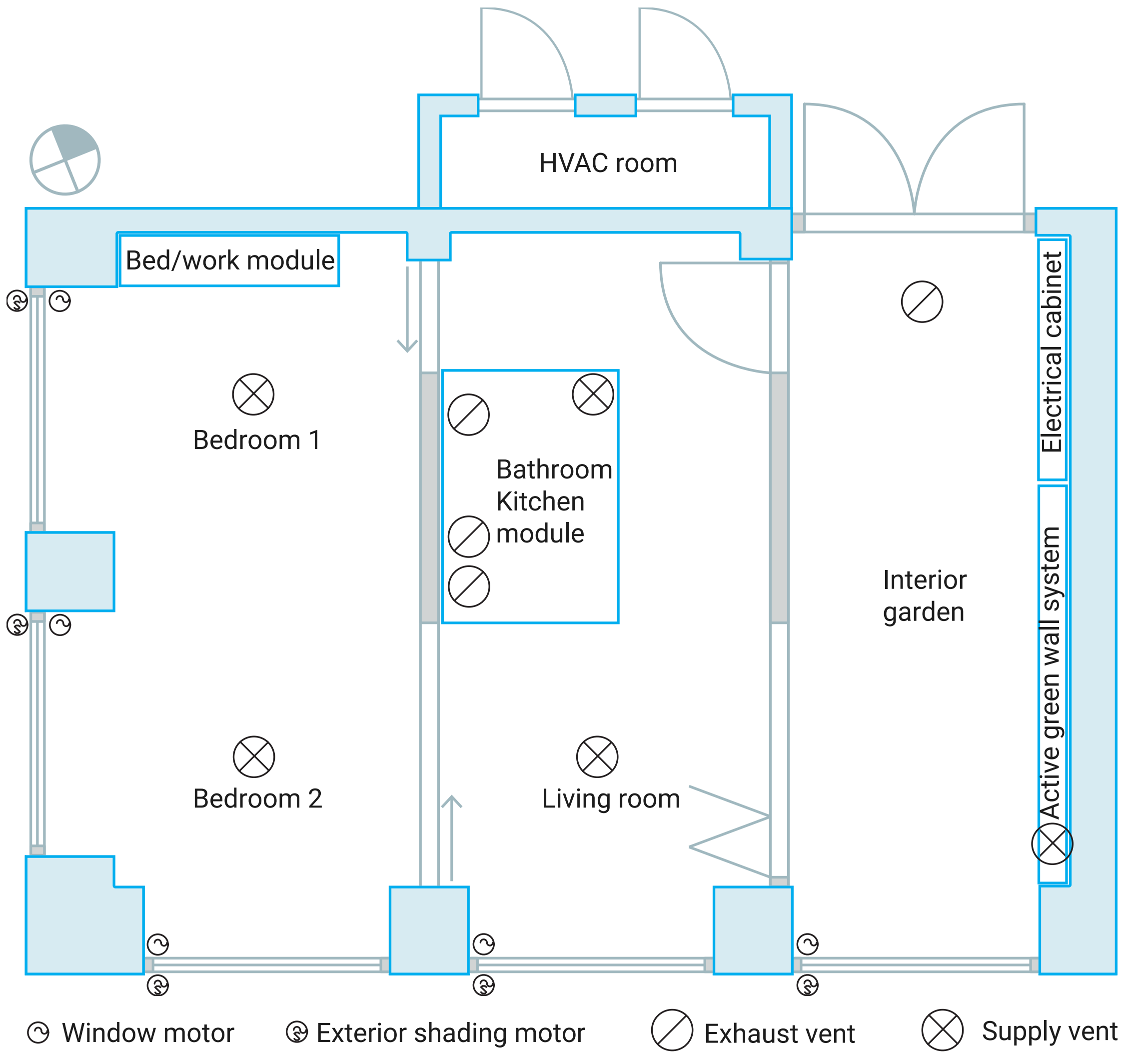


Figure 17: Location of actuators

Controller

The Priva Blue ID C-Line is a modular controller (see Figure 18) which makes it very flexible and adaptable. The controller handles the input and output based on control programmes loaded into the controller via the software Top Control 8. Because everything is software configurable it is easy to access for changes or expansions in the system. The software can also provide insight into installations and energy usage. The controller is located inside the HVAC room (see Figure 15 on page 24 or Appendix H).

Figure 18: Priva system inside MOR HVAC room

The two-wire port can reuse existing communication cables for IP-communication. This technology provides a stable communication connection because data rates are low (Bali, Half, Polle, & Spitz, 2018).

If the software fails the systems do not go offline but remain operational and revert to a user-configured state. The controller modules have manual override buttons for manual intervention which remain operational (Priva, n.d. b).

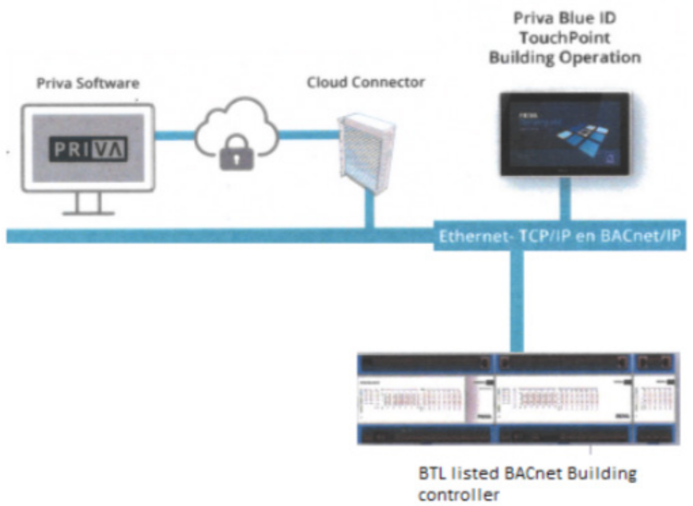


Figure 19: Priva building controller (MOR Team, 2019b)

BACnet

Priva Blue ID works with BACnet (Building Automation and Control network). BACnet is a standardised communication system (standards ASHRAE/ANSI Standard 135 or ISO 16484-5) developed in 1987 by ASHRAE. It is independent of any specific hardware or software and it also works with different communication protocols, which allows to connect to other (existing or new) systems (Bali, Half, Polle, & Spitz, 2018).

Priva hardware and software is BTL-Listed, which means it was tested for compliance and interoperability at a qualified BACnet Testing Laboratory. In the accompanying Protocol Implementation Conformance Statement (PICS), details about the BACnet functionalities it supports can be found (BACnet International, 2019). These tests are not mandatory (Bali, Half, Polle, & Spitz, 2018).

ASHRAE BACnet®

Figure 20: BACnet (BACnet International, 2019)

Functions

The building management system of the prototype has three main functions: Heating and cooling, air quality control, and heat and cold generation. For visual comfort, there are currently no light intensity sensors installed in the prototype and therefore the light controls have to be done manually by the residents. The designed settings, as programmed by CroonWolter&Dros in consultation with the MOR team are discussed below.

As explained in paragraph Chapter 3.1 “Passive systems” and Chapter 3.2 “Active systems”, the building management system has three stages: passive, semi-passive and active. Figure 22 on the next page shows the flowcharts where the decisions are made to start and stop passive or active systems.

Heating and cooling

The room temperature setpoint is set to 21,0 °C. There is an offset for this temperature of -1,0 °C for heating and +1,0 °C for cooling.

The different systems are set to a sequence control based on a percentage of heating or cooling demand. If the percentage of heating or cooling demand exceeds the upper limit the system will turn on. If the percentage of heating or cooling demand falls below the lower limit the system will turn off (see Figure 21).

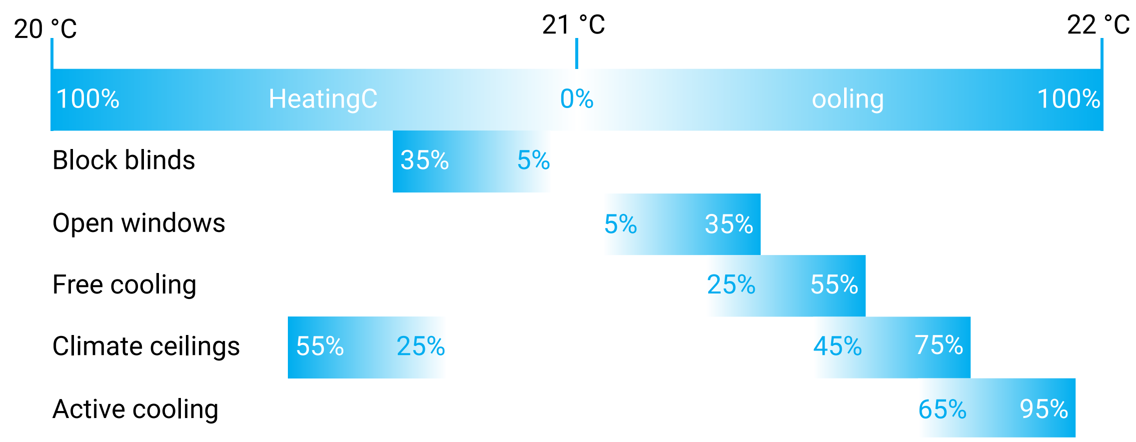
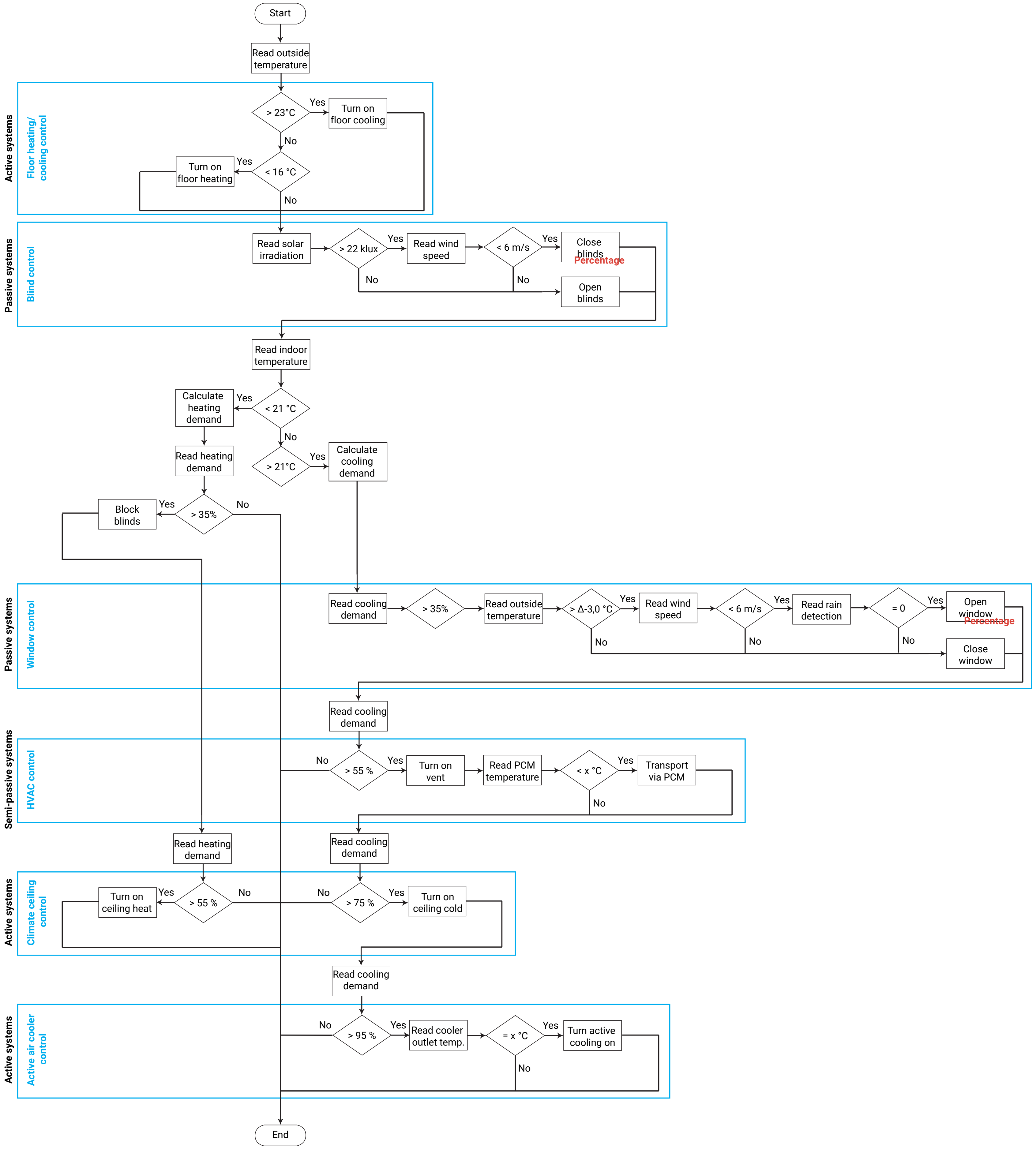


Figure 21: Sequence control



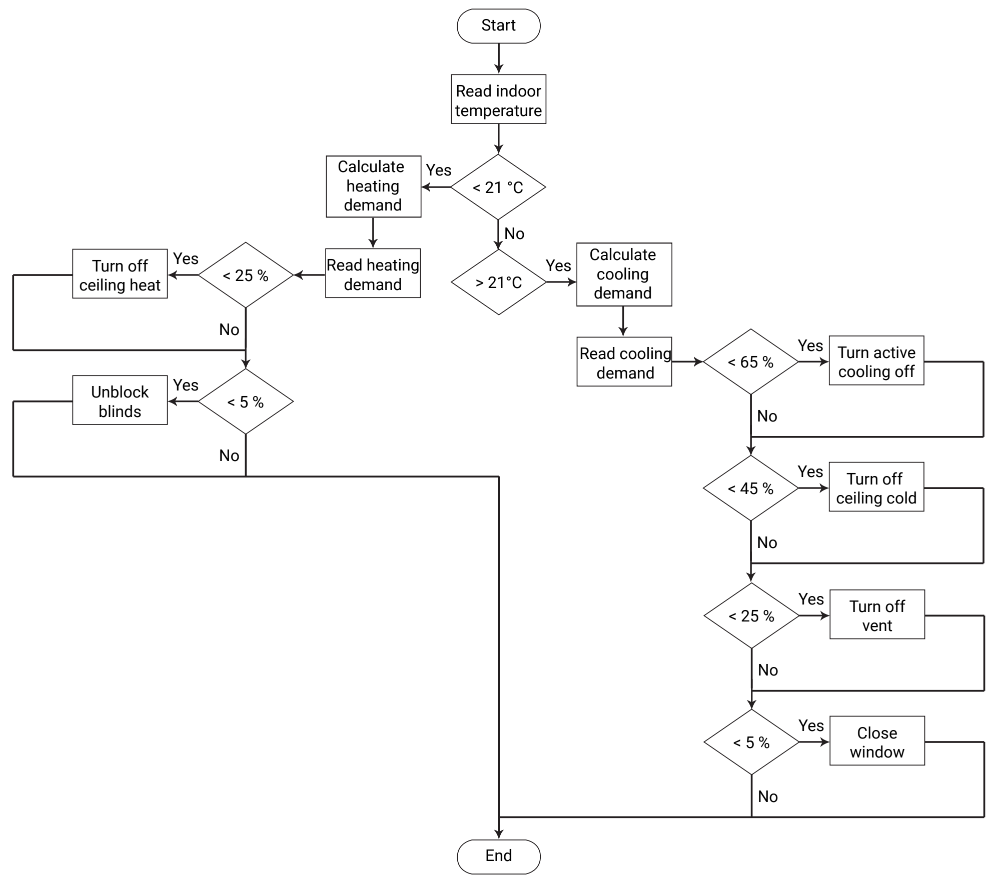


Figure 22: Flowchart heating and cooling control

The floor heating and cooling is only controlled by the outdoor temperature and therefore is not included in the sequence control. The floor heating turns on if the outdoor temperature falls below 16,0 °C, it turns off if the outdoor air temperature reaches 21,0 °C. The floor cooling will turn on if the outdoor temperature exceeds 23,0 °C, it turns off if the outdoor air temperature reaches 20,0 °C. All zones are controlled together. To keep the overview the floor heating and cooling will be mentioned at active systems even though it will possibly already be running.

The windows are able to open at different percentages. The climate ceilings and floor heating and cooling both have control valves to control the water flow. The mechanical ventilation has air valves to control the inlet flow.

Passive heating

1. If the solar radiation measured outside is higher than 22 klux (65 klux for the living room window) the blinds will close. If the system exceeds 35 % of heating demand the blinds will be blocked and (stay) open. In case of wind faster than 6,0 m/s, the blinds will (stay) open.

If the above measures are not sufficient the system will go to active measures.

Active heating

2. If the outdoor air temperature falls below 16,0 °C the floor heating will start to heat.
3. If the system exceeds 55 % of heating demand the climate ceiling islands will start to heat.

Passive cooling

1. At all times if the solar radiation measured outside is higher than 22 klux (65 klux for the living room window) the blinds will close. In case of wind faster than 6 m/s, the blinds will (stay) open.
2. If the system exceeds 35 % of cooling demand and the outdoor temperature has a minimum difference of -3,0 °C with the room temperature, the windows will be opened. In case of rain or wind faster than 6 m/s, the windows will be/stay closed.

If the above measures are not sufficient the system will go to semi-passive measures.

Semi-passive cooling

3. If the system exceeds 55 % of cooling demand, mechanical ventilation will be turned on without actively cooling. It is possible to transport the air past phase-change materials to pre-cool the air.

If the above measures are not sufficient the system will go to active measures.

Active cooling

4. If the outdoor air temperature exceeds 23,0 °C the floor cooling will start to cool.
5. If the system exceeds 75 % of cooling demand the climate ceiling islands will start to cool.
6. If the system exceeds 95 % of cooling demand and based on the cooler outlet temperature the central air cooler can pre-cool the distributed air.

Air quality control

Currently, only CO_2 sensors are installed for air quality control, therefore the system does not control the relative humidity inside the prototype.

Passive

1. If the measured CO_2 levels are higher than 700 ppm the windows will open. In case of rain or wind faster than 6 m/s the windows will be/stay closed.

If the above measures are not sufficient the system will go to semi-passive measures.

Semi-passive

2. Mechanical ventilation will be turned on without actively cooling.

Manual overrides for the window controls are available.

Visual comfort

Currently, no light intensity or occupancy sensors are installed for visual comfort. All lights are manually switched on and off by the residents.

Heat and cold generation

A detailed drawing of this system can be found in Appendix B.

Solar chimney

Currently, the control system of the solar chimney is a separate system that is not connected to the building management system of the prototype (MOR Team, 2019b).

Interior garden

The interior garden acts as a thermal buffer. Outside air will enter through the window in the garden before entering the apartment. Additionally, the phase-changing materials inside the active green wall can pre-heat or cool the air.

In order for passive pre-heating and cooling air in the interior garden to occur, the phase-change materials need to be charged with the respective cold or heat. The interior garden is not a climatised zone. Therefore in winter, the building management system will close the window to store the solar heat. In summer the building management system will open the garden window during summer nights in order to pass the cold nighttime air past the phase-change materials to solidify them. During the day the window will close if the outdoor temperature becomes too high in order to limit the heat gain in the interior garden. During the mid-seasons, the window will be opened during the day to store warmth in the interior garden. If the mechanical ventilation is active the window should never be closed completely but keep a minimal open setting (MOR Team, 2019b).

Active green wall

The interior garden also contains an active green wall. This system has two functions, first to load the PCMs with cold or heat, and second to use this cold and heat to pre-cool or heat the air going into the apartment.

Inside the active green wall containing the PCMs, a fan is controlled by the building management system based on the season. The building management system can calculate the season based on the outside air temperature of the past 5 days using a weighted average. Currently, it only takes the hourly average of the current day into account. If the calculated temperature falls between 5,0 °C and 19,0 °C the middle season is active. If it falls below 5,0 °C the winter season is active. If the temperature exceeds 19,0 °C The summer season is active.

The PCMs are loaded with heat if the air temperature in the garden is higher then the calculated heating setpoint (20,0 °C) and the middle- or winter season is selected. The PCMs are loaded with cold if the air temperature in the garden is lower then the calculated cooling setpoint (24,0 °C) and the summer season is active.

Air from inside the interior garden is used as supply air inside the apartment. The air can eighter come from the garden directly or via the active green wall containing the PCMs. The building management system uses two air valves to control whether the air comes from the active green wall or not. Heat from the PCMs is delivered to the ventilation air if the intake air is lower then the desired supply air temperature (18,0 °C) and the middle- or winter season is active. Cold from the PCMs is delivered to the ventilation air if the intake air is higher then the desired supply air temperature (18,0 °C) and the summer season is active. The heat and cold deliverance will be stopped

Heat pump

For heat and cold generation the prototype uses an air-to-water heat pump. It was to be connected to a PCM battery which eventually was not implemented due to time constraints. The heat pump supplies in cooling mode the central air cooler, floor cooling and climate ceilings with cold water and in heating mode the floor heating and climate ceiling with warm water (see Appendix B).

The heat pump has three controls:

1. Turning on or off.
2. Switching from heating to cooling mode.
3. Setpoint adjustment in heating or cooling mode.

Currently, heating is set to 30 - 35°C and cooling is set to 8 - 14 °C.

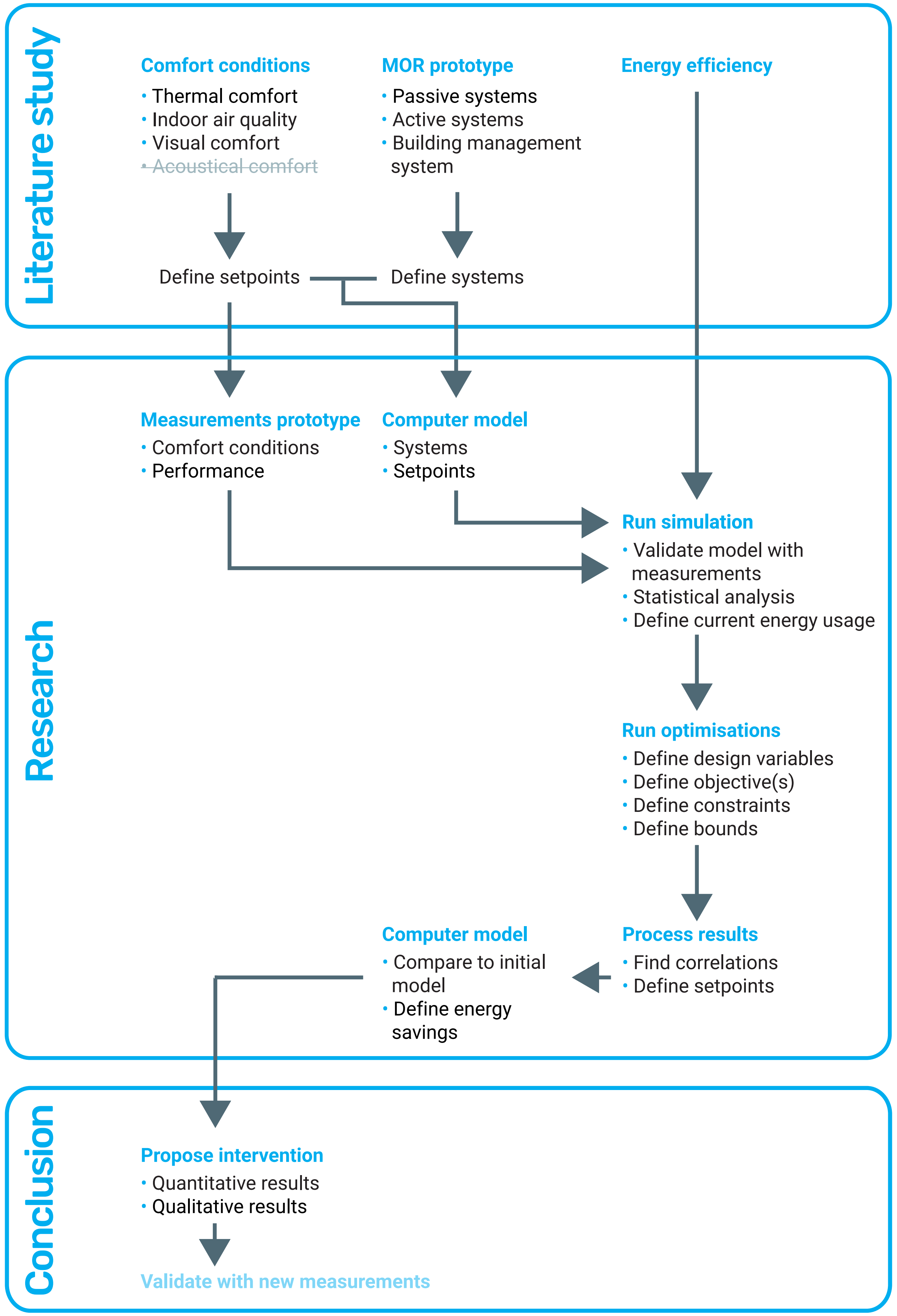


Figure 23: Optimisation workflow schematic

4. METHOD

A DesignBuilder model was used for calculations before the competition. This existing model could be used for optimisations. However, it was opted to use modeFRONTIER as optimisation software. Unfortunately, modeFRONTIER currently does not have a node for DesignBuilder integration. Therefore in order to optimise the building management system with modeFRONTIER, a Grasshopper model is built. This Grasshopper model uses components from the Grasshopper plugins Ladybug, Honeybee and Ironbug.

To see how the current settings of the building management systems function within the prototype, measurements are made. These measurements will be used to validate if the model created for optimisation is correct. Next to that, these results can be used to compare to the measurements taken after interventions are made in the prototype, in order to see if they truly work.

Software and versions
- ***modeFRONTIER 2019R3***
- ***Rhino version 6 SR24***
- ***Grasshopper build 1.0.0007***
- ***Ladybug version 0.0.68***
- ***Honeybee version 0.0.65***
- ***Ironbug Preview Release***
- ***Elements version 1.0.6***
- ***IBM SPSS Statistics version 24***
- ***DesignBuilder version 5.5.2.003***

4.1 Measurements

With the software from Priva, Top Control 8, measurements made with the sensors are automatically stored on a laptop inside the electrical cabinet. TC Operator visualises both HVAC schematics (see Figure 24) and ventilation schematics (see Figure 25 on the next page) as well as room schematics. When clicking on the data points a window pops up where all settings can be found and changed (see Figure 26 on the next page).

