



PANORAMA

The Effectiveness of Thermal Buffering Systems in
the Monumental Panorama Mesdag Museum

Elke Mulders
Master Thesis

MSc Architecture, Urbanism & Building Sciences
Track Building Technology

**Panorama: the effectiveness of thermal
buffering systems in the monumental
Panorama Mesdag museum**

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E.J.M. Mulders

4615212

MSc Architecture, Urbanism & Building Sciences
Track Building Technology
Faculty of Architecture and the Built Environment
Technische Universiteit Delft

First mentor: dr. ir. Z. Huijbregts
Climate Design, Building Physics and Services

Second Mentor: dr. ir. W.J. Quist
Heritage & Technology

in collaboration with ABT bv.
dr. ir. W.H. van der Spoel (supervisor)

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Abstract

The combination of the monumental building, the Rotonde, and the panoramic painting 'Panorama Mesdag' is one of the few remaining exhibitions of its kind. The organization of the museum aims to preserve the building and painting while also wanting to decrease the carbon footprint of the museum. The objective of this research is to design a sustainable climate solution using thermal buffering that creates an indoor climate that preserves the panoramic painting and reduces energy consumption of the minimally insulated building. The potential thermal buffering solutions were defined through literature research and the option of a PCM system secured to the interior façade was further elaborated on by estimating its effect on the indoor climate of the Rotonde through software simulations in DesignBuilder using EnergyPlus. The simulation results of multiple PCM types and thicknesses showed that the current indoor temperature of the Rotonde is too inconsistent during summer months for a PCM to reach the intended cooling effect. A simulation of a combination of improvements to the building envelope and the most effective PCM showed a cooling effect of two ° C on warm summer days and a decrease of 50% in heating demand during the winter. This research amplifies the importance of a well-insulated building envelope for a qualitative indoor climate and climate systems should be an additional step. The outcome of this research has the potential to be relevant for other monumental museums or other spaces that seek sustainable solutions to stabilize the indoor climate.

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Introduction

The eccentric panoramic exhibition in the Hague by painter Hendrik Willem Mesdag is a familiar sight in the Netherlands. The 360° panoramic painting of the dunes in Scheveningen has been part of the Dutch art history for 141 years (Fig. 1). The building, in which the painting is exhibited, is the last one standing of its kind in the Netherlands and it is also part of the small group of panorama exhibition buildings that has not been stripped down of their original panoramic painting.

The age of this exhibition and building are undoubtedly impressive, however the age also poses a problem. The non-insulated building envelope construction in combination with the absence of a floor construction, results in a building that does not comply with the modern-day sustainability goals. The building reacts rapidly to the changing outdoor environment creating an inconsistent indoor climate, which could also affect the preservation of the exhibition. Heating, cooling, and ventilation installations could manage the fluctuations, but are complex to integrate within the existing building and would increase the energy costs substantially.

A common passive solution, which does not require energy, is adding an insulating layer to the building envelope. Inserting the insulation on the exterior side of the façade is not favourable in the

case of the Rotonde, because it will affect the monumental façade. An insulation layer on the interior side increases the indoor temperature in the summer substantially, calculations show (de Bruin, Resultaten ruwe vergelijk berekening, 2022). Another proposal could be to abandon the building and house the exhibition in a modern museum, but the painting and building are inextricable. All elements in the space are specifically designed to fit the painting. The building is part of the paintings' history and separating those would be a loss of cultural heritage. The residual solution is to adapt the current building while not affecting its monumentality and the panoramic exhibition.

The combination of the non-insulated building envelope and the absence of an efficient climate control installation in the monumental Rotonde results in an inconsistent indoor climate which causes a risk of harming the painting and a substantial energy consumption for any applied climate installation (ASHRAE, 2019). The lack of specific reference projects of panorama exhibition buildings slows down the process of finding a climate control solution. Besides, the monumental state of the Rotonde constricts the intervention possibilities. The limited possibilities when trying to reduce the carbon footprint of the building is a common problem for monumental museums.



Fig. 1. Museum Panorama Mesdag, 2022.

Often a customized solution is needed that requires lots of resources and time.

Multiple adaptations to the building have been researched, but none show the desired result. This research focusses on the option of increasing the thermal buffering capacity of the building. Thermal buffering techniques can affect the indoor climate of a building by using the thermal storage and release capabilities of a material while not requiring additional energy. It appears to be a potential solution, because it can fulfil both a cooling and heating function, while creating a more favourable indoor climate for the preservation of the painting. This solution can help to stabilize temperature and moisture fluctuations and decrease the energy demand.

The aim of this research is to design a sustainable solution that creates an indoor climate that preserves the panoramic painting and reduces energy consumption, while minimizing interference with the monumentality of the exhibition building and the experience of the permanent Panorama Mesdag exhibition. Within the research there are multiple sub-objectives. This research assesses the current indoor climate of the Rotonde and defines the intended indoor climate that would preserve the painting. This research also aims to define the most suitable thermal buffering technique in the Rotonde and how it can be applied. Also, an objective is to define the relevance of the thermal buffering system for other monumental museums.

The final product of this research consists of a recommendation on a hands-on design solution that creates a more consistent indoor climate, specifically tailored for the monumental exhibition building of the Panorama Mesdag painting, which could also be relevant for other monumental buildings with a similar building envelope. The most noteworthy restriction for this design that is stated by the Panorama Mesdag Museum, is that the solution may not impact the experience of the permanent panorama exhibition in any way, which means that it may not be in the perspective from the visitors' platform or alter the incidence of natural light.

The main and sub questions of this research are as follows.

How can the Rotonde of the Panorama Mesdag Museum be adapted to increase the thermal buffering capacity of the building while not interfering with the monumentality of the exhibition building and the experience of the permanent Panorama Mesdag exhibition?

Sub-questions

1. *What is the current state of the monumental Panorama Mesdag exhibition, including the painting, the building, and the indoor climate?*
2. *What are possible techniques for increasing the thermal buffering capacity of a building and which one is most suitable to establish a more consistent indoor climate in the Rotonde of the museum?*
3. *How can the most suitable thermal buffering technique for the Rotonde be applied while minimizing interference with the monumentality of the building and the experience of the permanent panorama exhibition?*
4. *Can the application of the thermal buffering solution for the Rotonde be relevant for other monumental panorama buildings or any monumental building with a similar building envelope?*

This research focusses on a wide variety of subjects, including historic research, indoor climate control, thermal buffering techniques and the application and validation of the proposed system. Historic research into panorama exhibitions and buildings is essential to get a good understanding of the value of the Panorama Mesdag exhibition and the building. Indoor climate control is the monitoring of indoor environment and within this subject the current and desired indoor climate and installations can be defined. Thermal buffering techniques can affect the indoor climate of a building by using the thermal

storage and release capabilities of a material (Sarbu & Sebarchievici, 2018). Many materials and techniques are available, so research is presented within this subject determining suitable options the intended indoor climate in the Rotonde. The subject of application and validation of the proposed solution concerns creating and testing a design of the suitable thermal buffering technique specified for the Rotonde.

The main case study used for this research is the Panorama Mesdag museum and data is collected by literature research, site visits, documents from and conversations with the museum organization and installation consultancy group. The first chapter of this research focusses on the Panorama Mesdag museum itself, including the history and current state of the building and panoramic painting. For this chapter literature research, site visits and climate data analyses have been used.

The second chapter elaborates on climate control in museums, how it can affect the collection and in particular the damage risks on the Panorama Mesdag museum. In addition, an analysis of the current indoor climate in the Rotonde is presented, including data analysis of temperature and relative humidity, current installation and the climate requirements set by the organisation of the museum. This chapter finishes with the intended indoor climate of the Rotonde. The research method within this chapter are mostly literature research and data analysis of data provided by NIAG and the museum's organisation.

The third chapter presents literature research into thermal buffering installations in buildings. The chapter starts with an introduction into the underlying processes, materials, and commonly used installation types. Afterwards, the application of thermal buffering techniques in the Rotonde is discussed. The potential locations for the solution are presented in combination with the suitable techniques. Multiple possible installations are proposed, and an analysis is done on their feasibility, thermal storage capacity and their influence on the indoor climate of the Rotonde.

The fourth chapter elaborates on the most promising option and further designed in detail with the use of simulations and supplementary measurements. A simulation with the software 'DesignBuilder' is used to estimate the thermal buffering capacity and efficiency of the installations in the Rotonde. As a base of the simulation a digital model of the current situation is used in combination with specific outdoor climate characteristics, such as temperature and relative humidity which were measured locally outside the Rotonde. With the results from the simulations, the solution can be optimized to its final design. The final design is a detailed to a scale of 1:5 or 1:10, so in this phase there is more emphasis on building construction.

The fifth chapter presents a sidestep of the research, where the proposed solution for the Rotonde is theoretically applied to a similar monumental exhibition building. This concerns a building with a panoramic exhibition or another monumental building, but with a similar building envelope as the Rotonde. Literature research and calculations are used and a site visit to the proposed case study is advised.

This project is the combination of building physics and technology creating a sustainable climate solution that also ensures to preserve valuable cultural heritage, in this case a monumental building and art piece. The final product of this research, a custom fit climate solution for the Panorama Mesdag, could be directly relevant for other panorama exhibition buildings, but also for any monumental building with a similar building envelope. The product could help the sustainability problems that many monumental buildings face currently, wanting to adapt and decrease the carbon footprint of the building while having to work in a limited range of possibilities due to the monumentality.

The Panorama Mesdag

This chapter is an introduction to the Panorama Mesdag museum, focused on the panoramic exhibition and the monumental Rotonde. Afterwards, a detailed analysis of the exhibition building, and the panoramic painting are presented. The aim of this chapter is to create a knowledge foundation for the research into the Panorama Mesdag exhibition and contribute to the assessment of the need of preservation of the exhibition. This chapter also shines a light on the complexity and vulnerability of the case study.

The Museum

The panoramic painting by Mesdag has been housed in the Rotonde, since its opening in 1881, which is now part of the Panorama Mesdag Museum. The current Panorama Mesdag museum consists of multiple interconnected buildings and an overview of the museum is given in fig. 6 and 7.

Year(s)	Built in 1880, expanded in 1910, renovated in 1980 & 2010
Architect(s)	Original design by Gerard Klomp & Hendrik Willem Mesdag(1880), Braaksma & Roos (2010)
Location	Zeestraat 65, the Hague in the Netherlands
Function(s)	Museum, depot, restaurant, offices, educational spaces
Total area	2.680 m ²
Rotonde	1.200 m ²
The original exhibition started in 1881 with only the	

Rotonde. From 1910 Hendrik Willem Mesdag (1831-1915) was the owner of the exhibition and he decided to add multiple museum halls for exhibiting artworks that he had been creating and collecting over the years. After Mesdag passed away in 1914, the museum stayed within the ownership of the family and to this day it still is, which is most likely the reason it is still intact.

During the 20th century the number of yearly visitors kept increasing, partly due to a reduction of the entrance fee (Fruitema & Zoetmulder, 1981). In the 1980's the museum expanded again and the Rotonde was renovated, including an extensive restoration of the panoramic artwork. In 2010 to 2012 the museum was renovated by Braaksma & Roos architects, except for the Rotonde. The buildings were restored, expanded, and modified creating a more engaging route to and from the panorama (fig. 6). The routing now leads visitors through an exhibition about Mesdag's life before entering to the dark hallway, the beginning of the panorama experience. Afterwards visiting the panorama, supplementary exhibitions, the restaurant and shop can be visited.

The yearly visitors number has increased after the renovation to approximately 135.000, but have been low in the recent years, due to the covid pandemic (Panorama Mesdag, 2021). However, it is currently still one of the most well-known exhibitions in the Hague and arguably in the Netherlands.

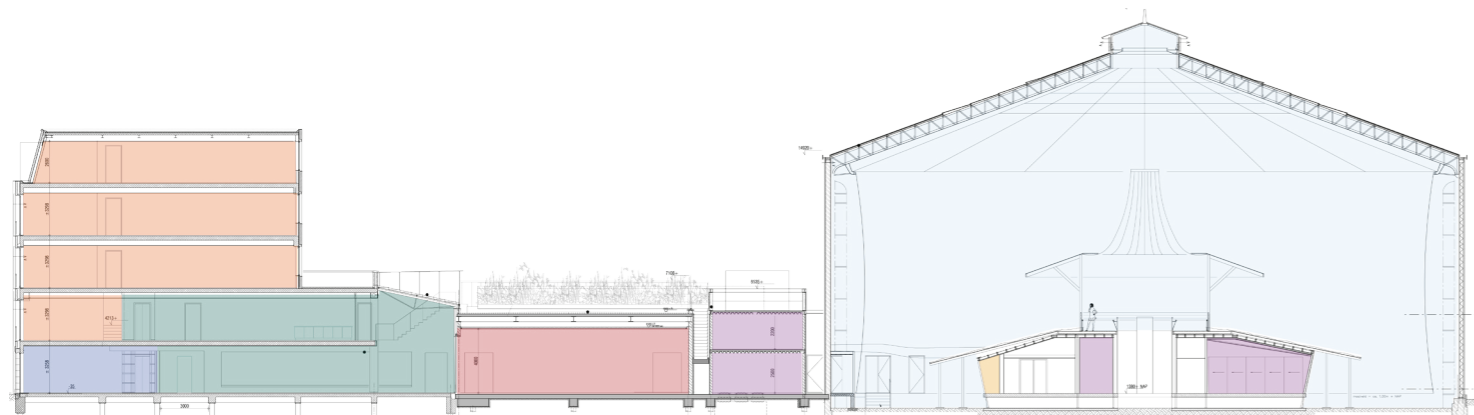


Fig. 2. section of the Panorama Mesdag museum with functions (source: own).