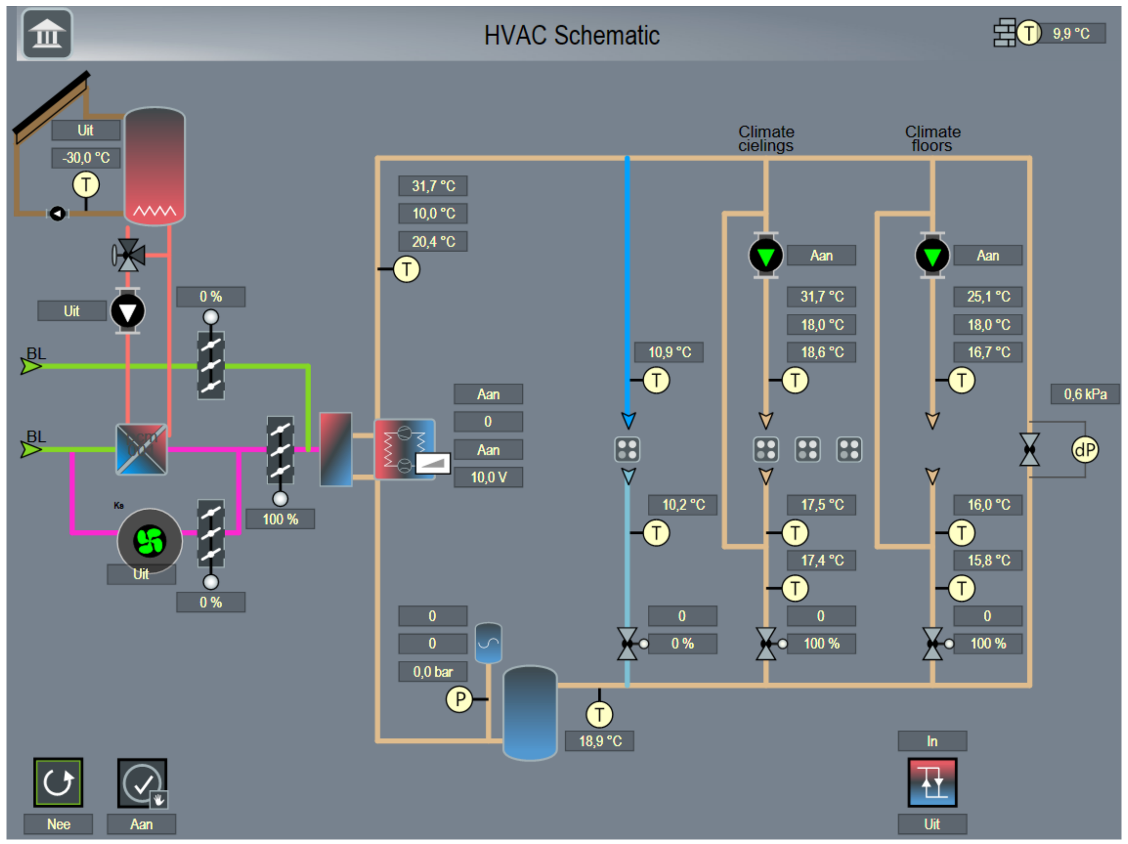


Figure 24: HVAC Schematic in TC Operator

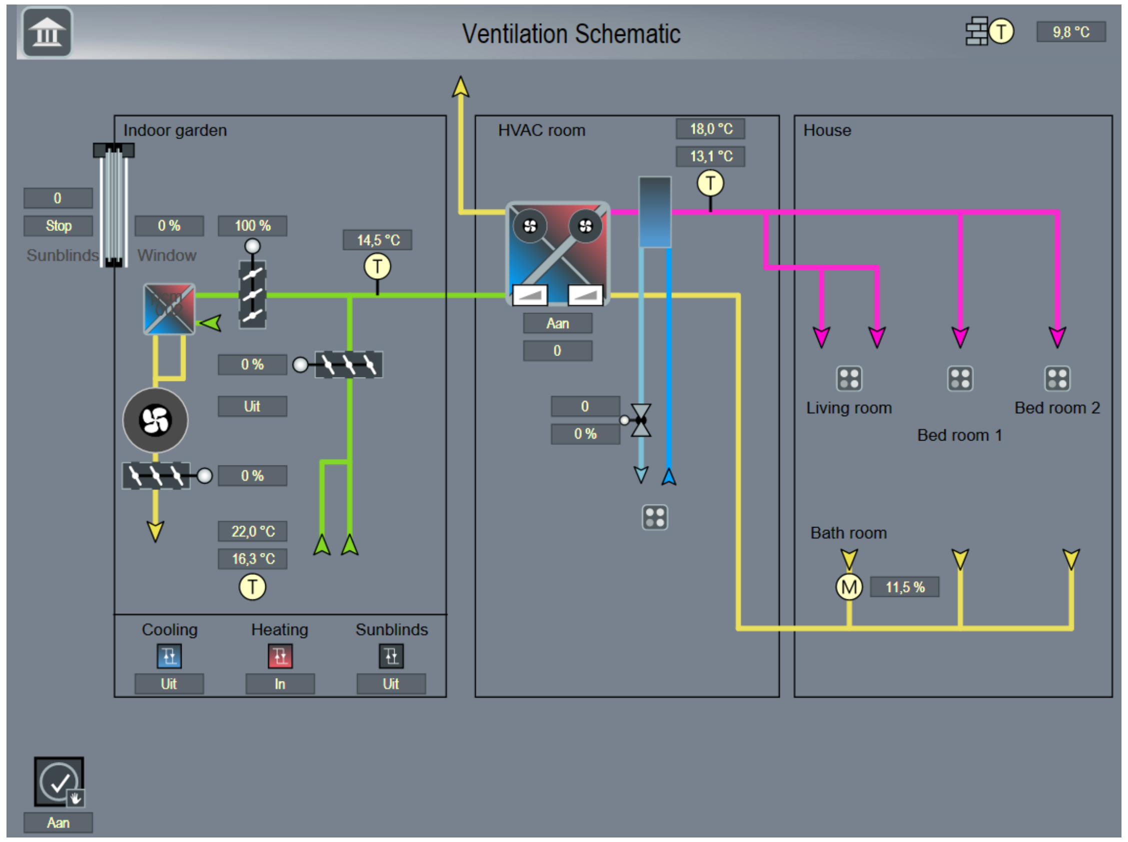


Figure 25: Ventilation Schematic in TC Operator

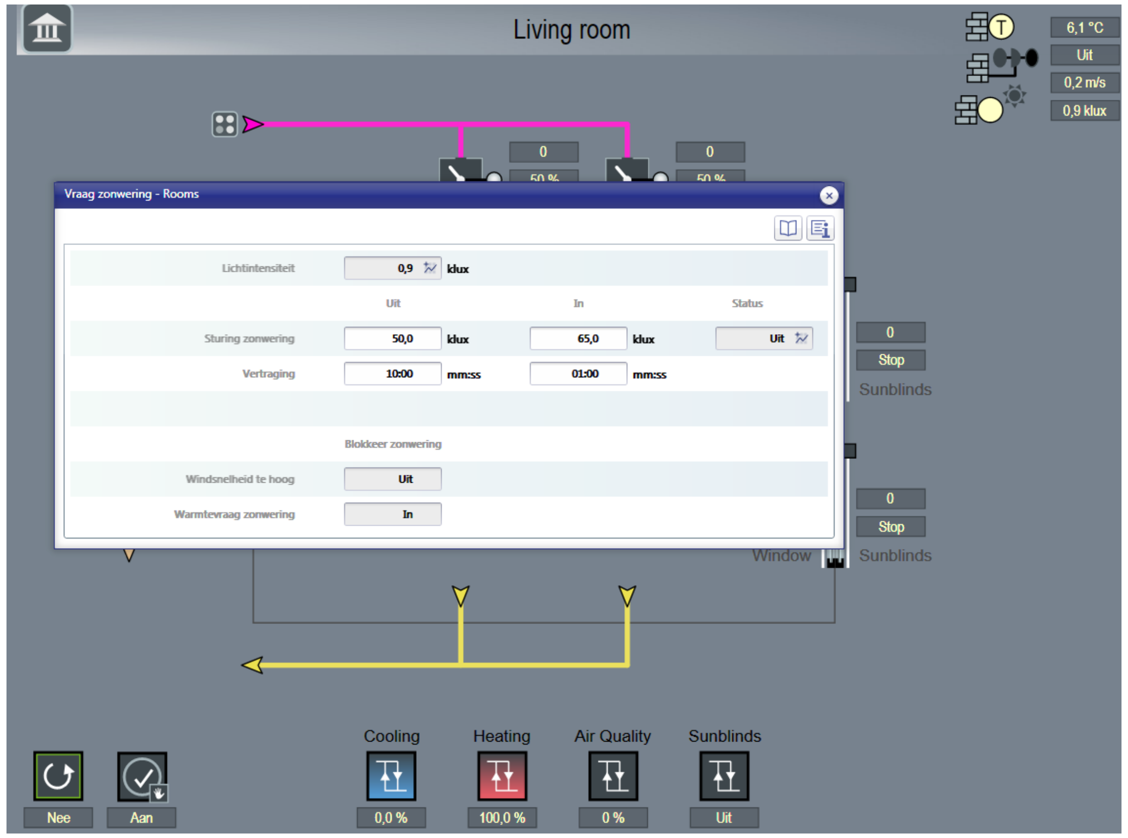


Figure 26: Blinds settings living room in TC Operator

When clicking a data point it can be selected to use TC History and store all measurements so they can be set into graphs or exported. Figure 27 shows clearly that the room temperature and supply temperature of both the climate ceilings and the floor heating follow the outside temperature. Figure 28 shows that the windows will open fully when the CO_2 levels inside the living room reach the (current) setpoint level of 700 ppm, disregarding the indoor or outdoor temperatures.

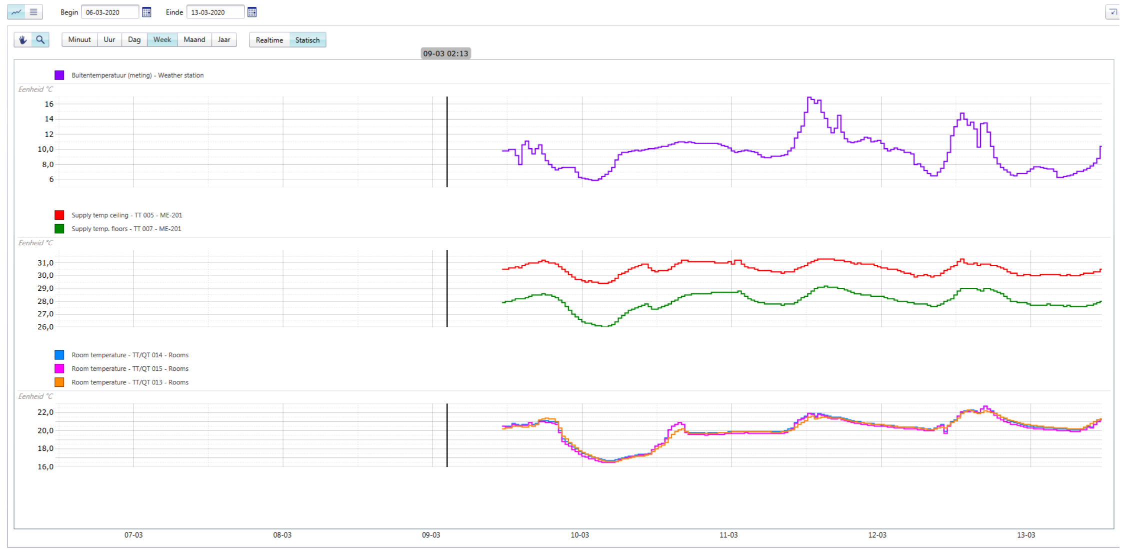


Figure 27: Temperature measurements over three days in TC Manager

Figure 28: Opening of the living room window in respect to the indoor air quality and room temperature over three days in TC Manager

Sensor data

Due to the coronavirus, the TU closed all facilities to students. Therefore all measurements made in the prototype since the 18th of March are of an empty prototype. It is not possible to check whether someone did still enter the prototype. Next to that, some work on the prototype was not finished (see Chapter 9.1 “Limitations” - “Prototype”).

Figure 29 on the next page, shows the indoor air temperature of all rooms of the prototype. Both bedrooms and the living room temperatures are really close due to the fact that the sliding partition walls are open most of the time, if not all of the time. The temperature in the garden (in red) is a little bit lower, this is limited due to the fact that also the garden door has been opened for a long period. Around the 18th of April the difference increases. This could be due to someone closing the garden door.

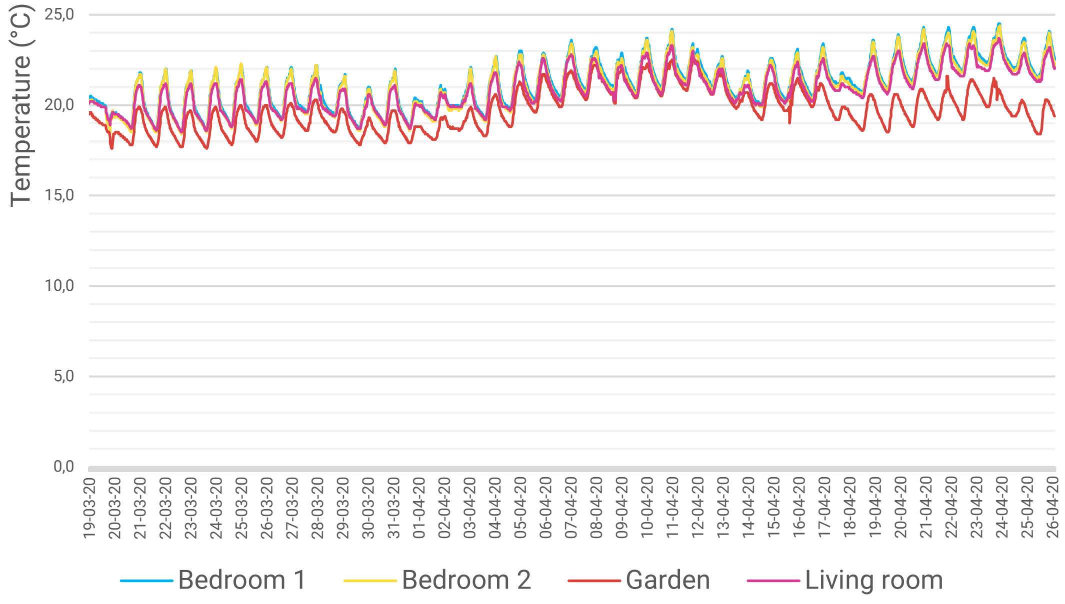


Figure 29: Indoor temperature measurements

Figure 30 shows the indoor air quality measurements. The CO_2 levels of the rooms stay well within a comfortable range. It shows two spikes that go above 700 ppm in the living room (in blue). One on the 8th of April and one on the 28th of April.

As can be seen in Figure 26 on page 40, there does seem to be a relative humidity sensor available inside the bathroom. This sensor was not mentioned anywhere in the documentation. Figure 30 shows the measurements done by the relative humidity sensor in the bathroom. This sensor measures a relative humidity of around 10 % at all times. This is very low, even for an empty building. These measurements could be considered to be false since these outcomes are very unlikely and since no documentation on the sensor is available.

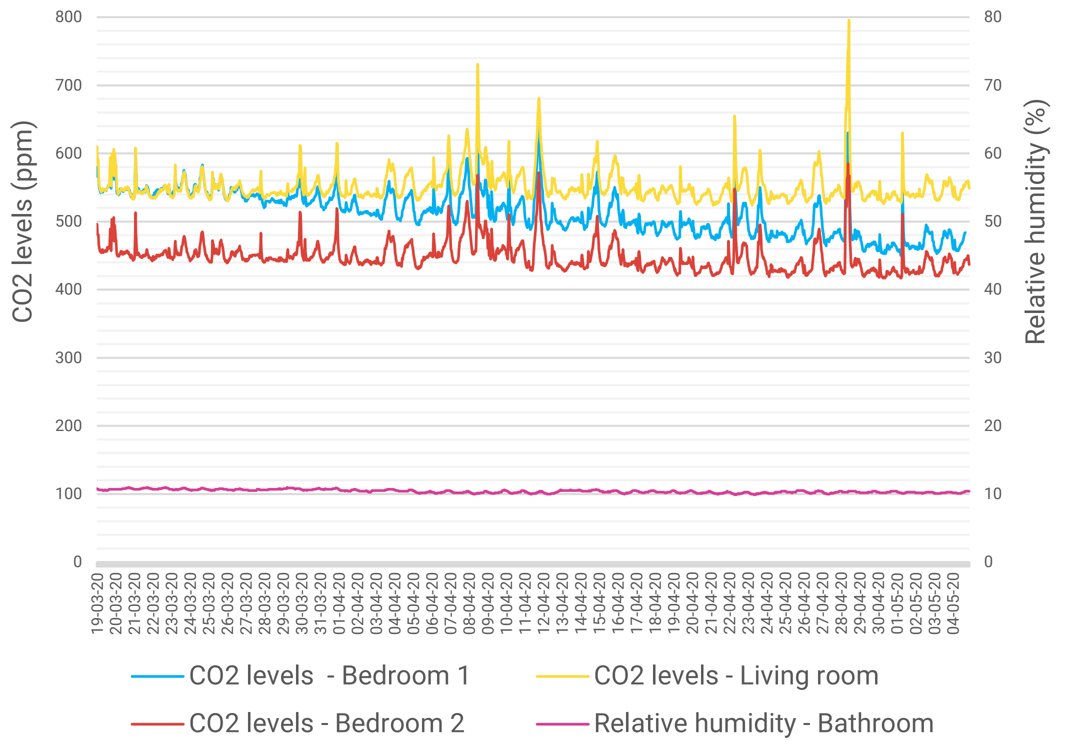


Figure 30: Indoor air quality measurements

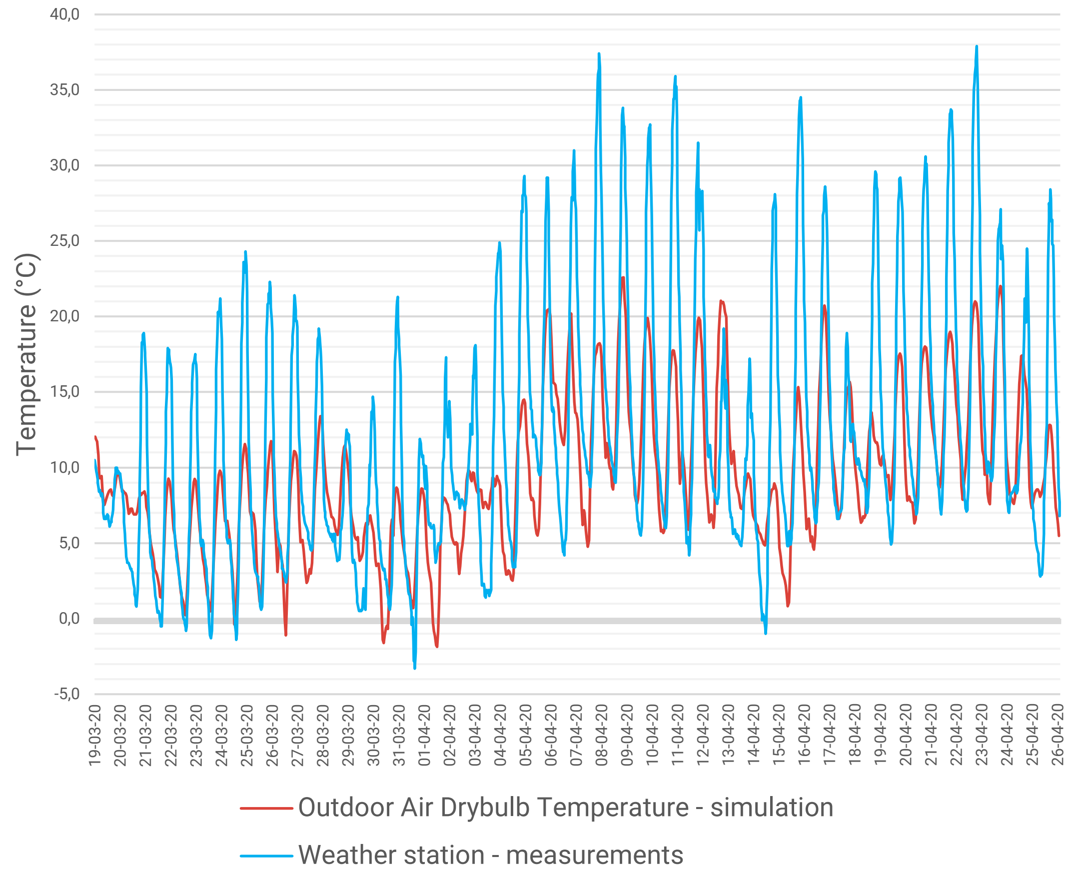


Figure 31: Outdoor air dry bulb temperature measurements from the weather station

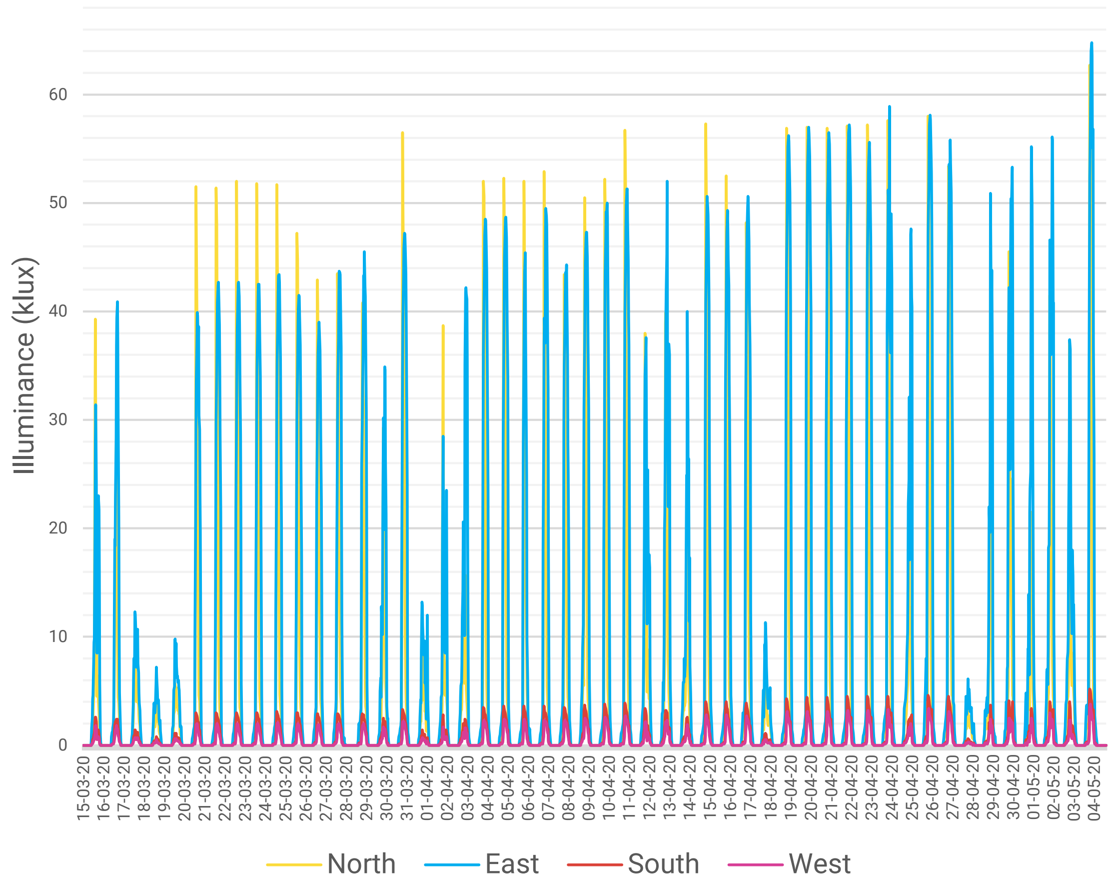


Figure 32: Illuminance measurements from the weather station

Weather station data

Figure 31 on the previous page, shows the temperature measurements registered by the weather station located on the roof of the prototype (in blue) and the temperature measurements registered by the KNMI weather station at Rotterdam airport (in red). This figure shows clearly that the measurements made by the prototype are not reliable. The weather station is located to close to the roofing and mostly registers the heat coming off the roof instead of measuring the outdoor air temperature.

Figure 32 on the previous page, shows the illuminance measured by the weather station. It is clear that the weather station is not rotated correctly as it measures more sunlight coming from the north.

4.2 Grasshopper model

For the optimisations, a working model of the prototype is needed. Since the existing DesignBuilder model will not work with modeFRONTIER, a new Grasshopper model is built.

Geometry

First, the geometry of the rooms and windows are drawn in Rhino (Figure 33) and set as Breps in Grasshopper. To simplify the model the interior modules are not drawn inside the prototype. The sliding partition walls and the garden wall are drawn but the outside door and apartment door are not.

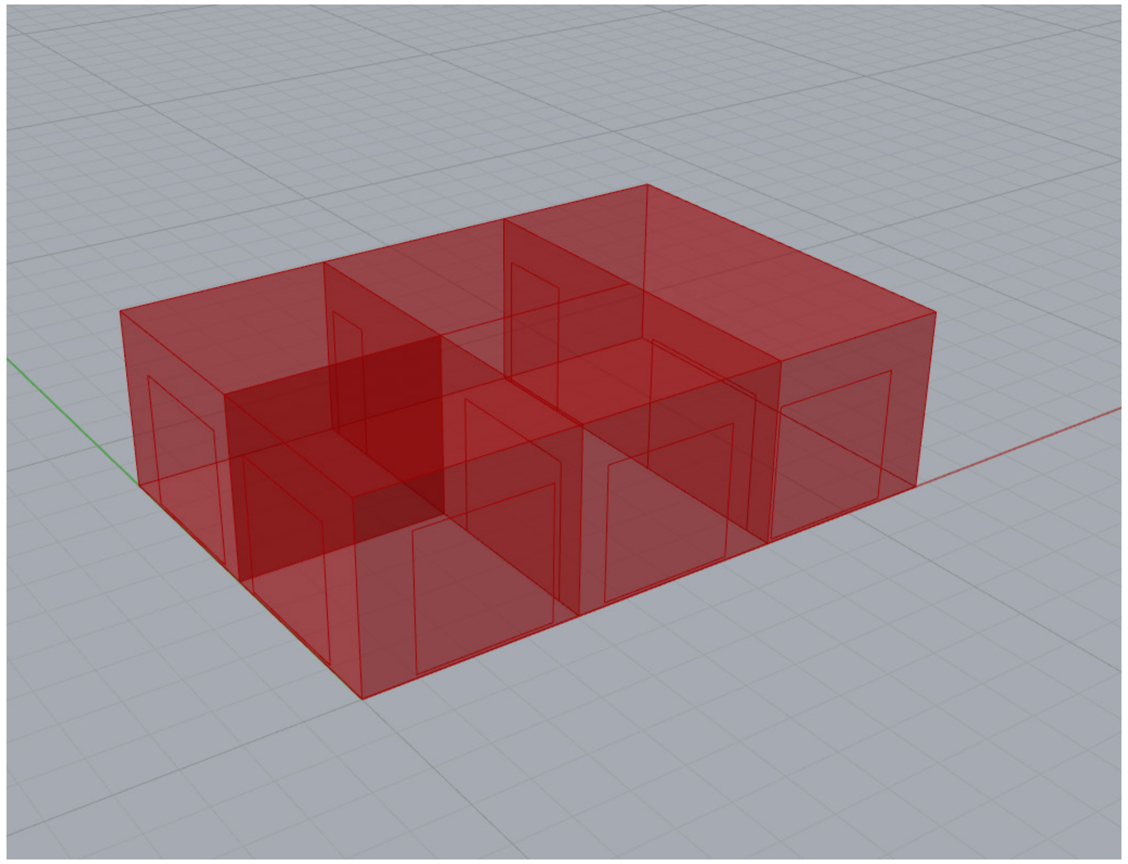


Figure 33: Geometry in Rhino

Materials

The materials are first defined as EnergyPlus materials and then layered together as EnergyPlus constructions. These are added to the project library and can then be set for the corresponding surfaces (see Appendix A).

Zones

The geometries are exploded and individually imported as geometries to be set as Honeybee Surfaces. Next to that the EnergyPlus constructions and surface types are set. The windows are scaled to account for the frames. Per room, these geometries are combined as Honeybee Zones (Figure 34). Since the prototype has sliding partition walls and a folding garden wall which can be opened these walls are set as Airwalls to simulate an open space with free-flowing air. Afterwards, these Honeybee Zones are combined while solving adjacencies (Figure 35). This component sets the shared (air)walls in the prototype.