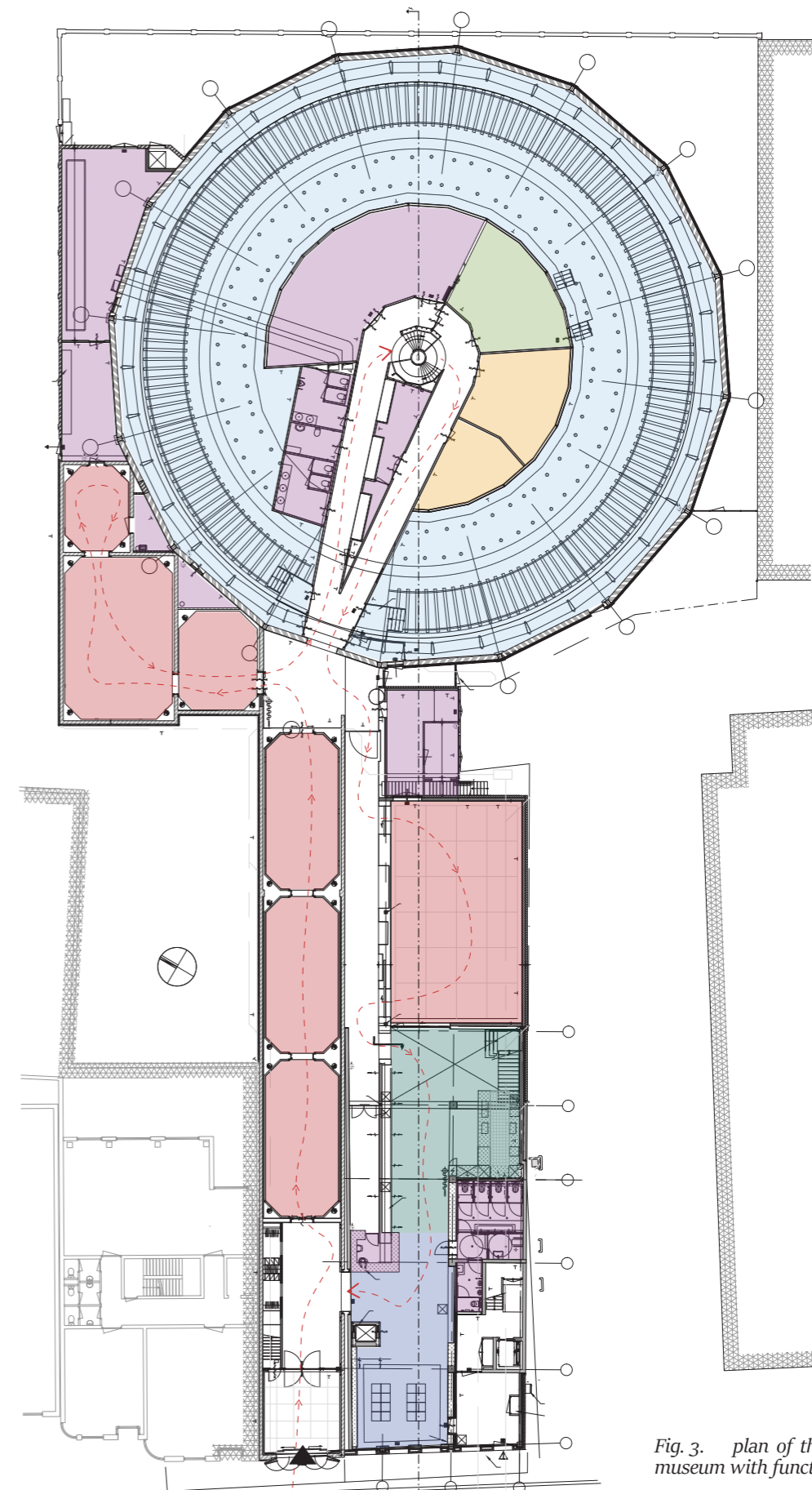


Fig. 3. plan of the Panorama Mesdag museum with functions (source: own).

■ Rotonde	■ Offices
■ Exhibition halls	■ Services
■ Cafe	■ Hallways
■ Shop	■ Educational space
■ Depot	

Cultural Heritage: the Panoramic Painting

The centrepiece of the museum is the 360° painting by Hendrik Willem Mesdag in 1880 (Fig. 4). Panoramic paintings were a popular recreational destination during the 19th century and the Panorama Mesdag is last remaining painting of this sort in the Netherlands.

Mesdag was asked by a Belgian enterprise to paint a panoramic sea view and he chose to paint the Seinpostduin in Scheveningen, most likely because construction work was planned for this area and Mesdag wanted to protest this (Fruitema & Zoetmulder, 1981). Mesdag stood on top of the Seinpostduin within a self-made glass cylinder on which he painted the outline of the 360 degrees view. Next, the outline was transferred to a flat sheet and a prototype was painted with sections. Together with a team of painters, the outline was enlarged per section on a canvas, which was already hanging in the Rotonde in the Zeestraat. Four months were needed to finish the 1660 square meter painting.

The exhibition, located in the Rotonde, was very well received by critics in 1881 due to the high quality of painting work (Fruitema & Zoetmulder, 1981). The choice of scene was unusual, because it could be visited in real life a few kilometres away, while most panoramas depicted a scene of a faraway location or an impressive battle. However, this did not affect the popularity of the panorama.

The exhibition is focused on creating the illusion of being present on the Seinpostduin in Scheveningen and for this reason the exhibition exists of more than just the painting. The illusional experience starts by entering a dark hallway that is deliberately under-exposed, because it intensifies the moment the visitor steps into the panorama

space (Fruitema & Zoetmulder, 1981). From the dark hallway, a spiral staircase leads upwards to the panorama that will disorient the visitors. When reaching the top of the staircase, the panoramic painting is supposed to take the visitors by surprise with the amount of light in combination with the infinite 360 °view (Fig. 5).

The view from the visitors platform, which is also called the Belvedere, has been designed carefully with a faux-terrain. This is the installation between the spectator's platform and the painting itself, often designed with a landscape and objects related to the depicted scene on the painting. Mesdag chose for imitation dunes around the Belvedere to create the illusion of the infinite view and the transition from sand to painting is hard to distinguish. Maritime objects in the sand have been placed carefully to align with the size and perspective of the depicted scene on the painting.

The exhibition in the Hague is a good example of the blueprint of panoramic exhibitions with its routing, faux-terrain and painting size. The phenomenon of a panoramic painting was first invented at the end of the 18th century which represents one of the first intentional expressions that combine art and science. The Irish painter Robert Barker was the first to create a panoramic painting. He wanted to catch the total view from Calton Hill in Edinburg in one painting, but he soon realised that his panorama had a strong illusional effect (van Eekelen, 1996). In 1793 Barker opened his first panorama exhibition in London in a circular building, especially designed to house two panoramic paintings on multiple levels.

The exhibition was a great success and inspired many other painters. During the 19th century hundreds of other panoramas were created in Europe and the United States, including the

painting by Mesdag. The popularity of this recreational exhibition fluctuated throughout the century and reached its lowest point when cinema was invented at the end of the 19th century (van Eekelen, 1996). Currently only a few panoramas still exist of which the majority is located in Europe and a few in Russia and North America (Fig. 6). A more elaborate overview of existing panoramas is available in appendix A.

Panoramas could be considered as the precursor of cinema because they depict a place on the world or an important historic event that most people were not able to experience in real life. Also, it has the same immersive capacities on people with the illusional effect which makes them believe the view is a real-life landscape. Panoramas could be categorised as immersive media, which is also known by modern technologies such as virtual and augmented reality (Panorama Council, 2022).

This similarity shows that these technologies are not just a passing trend but are rooted deeper in the development of art and recreational exhibitions. It is even more so important to preserve panorama exhibitions and their buildings from the 19th century.



Fig. 5. View of the panorama exhibition (source: own).



Fig. 4. photo of the Panorama Mesdag painting (Wikipedia, 2008).

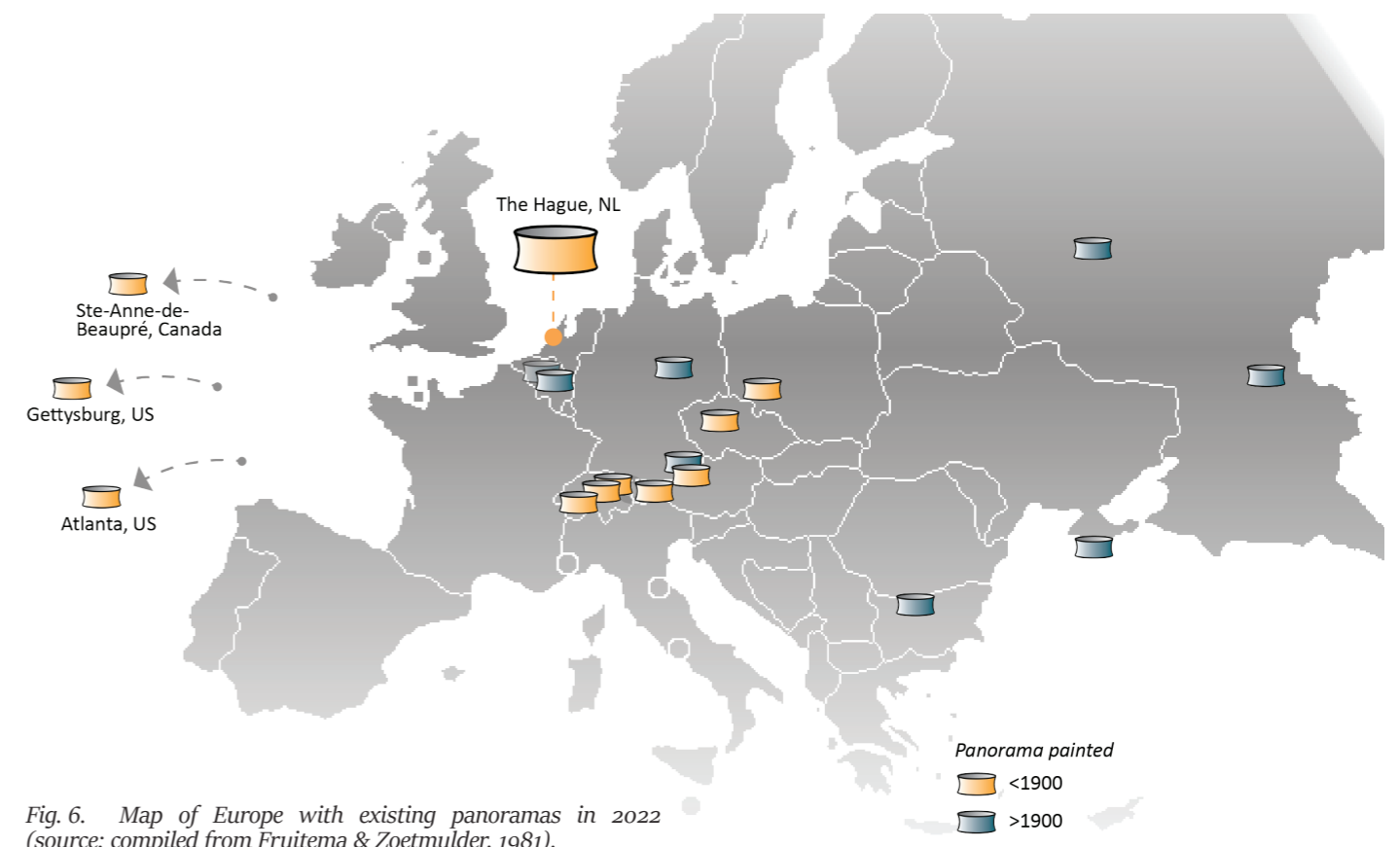


Fig. 6. Map of Europe with existing panoramas in 2022 (source: compiled from Fruitema & Zoetmulder, 1981).

The Monumental Rotonde

The Rotonde was built specifically for housing the panorama of the Seinpostduin in 1880 and it was designed by Gerard Klomp and most likely in cooperation with Mesdag himself (Fruitema & Zoetmulder, 1981). It is said that the absence of a floor construction was the idea of Mesdag, however this is complex to verify, since no original drawings or information are available of the Rotonde. The absence of the floor construction helps to preserve the large painting, because of the natural moisture control capacity of sand.

The circular building in the Hague follows the standardised diameter size, so the panoramic paintings of other exhibitions could be interchanged (Fruitema & Zoetmulder, 1981). The capacity to exchange and move panoramic paintings had been an important factor since the first exhibition structures were built at the end of the 18th century. Most of these were timber buildings and some even dismountable that allowed the painting to be displayed in different cities (Fruitema & Zoetmulder, 1981). The first structures were relatively small and had usually a maximum diameter of 15 meters. In some of the big cities in Western Europe, such as London and Paris, more professional structures were built mid-19th century made from stone or timber. The facades of these buildings stayed quite modest without any decorations but could be realised in larger sizes. The Panorama Mesdag

building could be classified as such a structure, even though it was realised later in the 1880's.