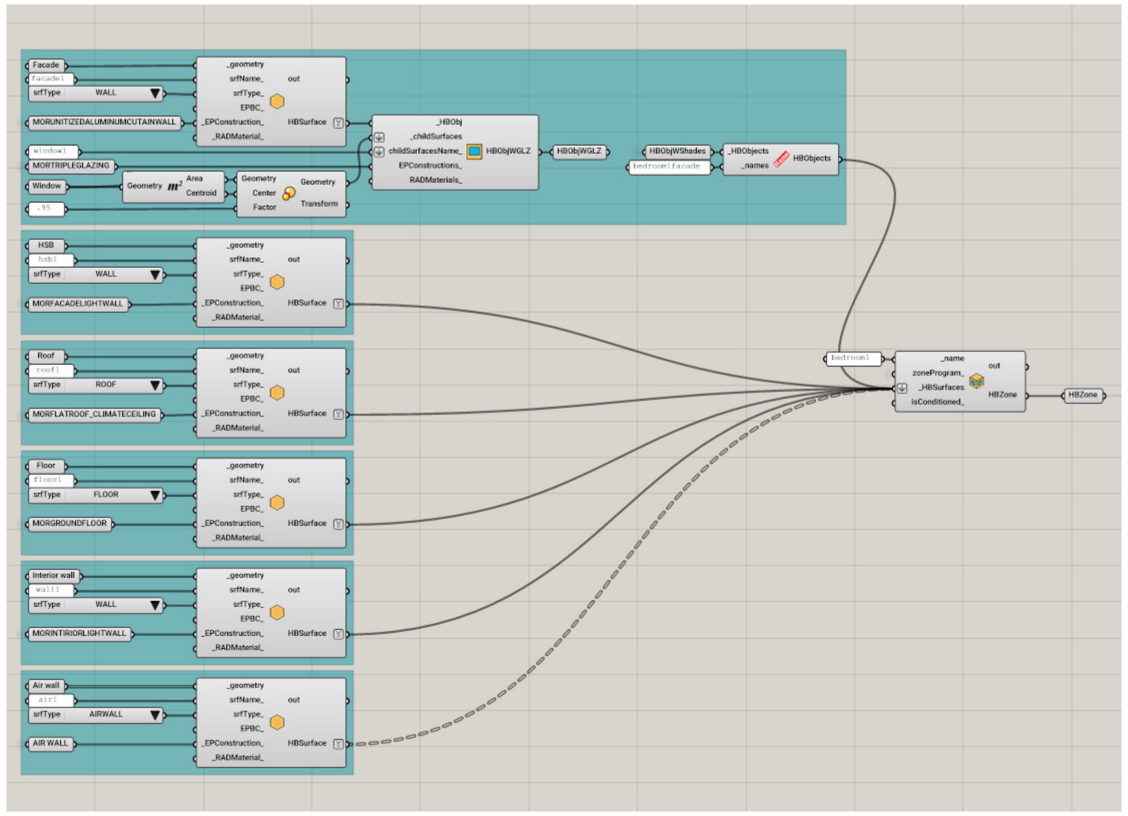


Figure 34: Bedroom geometry set as Honeybee Zones

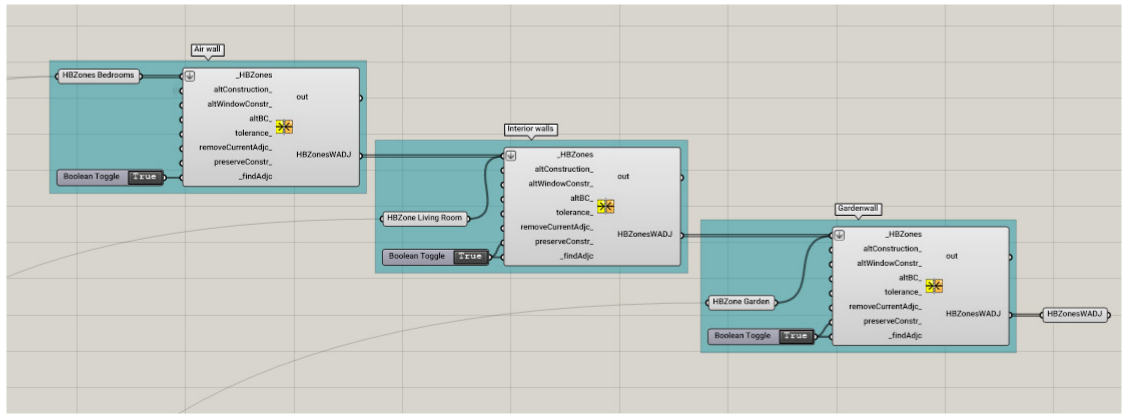


Figure 35: Solve Adjecencies

Shades

The shading is added to the windows before the Honeybee surfaces are combined into one Honeybee zone. In Figure 36 on the next page, the material for the shading is added. The control type is set to On if high zone air temperature to make sure the shading goes down if the cooling setpoint is reached. The schedule is used to set the radiation setpoint and the wind alarm. This means that the shading only goes down if all three conditions are met.

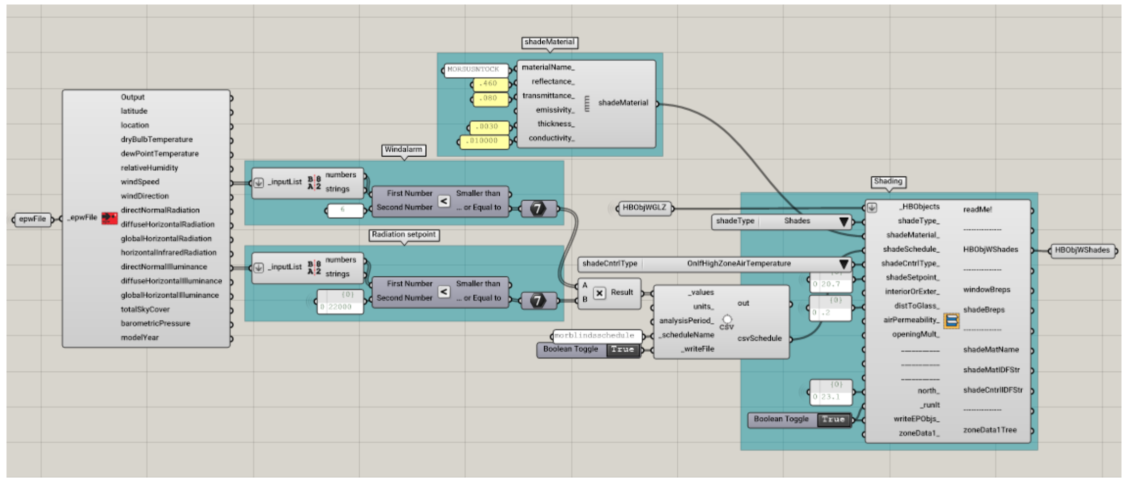


Figure 36: EnergyPlus Window Shade Generator and managing schedules

Internal loads, schedules and setpoints

Next, the internal loads are calculated for each room (Figure 37). For the calculations of the prototype's performance in Hungary, an equipment load of 6 W/m2 was used (MOR Team, 2019b). The infiltration rate per area façade is estimated at 0,0009 m3/s-m2 to account for the issues regarding the airtightness of the prototype. Therefore, the infiltration schedule is set to always on. The dutch building decree states a minimum ventilation rate of 0.9 L/s per m2 (MOR Team, 2019b). This number is converted to m3/s per m2 in Grasshopper.

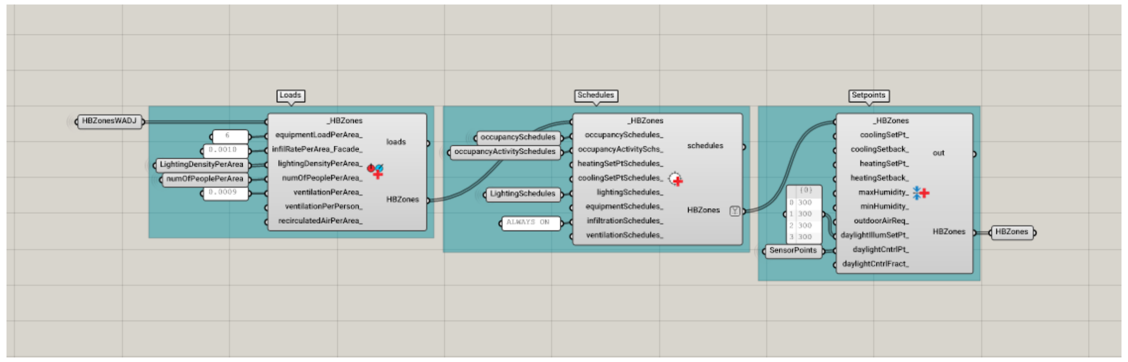


Figure 37: Set EnergyPlus Zone Loads, Set EnergyPlus Zone Schedules and Set Energyplus Zone Thresholds

In order to calculate the lighting density per area, the power in Watts of the individual lights is multiplied with the number of lights per room. They are then divided over the area of the rooms (Figure 38).

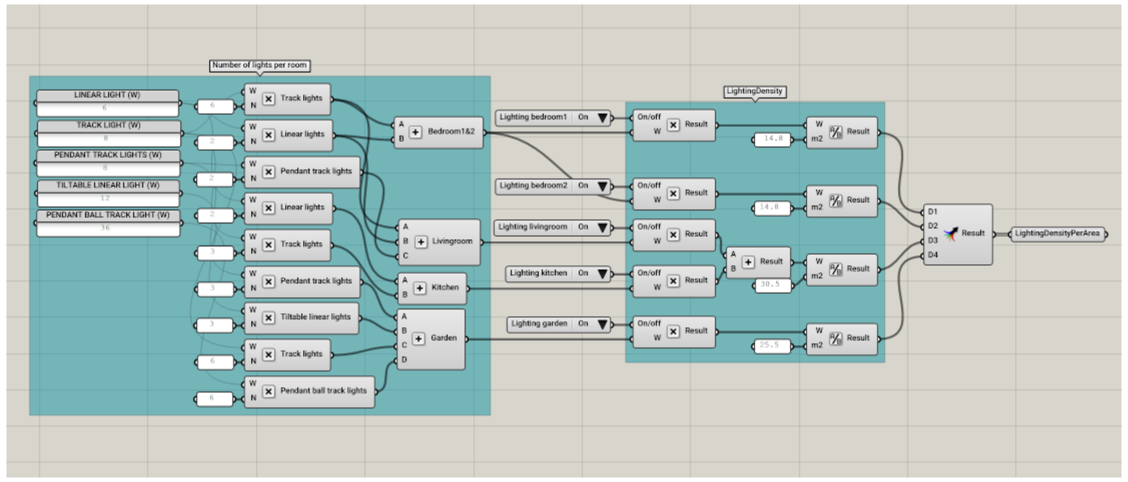


Figure 38: LightingDensityPerArea

Since the prototype was not occupied during the measurements the number of people is set to 0. Later, to simulate a reference period in the prototype this can be set to the number of residents the prototype is designed for, two. The number of people in the prototype is divided over the total area of all the rooms (Figure 39).

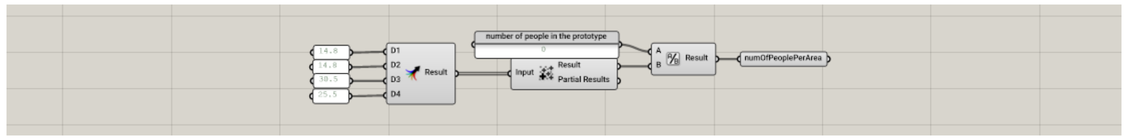


Figure 39: numOfPeoplePerArea

An occupancy schedule is generated to simulate when the residents are inside the prototype (Figure 40) and an occupancy activity schedule is generated to simulate the activity level during those times (Figure 41).

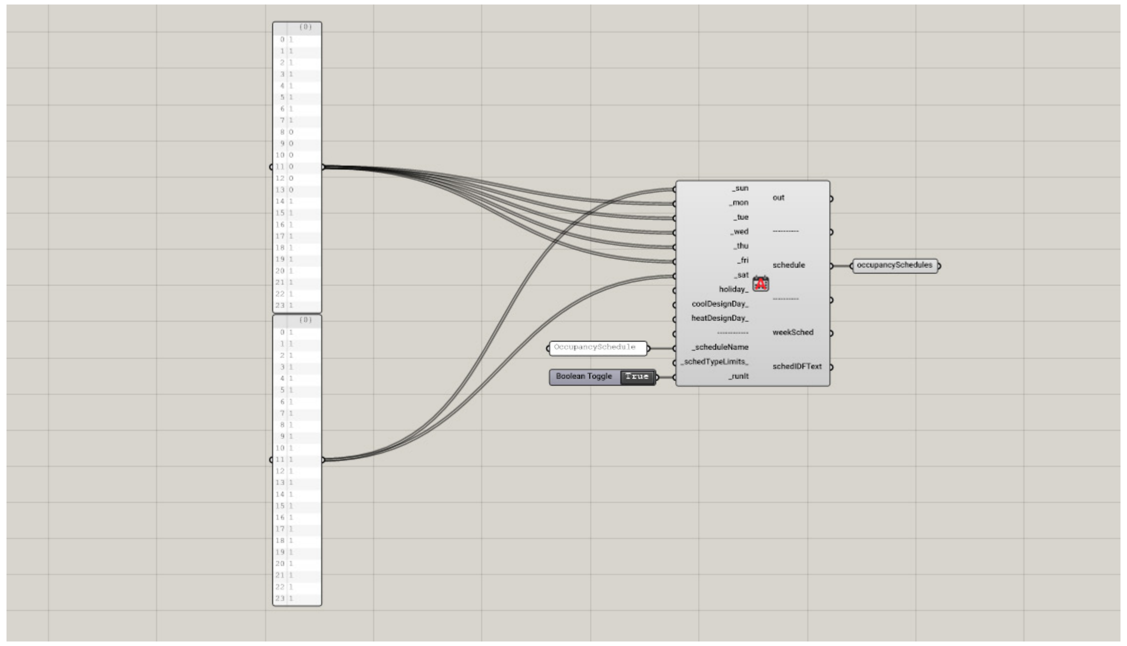


Figure 40: Occupancy Schedule

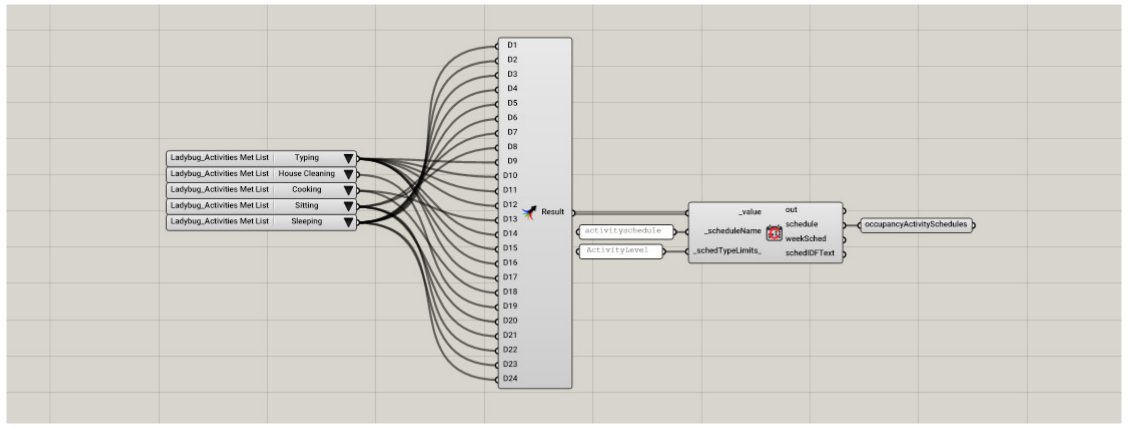


Figure 41: Occupancy Activity Schedule

To generate a lighting schedule, sensor points are generated in the centre of the rooms at a height of 0,8 m (Figure 42 on the next page). The lighting control type is currently set to manual on/off switch since this is not yet controlled by the building management system, but this can later be adjusted to find the best system to implement in the prototype. The sensor points are also used as daylight control points as can be seen in Figure 37. The daylight illuminance setpoint is set to 300 lux as found in literature.

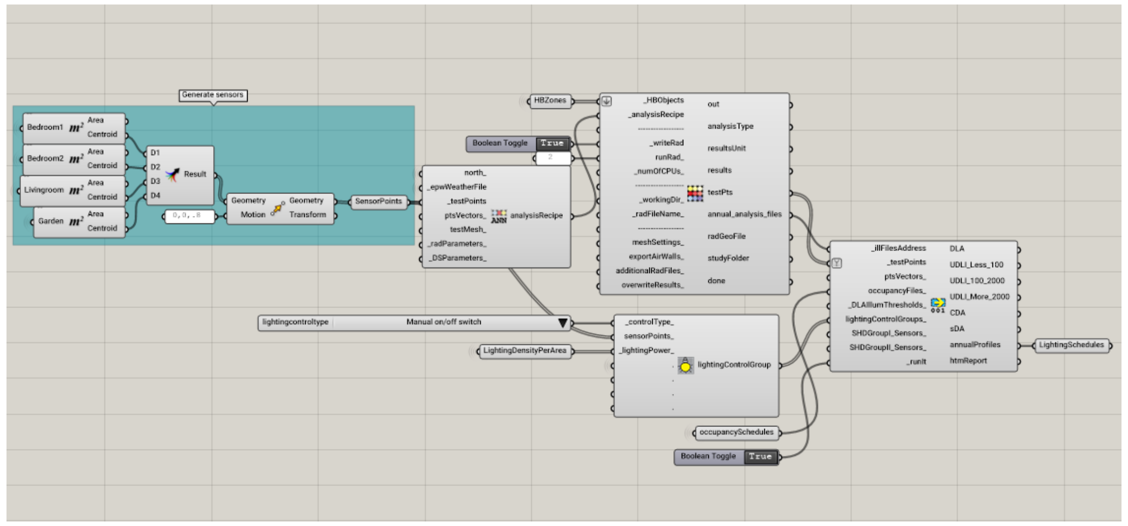


Figure 42: LightingSchedules

Natural ventilation

Natural ventilation is calculated using the set EnergyPlus Air Flow component (Figure 43). This component reads the glazed area of the zones and calculates the operable area based on the fraction of glazing height operable. For the prototype, this fraction is set to 0,45. To distinguish the difference between the garden and the other rooms in the prototype this part is split into conditioned zones and unconditioned zones (garden). For the conditioned zones the setpoint for natural ventilation is set to 21,2 °C which corresponds to 35% cooling demand. For the garden, the cooling setpoint is set to 24,0 °C.

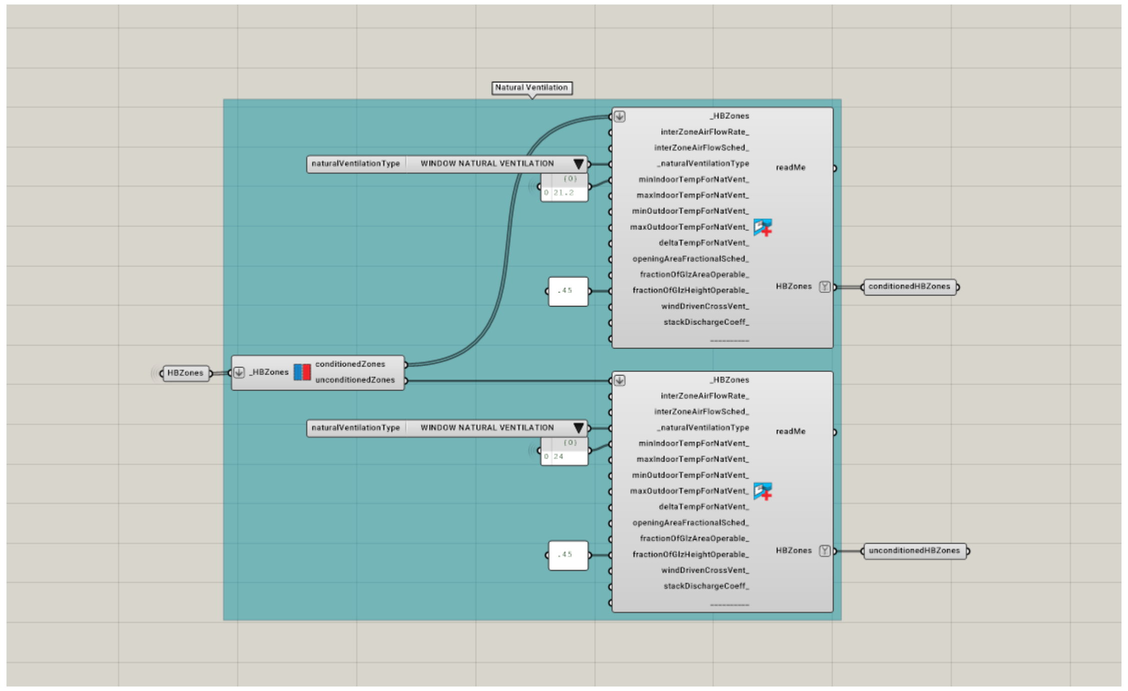


Figure 43: : Set EnergyPlus Air Flow

It is not possible to set a minimum of -3,0 °C temperature difference between the indoor and outdoor air temperature. The deltaTempForNatVent component only allows for a maximum temperature difference. Next to that this component does not allow for a setting indoor air quality setpoints. It is therefore not possible to set a maximum level of CO_2 for which the window will open to ventilate. Finally, it is not possible to set a wind or rain alarm to close the window when it starts raining or when the wind exceeds 6,0 m/s.

HVAC

For the conditioned zones an HVAC system is assigned to each thermal zone. Therefore the three rooms (bedroom 1, bedroom 2 and living room) are set as OpenStudio thermal zones using the Ironbug plugin (Figure 44). The thermal zones are connected to the AirLoopBranches component in Figure 48 on the next page.

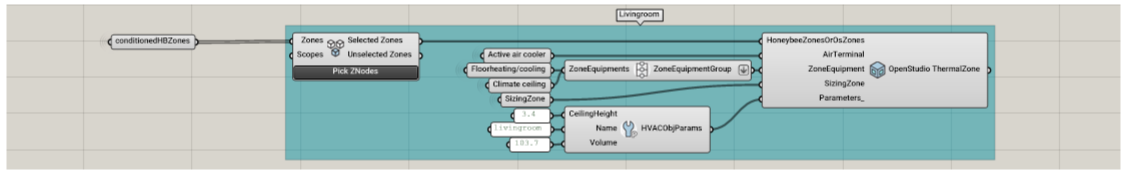


Figure 44: Set OpenStudio Thermal Zones

First, an air terminal is set (Figure 45). The active air cooler as mentioned in Chapter 3.2 “Active systems” is set as a chilled beam. This component is connected to the air terminal component in Figure 44. The coil cooling water is connected to the chilled water plant loop in Figure 53 on the next page.

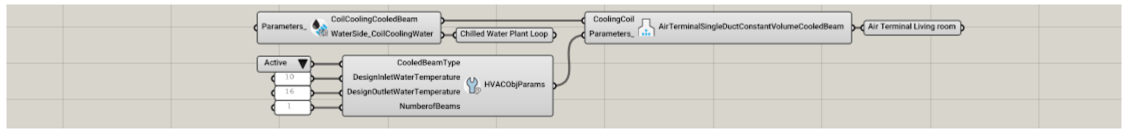


Figure 45: Air Terminal

The floor heating and cooling and climate ceilings are both set as low-temperature radiant systems with variable flow (Figure 46). The floor heating setpoint is set to an outdoor temperature of 16 °C and floor heating to and outdoor temperature of 23 °C. The climate ceiling heating setpoint is set to 20,8 °C indoor air temperature which corresponds to a 55% heating demand and the cooling setpoint is set to 21,4 °C indoor air temperature which corresponds to a 75% cooling demand. These components are connected to the ZoneEquipmentgroup component in Figure 44. The water-side of the heating coil is connected to the hot water plant loop in Figure 52 on the next page, and the cooling coil is connected to the chilled water plant loop in Figure 53 on the next page.

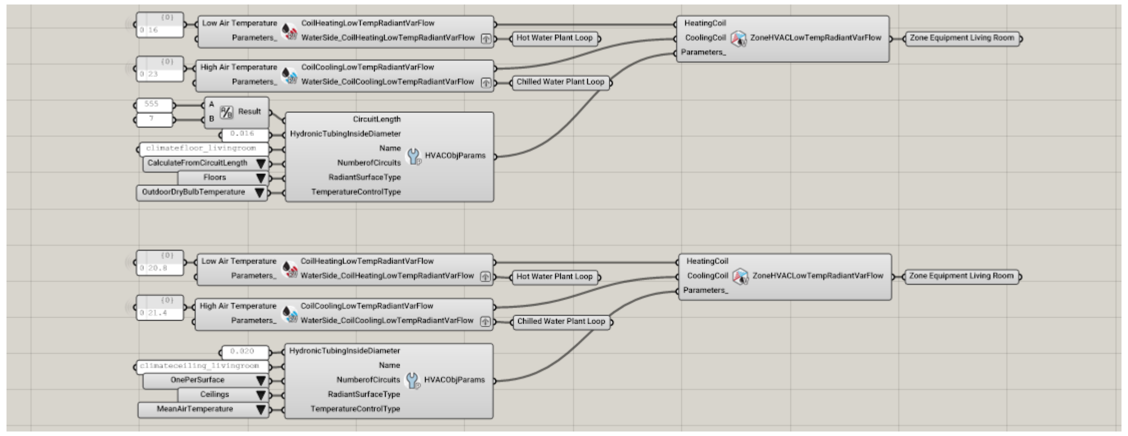


Figure 46: Low-Temperature Radiant Systems

The sizing zone component adds some additional ventilation parameters (Figure 47). The airflow rate of 125 m3/h is converted to m3/s for Grasshopper (MOR Team, 2019a). This component is connected to the SizingZone component in Figure 44.

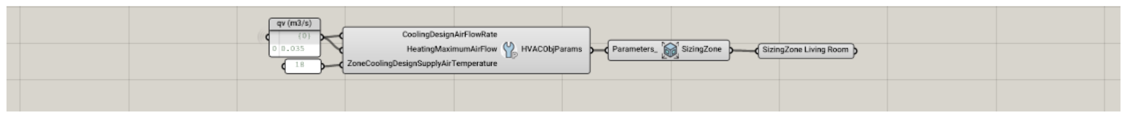


Figure 47: SizingZone

The thermal zones are part of the demand side of the air loop of the HVAC system (Figure 48). The supply side consists of a heat exchanger (Figure 49). The plant loops of the HVAC system consist of a condenser water plant loop (Figure 51), hot water plant loop (Figure 52) and chilled water plant loop (Figure 53).

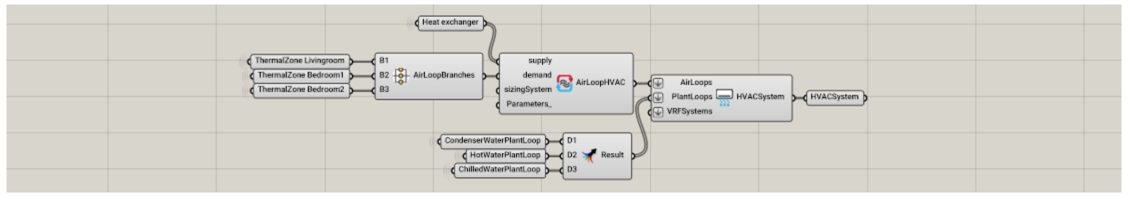


Figure 48: HVAC System

The air to air heat exchanger is set as an outdoor air system with two fans. This component is connected to the supply side of the air loop in Figure 48.

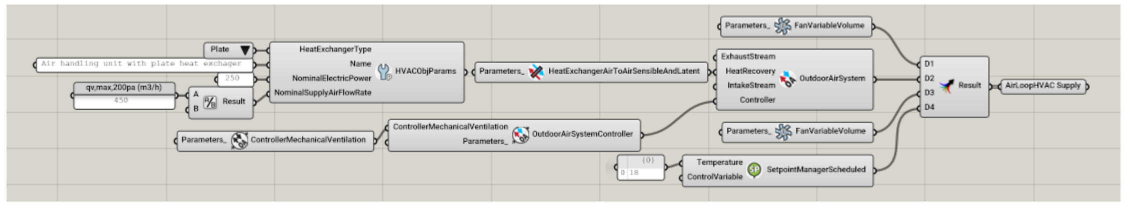


Figure 49: Heat Exchanger

The air-to-water heat pump (Figure 50) is connected to the demand side of the condenser water plant loop (Figure 51) and the supply side of the hot water plant loop (Figure 52) and chilled water plant loop (Figure 53). It is not possible to add a buffer tank.

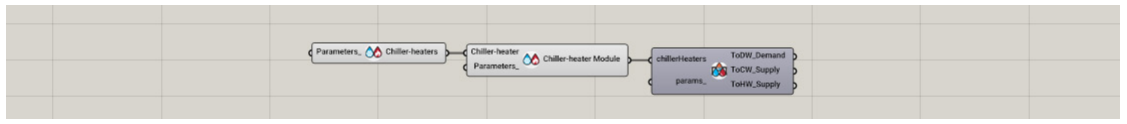


Figure 50: Heat Pump

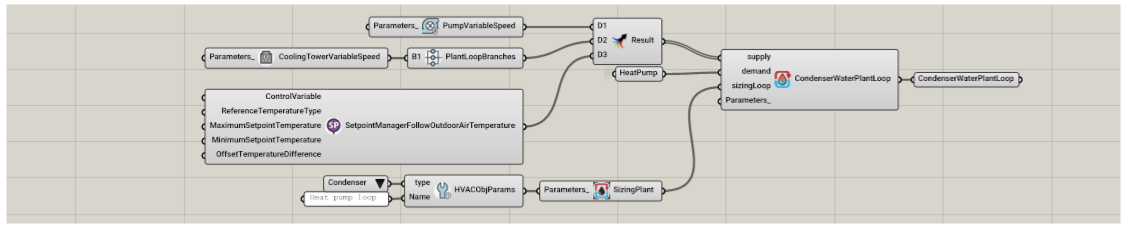


Figure 51: Condenser water plant loop

The hot water plant loop is connected to the heating coils of the floor heating and ceiling heating systems in Figure 46. This system has a variable setpoint between 30 – 35 °C. It is not possible to add pumps to the plant loop branches on the demand side. It is also not possible to add control valves.

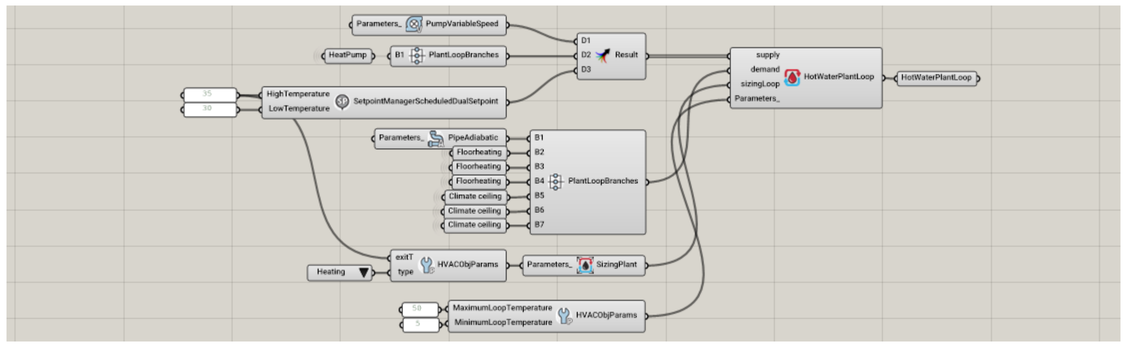


Figure 52: Hot water plant loop

The chilled water plant loop is connected to the cooling coils of the active air cooler (Figure 45) and floor cooling and ceiling cooling systems (Figure 46). This system has a variable setpoint between 8 – 14 °C. Here it is also not possible to add pumps to the plant loop branches on the demand side and to add control valves.

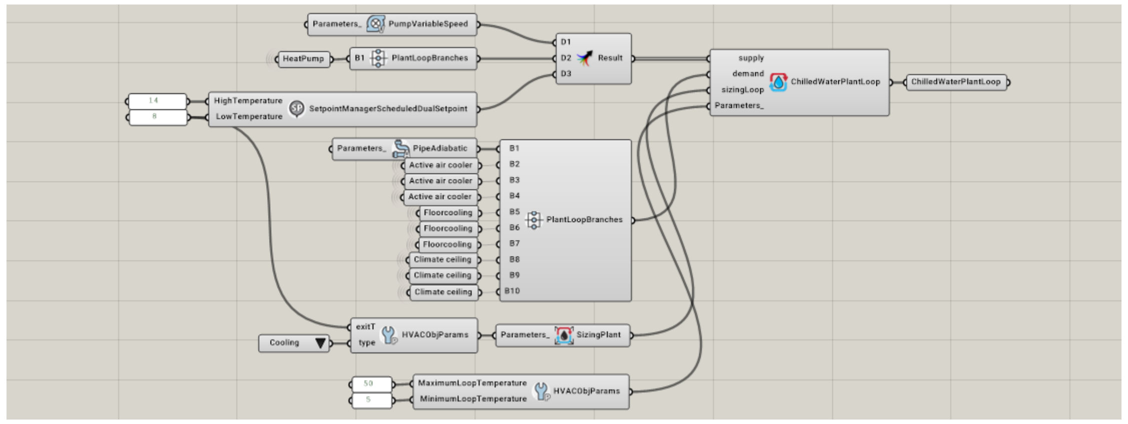


Figure 53: Chilled water plant loop

Energy generation

To calculate the energy produced by the prototype the Honeybee Generate PV System component is used. First, the inverter is generated. The same inverter is used for all PV systems. In Figure 54 the PV panels inside the solar chimney on the west façade are generated. In Figure 55 the coloured Building-integrated Photovoltaic (BIPV) panels are generated. In Figure 56 the black roof PV panels are generated. These systems are combined in Figure 57 on the next page, to one Generator system.

This system could be used to see if the prototype is still energy positive. PVT and solar chimneys panels are not added to the system yet.

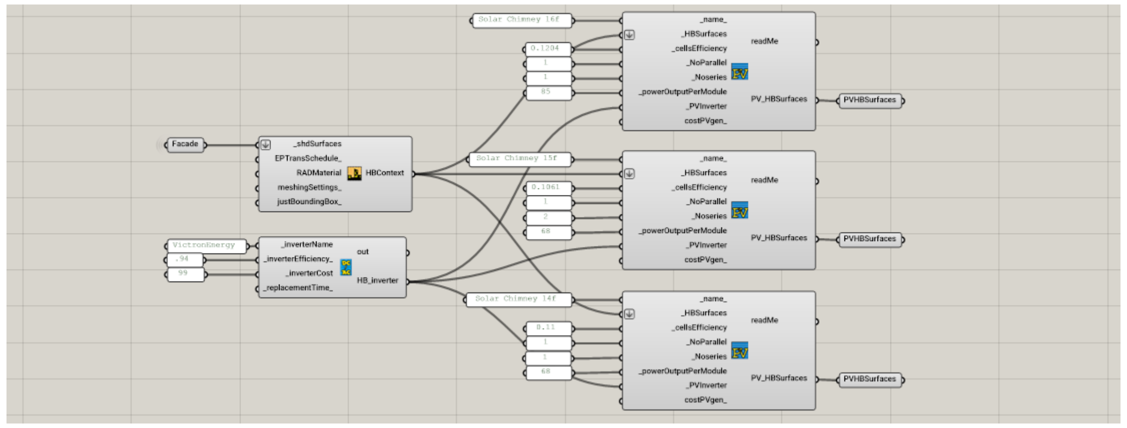


Figure 54: Honeybee Inverter and PV Generator for solar chimney PV panels

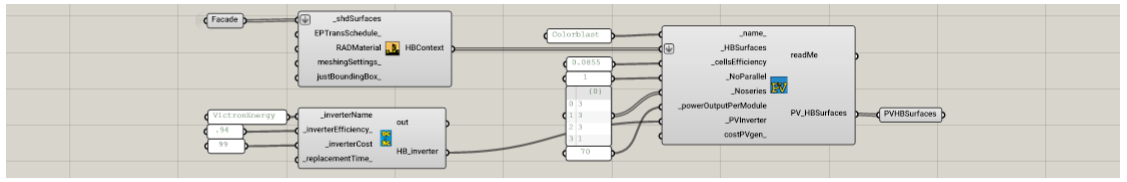


Figure 55: Honeybee Inverter and PV Generator for BIPV panels

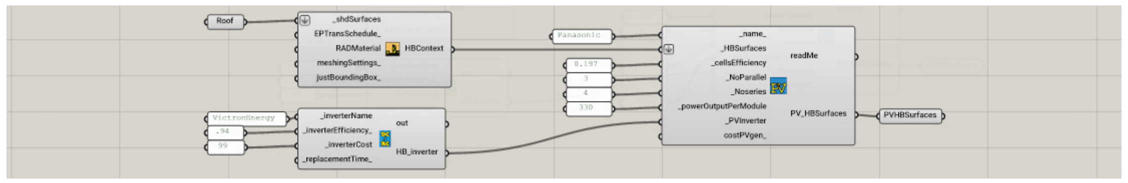


Figure 56: Honeybee Inverter and PV Generator for roof PV panels

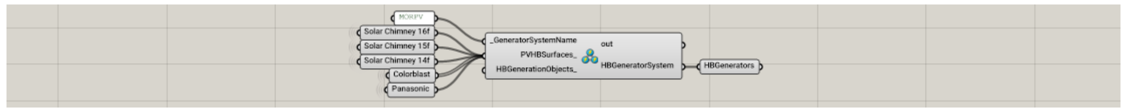


Figure 57: Honeybee Generator System

Weather data

In order to be able to compare the simulations to the measurements, an EnergyPlus Weather data file (.epw file) was needed. Only a file of Amsterdam is available online. This file uses reference years and will not use data of the current year. Next to that, Amsterdam is at a 45 km distance from the prototype.

Therefore Elements was used to convert KNMI data of the Rotterdam weather station to an .epw file. The Rotterdam weather station is only 6 km away from the prototype's location. And it is possible to use data from the current year. Since an .epw file needs global, direct and diffuse irradiation but the KNMI data only provides global irradiation, a template made by Dr. Regina Bokel was used to transform the sun data. This template uses the NEN 5060 model for separating the global irradiation into direct and diffuse irradiation.

The .epw file is stored locally on the computer and opened using the Ladybug open EPW Weather file component. It is then internalized into a data component, otherwise, it would prompt to select the file on startup of the model.

Simulation

Finally, an EnergyPlus simulation is set up in Grasshopper (Figure 58). To be able to compare the simulations to the measurements the analysis period is set to the same period that measurements of the prototype have been collected of. In order to be able to receive all data needed two extra simulations are carried out. In Figure 59 the simulation outputs are set so the illuminance results are output by the simulation. In Figure 60 the simulation outputs are set so the CO_2 results are output by the simulations.

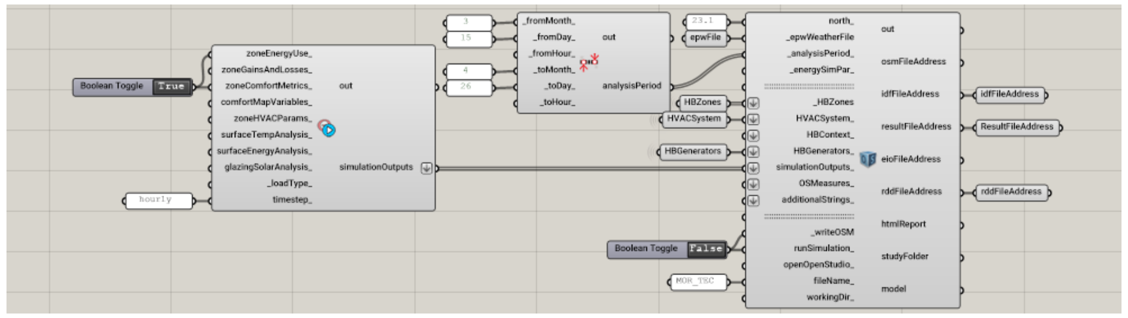


Figure 58: OpenStudio Simulation

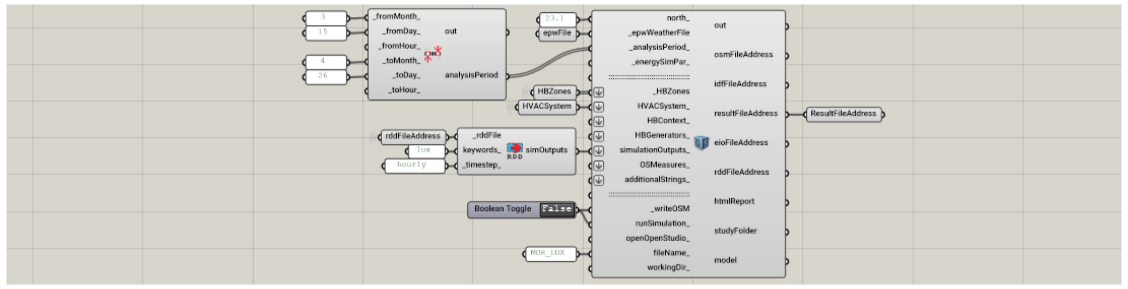


Figure 59: OpenStudio Simulation for receiving illuminance results

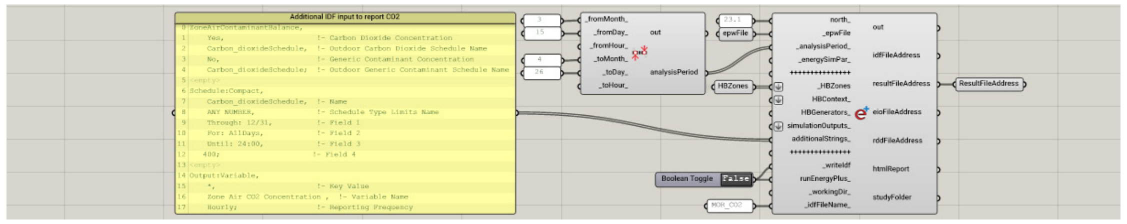


Figure 60: EnergyPlus Simulation for receiving CO_2 results

Outputs

Figure 61 shows all outputs needed to evaluate the model in modeFRONIER. These panels are grouped in a group called mf_out. This is necessary for modeFRONTIER to be able to find the outputs.

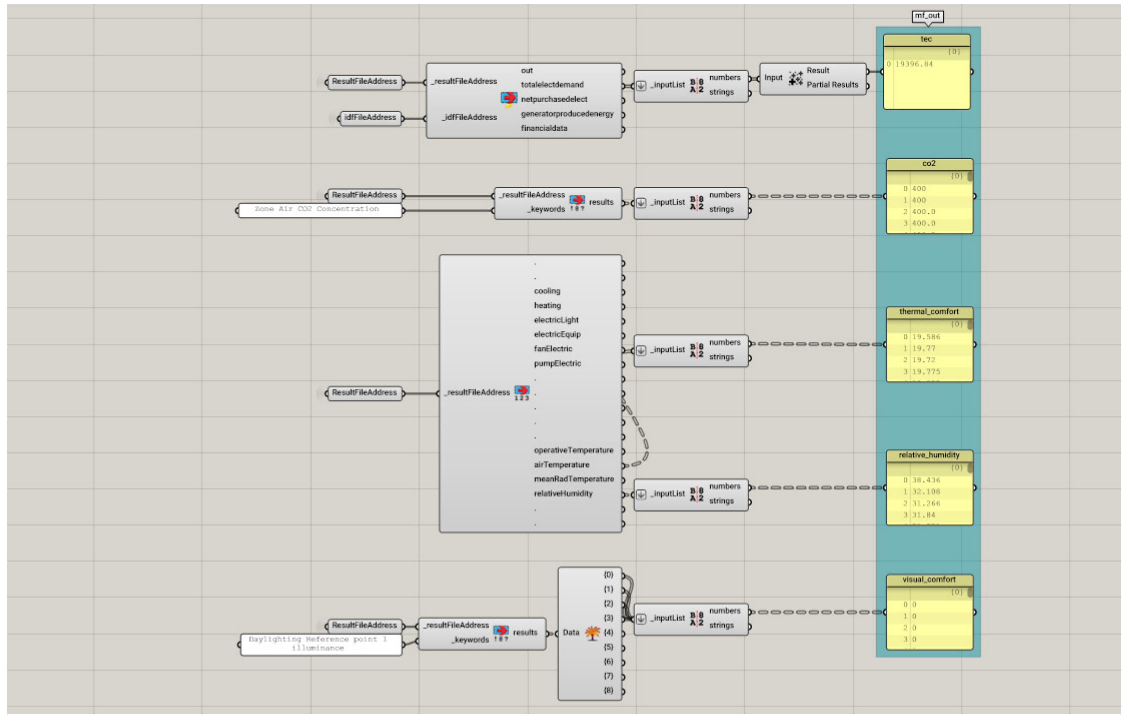


Figure 61: Outputs in Grasshopper to be read by modeFRONTIER

Thermal comfort

It is possible to use these outputs within Grasshopper to calculate whether the values fall within the comfort ranges. But since this model will be used by modeFRONTIER later. This will be set in modeFRONTIER to make adjusting the comfort ranges in a later stage easier.

In order to be able to use the adaptive temperature limits guideline, the adaptive comfort calculator is used to find the target temperature (Figure 62). This temperature can then be used to calculate the heating and cooling setpoints. If the application allows it, these setpoints could be used as input for the simulations.

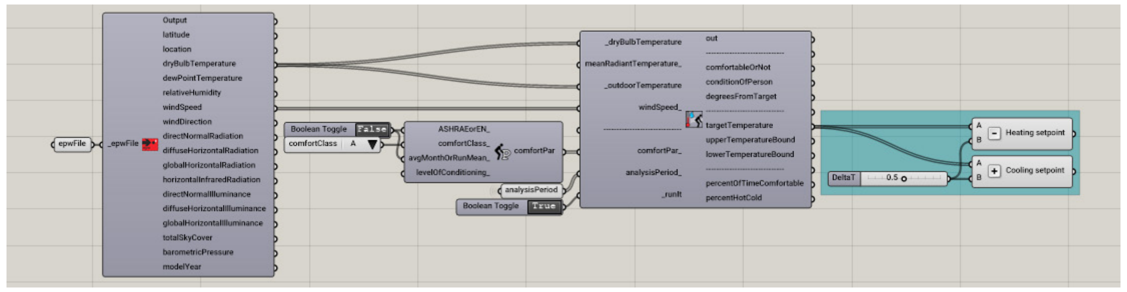


Figure 62: Adaptive Comfort Calculator

4.3 Simulations

The next step to be taken is comparing the outcomes of the simulation to the measurements taken inside the prototype.

Grasshopper model

Figure 63 shows the simulated (in red) and measured (in blue) indoor air temperatures inside bedroom 1. The amplitude of the simulations is much higher than the amplitude of the measured indoor air temperature. This means that the simulation cools down much more at night than the prototype actually does. It seems that the heating is not working properly.

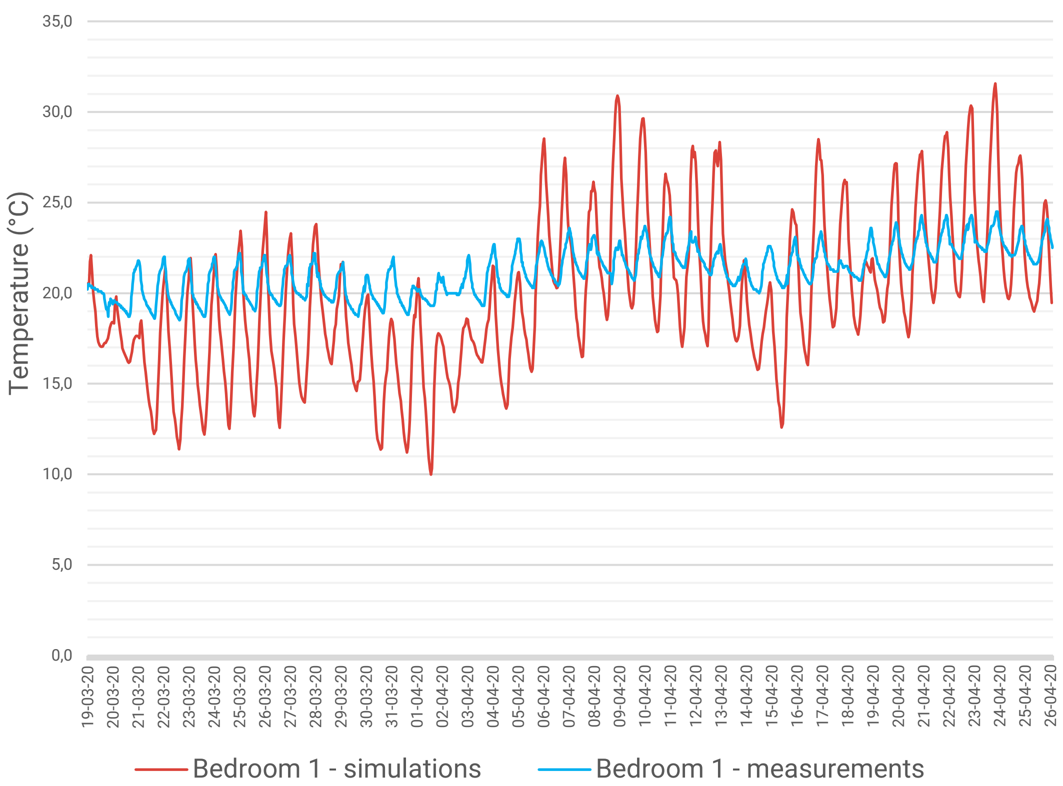


Figure 63: Comparison of simulated and measured indoor air temperature inside bedroom 1

In order to find out what causes this, data from the plant loop is extracted. Figure 64 shows the temperature inside the supply water loop. In the simulation, this is divided over three water loops, hot water, chilled water and condenser water, where the measurements only measure one pipe. The measured temperatures (in blue) are much higher than the temperatures inside the hot water loop. The setpoint for the hot water loop is set to 30 – 35 °C (see Figure 52 on page 50), while the figure shows that it never reaches that temperature. The setpoint for the chilled water loop is set to 8 – 14 °C (see Figure 53 on page 51), while Figure 64 shows that the temperature is much higher than that.

The impact of this discrepancy can be seen in Figure 65. This figure shows the temperatures inside the floor heating. For the climate ceilings the same issue is found.

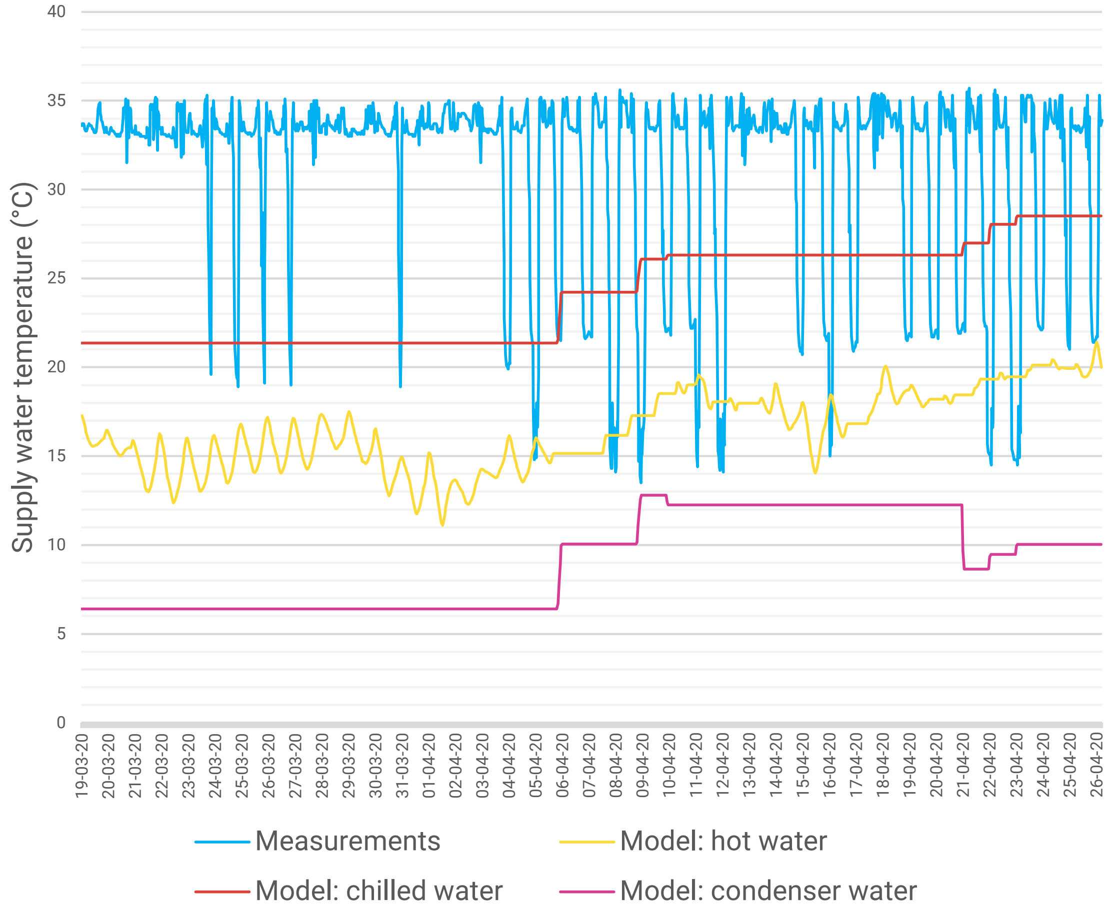


Figure 64: Comparison between simulated and measured supply water temperature

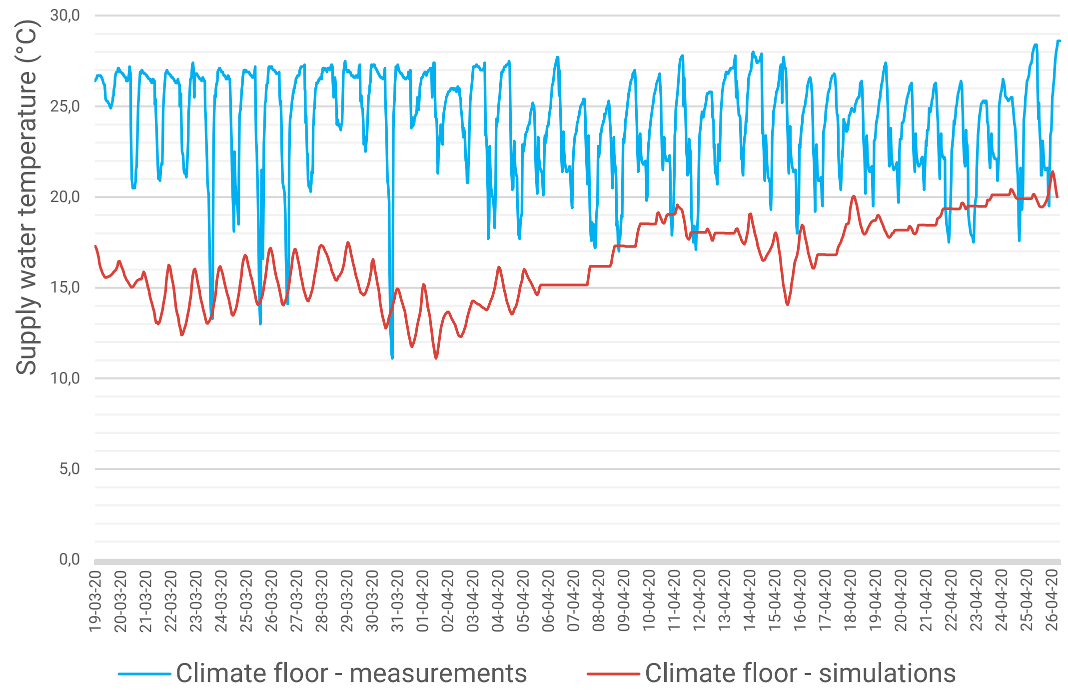


Figure 65: Comparison between simulated and measured climate floor supply water temperature

DesignBuilder model

As mentioned in the introduction of Chapter 4 "Method", the DesignBuilder model would not work with the modeFRONTIER optimisation software, instead, DesignBuilder has a built-in optimisation engine. In order to be able to achieve quantitative results, a simulation has been run with the existing DesignBuilder model. Since this model was used for calculations for the competition in Hungary some settings had to be changed to compare to the current state of the prototype. The change in settings for this adapted model (Dutch model current state) compared to the existing (Hungarian) model can be found in Table 6. Natural ventilation, shading and lighting were not in use during the measurements and are therefore turned off in the model.