In the second half of the 1800's, some exhibition structures were built that resembled professional theatres, instead of fairground attractions, so it would correspond to the architecture in the centre of large cities such as Berlin and Vienna. The facades were supposed to resemble the beauty that was exhibited inside and thus were extensively decorated, some even pompous.

Nowadays, only a few of the panorama buildings have survived, so they could be considered as unique as the paintings themselves. The reason most of the exhibition buildings were demolished is their unique shape and size, which made them difficult to house new functions when panoramic exhibitions were not profitable anymore at the end of the 19th century. Some buildings were transformed to industrial spaces, but most of them had to make way for housing or other building types in the city centres.

In the current day it is estimated that about 20 panoramic paintings from the 19th century are still intact, from which five have been translocated to a new building recently or already during the 20th century (Panorama Council, 2022). However, this does not mean that the other paintings are still in their original exhibition space. Multiple buildings have undergone drastic renovations, such as the exhibition building in Luzern, which is surrounded by a modern building (Fig. 7).



Fig. 7. photo of the Bourbaki-Panorama building in Luzern, Switzerland (Kümmerli, 2017).

In Luzern, Switzerland, the Bourbaki Panorama is on display in its original exhibition building which is now a monument. The building has been renovated extensively and it is surrounded by a new building which houses shops and a library. However, parts of the façade and the complete roof are still in its original state and because of this, the museum faces similar climate challenges as the museum in the Hague. For this reason the museum in Luzern is used as a reference project for this research.

The Mesdag exhibition, that still functions in its original arrangement of painting and building, is rare from an international perspective and for this reason one could argue that it should be preserved. The panorama buildings are part of the history of the painting and vice versa. Separating them would be neglecting a part of their history. Besides, moving more than 100-year-old fragile paintings, could have devastating consequences. Therefore, adapting the original buildings to the current needs is preferred over translocating the exhibition.

Future of Mesdag

The organisation of the Panorama Mesdag museum has defined a mission for the museum. The museum holds the heritage of the painter Mesdag and aims to preserve this for as long as possible and exhibit it to keep inspiring future generations (Panorama Mesdag, 2021). With preserving the distinctive panoramic exhibition, the museum hopes to inspire others to exhibit their art in an unique way instead of following the conventional path.

Besides preservation, the organisation aims to decrease the carbon footprint of the museum as much as possible. In a previous renovation in 2010, most of the buildings of the museum have been adapted including their climate installations, decreasing the energy demand.

However, for the Rotonde no suitable measures have been found so far that can reduce the energy demand while also preserving the exhibition and the monumental building.

Current State of the Panorama Mesdag Painting

The original panoramic painting is currently 141 years old, which is impressive for a painting of 1600 m² and 4500 kg (Fig. 8). The materials used for the paint are a emulsion oil, pigment and glue water. This solution dries quickly and has a matte finish which amplifies the illusion effect (Nederlof, 2006). Currently, the paint layer has become solid and porous resulting in a fragile painting which is complicated to retouch. The canvas is made from multiple strips of linen of a few meters wide to allow for easier transportation of the painting during the 19th century. The original linen shows some severe damage in the form of fractures, rips, and holes, which will be discussed in the next paragraphs (BV Panorama Mesdag, 1996).

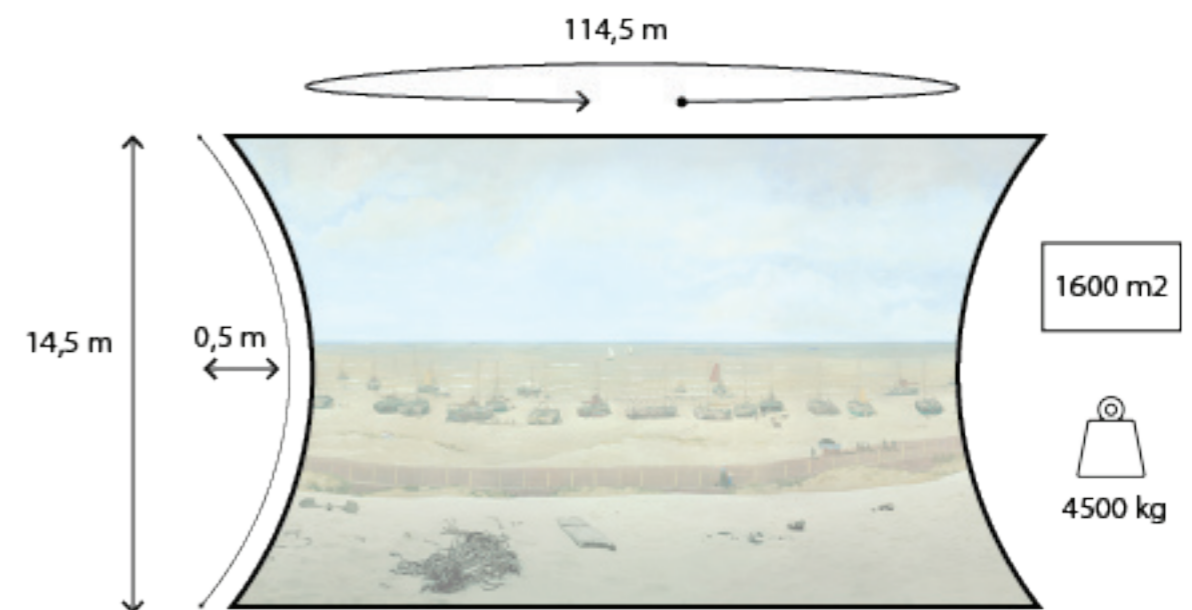


Fig. 8. Characteristics of the painting (source: own).

Impairments and Repairs

An overview of damages and their repairment techniques, if any, are shown in overview in Table 1. The sources for this overview are Nederlof (2006) and BV Panorama Mesdag (1996). An important repairment is the relining of the painting, because it helps to confine the severe fractures at the top of the painting, which was done in 1996. Also a steel rail was installed at the top of the canvas to take over the suspension function from the original wooden beam. Multiple experiments were done before applying the second canvas ensuring it would not further damage the original canvas. The following steps were taken in the process (BV Panorama Mesdag, 1996):

1. A glue solution in solid form was added to one side of the new nylon canvas.
2. A strip of new nylon canvas of 1,5 m wide was secured to the new suspension structure, so the new canvas is now hanging against the back of the original canvas. The nylon was roughened for proper adhesion and stretched at 180° C to create similar elasticity as the original linen canvas (Nederlof, 2006).
3. A vacuum installation is held against the back of the nylon canvas. The covered area is put under a vacuum and heated to a maximum of 140° C. While heating up the glue solution becomes fluid and sticks the new and original canvas together.
4. When cooling down, the glue hardens and secures the connection between the two canvasses. These steps were repeated 120 times over the whole area of the panoramic painting. This process on the Panorama Mesdag took approximately 4 months.

After the relining process the overall state of the panorama canvas was considered to be good, because previous damage has been confined and damaging processes are slowed down. However, regular monitoring is needed for air pockets between the new and original canvas that are appearing.

Future Restorations and Maintenance

The cleaning and monitoring process is advised to be repeated every five years, depending on possible building renovations and air circulation (Speldekamp, 2018). Protruding areas of the painting are advised to be cleaned more regularly than other areas. The regularity of retouches depends on multiple indoor environment factors, such as UV-exposure and can be determined during monitoring. The movable work platform on rails will be used during maintenance on the front side of the painting.

Bourbaki Panorama - Luzern Current State: Declining

The current state of the panorama painting in Luzern is in a declining state (Helm & Marty, 2021). Also in this case fractures at the top of the painting pose a risk on the art object. A new suspension structure has been installed, but the painting has not been relined, because this doesn't comply with the vision of the museum of minimal intervention. For this reason the fractures are less confined and are worsening.

	Damage	Year of repairment	Repairment technique	Repairment material(s)	Current state
Canvas	Holes	1988-1996	<ul style="list-style-type: none"> Remove previous repairs Fill holes 	Linen patches	Good
	Fractures	1988-1996	Relining canvas	<ul style="list-style-type: none"> Nylon canvas Thermoplastic glue 	Good
	Stretched areas	n.a.	-	-	Stable
	Glue residu	1988-1996	Removing residu	n.a.	Good
	Air pockets	n.a.	-	-	Declining
Paint	Detaching paint	2017	<ul style="list-style-type: none"> Confining paint with a resin Removing excess resin 	<ul style="list-style-type: none"> Aquazol 200 (synthetic resin) Isopropanol 	Good, if done regularly
	Deposits	<ul style="list-style-type: none"> 1910 1988-1996 2017 	Removing deposits with a brush, vacuum cleaner and/or sponge	n.a.	Good, if done regularly
	Pulverised and faded paint	<ul style="list-style-type: none"> 1910 1988-1996 2017 	Retouches	Pencils	Good, if done regularly

Table 1. Overview of damage types, repairments and the current state (compiled from Speldekamp (2018) and Nederlof (2006)).

State Description

Good = Repaired and no risk to art object.
 Stable = Not repaired, but not getting worse.
 Declining = Damage is getting worse.
 Bad = Severe damage with risk to art object.

Current State of the Rotonde

This chapter gives an elaborate description of the Rotonde, the building where the Panorama Mesdag painting has been located for almost 141 years. First, an overview of the construction characteristics and installations is given. Then, past renovations and modification of the building will be discussed, followed by future ambitions for the Rotonde defined by the museum organisation. To conclude, an overview is given of the specific requirements of this rare building that clarify what can and cannot be changed to the building.



Fig. 9. Interior of the Rotonde (source: own).

Construction characteristics

The Rotonde is a polygon shaped building with 16 sides, which was built for the purpose of exhibiting the Panorama Mesdag painting (Fig. 9). The painting covers the complete interior side of the facades and visitors are able to view the painting from the platform in the middle, called the Belvedere, which is surrounded by a faux terrain. The collaboration between the painting, faux terrain and the Belvedere creates a perspective for spectators that seems infinite and is hard to distinguish from real life.

Diameter 40,5 m
 Height 23,3 m
 Area 1200 m²
 Volume +- 20.000 m³

Interesting characteristics of the building are the absence of a floor construction, the disorganised masonry façade and the large area of skylights. As mentioned before, the sand layer is beneficial for the preservation of the painting. The irregularity of the masonry façade most likely stems from the expected short life time of the building when it was built. For this reason remnant bricks were used and resulted in the use of a variety of brick sizes and bonds, creating a disorganised masonry façade. Since the building has a monumental protective label, minimal interventions are allowed. For this reason only the roof is insulated and the rest of the building's envelope is not. An overview of the construction details is shown in Table 2.

Layers	Floor	Facade	Roof	Skylight
Exterior				
1.	200-250 mm peat soil	Cement plaster	EPDM roofing with fine aggregate	5 mm float glass
2.	1500 mm sand	400 mm steel columns	40 mm XPS insulation	15 mm air cavity
3.		350 mm brickwork	Vapour barrier	6,76 mm safety glass: • 3 mm float glass • 2 x 0,38 mm window safety foil • 3 mm float glass (translucent)
4.		cement plaster	Wooden boaring	Aluminium frame
5.			Steel trusses	
Interior				
U-value [W/m ² K]	n.a.	1,0- 2,0	0,714	2,975
Visual light transmittance [%]	n.a.	n.a.	n.a.	79,8
Solar heat gain [%]	n.a.	n.a.	n.a.	74,5

Table 2. The building envelope layers of the Rotonde and their characteristics (source: own).

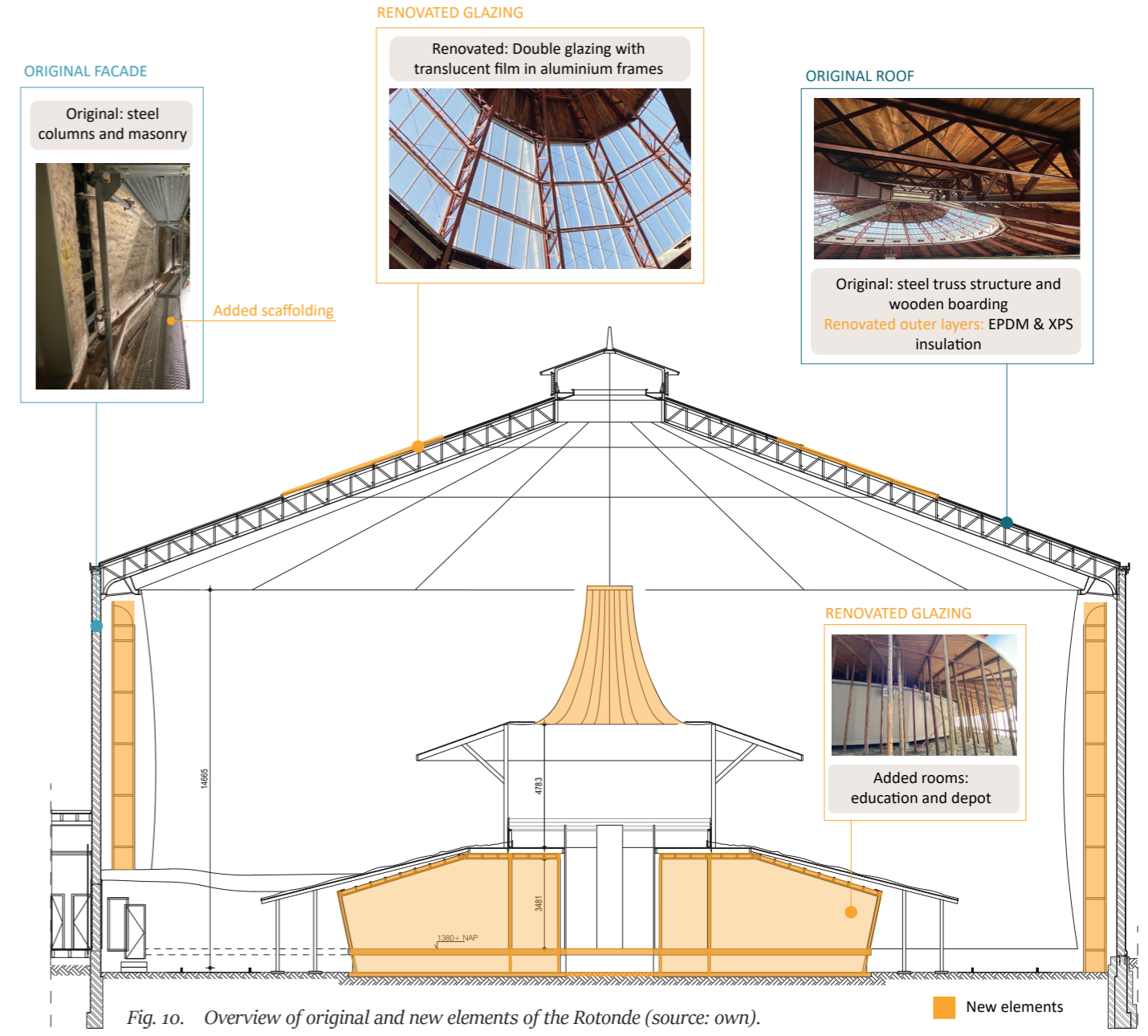


Fig. 10. Overview of original and new elements of the Rotonde (source: own).

In the 1980's urgent interventions were executed mostly focussing on increasing the monitoring and maintenance possibilities on the painting, such as installing a new movable work platform and permanent scaffolding (Fig. 10). Other interventions included reinforcing the steel roof structure and renewing the skylights.

Current installations in the Rotonde

The installations for climate control play an important role in the preservation of the painting and the building. Currently, multiple heating

installations are located in the Rotonde, but cooling is minimal through an additional ventilation installation. There is no direct humidity control in the Rotonde, but some conditioned air does overflow from the educational room to the Rotonde. With this ventilation overpressure is created within the Rotonde to prevent contamination to enter the building through the many cracks and openings (NIAG, 2021). An overview of the installations with their characteristics is presented in Fig. 11 and Table 3.

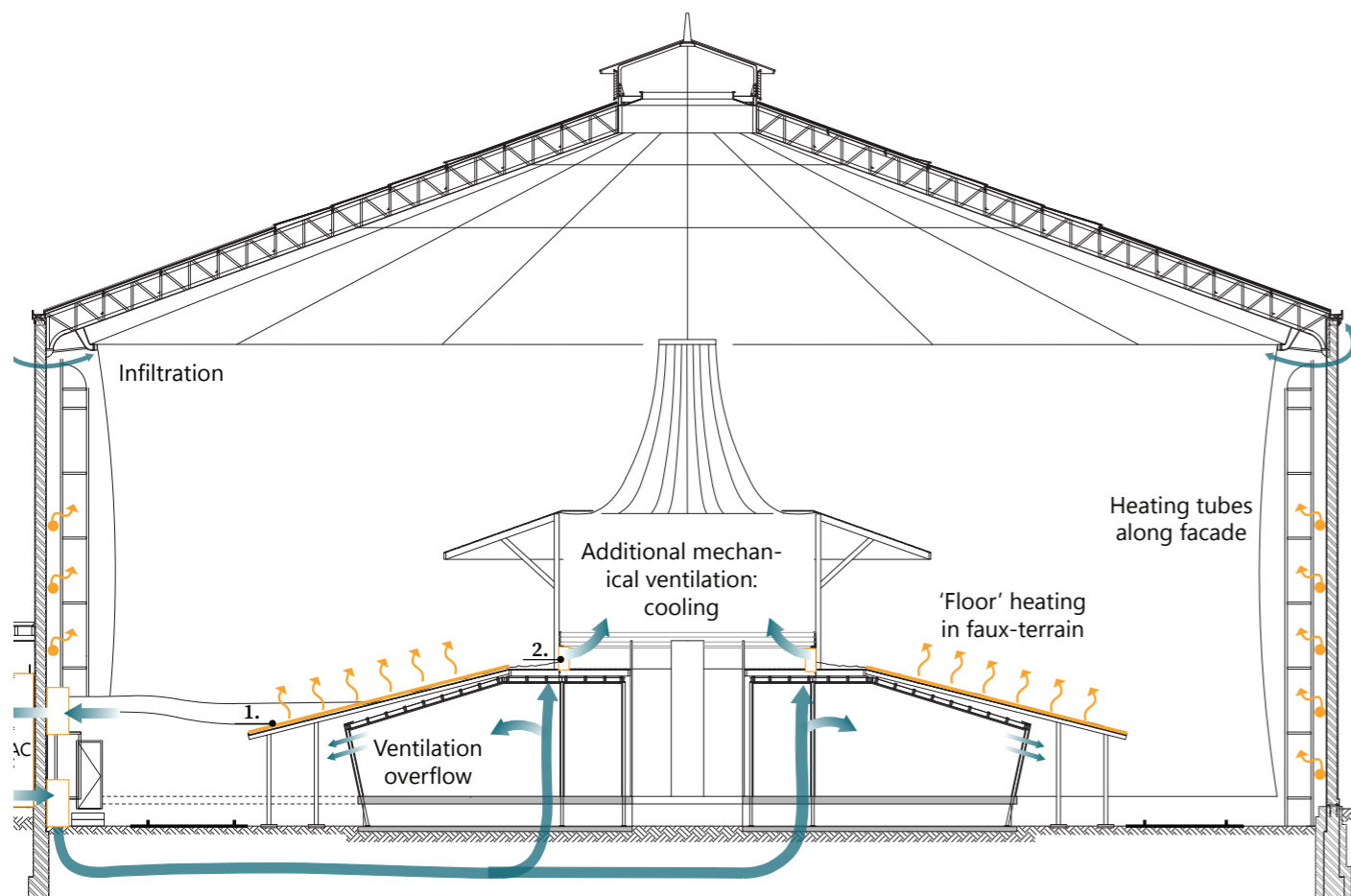


Fig. 11. Current climate installations in the Rotonde (source: own).

Installation	Mechanical ventilation (educational room)	Mechanical ventilation (belvedere)	Floor heating	Heating tubes
Heating/Cooling/Humidity control	Heating + cooling + humidity control	Cooling	Heating	Heating
Location (of Inlet/Extract)	<ul style="list-style-type: none"> Inlet: educational room Extract: behind canvas Overflow: to rotonde 	Inlet: Belvedere	Faux-terrain	Behind canvas
Thermostat Area	Educational room	Belvedere	Belvedere	Behind canvas
Setpoint [°C/%]	<ul style="list-style-type: none"> Cooling & heating: 21 °C Humidity control: 50% 	Manual activation	16 °C	16 °C
Supply [°C/%]	Variable	15 °C	Variable with max. 50 °C	Variable with max. 50 °C
Flow rate (water/air) [m3/s]	0,85	0,56	0,000667	0,003889

Table 3. Current climate installation in the Rotonde and their characteristics (source: own).

All installations operate between 09:00-18:00 Monday to Sunday. The heating tubes behind the canvas are planned to be removed, because it 30 to 40 years old and poses a damage risk to the painting due to leakage possibilities.

Datalogger sets in the Rotonde

Dataloggers that measure multiple variables of the indoor climate of the Rotonde are used to manage the climate installations, but also to study and monitor the preservation of the painting. Multiple datalogger sets are present and their data is used for different purposes (Fig. 12 & Table 4). A plan with datalogger location is present in appendix D.

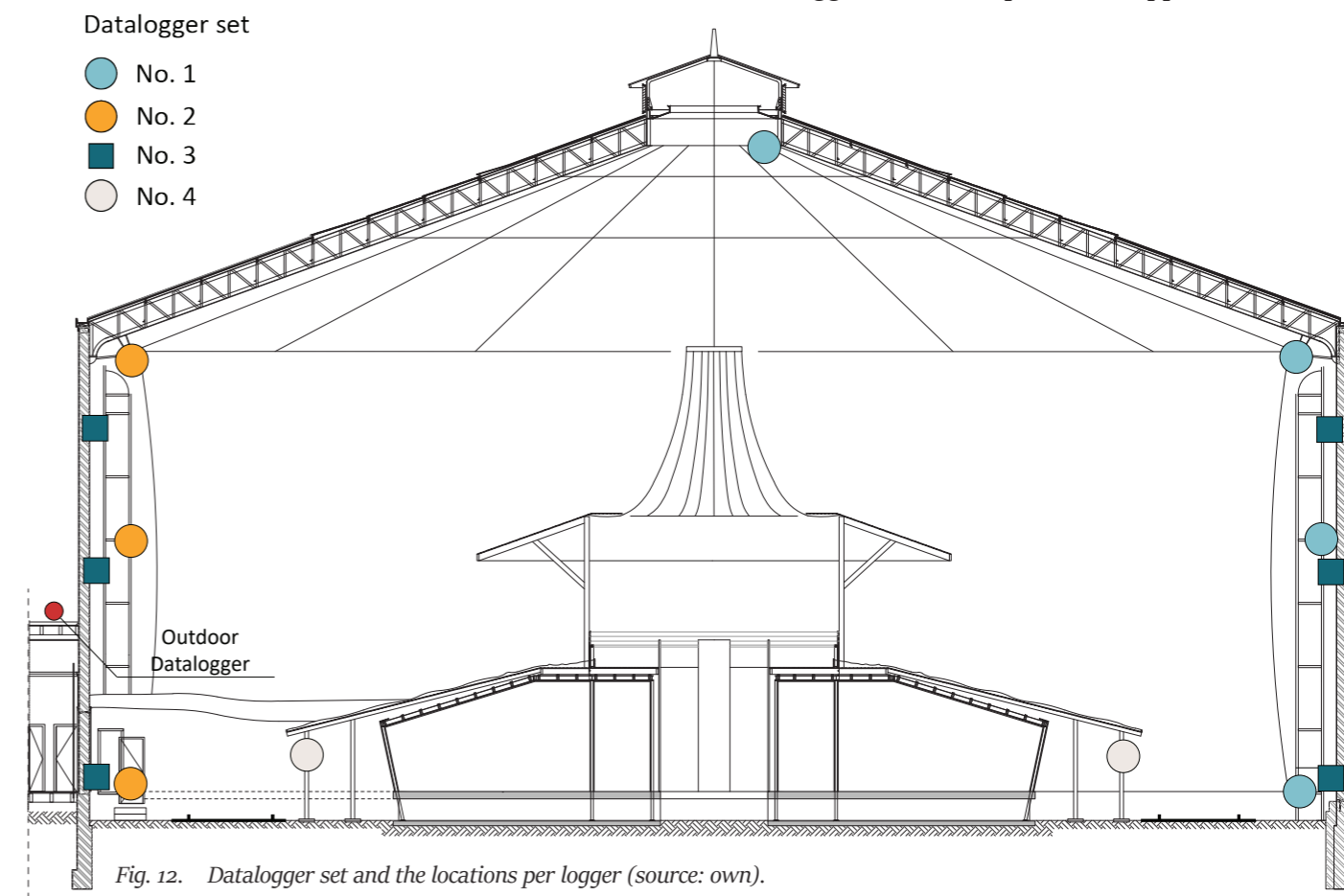


Fig. 12. Datalogger set and the locations per logger (source: own).

Datalogger set	1.	2.	3.	4.
Measurement	Operative temperature [°C]	Operative temperature [°C]	Surface temperature [°C]	Operative temperature [°C]
	Relative humidity [%]	Relative humidity [%]		Relative humidity [%]
Number of loggers	4	3	6	6
Locations	- 3x: behind canvas: north facade - 1x: roof	Behind canvas: south facade	Behind canvas: north & south facade	- 3x: behind canvas - 3x: Belvedere
Owner/Placer	NIAG	Elke Mulders / TU Delft	Elke Mulders / TU Delft	Museum
Logging period	September 2021 - September 2022	28th June 2022 - 1st of September 2022	28th June 2022 - 1st of September 2022	Ongoing
Purpose	Research	Research	Research	Manage climate installation

Table 4. Datalogger sets and their characteristics (source: own).

Climate zones in the Rotonde

Within the Rotonde where the Panorama Mesdag exhibition is located, multiple zones are distinguished that behave differently concerning the indoor climate and are suitable for monitoring through dataloggers. Three main zones are defined which can be seen in Fig. 13.