Setting	Hungarian model apartment	Dutch model current state apartment	Hungarian model garden setting	Dutch model current state garden
Number of people	2	0	2	0
Heating setpoint	21,0 °C	20,5 °C	18,0 °C	20,0 °C
Heating setback	12,0 °C	Off	Off	Off
Cooling setpoint	25,0 °C	21,5 °C	25,0 °C	24,0 °C
Cooling setback	28,0 °C	Off	Off	Off
Natural ventilation	On	Off	On	Off
Shading	On	Off	On	Off
Lighting	On	Off	On	Off

Table 6: Change in settings between existing (Hungarian) model and adapted model (Dutch model current state)

Figure 66 shows the temperatures of the measurements (in blue) and the simulations (in red). This figure shows that the during daytime the prototype will heat up but will always fall back to around 20 °C at nighttime.

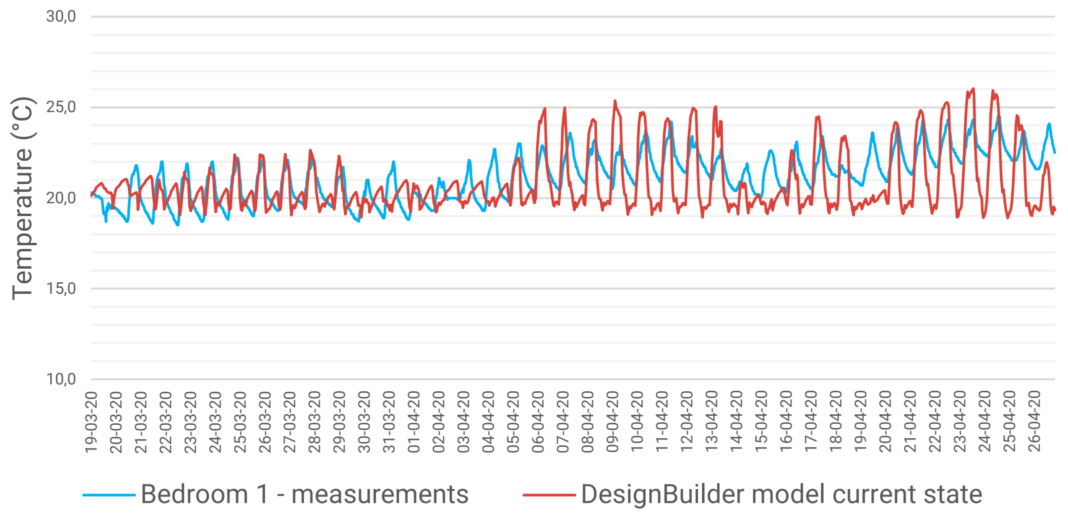


Figure 66: Comparison of simulated and measured indoor air temperature using the DesignBuilder model

Since some functions were currently not available in the prototype during the measurements they were switched off in the model. For optimising all functions of the building management system they will be switched on again for the optimisations. Unfortunately, these functions within the model were not verified with the measurements. The updated settings for these functions in the model that will be used for optimisations can be found in Table 7.

A simulation with these settings has been run for comparison to the optimisations later. It can already be seen that these functions impact the indoor air temperature (see Figure 67) and energy demand, especially heating 340,90 kWh (-30,45 %). Additionally, an annual simulation is run. Finally, for the optimisation, the weather file based on reference years is used instead of the data gathered as explained in Chapter 4.2 "Grasshopper model" - "Weather data".

Setting	Hungarian model setting	Optimisations model apartment setting	Optimisations model garden setting
Number of people	2	2	2
Shading	On	On	On
Shading solar setpoint	350 W/m²	174 W/m²	174 W/m²
Shading outside air temp setpoint	23,0 °C	20,65 °C	Only set to solar
Natural ventilation	On	On	On
Indoor min temperature control	23,0 °C	21,2 °C	21,2 °C
Indoor max temperature control	28,0 °C	Not set	Not set
Delta T limit control	Not set	3,0 °C	1,0 °C
Lighting	On	On	On
Target illuminance	250 lux	300 lux	300 lux
Infiltration rate	0,500 ach	3,2400 m³/h-m²	3,2400 m³/s-m²
Occupation schedule	9:00 – 22:00		

Table 7: Changes in settings between existing (Hungarian) model and model for optimisations

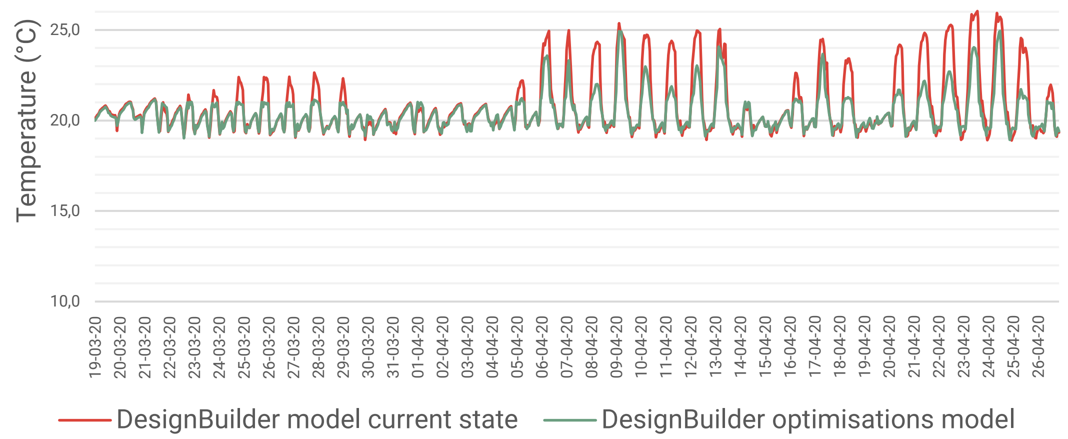


Figure 67: Comparison of simulations of the Dutch model current state and the model with added settings (optimisations model)

Statistical analysis

In order to do a statistical analysis of the results, from the simulations, the temperatures from the measurements and simulations are imported into IBM SPSS Statistics. These results consist of quantitative data on the interval level. This analysis will look at the difference between the results. Therefore, the Root Mean Squared Error (RMSE) will be calculated.

RMSE assumptions:

- Measurement level dependent variable (test variable): Interval
- Measurement level independent variable (grouping variable): Interval
- Differences between the model predictions and the real measured values.

The test variables are the temperatures from the measurements. The grouping variables are the temperatures from the simulations (Grasshopper model and DesignBuilder model).

First, the means are compared. In Table 8 the descriptive statistics can be found. The mean of the measurements is slightly higher than both models.

Model	N	Minimum	Maximum	Mean	Standard Deviation
Measurements	1011	18,5	24,5	21,189	1,292
Grasshopper model	1011	10,0	31,6	19,627	4,151
DesignBuilder model	1011	18,9	26,0	20,774	1,577

Table 8: Descriptive statistics

Unfortunately, IBM SPSS Statistics does not calculate the MBE and RMSE. Therefore, Microsoft Excel was used to calculate the following equations, where N is the number of data points, and ŷt and yt are the predicted and the measured values of variable y at time instance t and $\bar{y}$ is the average of the measured values (Hietaharju, Ruusunen, & Leiviskä, 2018):

$$MBE = \frac{\frac{1}{N}\sum_{t=1}^{N}(\hat{y}_t - y_t)}{\bar{y}}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(y_t - \hat{y}_t)^2}$$

The acceptable calibration values are (Gucyeter, 2018):

- CV(RMSE) < 30 %
- MBE < ± 10 %

The coefficient of variation of the RMSE (CV(RMSE)) is calculated by dividing the RMSE with the range of the measured data (6,0 °C). Table 9 proves that the DesignBuilder model is statistically more accurate (CV(RMSE) = 25,4 %) than the Grasshopper model (CV(RMSE) = 58,5 %).

Model	MBE	RMSE	CV(RMSE)	Pearson's correlation coefficient (r)
Grasshopper model	-7,4 %	3,510 °C	58,5 %	0,84
DesignBuilder model	-2,0 %	1,526 °C	25,4 %	0,49

Table 9: MBE, RMSE and correlation coefficient of models compared to the measurements

4.4 Optimisations

The next step in the process is running the optimisation. It was intended to use modeFRONTIER as optimisation software. Since the Grasshopper model is currently not accurate enough and DesignBuilder cannot use the modeFRONTIER optimisation and optimisation is run within the DesignBuilder software.

In this chapter, the DesignBuilder workflow will be explained. The workflow in modeFRONTIER can be found in Appendix I. The results from the DesignBuilder optimisation will be exported to a .csv document and imported into modeFRONTIER for post-processing. These results will be discussed in Chapter 5 "Results".

DesignBuilder has a built-in optimisation function. Though this function is very limited, cooperation with modeFRONTIER which has more optimisation algorithms and freedom in decision variables would be beneficial, this is currently not available.

Due to limitations within the DesignBuilder software the objectives, constraints and design variables had to be adjusted. DesignBuilder only allows for a limited list where these functions can be picked from. This would not allow for setting the comfort conditions as constraints. It was possible to set adaptive comfort as a second objective, making it a multi-objective optimisation. Discomfort summer CEN 15251 adaptive category II was set as the second objective. This calculates the total hours that the thermal comfort limits are not met. The discomfort summer CEN 15251 adaptive category II only takes thermal comfort into account. It is not possible to optimise for the indoor air quality and visual comfort or use these as constraints.

Next to this, it was not possible to choose all the design variables that were initially intended (see Appendix I). Only the general heating and cooling setpoints could be used as design variables. The individual setpoints for each different system could not be optimised. But also the shading solar setpoint, shading outside air temperature setpoint and the target illuminance, could not be set as design variables.

Problem formulation

This optimisation is a multi-objective optimisation: Minimising energy consumption and discomfort.

- Objectives: minimise total site energy and minimise discomfort summer CEN 15251 adaptive category II.
- Constraints: none.
- Design variables: heating setpoint temperature, heating setback temperature, cooling setpoint temperature, cooling setback temperature, natural ventilation setpoint temperature, natural ventilation maximum temperature difference, mechanical ventilation setpoint temperature, mechanical ventilation maximum temperature difference, mechanical ventilation rate.
- Bounds and types: dependent on different setpoint ranges (see Table 10 on the next page).

Design variable	Lower bound	Upper bound
Cooling setpoint temperature	15,00 °C	35,00 °C
Heating setpoint temperature	10,00 °C	25,00 °C
Natural ventilation setpoint temperature	15,00 °C	35,00 °C
Natural ventilation maximum temperature difference	-30,00 °C	2,00 °C
Mechanical ventilation setpoint temperature	15,00 °C	35,00 °C
Mechanical ventilation maximum temperature difference	-30.00 °C	2,00 °C
Mechanical ventilation rate	1,00 ach	10,00 ach

Table 10: Upper and lower bounds as setup in DesignBuilder

For the optimisation, the Open Beagle engine is used. The settings can be found in Table 11.

Setting	Value
Maximum generations	100
Initial population size	30
Maximum population size	30
Tournament size	2
Crossover rate	1
Individual mutation probability	0,4

Table 11: Optimisation settings Open Beagle engine

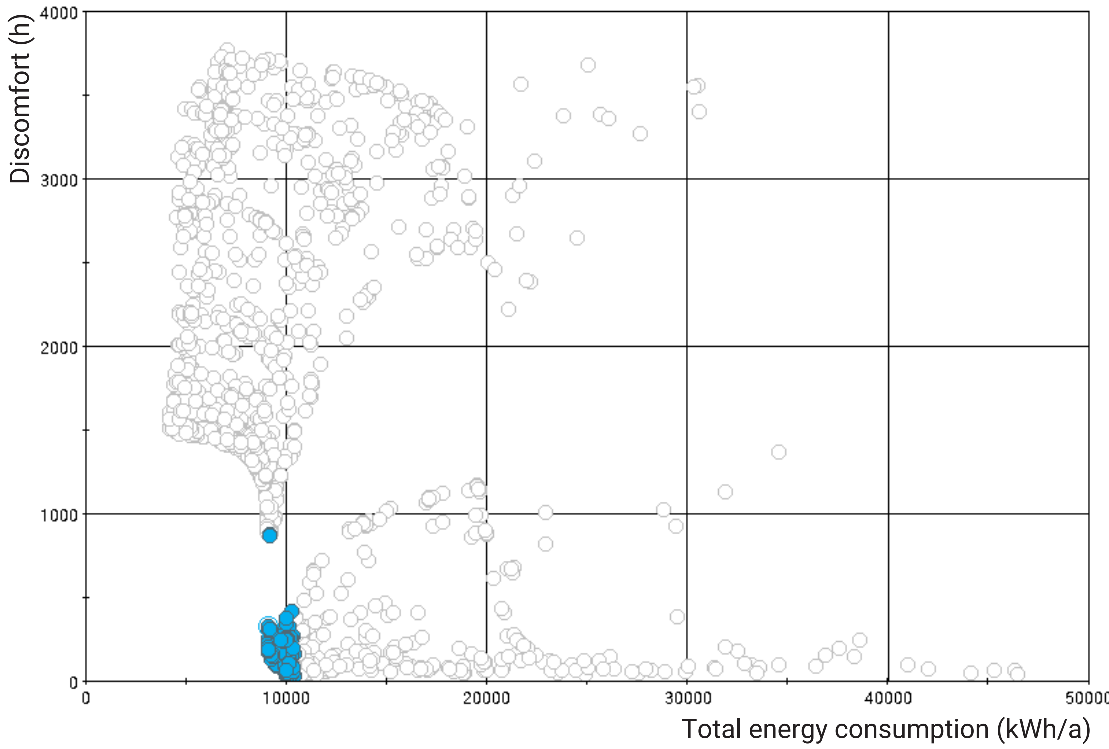


Figure 68: Scatter diagram of optimisation iterations

5. RESULTS

Unfortunately, statistical analysis of the Grasshopper model shows a statistically significant difference in the results of the test simulations that ware run with this model in comparison to the measurements taken at the prototype for the last months. It is therefore not accurate enough to use for optimisations. The existing DesignBuilder model can still be used for optimisations even though the options of the built-in optimisation engine are limited (see Chapter 4.4 "Optimisations").

Before running the optimisation a couple of simulations are run (as described in Chapter 4.3 "Simulations" – "DesignBuilder model"). The comparison in energy demand can be found in Table 12. The first column shows the total energy consumption of the prototype in the current state. This is the model that was compared to the measurements. The second column shows the total energy consumption of the model with all systems functioning. This means that not all systems in this model are compared to measurements. For the comparison of the simulations to the measurements, a new weather file was created with measurements of this year (see chapter 4.2 Grasshopper model - Weather data). For the optimisations, the weather file based on reference years is used. The last column shows the results from an annual simulation with this weather file.

End-use	Dutch model current state	Optimisations model	Optimisations model using reference year weather file
Heating	7062,51 kWh/a	5265,97 kWh/a	6674,70 kWh/a
Cooling	218,57 kWh/a	234,38 kWh/a	223,12 kWh/a
Lighting	0,00 kWh/a	2434,87 kWh/a	2434,87 kWh/a
Equipment	1130,94 kWh/a	1090,00 kWh/a	1090,00 kWh/a
Total	8412,02 kWh/a	9025,22 kWh/a	10422,69 kWh/a

Table 12: Energy usage by end-use comparing the model of the current state of the building, the optimisations model and the optimisations model with the reference year weather file

In order to be able to check if the comfort levels are met the occupancy schedule is changed to 24/7 (see Table 7) because DesignBuilder will only check during occupied hours. The amount of time the Adaptive Comfort model CEN15251 Category II, which closest relates to the Adaptive Comfort Limits guideline Class B as discussed in Chapter 2.2 "Comfort conditions"– Chapter "Thermal comfort", is not met can be found in Table 13.

Thermal comfort	Dutch model current state	Optimisations model	Optimisations model using reference year weather file
Not met	N/A	1832 h	1735 h

Table 13: Time adaptive comfort not met

Using the model in the last column the optimisation is run with the settings as described in Chapter 4.4 "Optimisations". Post-processing is done using the design exploration of modeFRONTIER.

A total of 3028 iterations have been made. 5,8 % of the iterations came back with a calculation error. These errors can be caused for example because the heating setpoint was higher than the cooling setpoint. This leaves 2851 iterations for comparison. A scatter diagram of the iterations without errors can be found in Figure 68.

Design variable	Range	Median	Average	Iteration 1983
Cooling setpoint temperature	32,8 °C – 35,0 °C	34,1 °C	34,0 °C	34,1 °C
Heating setpoint temperature	20,8 °C	20,8 °C	20,8 °C	20,8 °C
Natural ventilation setpoint temperature	33,9 °C - 35,0 °C	34,3 °C	34,3 °C	34,3 °C
Natural ventilation maximum temperature difference	-29,2 °C - 1,0 °C	-17,1 °C	-18,0 °C	-17,1 °C
Mechanical ventilation setpoint temperature	15,8 °C – 32,6 °C	17,6 °C	18,4 °C	17,6 °C
Mechanical ventilation maximum temperature difference	-28,5 °C - -4,0 °C	-24,0 °C	-22,6 °C	-22,1 °C
Mechanical ventilation rate	1,0 ach	1,0 ach	1,0 ach	1,0 ach

Table 14: Setpoint ranges found for a total energy consumption of 9094,72 kWh/a and 327 hours of discomfort (n = 129)

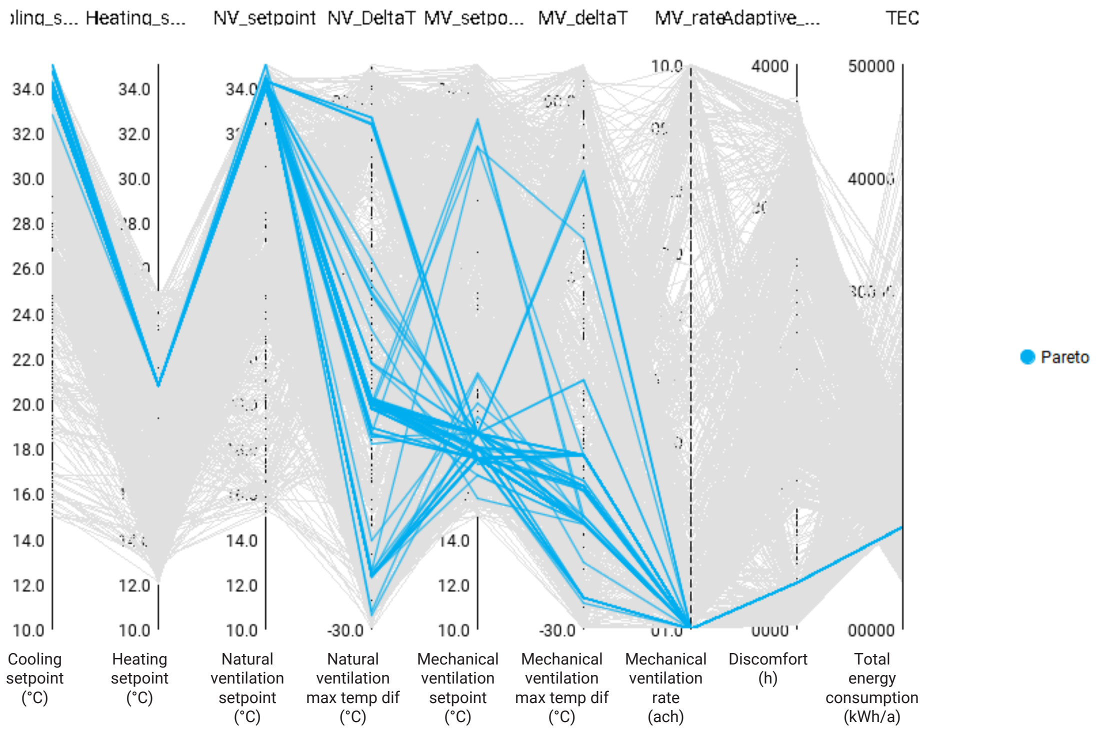


Figure 69: Parallel coordinates diagram highlighting the designs with a total energy consumption of 9094,72 kWh/a and 327 hours of discomfort (n = 129)

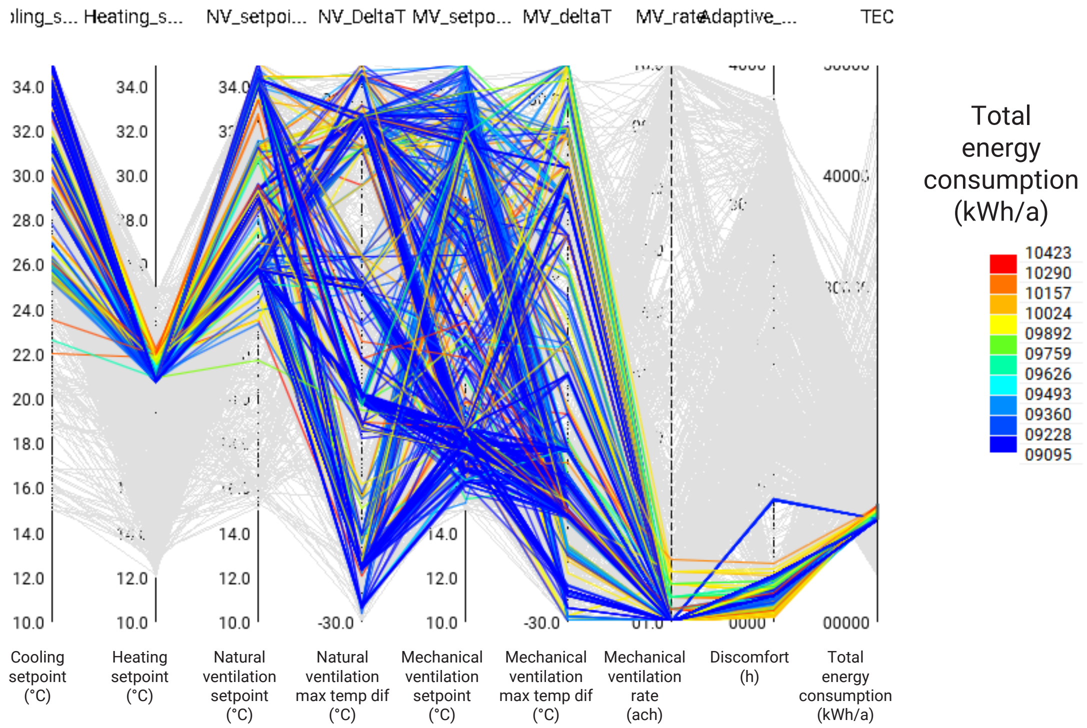


Figure 70: Parallel coordinates diagram showing the energy consumption in kWh/a

Since this optimisation is a multi-objective optimisation two objectives have to be minimised: the total energy consumption and the hours of discomfort. In order to find the most optimal solution, two constraints are added. The current energy consumption of the prototype is calculated to be around 10422,69 kWh/a, therefore all iterations with a higher total energy consumption are excluded. A year consists of 8760 hours. It is allowed to exceed the temperature limits 10% of the time and therefore all iterations with a total time of discomfort higher than 876 hours are excluded. This leaves 654 iterations for comparison. Figure 68 on the previous page, shows the iterations that fall below these numbers In blue and the iterations that will be excluded in grey.

Figure 70 shows the inputs and outputs of each iteration. Each line shows the inputs and outputs of each iteration. The colour shows the total energy consumption in kWh/a. The excluded iterations are visible in grey. This figure already shows that the cooling setpoint temperature ranges from 22,0 °C – 35,0 °C, whilst the heating setpoint temperature ranges from 20,7 °C - 22,2 °C. The natural ventilation setpoint ranges from 21,7 °C – 35,0 °C. Next to that, it can already be seen that a low mechanical ventilation rate of maximum 2,0 ach is desirable. The maximum temperature difference for natural and mechanical ventilation and the setpoint temperature for mechanical ventilation still show a wide range.

The lowest total energy consumption (129 iterations) that can be reached within the constraints is 9094,72 kWh/a which compared to 10422,69 kWh/a is a 13 % reduction. The ranges for each setpoint at this energy consumption can be found in Table 14.

It is allowed to exceed the temperature limits 10 % of the time, a maximum of 876 hours. The total time of discomfort for all these iterations is 327 hours (4 % of the time). In the initial simulations (Chapter 4.3 “Simulations” – Chapter “DesignBuilder model”) a much higher discomfort of 1735 hours was found, this is equal to 20 % of the time. This optimisation improves the thermal comfort with 16 %.

In Table 14 it can be seen that, for the cooling setpoint temperature a high range of 32,8 °C – 35,0 °C with a median and average of around 34 °C is found. Because the cooling setpoint temperature range is close to the bound chosen in chapter Chapter 4.4 “Optimisations”, it had to be checked if a higher bound or more generations would lead to a more optimal

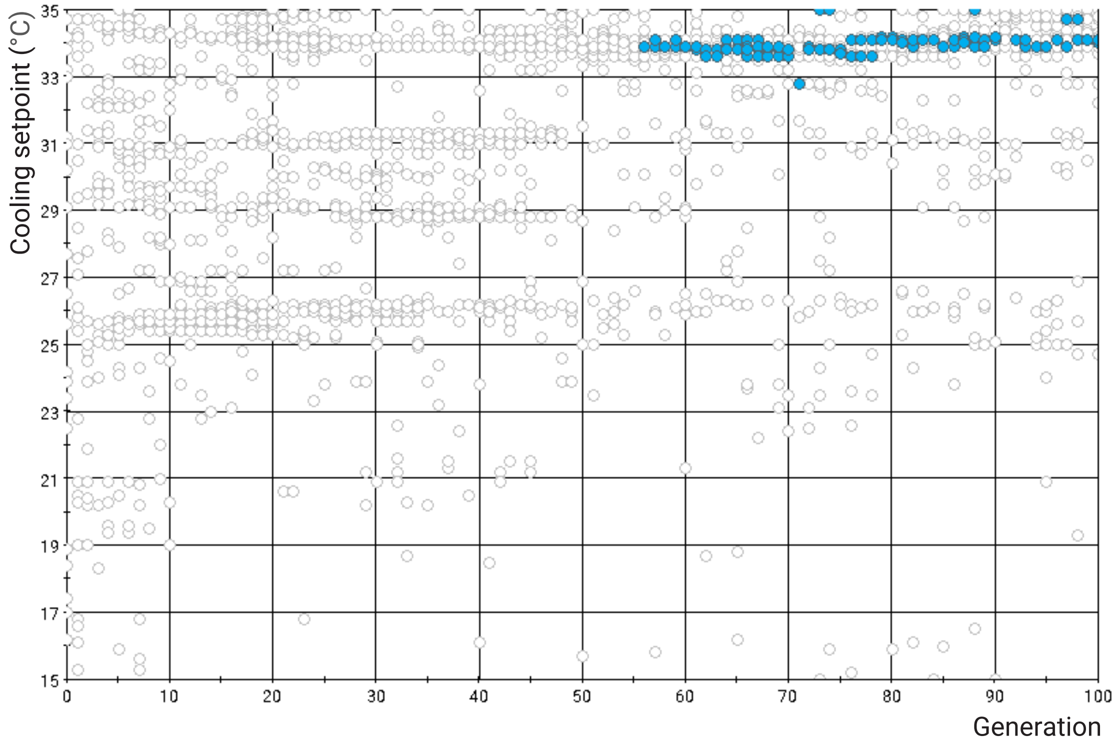


Figure 71: Scatter diagram of cooling setpoint temperature per generation with the 129 most optimal iterations in blue

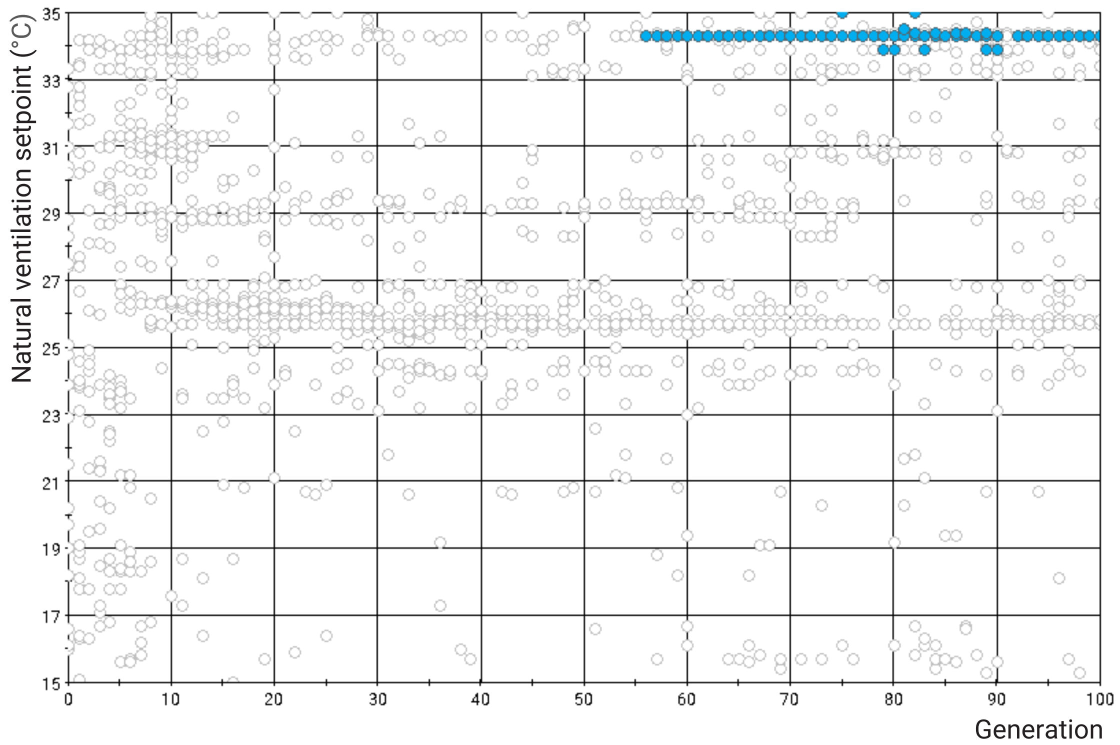


Figure 72: Scatter diagram of natural ventilation setpoint temperature per generation with the 129 most optimal iterations in blue

iteration. Figure 71 shows that the 129 most optimal iterations are found in the second half of generations. But this figure also shows that over time the iterations start to stabilize around 34 °C. It is therefore unlikely that the optimisation algorithm would find an even higher cooling setpoint temperature if more generations are made. The same can be concluded for the natural ventilation setpoint in Figure 72.

Another question to be asked due to the high cooling setpoint temperature is if this means that it is not necessary to cool at all. In order to answer this question, a simulation is run with the lowest cooling setpoint temperature (32,8 °C, iteration ID 2156). As well as for the lowest natural ventilation setpoint temperature (33,9 °C, iteration ID 2412). After running these simulations the highest indoor temperature was found to be 31,5 °C (outdoor temperature 32,5) (see Figure 73) and the energy usage for cooling is 0,00 kWh/a. As stated before, it is allowed to exceed the temperature limits calculated by the adaptive comfort category II of CEN 15251 10 % of the time. It seems that this 10% allowance is occurring during extremely high or low temperatures.

Figure 74 shows a close up of Figure 73. The limits of the adaptive comfort category II are shown in red (upper limit) and pink (lower limit). It can clearly be seen that the temperature falls below the lower limit a lot, more than 4 % of the time. Further research into how DesignBuilder calculates the total hours of discomfort shows that they only calculate this for summer. This means that in winter the total hours of discomfort is much higher.

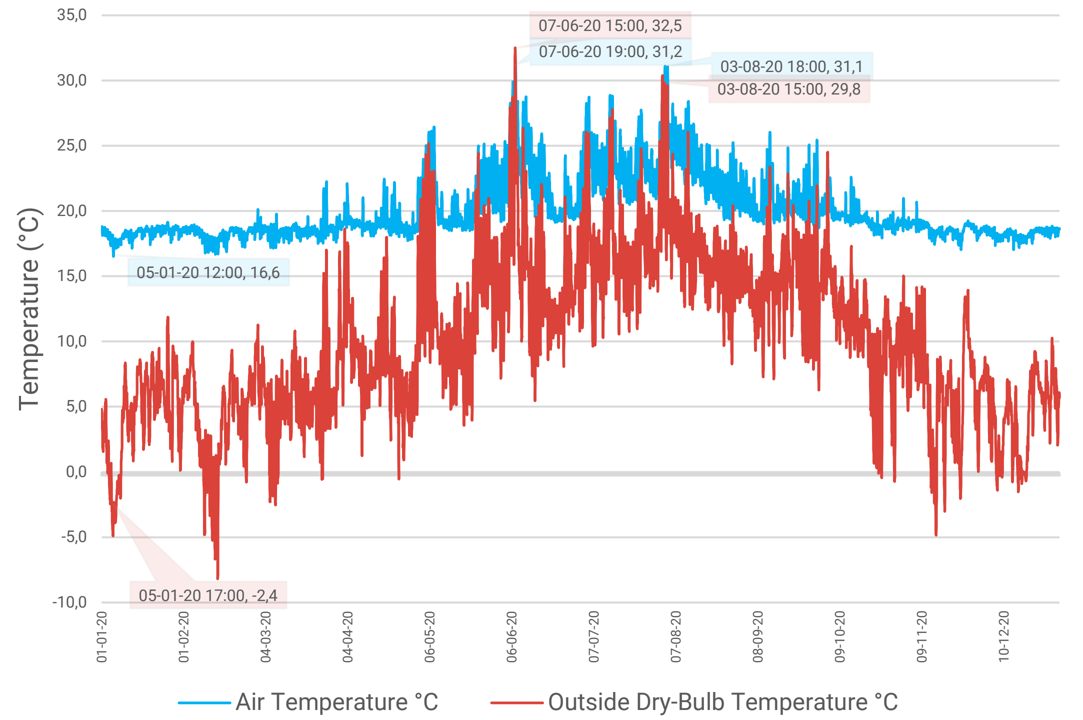


Figure 73: Indoor air temperature (in blue) and outdoor air temperature (in red) during a simulation of iteration 2156

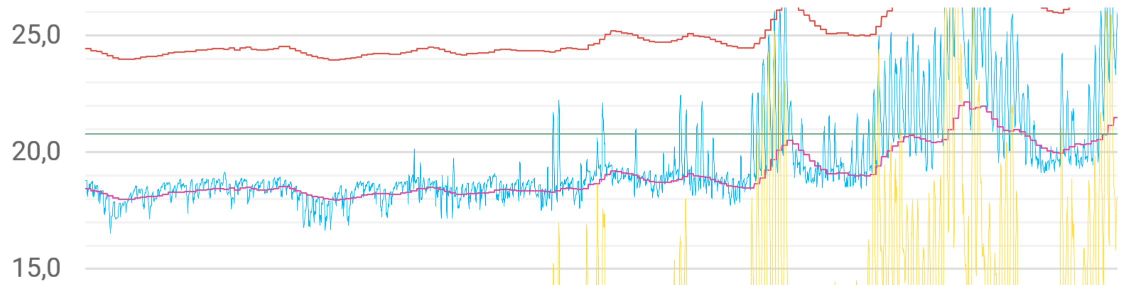


Figure 74: Close up of Figure 73

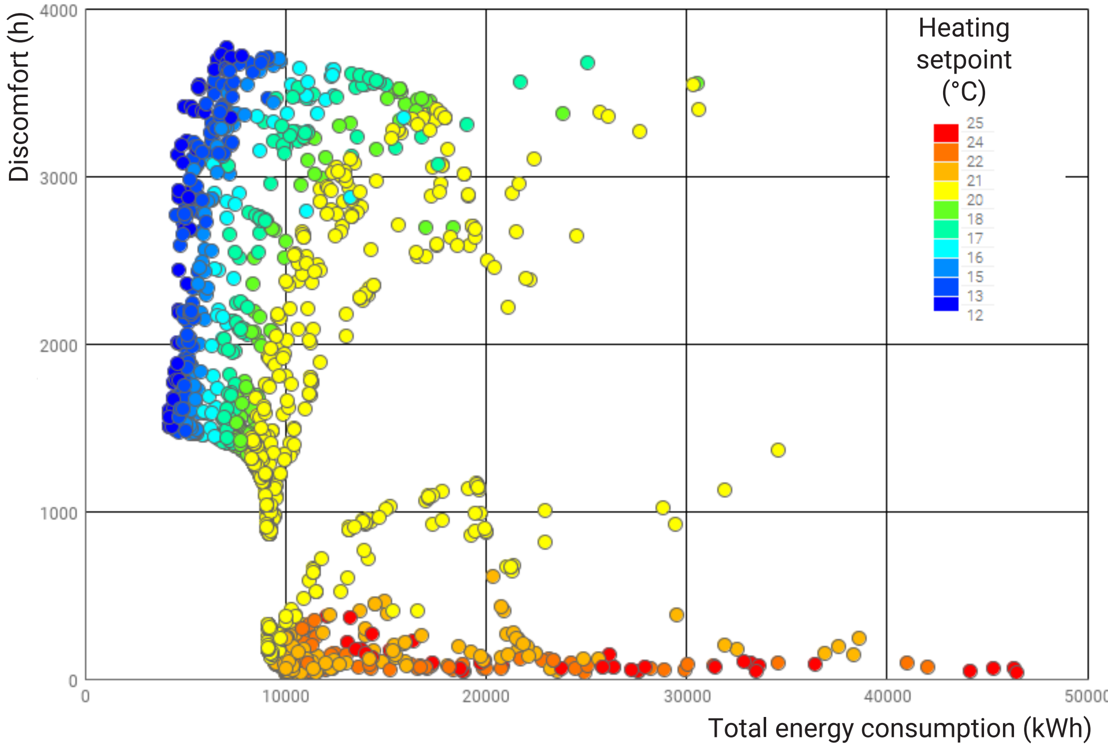


Figure 75: Bubble diagram showing the effect of heating setpoint on the energy consumption and discomfort

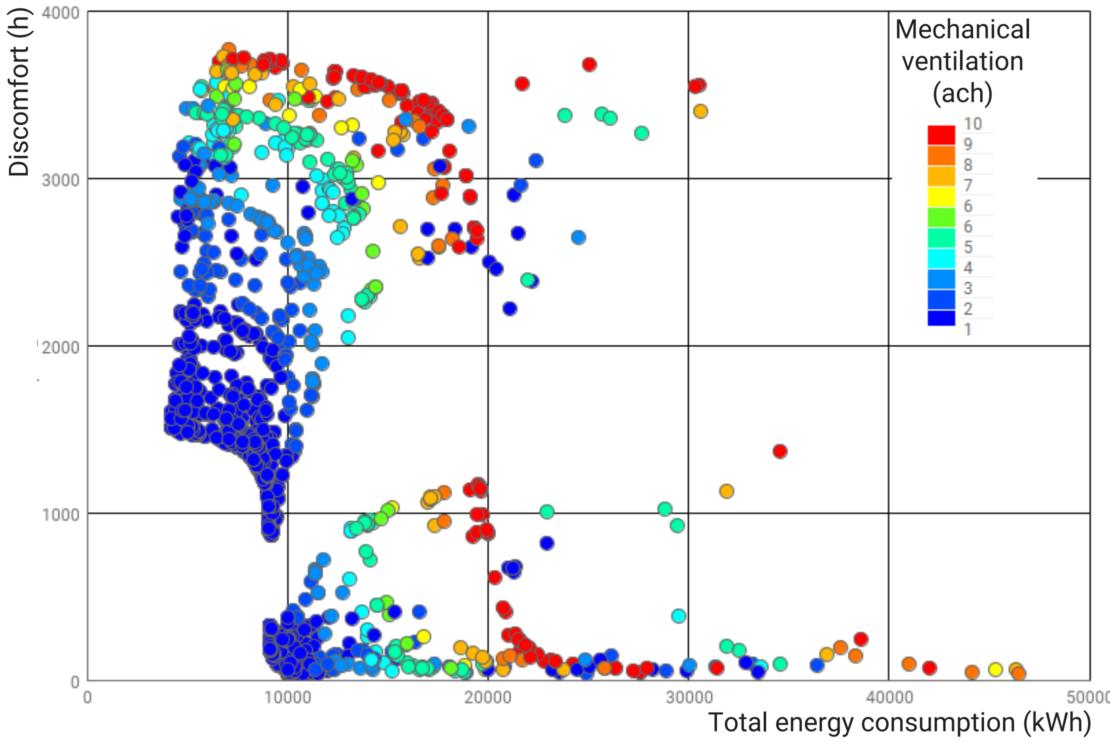


Figure 76: Bubble diagram showing the effect of the mechanical ventilation rate on the energy consumption and discomfort

Some of the design variables seem to have a direct correlation with the hours of discomfort and the total energy consumption. Figure 75 shows the effect of the heating setpoint and Figure 76 shows the effect of the mechanical ventilation rate. This clearly shows why the heating setpoint does not result in a range but in 20,8 °C and a mechanical ventilation rate of 1,0 ach. Figure 76 shows the correlation of all inputs and outputs.

Using the modeFRONTIER sensitivity tool the effect of each design variable on the objectives was found (see Table 15). It can be concluded that 80% of the total energy consumption is defined by the heating setpoint temperature and the mechanical ventilation rate. 95% of the hours of discomfort is defied by the heating setpoint temperature and the mechanical ventilation rate.

Design variable	Hours of discomfort	Total energy consumption
Cooling setpoint temperature	0,006	0,006
Heating setpoint temperature	0,650	0,431
Natural ventilation setpoint temperature	0,035	0,187
Natural ventilation maximum temperature difference	0,001	0,001
Mechanical ventilation setpoint temperature	0,001	0,000
Mechanical ventilation maximum temperature difference	0,004	0,004
Mechanical ventilation rate	0,302	0,371

Table 15: Effect table

Knowing that these design variables have such a big effect on the design objectives, it is also clear that this effect is also visible in the scatter diagram (see Figure 68 on page 62). Figure 77 shows that the gap in the lower left corner of the graph is caused by the heating setpoint. A heating setpoint of lower than 20,8 °C immediately leads to an increased number of hours of discomfort. Figure 78 shows that the mechanical ventilation rate is responsible for the empty line in the middle of the graph. Even though it is still not clear why this occurs.

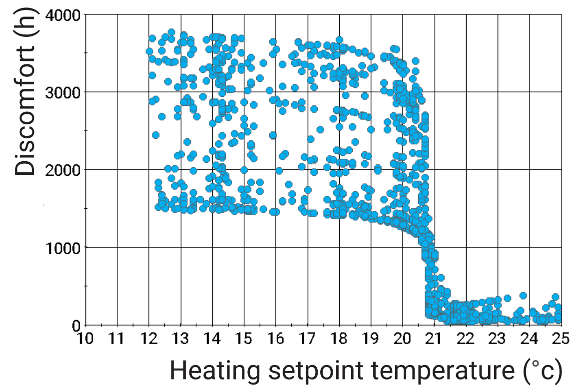


Figure 77: Scatter diagram showing the effect of the heating setpoint temperature on the shape of the graph

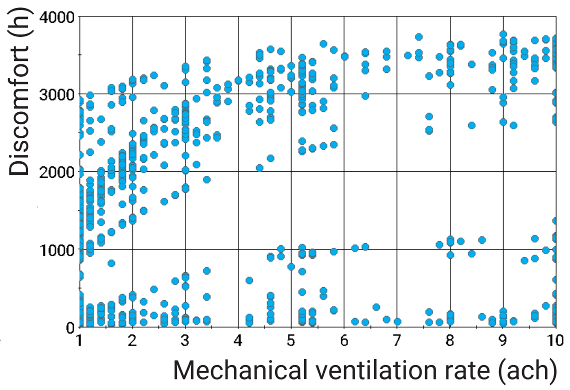


Figure 78: Scatter diagram showing the effect of the mechanical ventilation rate on the shape of the graph

6. INTERVENTION

In this chapter, an intervention for the MOR prototype is suggested to improve the energy efficiency of the systems and improve the comfort conditions. This recommendation is split up into two parts: quantitative results and qualitative results. Quantitative results are based on the optimisations. Qualitative results are based on the research.

Quantitative results

The optimisations show very high cooling setpoint temperatures between 32,8 °C – 35,0 °C, higher than the indoor air temperature will reach. The highest indoor air temperature that was found is 31,5 °C, while the outdoor air temperature is 32,5 °C. Since the Adaptive Temperature Limits guideline will allow for higher indoor temperatures as discussed in Chapter 2.2 “Comfort conditions” – “Thermal comfort”, and as discussed in Chapter 5 “Results” it is allowed to exceed the comfort conditions 10 % of the time. It seems that this 10% allowance is occurring during extremely high or low temperatures. This might be undesirable although it is possible that the phase-changing materials are sufficient as a heating or cooling strategy during these periods. Thus it can be concluded that active cooling in the current climate for the MOR prototype is unnecessary. The current energy usage for cooling according to the simulations lays around 223,12 kWh/a. Bringing this down to 0,00 kWh/a results in a saving of 2% on the total energy consumption.

For the natural ventilation setpoint temperature, a range of 33,9 °C - 35,0 °C is found. This is also higher than the indoor air temperature will reach. Since natural ventilation can be used as a cooling strategy this will also suggest that cooling is unnecessary for the MOR prototype in the current climate. But this is only based on temperature. Natural ventilation can also be used for improving the indoor air quality. In the current DesignBuilder model this was not setup. More research has to be done to see if a maximum CO_2 level is set, for which temperatures natural ventilation would be allowed and what the impact on the total energy consumption would be. For now, the high natural ventilation setpoint should be interpreted as a cooling strategy which, as concluded in the previous paragraph, is in the current climate unnecessary for the MOR prototype. This could also explain the wide range of natural ventilation maximum temperature difference setpoints (-29,2 °C - 1,0 °C) since no natural ventilation is occurring.

The heating setpoint and mechanical ventilation rate seem to have a direct correlation with the hours of discomfort and the total energy consumption (as can be seen in Figure 77 and Figure 78 on page 69). This results in two clearly defined setpoints. For heating, the setpoint could be raised to 20,8 °C, which is currently set to 20,5 °C. This would lead to a saving of 17% on the energy consumption for heating based on the simulations. The mechanical ventilation rate could be lowered to 1,0 ach, which is also the minimum required by the dutch building decree. This is currently set to 1,3 ach. Unfortunatly, it seems that the heating setpoint is only sufficient in summer. Further research into a setpoint temperature in winter is needed.

Finally, very little influence of the mechanical ventilation setpoint temperature and maximal temperature difference are found. The ranges (setpoint 15,8 °C – 32,6 °C and temperature difference -28,5 °C - -4,0 °C) could mean that these have very little impact on the total energy consumption and thermal comfort.

Qualitative results

Next to the quantitative results some conclusions from researching building management systems and the MOR building management system can be drawn as well. Some possible functions are currently unused.

When comparing the comfort conditions found in literature to the setpoints of the building management system, you can see that the temperature setpoint currently used is 21 °C all through the seasons, where the adaptive temperature limits guideline suggests a comfortable range depending on the running mean outdoor temperature. During the summer hot period, the setpoint of 21 °C will even fall below the comfortable range. It could be possible to save energy on space cooling during this period and heating during the colder period. It would be very interesting to see if it is possible to use the Adaptive Temperature Limits guideline as a dynamic setpoint for the system. Grasshopper is able to calculate this as discussed in Chapter 4.2 “Grasshopper model” - “Thermal comfort”. Next to that, the system is already storing 5 days of average daytime temperatures.

The floor heating and cooling is controlled only based on the outdoor temperature, not taking into account the indoor temperature. It could possible to save energy on heating if a maximum indoor air temperature is set for the floor heating.

It could be beneficial to put the shading down at night in order to capture more of the heat. The solar radiation sensors could be used to program this. This could lead to more energy savings on heating.

Comparing the indoor air quality to the current setpoints in the prototype it can be concluded that the CO_2 level setpoint of 700 ppm could be increased to 1000 – 1200 ppm. Almost every time the prototype is occupied the setpoint of 700 ppm is reached. Energy could be saved on ventilation. This unnecessary ventilation could lead to heat loss.

Currently, there are no relative humidity sensors inside the prototype. During the competition, the prototype scored very low for relative humidity during the comfort conditions contest. At some points during the competition, the relative humidity exceeded 70 % (MOR Team, 2020). It could be interesting to see how the prototype is performing and what effect adding a relative humidity sensor in each room in combination with dehumidification would have on the energy consumption of the prototype and the comfort conditions. As found in literature the comfortable range for relative humidity at an indoor temperature of 18 to 24 °C can vary between 30 – 70 %.

For visual comfort, there currently are no illuminance sensors inside the prototype. The lighting is manually controlled but could be added to the building management system. The prototype also has no automated artificial lighting controls such as switching and dimming. Therefore the controllability of the artificial lighting is fully up to the residents. Connecting these to indoor illuminance sensors or occupancy sensors could automate this. These occupancy sensors could also be used to automatically close the windows when the prototype is empty or turn off other systems. It should be possible to use the CO_2 sensors as occupancy sensors, or motions sensors could be added to the prototype.

Next to outdoor shading which is automatically controlled, the prototype also includes interior shades. These interior shades are manually controllable. The view outside is mainly influenced by the large windows covering a high percentage of the façade. In a questionnaire held inside the prototype by students of the Technoledge Climate Design course, the view outside is rated very good. Only in the living room, 17 % of the respondents state that they do not have a good outside view. More respondents state that they experience glare, 19% in the bedroom and 31% in the living room. It could be interesting to see how the prototype functions and what the effect of automated lighting control on the prototype could be. As found in literature an illuminance level of at least 300 lux is desirable.

The exterior shading on all windows goes down when the solar radiation measured outside exceeds 22 klux. Only for the living room, this is set to exceed 65klux. There is no documentation on why this is much higher than all other rooms. It could be because the room is relatively larger compared to the other rooms and the light does not reach deep enough into the space, due to the bathroom/kitchen module. Next to that, the direction of the sunlight is not taken into account and therefore all shading will go down, disregarding their orientation.

A building management system is sometimes equipped with an interface. This interface could give direct access to controls and insight into the current energy consumption or indoor and outdoor measurements. Since the rooms inside the prototype are used for multiple functions, especially in the bedroom/office, different modes could be activated on this interface as well.

This could allow, for example, to change the illuminance setpoint based on the function of the room, such as increasing the setpoint to 500 lux for the office function.

Extra functions such as safety and security and predictive maintenance could be added as well.

Figure 79: Part of the façade that was cut off to be able to fit it to the Hungarian concrete structure, before and after

7. THE INFLUENCE OF DEMOUNTABLE BUILDING (AND BUILDING THE PROTOTYPE THREE TIMES) ON THE BUILDING MANAGEMENT SYSTEM

This chapter is added as part of the graduation annotation Technology in Sustainable Development (TiSD) and is aimed at elaborating sustainable development to a next level.

The MOR prototype has fist been built in the spring of 2019. After its first opening on the 3rd of June, it was demounted and prepared for shipping to Hungary, leaving only the prefab concrete structure behind. In Hungary, a second concrete structure was waiting and the prototype was rebuilt in just 15 days. After three weeks of testing, on the 28th of July the final award ceremony awarded the prototype with 8 awards in the 10 contests and the overall second place. The prototype was then left in Hungary for three months for the extended exhibition. In October the prototype was disassembled and prepared for transport again. When it returned in Delft, it was rebuilt for the final time using the same concrete structure that was left behind. It was finally re-opened on the 6th of February but still not fully finished. Currently, The Green Village, where the prototype is located, is closed due to the coronavirus and the small maintenance that still needs to be done has to be postponed.

So far this prototype has been build three times and demounted twice. It has travelled around 1450 km back and forth and has laid on a construction site waiting to be built for months. What influence has the demountability, and everything that comes with it, on the building and especially the building management system?

First of all this building was not only designed for disassembly it was actually disassembled and rebuilt. Since this still is a rather new concept not a lot of buildings that are designed for disassembly have been demounted yet, let alone been rebuilt.

The SDE organisation offered to build a concrete structure in Hungary. Because it is not economical to transport the heavy concrete structure, it was decided to have a second structure in Hungary. It would also save time during the rebuilding of the prototype to have the structure ready. Where in Delft we had a prefab concrete structure, in Hungary, it was cast in-situ. This meant the first thing that had to be done when arriving at the site, was to measure all the concrete in order to see if everything would still fit. It turned out that there were a couple of places that were not as neatly calculated in Hungary. This eventually led to having to cut a part of the façade. Figure 79 shows the before and after image of this cut. Currently, the edges are still sharp and covered with tape for safety. A gap of about 3 cm is now left between the concrete and the façade.

When the prototype was returned to Delft, it was not possible to store everything on site. The TU Delft allowed the team to store one truck worths of building materials next to the old chemistry building. Everything was packed with tarps since it was the fall season. But since it was not at the site, it was not possible to keep an eye on everything. This, unfortunately, lead to a lot of water damage and a lot of mould growth. The complete Marmoleum flooring was unusable and had to be replaced. And a lot of the wooden modules had to be treated and sanded to remove all the mould.

Not all systems are designed for disassembly. For example the climate ceilings. The ceiling islands consists of four panels. The panels are connected to each other with flexible tubes. In order to make a watertight connection, these tubes are pressured onto the pipes. This is not a demountable solution. It was, therefore, decided not to do this in back in Delft since the system would not be used. But in Hungary, the tubes would be filled with water. When disassembling the ceilings, some pipes were cut but the four panels had to stay connected together in order to be able to reassemble it back in Delft. This made transporting the climate ceilings harder. During the transport some panels got bend and the paint is peeling off in some spots (see Figure 80).

Next to that, due to the issues regulating the relative humidity inside the prototype during the competition, the project engineer had placed plates with salt on top of the climate ceilings near the air inlet of the HVAC system in order to try and regulate the moister content in the air. The salt had leaked onto the copper piping of the ceiling panels which only accelerated the corrosion processes (see Figure 80).

Figure 80: Damage done to the climate ceilings

Due to longterm storage on-site, transportation and disassembling the system a lot of the air ducts are damaged. Some even had to be replaced. While storing the ducts on site, they were not always covered well enough with tarps. They would lay on the ground and would get covered with sand. Some sand even ended up inside the ducts. Scratches on the ducts could remove the protective zinc layer and should be treated with corrosion-resistant zinc paint. Dents in the ducts could reduce the airtightness, the dimensional stability or airflow (Nijburg Klimaattechniek BV).

One of the air ducts and some electrical cables exit the HVAC room to enter the prototype through one of the HSB walls (see Figure 81). This was originally covered by the aquaponics system. This system has not been rebuilt in Delft. The duct is currently not covered and not insulated. This could impact the air temperature inside.

Figure 81: Visible damage done to the climate ceilings

The project engineer has stated that the air handling unit makes a whistling noise. This indicates that there still is some air leakage somewhere in the ducts. He has suggested that all ducts should be checked for leakages and all duct tape should be replaced.

But the rest of the building still has issues with airtightness as well. Because the outside unit of the air-to-water heat pump releases air underneath the prototype there still needs to be a tube attached to lead this air outside. Only then the basement of the prototype can be properly sealed off. And since the building is not sealed between the windows and the concrete a draft can be felt. Once the basement of the prototype is closed off the infiltration should be limited.

The floor heating and cooling system consist of 7 groups of flexible PE pipes with a total length of 555m. While these groups were labelled they were cut to fit in Hungary, back in Delft these pipes did not fit anymore. Next to that, the pipes were bent and in some places, a dent would cause a limited water flow. Some parts were therefore cut and a connector was used to rejoin the pipes. Figure 82 shows one of these connectors near the distributer. Some of these connections are also located within the layers of the floor. Connections are generally the weakest points in the circuit and should, therefore, be limited.