1. Behind the canvas

Volume: 3150 m³

This zone is the space between the 360 degrees canvas and the façade. Because this zone is unoccupied, it is used primarily to define the indoor climate that the painting is exposed to. Also, this zone is connected to the open space through openings above and below the painting. This allows for air circulation in both directions between the two zones. Within this zone there are three subzones on levels where dataloggers are located, the bottom, middle and top subzone.

2. Open space

Volume: 19.000 m³

This zone is the open space in the middle of the Rotonde and it is the only zone with daylight exposure through the skylights. Within this zone there are two subzones, the roof and the Belvedere. This zone is connected with the zone behind the canvas and is mostly used to define the indoor climate that the visitors experience.

3. Closed rooms

Volume: 1650 m³

Underneath the platform and the faux-terrain multiple closed rooms are located with functions, such as a depot, storage and educational room. The indoor climate of this zone is not analysed, but it is of significance for the ventilation estimations of the Rotonde, because of overflow vents from the rooms to the open space. The influence on the indoor climate between the two zones is one-sided, because air can only flow from the room to the open space.

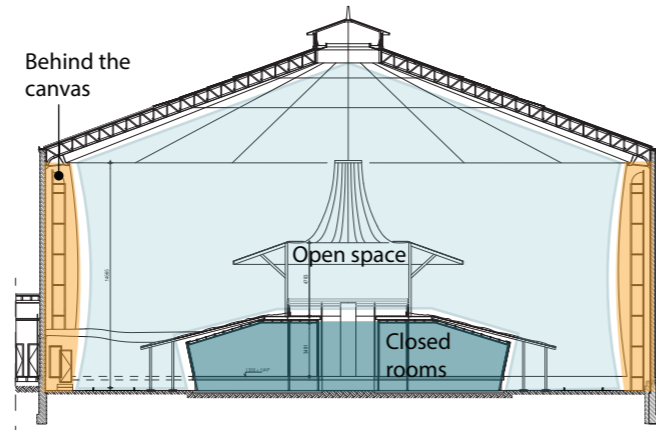


Fig. 13. Section of the Rotonde and the climate zones (source: own).

Energy consumption and costs of the Rotonde

An estimation of the energy consumption of the museum was done by NIAG (2020) and in combination with the current energy prices of 2022 defined by CBS (2022) an estimation is made of the total energy costs for 2022. The total costs would range around 230.000 euros per year of which 33% is for the demand of the Rotonde (Fig. 15). In the chart it is clear that most of the energy demand stems from heating the Rotonde during the winter (Fig. 14).

To be able to review these figures, a comparative analysis of average energy consumption for museums in the Netherlands is presented. The average data is collected by Milieubarometer (2022) by examining fourteen museums in 2016 to 2017 in the Netherlands of which most are located in the Hague and some are in monumental buildings (Fig. 16).

When comparing the electricity consumption it seems that the Rotonde uses a minimal amount of energy compared to the museum and national average, as the Rotonde has a very low amount of installations that use electricity, such as lighting and ventilation. The other museum spaces have an elaborate lighting installation and climate class B is maintained through a HVAC system. However, the gas consumption of the Rotonde is high, mostly due to heating and for that reason the total building-related energy per square meter of the Rotonde is higher than average in Dutch museums. The gas

consumption per cubic meter of the Rotonde is lower than average and the reason for this is the high volume of the Rotonde compared to its square meters.

Even though the Panorama Mesdag museum is not an ordinary museum its energy consumption is not excessively deviant from an average of the museums in the Netherlands, especially when compared to the amount of visitors. Besides, within the museum just over 30% of the annual energy bill is for the demand of the Rotonde. However, it is still pressing to decrease the energy consumption of the museum to lower its carbon footprint.

Energy demand of the Rotonde [kWh]

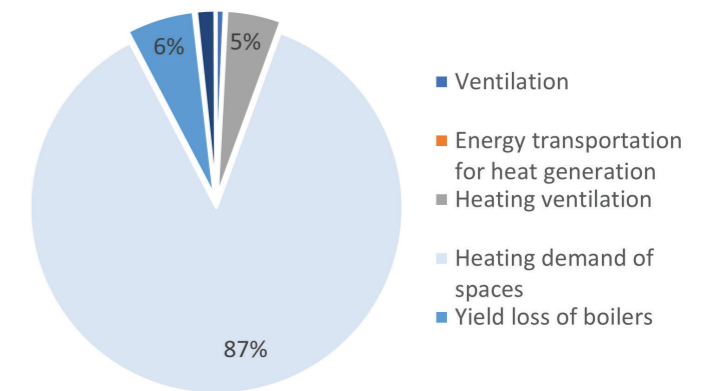


Fig. 14. Energy demand of the Rotonde (NIAG, 2020)

Yearly energy consumption Panorama Mesdag

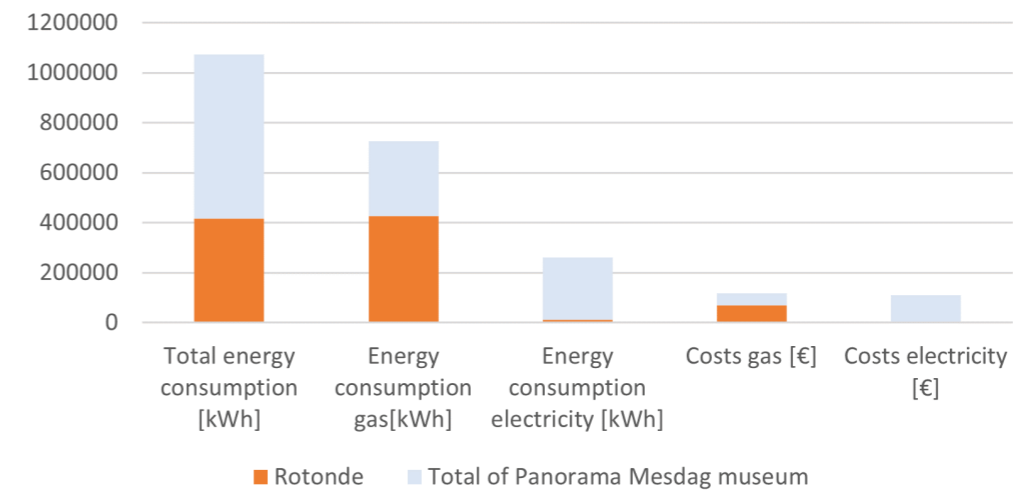


Fig. 15. Yearly energy consumption of the Panorama Mesdag museum (NIAG, 2020).

Comparing energy consumption in museums

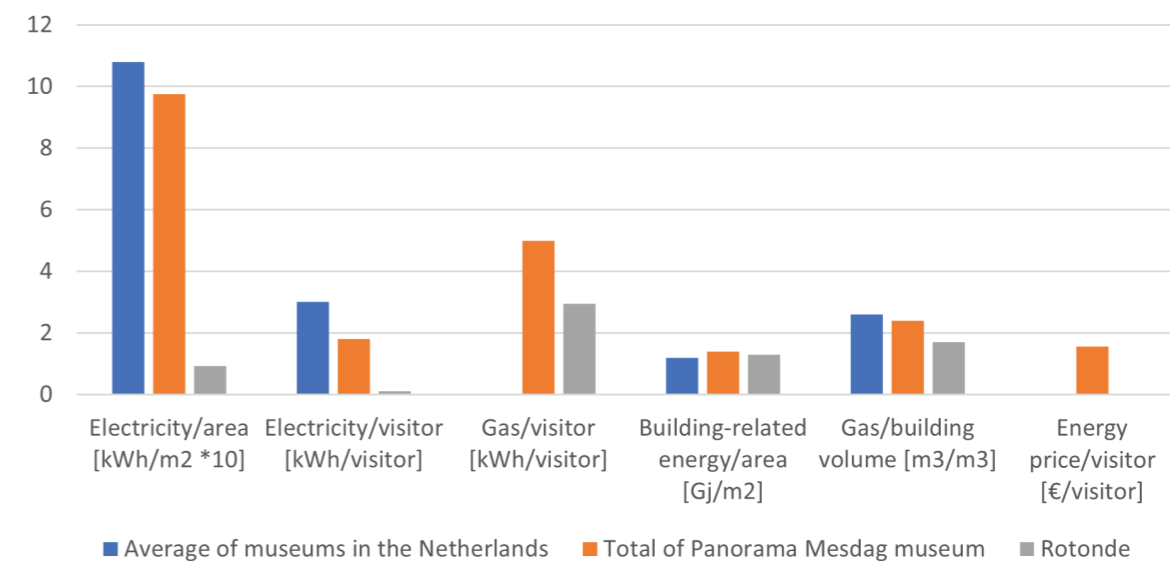


Fig. 16. Comparing energy consumption of the Panorama Mesdag museum including the Rotonde and Rotonde separately with the average of museums in the Netherlands (source: own).

Previous Research and Ambitions

The organisation of the Panorama Mesdag museum aims to make the Rotonde, more sustainable and create a better indoor environment for the painting. Research was previously conducted by the organisation of the museum to determine the effect of interior and exterior insulation layer.

However, these options were not favourable, because there was a risk of increasing the indoor temperature during the summer with this measure, which is not preferable, while it also affects the monumental façade (de Bruin, Resultaten ruwe vergelijk berekening, 2022). Calculations shows a substantial increase in indoor temperature, especially during warmer periods (de Bruin, Resultaten ruwe vergelijk berekening, 2022). During the winter season this could be beneficial while it lowers energy consumption, but during the summer season a cooling installation would be needed to lower the temperature.

The reason for the temperature increase is most likely stemming from the large solar gain through the glass roof combined with the better insulated facades, which results in heat built-up within the space. In conclusion, this measure would not be beneficial for the indoor climate or energy consumption.

Another possible measure is the application of sun control films on the glass panes to decrease the solar gain. The film would be placed on the exterior side of the outer glass pane, which is the best location when trying to lower the solar heat transmission throughout the year. The amount of solar heat transmission of this new glass configuration would be 47% lower than the current configuration (Fleiderus, 2020).

However, also the visual light transmission would be 20% lower, which could have a negative effect on the light incidence on the panorama exhibition. Testing of the application of films on existing glazing showed that this process is problematic and replacement of the films would be needed every few years. This is unfavourable and it is decided to install new glazing in the near future with incorporated solar control films.

The current focus is to lower the heating and cooling demand of the Rotonde with a passive solution using thermal buffering. This could result in a decrease in the energy demand and lower the carbon footprint of the building.

Spatial requirements

With the future ambitions in mind, the organisation has set strict boundaries of what cannot be adapted in the exhibition of the Panorama Mesdag painting and the monumental building itself, since the exhibition is quite fragile, and any small adaption could impact the experience of the visitors. An overview of elements that cannot be changed, is shown in Fig. 17.

Exhibition elements

The faux terrain, belvedere and hallway may not be changed, because this will directly change the experience of the exhibition.

Incidence of light

No object may be changed or added that could impact the incidence of natural daylight on the panoramic painting.

Visitors' perspective

No objects may be changed or added that are within the perspective of the visitors on the Belvedere, because this will directly change the exhibition.

Scaffolding accessibility

The scaffolding structure behind the painting needs to stay fully accessible, but objects are allowed to be connected or secured to it, if it doesn't affect the accessibility.

Foundation of rails & scaffolding

Changes to the soil underneath the Rotonde are allowed, also underneath the rails and scaffolding, but every few meters an area of the current sand soil needs to stay intact to ensure a solid foundation.

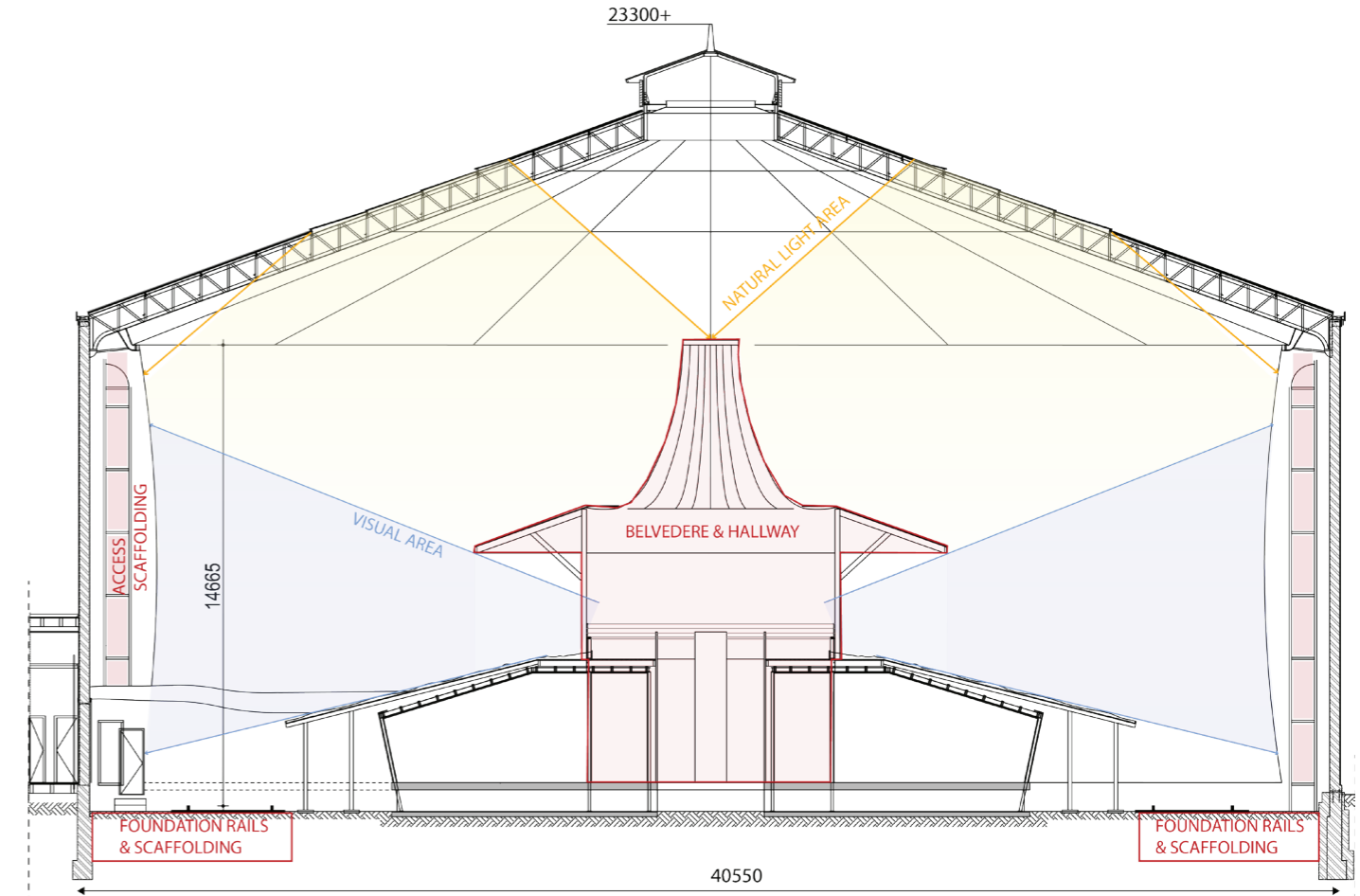


Fig. 17. Section of the Rotonde with spatial requirements (source: own).