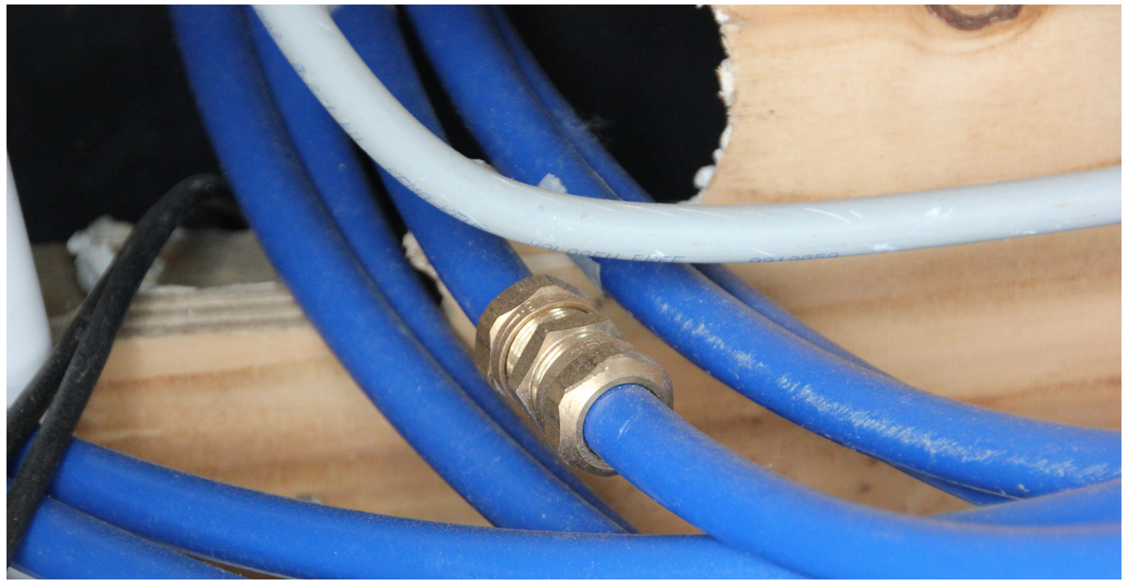


Figure 82: Connector in floor heating pipes

The floor is built up from 5 layers that cover the whole apartment floor (see Figure 83). The modules stand on top of this floor. If at some point any leakages within the floor will occur, the modules have to be removed to be able to take out the top floor layers one by one. It is not possible to open up only one part of the floor due to all the lap joints in the different layers. This makes it very hard to do some repairs that could have been simple. Further research into a more modular floor could fix this problem.

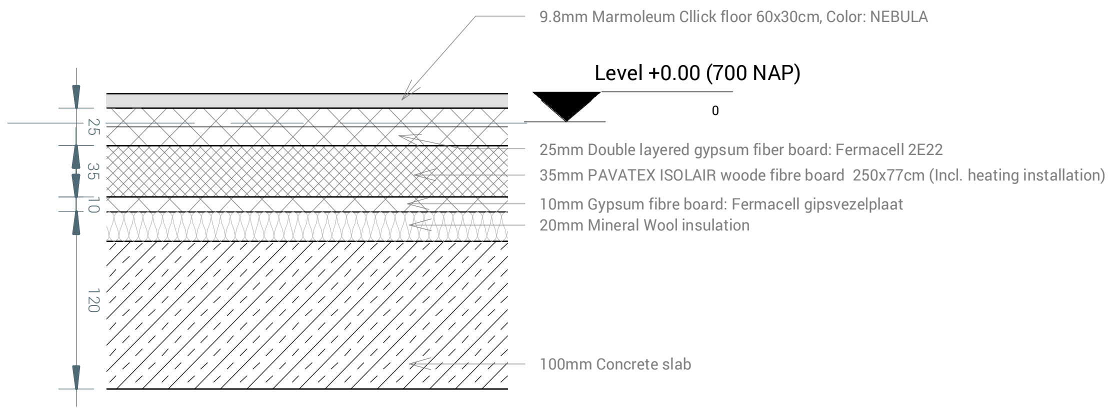


Figure 83: Different floor layers (MOR Team, 2019a)

Monitoring

Due to the limited time that was left after the first time the prototype was built, the initial testing of the system was not fully carried out. Partly because of this the building management system was not used in Hungary. It would be a pity if point got lost because of a malfunctioning system. Therefore, during the competition, a couple of people were constantly monitoring the prototype to see if any interventions were necessary. Now that the prototype is back in Delft, there is little monitoring of the system. The few people that know how the system works are no longer in charge of the prototype. The knowledge is not documented or shared well enough. If this system would be used in, for example, the Marconi towers, a superintendent would be in charge of monitoring. But with smaller projects like this one, who is in charge?

In order to maintain a building management system regular monitoring and upgrading to maximize efficiency should occur regularly. This all starts during the design phase where the system should be optimised to the context. After instalment into the building, a functional verification should occur to check if the installation is equal to what was ordered and everything is running correctly. If applicable a report could be made to assign a performance class as mentioned in standard NEN-EN 15232-1 or to apply for certification as provided by the eu.bac association (see chapter Chapter 2.3 "Building management system"). From then on recurring maintenance and audits should occur every twelve to thirty-six months, depending on the complexity of the installations (Bali, Half, Polle, & Spitz, 2018), to assure equipment availability and system functionality. But also to check if the comfort requirements are met, to check parameterisation and to check if the specified energy performance class is met (Napar, Ulllmann, & Waechter, 2016). If this does not happen the energy consumption of the building could go up over time (see Figure 84).

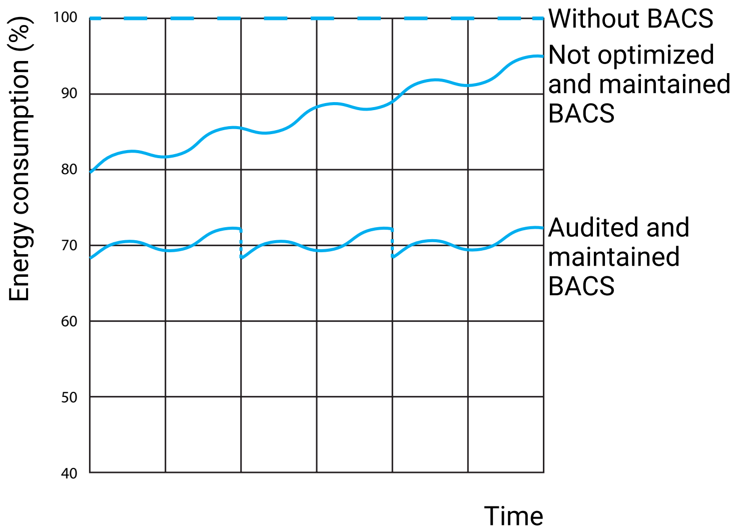


Figure 84: Performance of an audited and maintained building management system (Napar, Ulllmann, & Waechter, 2016)

Conclusion

There is still a lot of work that needs to be done. Not only for the MOR prototype but also demountable building in general. One of the most important tasks is to find proper storage for the building parts. This will limit weather damage and damage done to the construction parts because of the continuous traffic and moving. It is simply not possible to store everything on site. Compared to "regular building" parts are delivered mostly based on when they are needed.

More products on the market should allow for easy disassembly in order for it to be able to be reused. In order to achieve that it is important that the manufactures stay responsible for their products, moving towards a leasing economy where products are a service. This way the manufacturer will be forced to think about the disassembly and repair of their products.

It is also very important that the different aspects of the building are properly audited and maintained by professionals such as the manufacturers. In order to prove the concept with further testing, it is key that all systems reach their maximum efficiency.

This project, being a student project, the team building the prototype was still learning on the go and multiple mistakes were made that maybe professional builders would have prevented. And next to that a better understanding of the whole process could lead to better insights beforehand and better planning. This can only occur if the people making the planning have hands-on experience on the building site. With this project at least 40 students have gained these insights.

8. DISCUSSION

Due to the fact that not all systems are up and running yet, not all settings of the system could be verified with measurements. Despite this, they were included in the optimisation. This could affect the results.

Because of the limitations of the software, it was not possible to optimise all the setpoints for each system. Only the overall heating and cooling setpoints are used in the optimisation. But, as discussed in Chapter 3.3 “Building management system”, each system has its own setpoint based on sequence control. It was intended to optimise the setpoint of each system individually to see if this sequence control could be optimised as well.

Next to that, it was only possible to optimise the temperature setpoint for natural ventilation. The air quality setpoints could not be optimised with DesignBuilder. Therefore, the conclusion is that natural ventilation as a cooling strategy is unnecessary. It could be possible that natural ventilation as an air quality control strategy is indeed necessary.

It was also not possible to set the comfort conditions as constraints. In order to still be able to include this the adaptive comfort was set as a design objective as minimising discomfort. This is calculated by DesignBuilder as total hours of discomfort using the CEN 15251 adaptive category II. Since DesingBuilder will only check for discomfort if the model is occupied, the occupancy schedule was set to 24/7. Somehow this still led to very low temperatures, at the lower bound . When looking into why this happened, it was found that DesignBuilder only checks for discomfort during summer. This means that a different setpoint for heating should be researched for winter.

For the adaptive comfort, it was allowed to exceed the limits 10 % of the time. It looks like this is especially happening during extremely high temperatures. This could be undesirable.

Due to time constraints and other issues, some other problems occurred. The bounds that were chosen are based on estimations. Looking back, these bounds could have been narrower. This could have probably led to a lower number of excluded iterations. If there was more time for further research a new optimisation with smaller bounds and a higher number of iterations could have been run. It would also have been possible to use the other optimisation engine of DesignBuilder to see if this would lead to other results.

Running an initial optimisation and evaluating the results could have shown which design variables have big effects and which have almost no effect. Taking this into account for a new optimisation could also lead to better results with less excluded iterations.

The relatively low number of iterations that could be used for the optimisation can lead to inaccurate results. A higher number of iterations could solve this problem.

9. CONCLUSION

This research aimed to optimise the building management system of smart passive buildings using optimisation software. The MOR prototype was used as a case study for this research.

To find which parameters currently have the biggest influence on the total energy consumption of the building a literature review was performed since it is not yet known how the prototype performs. Chapter 2.1 “Energy usage (Efficiency)” shows that space heating (16 %) and water heating (21 %) are both big contributors to the total energy consumption of buildings. The biggest is electrical appliances (33 %) but these are not influenced by the building management system.

Next, it was important to find the comfort conditions that the building management system has to reach. In Chapter 2.2 “Comfort conditions” these limits are discussed. For thermal comfort, the Adaptive Temperature Limits guideline suggests a range of temperatures based on a calculated average of the four preceding days. For indoor air quality, a maximum CO_2 level was found of 800 ppm above the normal outdoor level of around 400 ppm. And for relative humidity, a range of 30 – 70 % was found for an indoor temperature of 18 – 24 °C. For visual comfort, there are no standards for residential buildings. A recommendation for the amount of light needed in a room is based on the activities. For the average room, a minimum of around 300 lux is found. For areas with more precise work such as the workstation, kitchen counter or bathroom mirror, a minimum of 500 lux is recommended.

In order to see if simulations can optimise the building management systems’ setpoint, a computer model was needed. The Grasshopper model does not yet accurately simulate the systems inside the prototype. In order to be able to draw quantitative conclusions an optimisation is run with the existing DesingBuilder model. The built-in optimisation engine is not as elaborated as modeFRONTIER therefore only the general heating and cooling setpoint temperatures could be optimised and not the setpoints for all individual systems.

For the MOR prototype, an energy consumption reduction of 11 % per year could be realised if the heating setpoint is raised from 20,5 °C to 20,8 °C and the mechanical ventilation rate is reduced from 1,3 ach to 1,0 ach. Unfortunately this setpoint seems not to be sufficient during winter. More research is needed in order to find a suitable heating setpoint during winter.

An additional 2 % could be saved by not using active cooling. The prototype has a lot of passive and active cooling strategies that were designed for the competition in Hungary. This research shows that active cooling is unnecessary for the MOR prototype in the current climate. But maybe in the future when more extreme temperatures are occurring, this could be necessary again.

Due to the limitations of the software no CO_2 level setpoint for natural ventilation could be set. Therefor natural ventilation was only used as a cooling strategy instead of air quality control. This could be the reason that the optimisations show that no natural ventilation is necessary.

This report contains a lot of information about the building management system of the MOR prototype and building management systems in general. These systems have a lot of possibilities that are currently still unused. Some suggestions for improving the energy efficiency and comfort conditions of the prototype are: adding motions, indoor illuminance and relative humidity sensors, automating lighting control, increasing the CO_2 level setpoint from 700 ppm to 1000 – 1200 ppm, adding an indoor temperature limit to the floor heating, programming a dynamic heating and cooling setpoint based on the Adaptive Temperature Limits guideline and adding safety and security and predictive maintenance functions to the system.

All of the interventions mentioned in this report will be discussed with the MOR team. These interventions could be implemented in the prototype. New measurements can then be compared to the simulations to see if the results are as expected. And if these interventions do indeed minimize the energy consumption and improve the comfort conditions.

The workflow as described in this report can be used for optimising the setpoints in other buildings using building management systems. A better understanding of the Ironbug plugin is necessary to be able to find the causes of the current issues, in order to be able to make a model that works well enough to be used in the described optimisations. Once this model is improved or a better model is built, it can be used with modeFRONTIER as described in Appendix I, which allows for better optimisation algorithms and more freedom in choosing variables. Then the individual setpoints of all systems can be optimised as well.

Some suggestions for further research can be found in Chapter 9.2 "Recommendations and further research".

9.1 Limitations

While working on this research some limitations were found. The prototype was not fully finished yet and the software used does not allow for all the options needed to fully perform the research as intended.

Prototype

The prototype is unfortunately not finished yet. This means that the windows have not been properly tested. The connection between the building management system and the window motors seemed unreliable during the setup and still needs to be properly tested before turning the automated control on. For the time being the windows are turned off in order to make sure the windows stay closed and no damage can be done.

Next to that the shading still has to be connected to power. The power for the shading runs on top of the roof. This was not yet connected before the measurements started.

The combined temperature and CO_2 sensors were originally located above the climate ceilings. This limited the heating capacity of the prototype since the sensors were measuring the temperature near the heat source. They have temporarily been relocated to approximately 1,5 m height against the wall. A final location for these sensors should still be found and they need to be fixed properly.

Currently, the weather station is not positioned properly. It is too close to the roofing which causes the weather station to measure the roof temperature instead of the outdoor air temperature. This lead to inaccurate outdoor air temperature measurements during this research. The weather station is also not rotated to face the north which leads it to register more sunlight coming from the north and inaccurate wind direction measurements.

Next to that the building still is not airtight yet. Because the outside unit of the air-to-water heat pump releases air underneath the prototype there still needs to be a tube attached to lead this air outside. Only then the basement of the prototype can be properly sealed off.

But also in the software, some details are not put in the schedules correctly. In TC Operator the living room consists of two windows instead of one of the bedrooms. This bedroom window will, therefore, be controlled based on measurements inside the living room.

The humidity sensor that can be found in TC Operator is labelled bathroom. There is no further documentation available on this sensor. Next to that, this sensor measures a relative humidity of 10 % at all times. It is therefore unlikely that it was properly installed.

During the measurements, the phase-changing materials were not placed inside the active green wall yet. Derek Wasylyshen has been working with Orange Climate for his graduation on

the active green wall system to get new phase-changing materials with the right temperatures for the Dutch climate.

Currently the window setting for the garden as described in Chapter 3.3 "Building management system" – "Heat and cold generation" are not programmed in the software. In order to use the garden as a buffer zone, this is key. Since the apartment takes its air from the garden the window should never be fully closed.

Grasshopper model

Ironbug is still a relatively new plugin with very limited documentation available online. This makes it hard to learn to use this system and will lead to a lot of error messages when running a simulation. When finally, a working model was produced, not all aspects of the prototype could be modelled due to limitations of the applications.

Honeybee does not allow to set natural ventilation based on indoor CO_2 levels, this is right now only based on indoor temperature. This component also only allows setting a maximum temperature difference between indoor and outdoor air instead of a minimum difference as is implemented in the building management system of the prototype. It will also not allow for a wind or rain alarm to close the windows.

In order to simplify the model, the interior modules are not drawn as geometries inside the prototype. Also, the outside door on the north side of the building is not drawn. It is not possible to set door constructions. Since it is a large glass surface it could be set as a window surface.

Next to that the sliding partition walls and folding garden door are currently modelled as air walls. There still has to be found a way to make a schedule to simulate when these openings are closed in order to limit airflow. This could be done using the Honeybee airflow component and setting a schedule for the interzone airflow.

In the prototype, the outdoor air will enter through the garden window before entering the apartment, there has not been found a way to simulate that in the model yet. One way that was thought of was to set a heat exchanger with the current indoor temperature but this was found to not be possible with the plugins.

Also, the phase-changing materials were not implemented in the model, mainly due to the fact that they were not replaced in the prototype yet.

The building management system of the prototype works with two setpoints one when the system turns on and one when the system turns off as is discussed in "Building management system". Grasshopper only lets you set one setpoint per system.

Finally, it is not possible to set a buffer tank in the plant loop. Ironbug also does not allow for extra pumps on the demand side of the water loops. And there is no option to set control valves.

DesignBuilder model

The DesignBuilder model was built before the competition, however, some small adjustments to the model were made as explained in Chapter 4.3 "Simulations" – "DesignBuilder model". Currently, the model is set to simple HVAC. This led to limited options for optimisation. The individual setpoints of the different systems (such as floor heating and cooling, climate ceilings and the active air cooler) were not changeable. If the model was set to detailed HVAC, it would also have been possible to set a maximum CO_2 level for natural and mechanical ventilation.

Next to that, the model is built as two rooms, the apartment and the garden. To make the model more detailed the two bedrooms and living room could be separated from each other by modelling the interior walls and sliding partition walls.

DesignBuilder uses a lot of schedules to define when systems are running or not. The heating and cooling schedules even include the option to use setpoints and setbacks. Since the prototype only uses one setpoint during the whole day, only the setpoints were used during the optimisations. The setbacks were taken out of the schedules.

The optimisation engine within DesignBuilder is limited. Only two Genetic Algorithms are available to choose from, Open Beagle and JEA. It was opted to use the Open Beagle engine since this includes a Pareto archive which feeds previously identified “best so far” solutions into the population to encourage exploration around previously identified Pareto optimal designs. This option can help the solution to progress more quickly. On the other hand, it can also lead to early convergence so some experimentation may be required to find the best setting for each new analysis (DesignBuilder, n.d.).

Next to that, objectives, constraints and design variables can only be chosen from a list. This did not allow for setting the comfort conditions as constraints or optimising the setpoints of the different systems (such as floor heating and cooling, climate ceilings and the active air cooler) or for shading and lighting. Instead of setting the comfort conditions as constraints, it was opted to set thermal comfort as a second objective. It was possible to choose from CEN 15251 or ASHRAE 55. It was not possible to choose the Adaptive Temperature Limits guideline, but the CEN 15251 adaptive category II was closest to this guideline.

9.2 Recommendations and further research

The Top Control software from Priva has a lot of different packages where new licences need to be requested for. During this research, the licence for TC History has been provided by CroonWolter&Dros in order to log the measurements that TC Operator was taking. Another software package that is available is TC Energy. This allows you to gain insight into the actual energy usage of the building. Obtaining a licence for this software could lead to more insights into the energy efficiency of the prototype.

New optimisations can be performed using the same model in combination with a climate change weather file. This could show the results in a future (warmer) climate. It is possible that active cooling will be necessary in the future.

Energy efficiency is not only based on consumption. More research could be done looking at energy production, conversion, storage and usage within the prototype. It could also be interesting to see if a building management system can manage peak demands. If the system could measure the energy that the building is generating, it could steer towards using more energy when it is available, and using less energy when it is not being generated.

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APPENDIX A: MATERIALS

Material	Property	Value
Lightweight Metallic Cladding	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0600 m 0,2900 W/m-K 1250,00 kg/m3 1000,00 J/kg-K 0,9000000 0,400 0,400
MOR Unitized Aluminium Curtain Wall	R Value Thermal absorptance Solar absorptance Visual absorptance	4,5 m2-K/W 0,9000000 0,700 0,700
Air gap	Thickness	0,0600 m
Cast Concrete	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,5600 m 1,1300 W/m-K 2000,00 kg/m3 1000,00 J/kg-K 0,9000000 0,600 0,600

Table 16: Façade properties (MOR Team, 2019b)

Material	Property	Value
Ecoplex	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0180 m 0,1500 W/m-K 560,00 kg/m3 2500,00 J/kg-K 0,9000000 0,780 0,780
Vaporseal	R Value Thermal absorptance Solar absorptance Visual absorptance	0,2100 m2-K/W 0,9000000 0,700 0,700
Light Timber Frame	R Value Thermal absorptance Solar absorptance Visual absorptance	6,0000 m2-K/W 0,9000000 0,700 0,700
Plywood	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0180 m 0,1500 W/m-K 560,00 kg/m3 2500,00 J/kg-K 0,9000000 0,780 0,780

Table 17: HSB exterior wall properties (MOR Team, 2019b)

Material	Property	Value
OSB Colorvlok	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0130 m 0,2900 W/m-K 1250,00 kg/m3 1000,00 J/kg-K 0,9000000 0,400 0,400
Light Timber Frame	R Value Thermal absorptance Solar absorptance Visual absorptance	3,9500 m2-K/W 0,9000000 0,700 0,700
Vaporseal	R Value Thermal absorptance Solar absorptance Visual absorptance	0,2100 m2-K/W 0,9000000 0,700 0,700
Plywood	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0180 m 0,1500 W/m-K 560,00 kg/m3 2500,00 J/kg-K 0,9000000 0,780 0,780

Table 18: HSB garden wall properties (MOR Team, 2019b)

Material	Property	Value
Ecoplex	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,012 m 0,1500 W/m-K 560,00 kg/m3 2500,00 J/kg-K 0,9000000 0,780 0,780
Everuse Insulation	R Value Thermal absorptance Solar absorptance Visual absorptance	1,06 m2-K/W 0,9000000 0,700 0,700
Air gap	Thickness	0,030 m
Ecoplex	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,012 m 0,1500 W/m-K 560,00 kg/m3 2500,00 J/kg-K 0,9000000 0,780 0,780

Table 19: HSB interior wall properties (MOR Team, 2019b)

Material	Property	Value
Triple clear	U Value Solar heat gain coefficient Visible transmittance	0,650 W/m2-K 0,350 0,600

Table 20: Window properties (MOR Team, 2019b)

Material	Property	Value
Triple clear	Reflectance Transmittance Emissivity Thickness Conductivity	0,450 0,080 0,900 0,0030 m 0,010000 W/m-K

Table 21: Shading properties (MOR Team, 2019b)

Material	Property	Value
Roofing	R Value Thermal absorptance Solar absorptance Visual absorptance	0,0270 m2-K/W 0,9000000 0,700 0,700
Kingspan Quadcore	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,1500 m 0,0220 W/m-K 35,00 kg/m3 1590,00 J/kg-K 0,9000000 0,600 0,600
Air gap	Thickness	0,3000 m
Vapor seal	R Value Thermal absorptance Solar absorptance Visual absorptance	0,2100 m2-K/W 0,9000000 0,700 0,700
Cast Concrete	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,1000 m 1,1300 W/m-K 2000,00 kg/m3 1000,00 J/kg-K 0,9000000 0,600 0,600

Table 22: Flat roof properties (MOR Team, 2019b)

Material	Property	Value
XPS Extruded polystyrene	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,1200 m 0,0340 W/m-K 35,00 kg/m3 1400,00 J/kg-K 0,9000000 0,600 0,600
Cast Concrete	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,1000 m 1,1300 W/m-K 2000,00 kg/m3 1000,00 J/kg-K 0,9000000 0,600 0,600
Rockwool	R Value Thermal absorptance Solar absorptance Visual absorptance	0,5500 m2-K/W 0,9000000 0,700 0,700
Fermacell 2E22	R Value Thermal absorptance Solar absorptance Visual absorptance	0,0300 m2-K/W 0,9000000 0,700 0,700
Pavatex Isolair	R Value Thermal absorptance Solar absorptance Visual absorptance	0,7500 m2-K/W 0,9000000 0,700 0,700
Fermacell 2E22	R Value Thermal absorptance Solar absorptance Visual absorptance	0,0300 m2-K/W 0,9000000 0,700 0,700
Timber Flooring	Thickness Conductivity Density Specific Heat Thermal absorptance Solar absorptance Visual absorptance	0,0200 m 0,1400 W/m-K 650,00 kg/m3 1200,00 J/kg-K 0,9000000 0,780 0,780

Table 23: Ground floor properties (MOR Team, 2019b)

APPENDIX B: HVAC SCHEMATIC

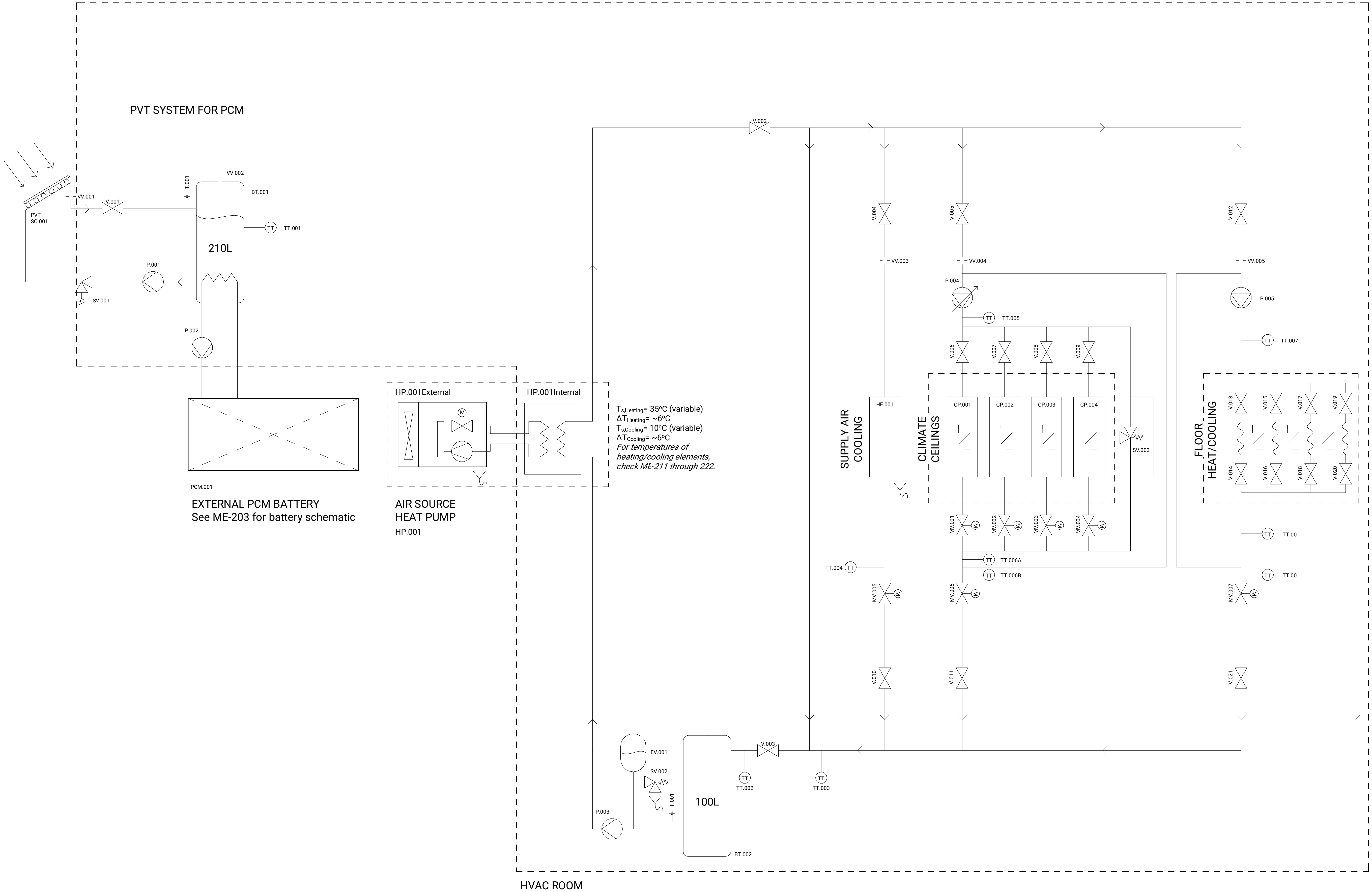

Figure 85: ME-201 HVAC schematic (MOR Team, 2019a)