Climate control

The indoor climate in museums, or other buildings exhibiting or storing fragile objects, is an important factor for the preservation of art pieces. When the indoor climate is not suitable for a specific art piece or collection, it can have a negative effect on the lifetime of the objects. In cases of loan art pieces, the owner of the art can demand specific indoor climate requirements to ensure the safety of the loaned pieces (SMK, The National Gallery of Denmark, 2022). In the case of the Panorama Mesdag exhibition, the art piece is unique with its large area and old age, most likely requiring a specific indoor climate for preservation.

First, commonly used climate standards for museums will be discussed for reference. Next, the specific risks and needs of the Mesdag painting will be presented, from which suitable climate requirements can be chosen in favour of preservation of the painting. Afterwards, the current climate installation and indoor climate data analysis is presented. The results from this chapter will help to define a framework in which the proposed climate solution of thermal buffering will need to function, the intended indoor climate.

Indoor climate damage risks on art pieces

The ASHRAE standard (2019) describes the possible damage sources on art pieces, which are physical forces, thieves and vandals, fire, water, pests, pollutants, light, temperature and relative humidity. This research focusses on risks by temperature and relative humidity, because those factors are controllable with an indoor climate installation, such as a HVAC system. When temperature is mentioned, often the air temperature of the space is referred to. Relative humidity is the concentration of moisture in the air and this is dependent on the air temperature (Nguyen, Schwartz, & Dockery, 2013). The level of damage risk in a specific climate differs per art piece, because every material reacts differently to temperature and relative humidity.

However, on average when temperature increases, the chemical processes that can damage the collection are accelerated. Also, an increase or decrease of relative humidity can be a damage risk, because any organic or hygroscopic material is influenced by the humidity of the air because it influences the chemical, physical and biological stability of the object. One of the damages that can occur from a high relative humidity level is mould, because the humidity levels in or on the surface of an object increase and this can create a suitable environment for the growth of mould (ASHRAE, 2019).

Another factor that increases the risk on mould is the deposit of substances such as dust and sand on the surface of an object because it increases the hygroscopic capacity. Therefore, the cleaning of paintings and other objects is important for preservation.

Another type of damage that can occur in unsuitable temperature and relative humidity levels is mechanical damage, such as fractures and deformation. These are often caused by a change in dimensions of the object in combination with a type of internal or external restraint (ASHRAE, 2019). An object often consists of multiple components and each component has different material characteristics. When one of these components is restricted in dimensional change, stresses occur within the component.

Another type of internal constraint is caused by a gradient in temperature or moisture level within the object itself. This occurs more frequently in large objects, such as the Panorama Mesdag painting, because they could experience multiple micro climates within a space.

The behaviour of objects when experiencing dimensional changes is dependent on the levels of relative humidity and temperature, but also on the fluctuation of these values. The period in which these fluctuations happen can be in a day or longer periods such as days, weeks or a season. The time frame of the fluctuations define the speed of the dimensional changes indicated with strain rate

(ASHRAE, 2019). Generally, there are two behavioural phases of materials: the 'glassy' and 'rubbery' behaviour. A material in the 'glassy' phase is brittle and has small tolerable strains, occurring at low temperatures, fast rates of strain and low relative humidity. A material in the 'rubbery' phase has large tolerable strains and occurs during high temperatures, slow rates of strain and high relative humidity.

Generally, dimensions changes caused by temperature happen over a shorter period, but the dimensional changes that occur are smaller than caused by relative humidity changes (ASHRAE, 2019). This indicates that fluctuations in relative humidity are more damaging than temperature fluctuations.

In addition to this, there are three aspects that also influence the risk on mechanical damage. The first one is stress relaxation. This is the phenomenon of a material being able to withstand about twice as much dimensional change when they occur over a period of months compared to a period of hours. For this reason, a larger percentage of relative humidity changes are allowed for seasonal changes than short-term fluctuations, respectively 10% and 5% changes in relative humidity.

The second aspect is stress concentration, which can increase the sensitivity to restraints (ASHRAE, 2019). This occurs when a component contains a flaw, hole or groove which increases the stress locally. These weak locations are often more sensitive to dimensional changes and can be the starting point for cracks.

The third aspect that has to do with mechanical damage is proofed fluctuation. This is the process of a component that already contains fractures created by earlier experienced dimensional changes and the component will not fracture more unless a fluctuation exceeds the past fluctuation (ASHRAE, 2019). In addition to this, fatigue can influence this process. For an existing fracture to grow, an accumulation of at least as many fluctuations that have already occurred, are needed.

Overall, the short-term frequent fluctuations in the indoor environment are less likely to cause

mechanical damage. The large and long fluctuation cause the greatest risk, so optimizing the indoor climate for long-term reliability should be given priority over short-term fluctuations.

Climate Standards for Museums

The commonly used standard internationally is ASHRAE (2019) and a standard that is applicable for Dutch museums is written by Ankersmit & Stappers (2020). The organisation of ASHRAE, American Society for Heating, Refrigeration and Air-Conditioning Engineers, has defined standards for interior climate aspects, such as ventilation, indoor temperature, and interior relative humidity concentrations. A specific category for museums, galleries, archives, and libraries is defined within the standard and will be used in the continuation of this research.

The advice includes a range of climate control categories (Table 5) which give a set of relative humidity and indoor temperature values with outer limits, annual averages, seasonal adjustments, and short-term fluctuations. The climate categories are mostly used as a guiding line when defining the desired indoor climate of a museum. The handbook mentions the following aspects that are relevant to determine, because they influence the suitability of the climate categories.

The relevant aspects of the concerning collection are the materials, construction and assembly, condition and vulnerability, the current and intended use of the collection, the frequency and kinds of access and specific climate history (ASHRAE, 2019).

For the exhibition building the following characteristics are important to determine; the materials and construction, condition and vulnerability, current and intended use of the building and history and changes to the building. Also, human needs are essential to consider including the number of staff and visitors and their current and/or intended activities, the current and

Table 13A Temperature and Relative Humidity Specifications for Collections in Buildings or Special Rooms

Type of Collection and Building	Type of Control	Long-Term Outer Limits ^a	Annual Averages	Seasonal Adjustments from Annual Average ^b	Short-Term Fluctuations plus Space Gradients ^c	Collection Benefits and Risks ^d
Museums, Galleries, Archives and Libraries in modern purpose-built buildings or purpose-built rooms	AA Precision control, no seasonal changes to relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C		No change to relative humidity Increase by 5 K; Decrease by 5 K	±5% rh, ±2 K	Mold germination and growth, and rapid corrosion avoided. No risk of mechanical damage to most artifacts and paintings. Some metals, glasses, and minerals may degrade if rh exceeds a critical value.
	A1 Precision control, seasonal changes in temperature and relative humidity	≥35% rh ≤65% rh ≥10°C ≤25°C	For permanent collections: historic annual average of relative humidity and temperature. In public display areas, human comfort temperatures can apply.	Increase by 10% rh. Decrease by 10% rh. Increase by 5 K; Decrease by 10 K	±5% rh, ±2 K	Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher. Mold germination and growth, and rapid corrosion avoided. No mechanical risk to most artifacts, paintings, photographs, and books; small risk of mechanical damage to high-vulnerability artifact.
	A2 Precision control, seasonal changes in temperature only	≥35% rh ≤65% rh ≥10°C ≤25°C		No change to relative humidity. Increase by 5 K; Decrease by 10 K	±10% rh, ±2 K	(Current knowledge considers the specifications A1 and A2 as causing the same low risk of mechanical damage to vulnerable collections. Slow seasonal adjustment of 10% rh is estimated to cause the same mechanical risk as rapid fluctuations of 5% rh, because of significant stress relaxation occurring within three months of a slow transition.) Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher.
Museums, galleries, archives, and libraries needing to reduce stress on their building (e.g., historic house museums), depending on climate zone ^e	B Limited control, seasonal changes in relative humidity and large seasonal changes in temperature. ^f	≥30% rh ≤70% rh ≤30°C	For permanent collection: historic annual average of relative humidity and temperature.	Increase by 10% rh Decrease by 10% rh Increase by 10 K Decrease by up to 20 K	±10% rh, ±5 K	Mold germination and growth, and rapid corrosion avoided. Chemical deterioration halts during cool winter periods. No risk of mechanical damage to many artifacts and most books. Tiny risk to most paintings, most photographs, some artifacts, some books. Moderate risk to high-vulnerability artifacts. Objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas, need special care when handling in cold temperatures.
	C Prevent relative humidity extremes (damp or desiccation) and prevent high temperature extremes.	≥25% rh ≤75% rh ≤40°C ^g	Within 25% to 75% rh year-round. Temperature usually below 25°C		Not continually above 65% rh for longer than X days. ^h Temperature rarely over 30°C	Chemically unstable objects deteriorate significantly within decades at 20°C, twice as fast each 5 K higher. Mold germination and growth, and rapid corrosion avoided. Tiny risk of mechanical damage to many artifacts and most books; moderate risk to most paintings, most photographs, some artifacts, some books; high risk to high-vulnerability artifacts. Even greater care is needed than provided in B when handling objects made with flexible paints and plastics that become brittle when cold, such as paintings on canvas.
	D Prevent very high relative humidity (dampness)	≤75% rh	Relative humidity reliably below 75% rh		Not continually above 65% rh for longer than X days. ^h	Chemically unstable objects deteriorate significantly within decades at 20°C, and twice as fast each 5 K higher. Conversely, cool winter season can extend their life. Mold germination and growth, and rapid corrosion avoided. High risk of sudden or cumulative mechanical damage to most artifacts and paintings because of low-humidity fracture; but avoids high-humidity delamination and deformations, especially in veneers, paintings, paper, and photographs.

Table 5. Climate control categories for museums, galleries, archives, and libraries (ASHRAE, 2019)

intended uses of spaces and expected kinds of clothing (ASHRAE, 2019).

After defining those aspects, the risks and needs of the building and exhibition can be determined from which a suitable climate category can be chosen (Table 5). However, it is important to mention that a more strictly controlled climate, such as classification AA, is not the best choice, as is stated by Ankersmit & Stappers (2020). It depends on the specific situation of the exhibition and building, but also the resources of the museum.

For this reason, Ankersmit et al. (2018) have built upon the climate control categories defined by ASHRAE (2019) and have defined process steps on how to choose the desired climate control category (Fig. 18). When a desired climate category is chosen, a suitable heating, ventilation, and air conditioning

installation (HVAC) can be determined for the museum.

The organisation of the Panorama Mesdag museum have already defined a desired climate classification, as is described in paragraph ‘C. Climate requirements by the museum’. This research is part of the process of finding a suitable HVAC system for the Rotonde, so it is suitable to follow the defined climate category. However, to get a full understanding of the indoor climate of the Rotonde and the choice for the defined climate category, the process steps described in Fig. 18 will be followed.

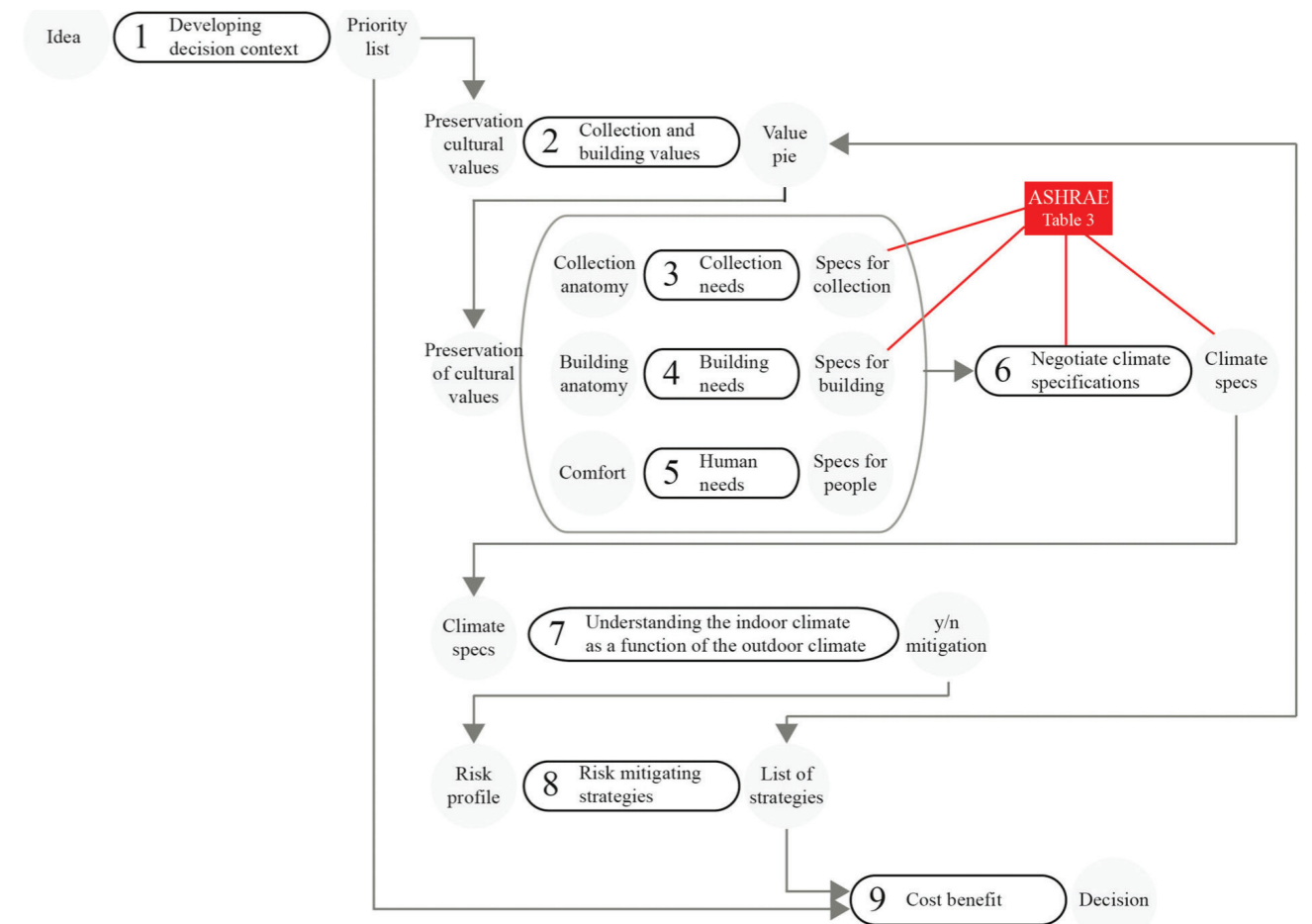


Fig. 18. Nine-step process of ‘managing indoor climate risks (Ankersmit, Stappers, & Kramer, Guideline in Jeopardy: Observations on the Application of the ASHRAE Chapter on Climate, 2018).

Current Indoor Climate in the Rotonde

This chapter elaborates on the indoor climate of the Rotonde, the exhibition building of the Panorama Mesdag painting. First, a damage risk analysis is done for the defined climate zones in the chapter ‘The Current State of the Rotonde. B: Climate zones in the Rotonde’. Next, the required indoor climate is presented and the concerning zones are examined on their requirements. Finally, the suitability of the stated requirements by the organisation of the museum are evaluated.

The two zones that are adjacent to the canvas are analysed, the zone behind the canvas and the open space. The measured data of the open space is considered to be less representative of the climate that is experienced by the canvas, because it is six times larger in volume than the zone behind the canvas, but it is measured by four dataloggers that

are all located meters away from the canvas. On the other hand, the zone behind the canvas is measured with three dataloggers within a meter from the canvas and is therefore considered to be most representative of the climate that is experienced by the canvas.

The indoor climate analyses is done using temperature and relative humidity measured data from datalogger sets in the Rotonde, as presented in Table 4. Datalogger set 1 is used for the zone behind the canvas and datalogger set 4 for the Belvedere zone. For representative data the data of the multiple dataloggers per zone are combined into average values. The average and separate data of the dataloggers is used when appropriate.

Damage Risk Analysis

Based on the average yearly temperature and relative humidity data, multiple analyses are executed, including a damage risk analysis, through the website Bouwfysica van Monumenten (Smulders & Martens, 2014). A full overview of the results of the analyses are presented in appendix E.

Zone Behind the Canvas

A damage risk plot is created for multiple materials, including paintings, based on the indoor climate data. For the canvas the materials paper and panel painting are representative. The Panorama Mesdag painting is made of linen which does not directly fit into one of these categories, but is less fragile than paper, but more fragile than panel paintings.

The results from this analysis are compiled into Table 6 and the indoor climate of the zone behind the canvas does not create a risk of mould on any material mentioned. However, the lifetime multiplier shows a value below one for paper in which means that the indoor climate behind the canvas could negatively impacts the lifetime of a paper object and shortens it. The lifetime multiplier plot of Fig. 19 shows that the value is below one during the summer and above one during the winter time, meaning that the summer indoor climate has a negative effect on the lifetime of the painting.

Fig. 20 shows that the annual relative humidity in the zone behind the canvas does not pose a risk on a painting, such as the Panorama Mesdag. The damage risk analysis of the zone behind the canvas shows that no substantial risks are present, but that increasing the quality of the indoor climate during the summer can help extend the lifetime of the panoramic painting.

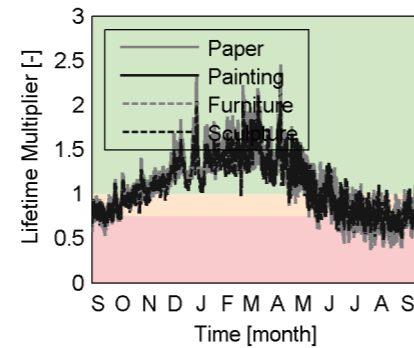


Fig. 19. Lifetime multiplier plot based on the indoor climate behind the Panorama Mesdag canvas (Smulders & Martens, 2014).

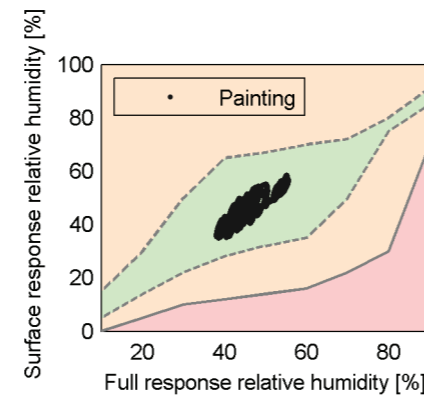


Fig. 20. Response relative humidity plot based on the indoor climate behind canvas (Smulders & Martens, 2014).

Belvedere

The results of the damage analysis of the indoor climate in the Belvedere are compiled in Table 7. In this zone there is no risk of mould for any of the mentioned materials, however the lifetime multiplier is below one for all materials. This means that the indoor climate of the Belvedere zone can have a negative impact on the lifetime of an object of the mentioned materials. According to Fig. 21 the summer period is responsible for this negative impact on the lifetime of art object and for this reason an improvement of the summer indoor climate in the open space is suggested to ensure the safety of the Panorama Mesdag canvas.

	Mould	LM	Base material	Pictorial layer
PAPER	safe	0.95	-	-
PANEL PAINTING	safe	1.01	safe	safe
FURNITURE	safe	1	safe	-
SCULPTURE	safe	1.01	safe	-

	Mould	LM	Base material	Pictorial layer
PAPER	safe	0.866	-	-
PANEL PAINTING	safe	0.946	safe	safe
FURNITURE	safe	0.946	safe	-
SCULPTURE	safe	0.946	safe	-

Table 7. Specific Damage Risks based on the Belvedere zone (Smulders & Martens, 2014).

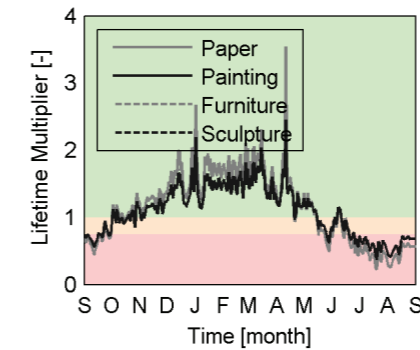


Fig. 21. Lifetime multiplier plot based on the indoor climate of the Belvedere zone (Smulders & Martens, 2014).

Specific Damage Risks of the Panorama Mesdag

The Panorama Mesdag painting is a unique art piece and this also creates some unusual risks that can be caused by the indoor climate of the exhibition space that have not been taken into consideration in the standard damage risk analysis discussed in the previous paragraph.

The first factor that poses some problems is the large area of the painting, 1600 m². This large size makes it more likely for temperature and humidity variations to occur over the object at one point. This could cause an interior restraint which can result in mechanical damage. The amount of temperature and humidity difference that is allowed within the canvas at a specific point has not been defined by the museum. However, the canvas is made from multiple parts which could decrease the impact of the temperature and humidity differences (Fruitema & Zoetmulder, 1981). Also, the restoration of the painting has been done after extensive research, so no behavioural changes of the canvas are expected (Nederlof, 2006).

The age of the paint layer could also cause some specific challenges for preservation. The paint layer is rigid and has a medium to high sensitivity to

relative humidity fluctuations. Fluctuations to low relative humidity levels create the greatest risk to the painting, but relative humidity levels above 85% can also cause shrinkage and flaking of paint layers. Also, the temperature can cause some problems for the rigid paint layer. If it drops below 10 °C, the paint layer enters a 'glassy state', which makes it brittle (ASHRAE, 2019). This can cause cracking or other mechanical damage.

Furthermore, fluctuations over time of temperature and relative humidity will most likely not cause substantial problems, as long as the fluctuations will not exceed the past fluctuations of the indoor climate according to the concept of proofed fluctuation. Because the Mesdag painting has been exposed to frequent fluctuations over the 140 years in the non-insulated building, adapting the indoor climate to a strict profile is not needed for the preservation of the painting. However, minimizing the short term fluctuation in temperature and relative humidity should always be a target, to decrease stresses within the canvas and prolong its lifetime.

Climate Requirements

The organisation of the Panorama Mesdag have defined requirements concerning the interior temperature and relative humidity in the Rotonde (NIAG, 2021). These requirements have been defined with preserving the painting in mind while also considering the sustainability ambitions of the museum. The requirements use a climate class by Ankersmit (2020) as a base with some additional requirements set by NIAG (2021).

C-class by Ankersmit

Allowed temperatures: 15 – 25 °C.
 Allowed relative humidity: 25 – 75%

Additions by NIAG (2021)

Allowed temperatures during extreme outdoor temperatures: 10 – 30 °C
 Temperature Fluctuations: < 5°C/24h

Zone behind the canvas

To determine if the zone behind the canvas complies with the indoor climate requirements, the measured data of operative temperature and relative humidity are examined. Full size graphs of the data from dataloggers of set 1 are available in appendix B. After analysing these graphs it is clear that the relative humidity of all levels in the zone behind the canvas are within the required range. However, large daily fluctuations of approximately 10 % are present during summer months (Fig. 22). Also, variations between the multiple dataloggers at one point in time are visible, most frequently during the summer period.

The operative temperatures consistently exceed the maximum value of 25 °C and even of 30 °C during the summer for all dataloggers, but most frequently by the datalogger at the top of the canvas. Also, the daily fluctuation of operative temperatures during July is 3.9 °C and multiple daily fluctuations of more than 5 °C are found. For these reasons the zone behind the canvas does not comply with the required indoor climate. Besides, also variations of temperatures of 3 to 5 °C at one point in time are found between the bottom and top dataloggers, which could create internal constraint in the canvas. In addition, the datalogger at the ridge of the roof shows the largest short-term fluctuations in almost all graphs, which is most likely a result of sun exposure.

In terms of vertical differences in temperature, in spring and summer the distribution seems logical, but during the winter the distribution is divergent. As would be expected, during warmer

periods the higher the datalogger is in the space, the higher the measured temperature is. This is logical since hot air travels upwards and get trapped underneath the roof. However, during the winter datalogger of the bottom zone shows the higher consistent temperatures. Possible explanations are the impact of a nearby heating installation or the thermal buffering effect of the sand base the indoor temperature. Further research is needed to explain this observation.