APPENDIX C: VENTILATION SCHEMATIC

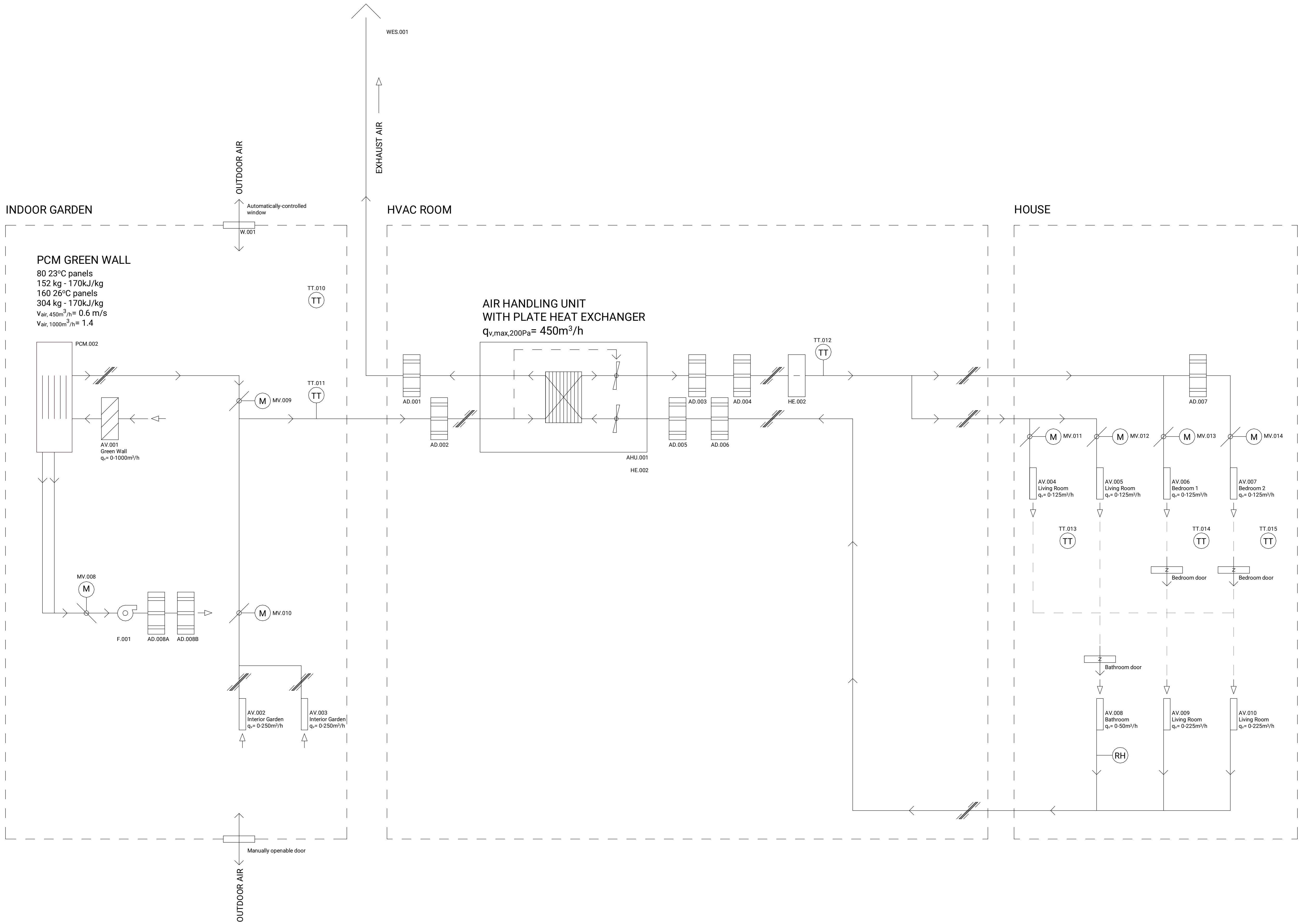

Figure 86: ME-202 Ventilation schematic (MOR Team, 2019a)

APPENDIX D: PLUMBING SCHEMATIC

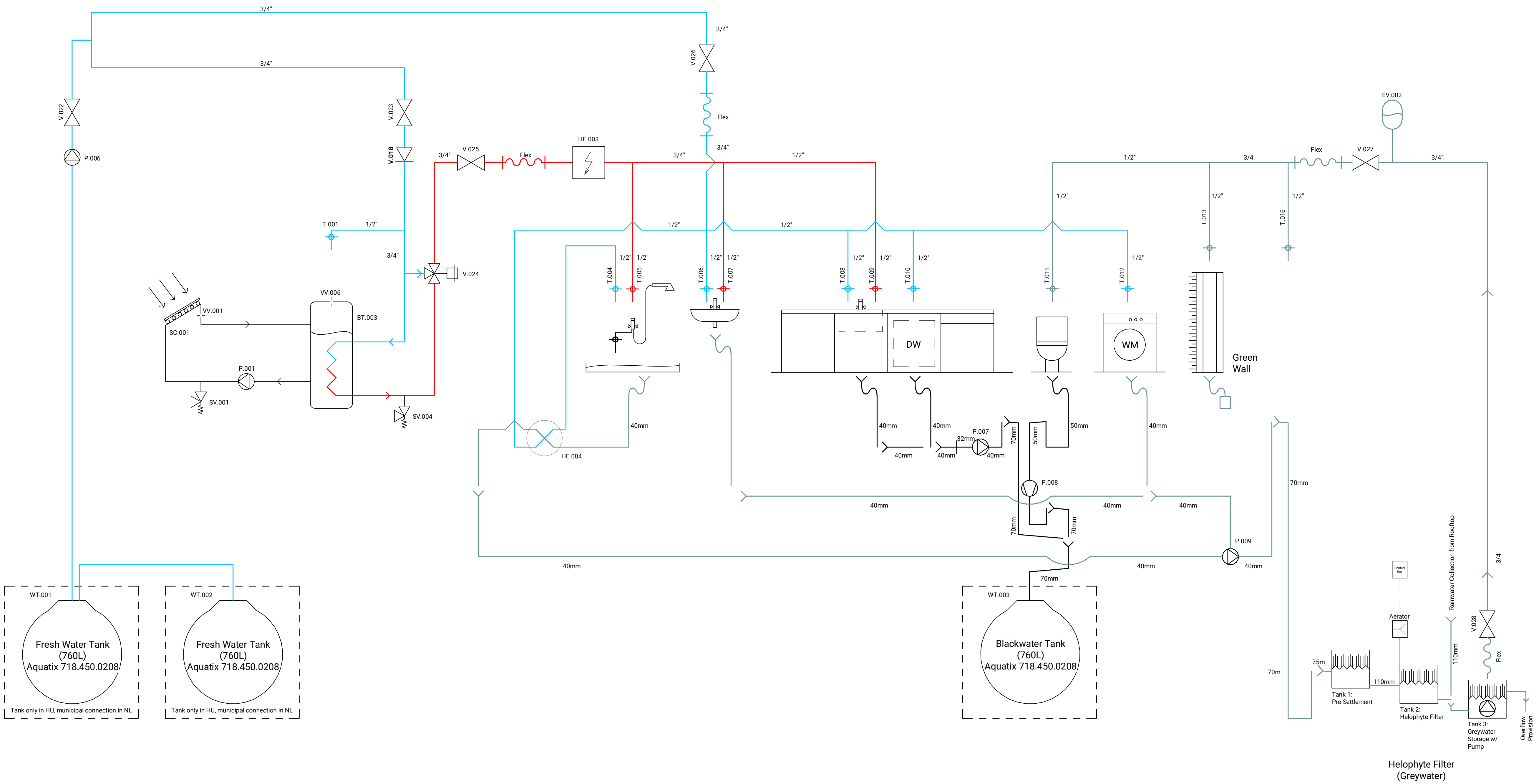

Figure 87: PC-101 Plumbing schematic (MOR Team, 2019a)

APPENDIX E: FLOOR HEATING SCHEMATIC

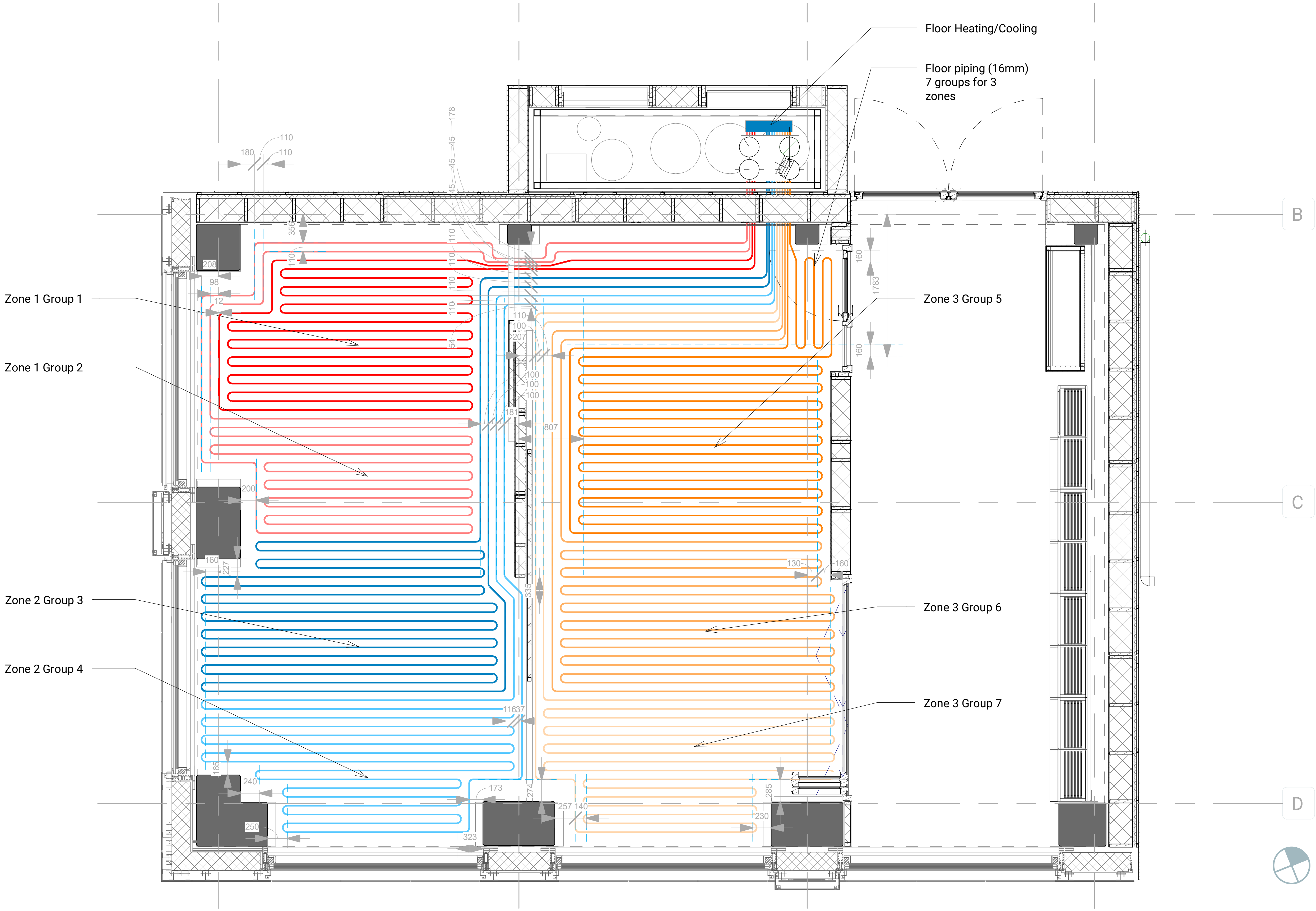

Figure 88: ME-005 HVAC distribution floor piping plan(MOR Team, 2019a)

APPENDIX F: BMS SCHEMATIC

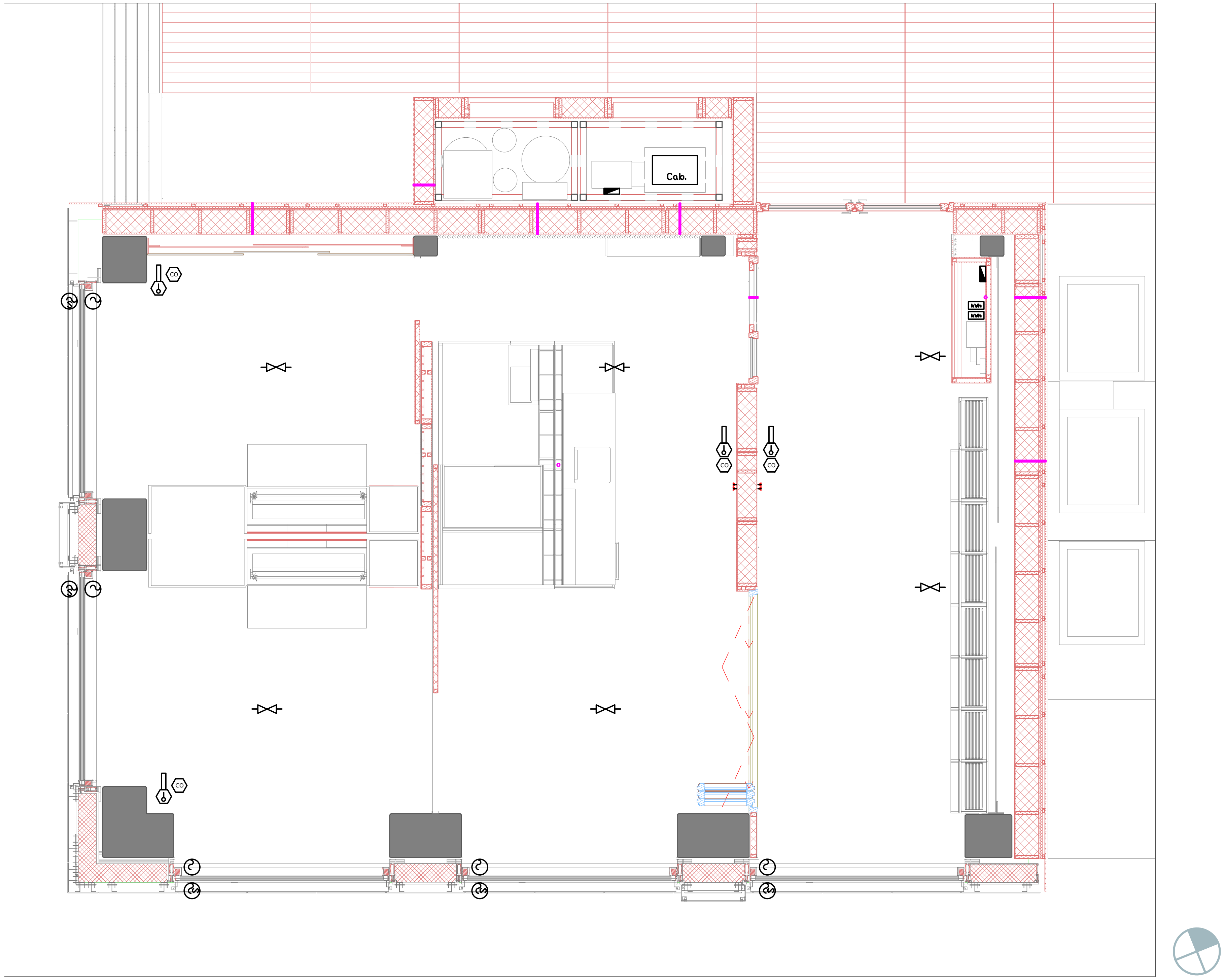

Figure 89: BAS-001 BAS wiring plan (MOR Team, 2019a)

APPENDIX G: HVAC DISTRIBUTION PLAN

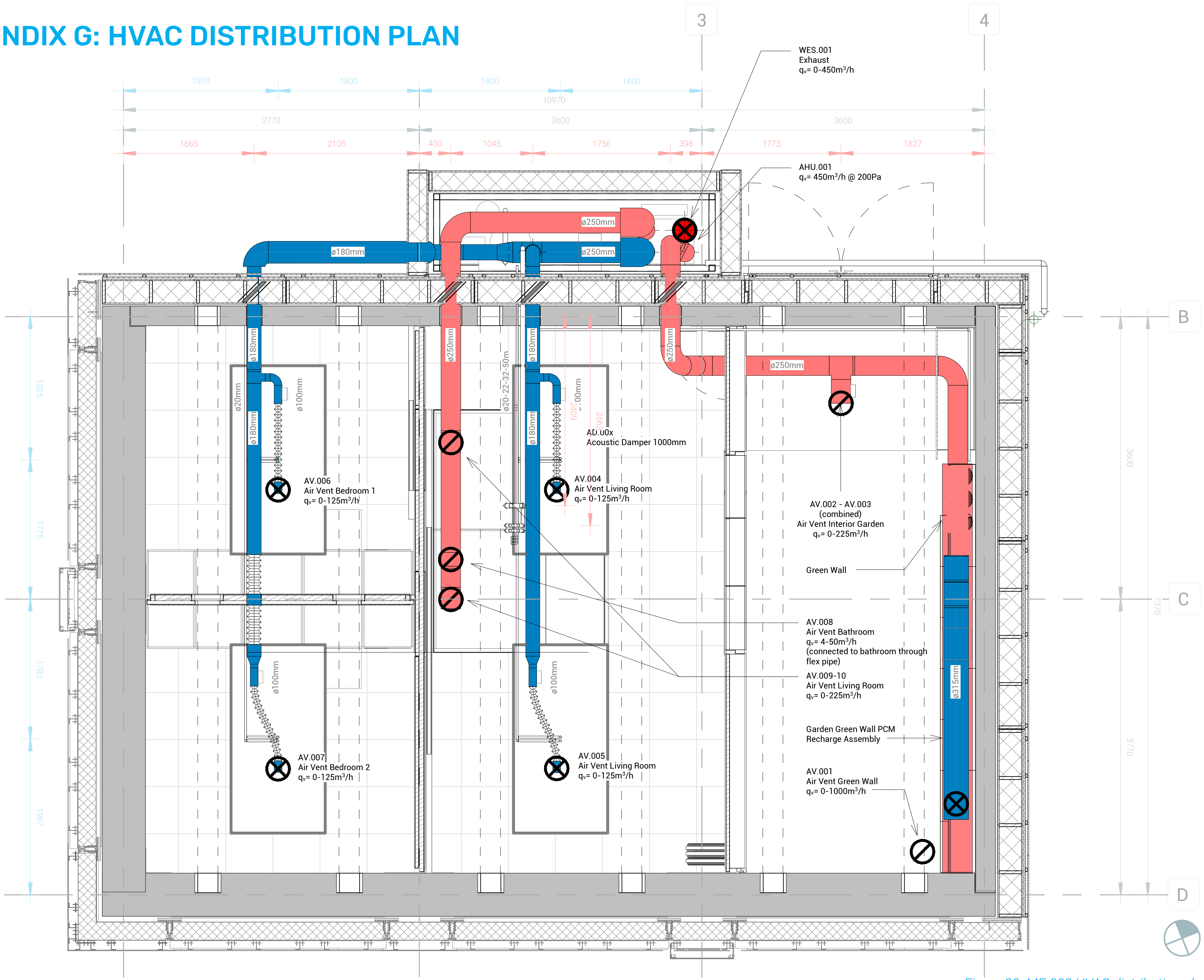

Figure 90: ME-002 HVAC distribution plan (MOR Team, 2019a)

APPENDIX H: MONITORING PANEL ROOM

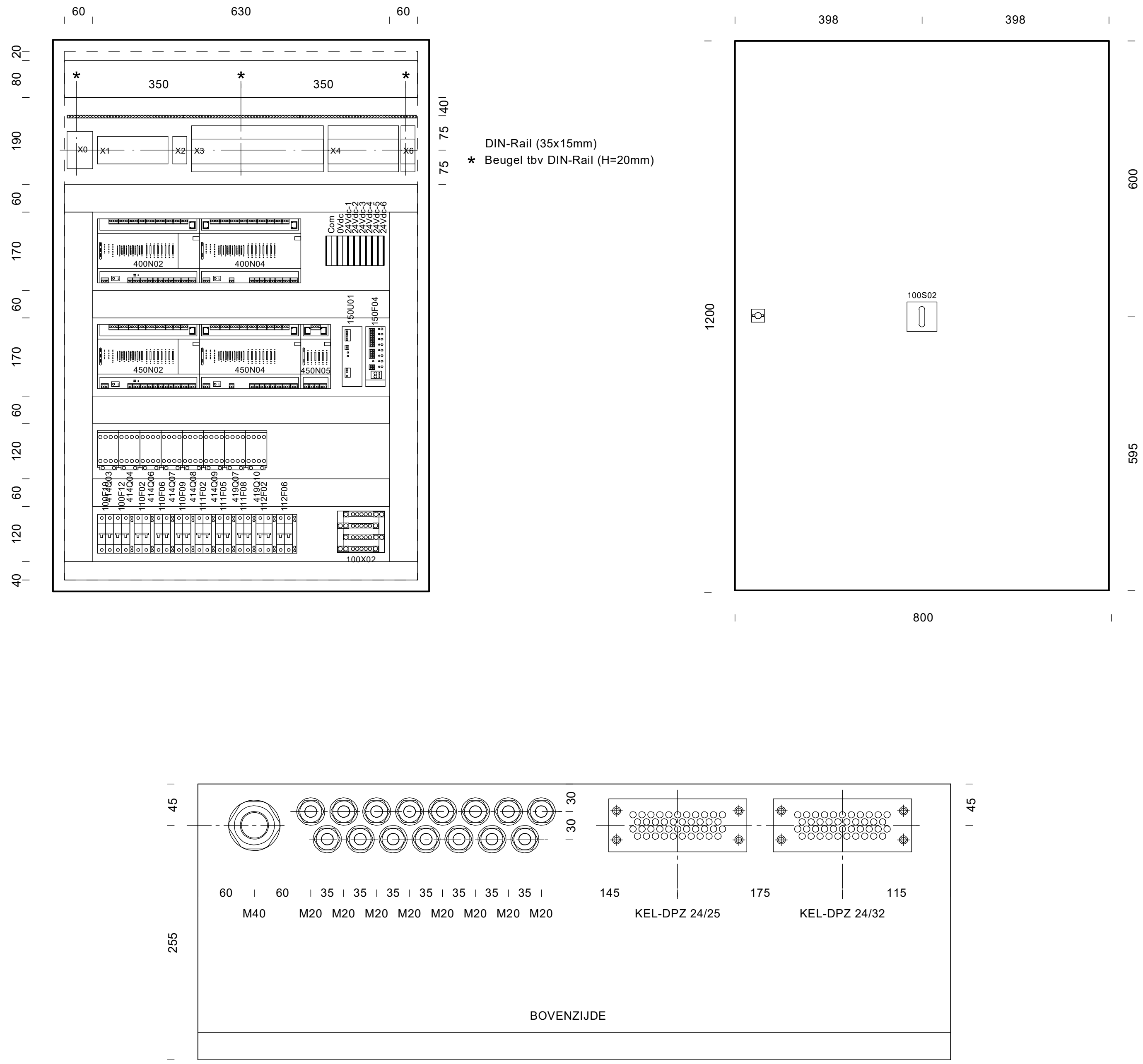

Figure 91: ID-002 Monitoring panel room (MOR Team, 2019a)

APPENDIX I: OPTIMISATION WORKFLOW

modeFRONTIER optimisation workflow

For the optimisation process, modeFRONTIER was chosen as optimisation software. This software allows for coupling with different software packages. The Grasshopper add-on node allows for integrating a Grasshopper file into the workflow.

Problem formulation

This optimisation is a constraint single-objective optimisation: Minimising energy consumption subject to comfort conditions.

- Objective function: minimise total energy consumption.
- Decision variables: shades, windows, mechanical ventilation, floor heating/cooling, climate ceilings, active air cooler (and their respective setpoints).
- Bounds and types: dependent on different setpoint ranges (see Table 24).
- Constraints: Comfort conditions (may be exceeded 10% of the time).

Surrogate models

It might be needed to use surrogate models if the optimisation takes too long. It is also possible to use the RenderFarm if needed. A test run of 10 evaluations should be run in order to calculate the expected time for the optimisation process.

Workflow

The workflow as setup in modeFRONTIER can be found in Figure 92. The process flow starts at the SchedulingStart node. The pilOPT algorithm is programmed for this workflow. The Grasshopper node is linked to the file as described in Chapter 4.2 “Grasshopper model”.

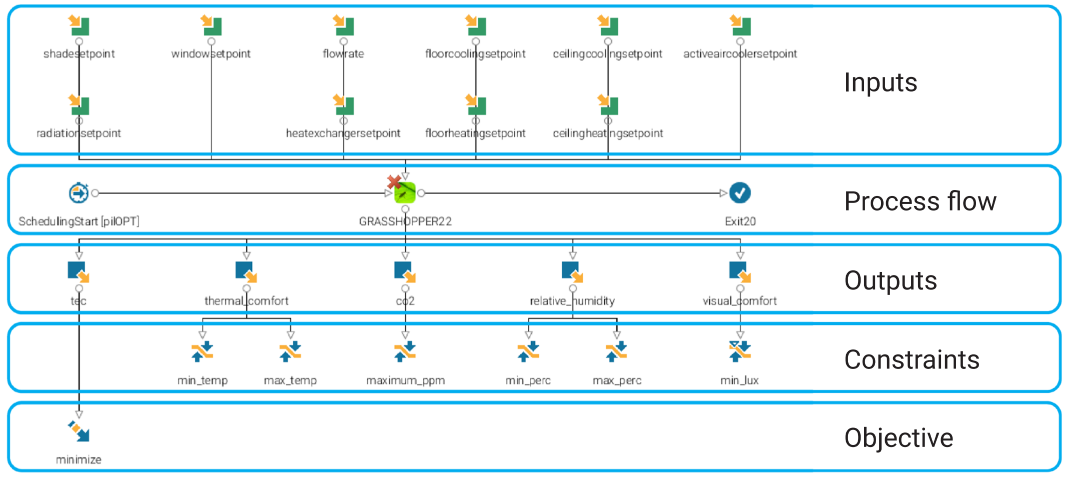

Figure 92: Setup for the model in modeFRONTIER

The different setpoints for each system are set up as sliders in Grasshopper (see Chapter 4.2 “Grasshopper model”). These inputs are set with an upper and lower bound (see Table 24) between which it will search for the optimal setpoint. The sliders are set with the same upper and lower bounds. For each setpoint modeFRONTIER will change the position of the slider in Grasshopper. Currently, the setpoints for all rooms are the same. It could be decided to make separate inputs and sliders for each room to see what difference this could make.

The outputs are taken from the mf_out group (see Figure 60) in Grasshopper. These will then be tested by the constraints (see Table 25). The constraints consist of the comfort conditions limits that have been found in literature. It is allowed for the system to exceed these limits 10 % of the time.

Finally, the design objective is to minimize the total energy consumption of the prototype.

Input	Lower bound	Upper bound
Shade setpoint	15,0 °C	35,0 °C
Radiation setpoint	0 klux	1000 klux
Window setpoint	15,0 °C	35,0 °C
Flowrate	0,0 m^3/h	125,0 m^3/h
Heat exchanger setpoint	15,0 °C	35,0 °C
Floor cooling setpoint	15,0 °C	35,0 °C
Floor heating setpoint	15,0 °C	35,0 °C
Ceiling cooling setpoint	15,0 °C	35,0 °C
Ceiling heating setpoint	15,0 °C	35,0 °C
Active air cooler setpoint	15,0 °C	35,0 °C

Table 24: Upper and lower bounds as setup in modeFRONTIER

Output	Constraint name	Type	Limit
Thermal_comfort	min_temp	Greater than	ATG
Thermal_comfort	max_temp	Less than	ATG
CO_2	max_ppm	Less than	1200 ppm
Relative_humidity	min_perc	Greater than	30%
Relative_humidity	max_perc	Less than	70%
Visual_comfort	min_lux	Greater than	300 lux

Table 25: Design Constraints as setup in modeFRONTIER