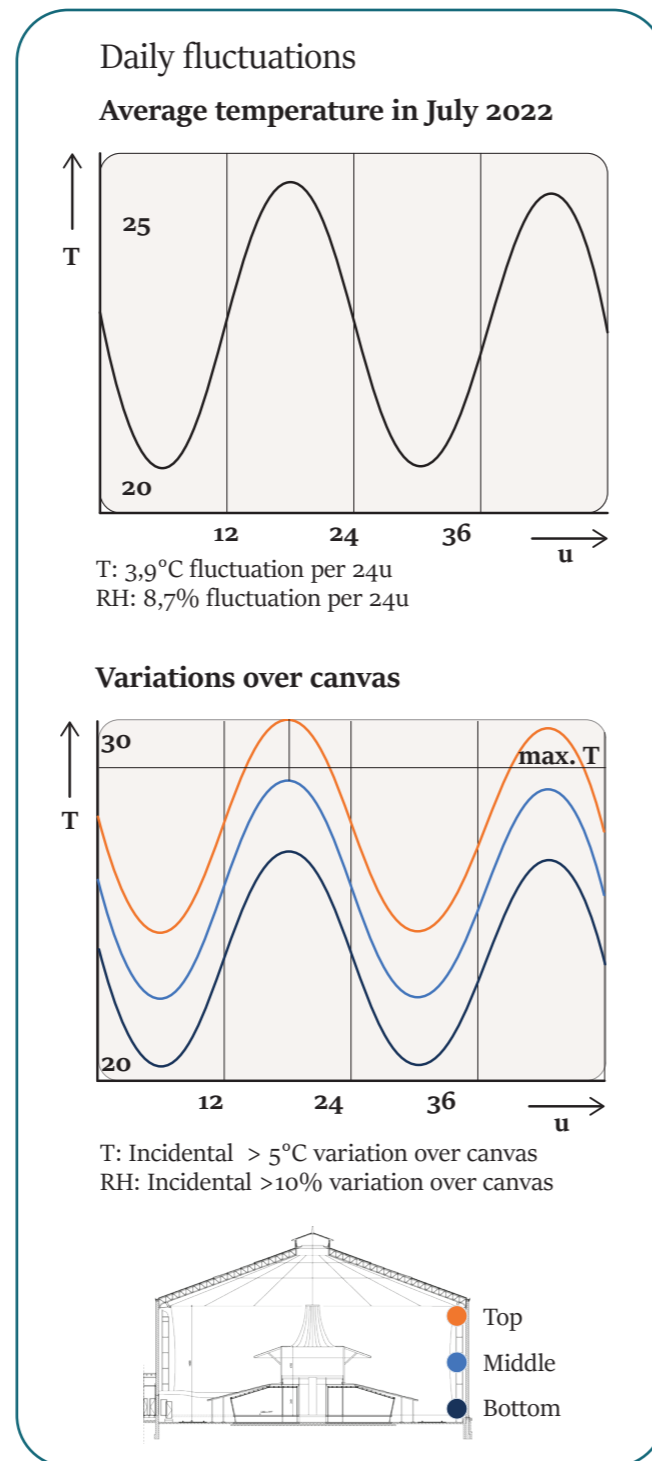
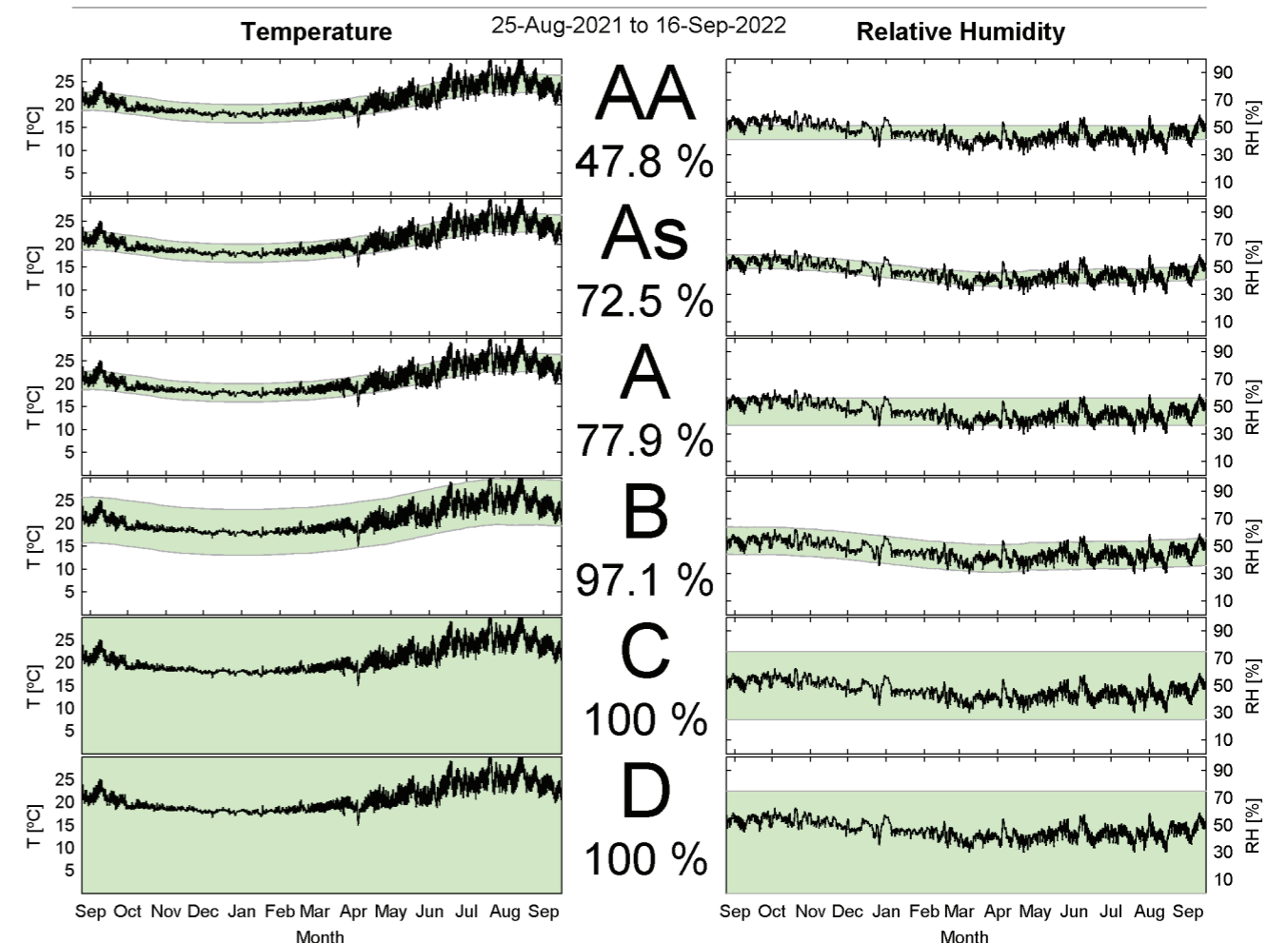


Fig. 22. Daily fluctuations and variations over the canvas (source: own).

Another observation is the difference in fluctuation between warmer and colder periods. Daily or short-term fluctuations in both temperature and relative humidity seem to be larger in warmer periods than in colder periods. This difference in fluctuations is more extensive in temperature than in relative humidity. This phenomenon could be explained by direct sunlight exposure in warmer periods.

Also, an analysis is done of the average data of the zone behind the canvas, combining the data of the bottom, middle and top level. Fig. 23 present the examination of the average data behind the canvas and this shows that the average data does comply with climate class C by ASHRAE. However, this climate class C has no requirements for temperature and fluctuations. The maximum average temperature is given as 30,9 °C, which means that also the average indoor climate in the zone behind the canvas does not comply with the requirements.

The Mollier diagram in Fig. 24 also shows the fluctuations per hour and day for temperature and relative humidity of the average indoor climate behind the canvas. This shows that the largest fluctuations in temperature and relative humidity occur during the summer and spring period, while more smaller fluctuations happen during the winter and autumn.



$T_{average} = 20.7\text{ °C}$, $T_{drop} = 2.6\text{ K}$, $T_{rise} = 4.1\text{ K}$, $T_{min} = 15\text{ °C}$, $T_{max} = 30.9\text{ °C}$, $RH_{average} = 46.3\%$, $RH_{drop} = 5.5\%$, $RH_{rise} = 7.8\%$, $RH_{min} = 30.1\%$, $RH_{max} = 62.5\%$

Fig. 23. ASHRAE climate class examination of the average indoor climate behind the canvas (Smulders & Martens, 2014).

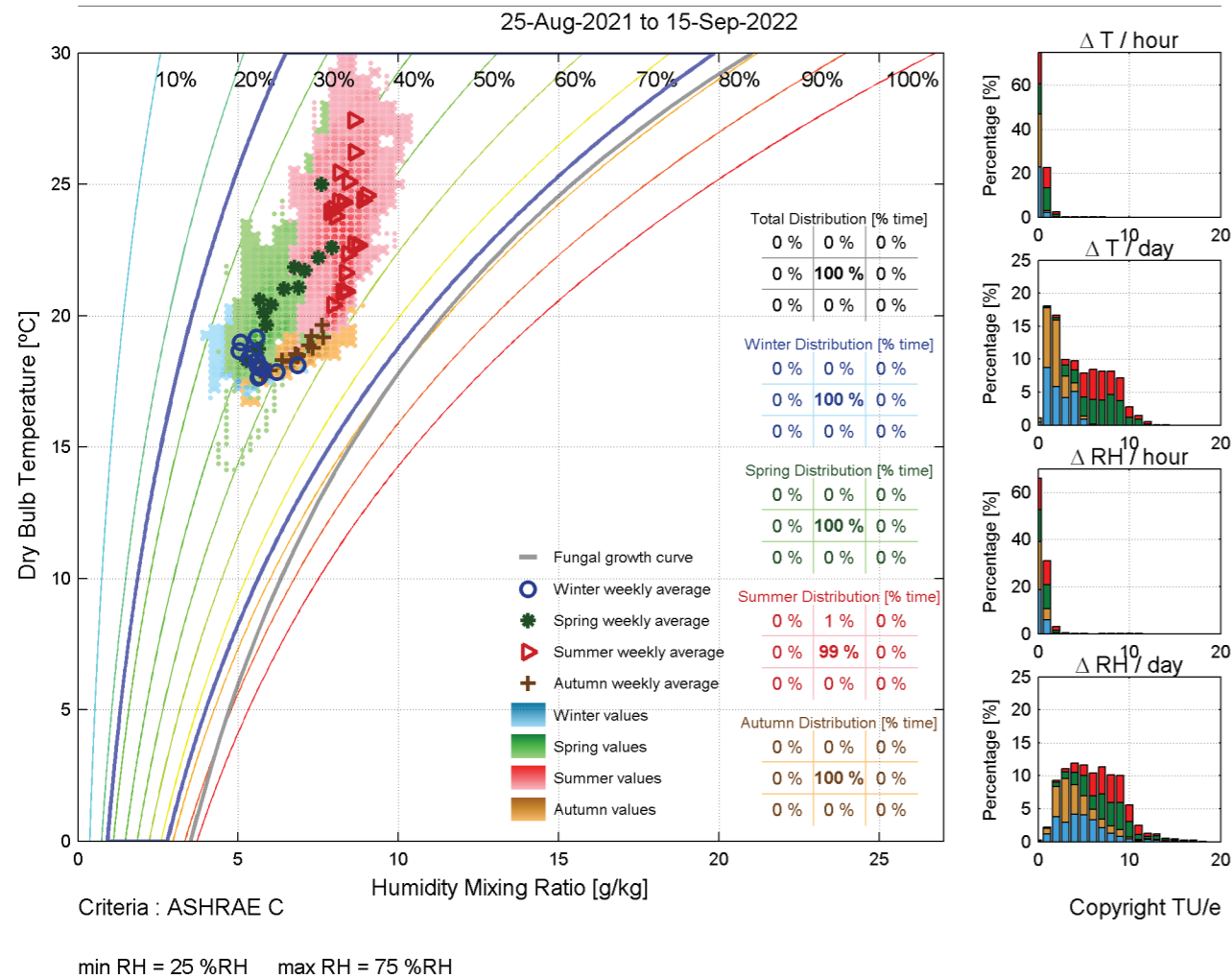


Fig. 24. Mollier diagram and fluctuation of the average indoor climate behind the canvas (Smulders & Martens, 2014).

Belvedere zone

The data of the dataloggers set 4 that are located in the open space (Fig. 12 & Fig. 13) are combined into an average value. Separate analysis per datalogger is not executed, because this zone is less representative for the climate that the canvas experiences. The average annual data of operative temperature, relative humidity in the Belvedere zone is presented in Fig. 25. From this graph it is apparent that the maximum temperature limit is exceeded frequently during July and August. Also, the maximum temperature fluctuation of 5 °C is exceeded. The relative humidity however is within the required range of 25 to 75 %. This means that the indoor climate requirements are not met in the Belvedere zone.

Conclusion

Both of the zones that are adjacent to the Panorama Mesdag painting do not meet the indoor climate requirements set by the organisation of the museum. The temperature during the summer is the most critical aspect, because the maximum value is exceeded frequently in both zones. Besides, large daily fluctuations of more than 5 °C have been measured and variations in temperature over the canvas of a few degrees, especially during the summer period. The relative humidity react to the high and fluctuating temperature with large daily fluctuations, sometimes larger than 10%. When comparing the two zones, the zone behind the canvas seems more stable with a smaller measured temperature and relative humidity range.

However, one of the most important aspect for preservation of art object is less monitored with the current indoor climate requirements. The

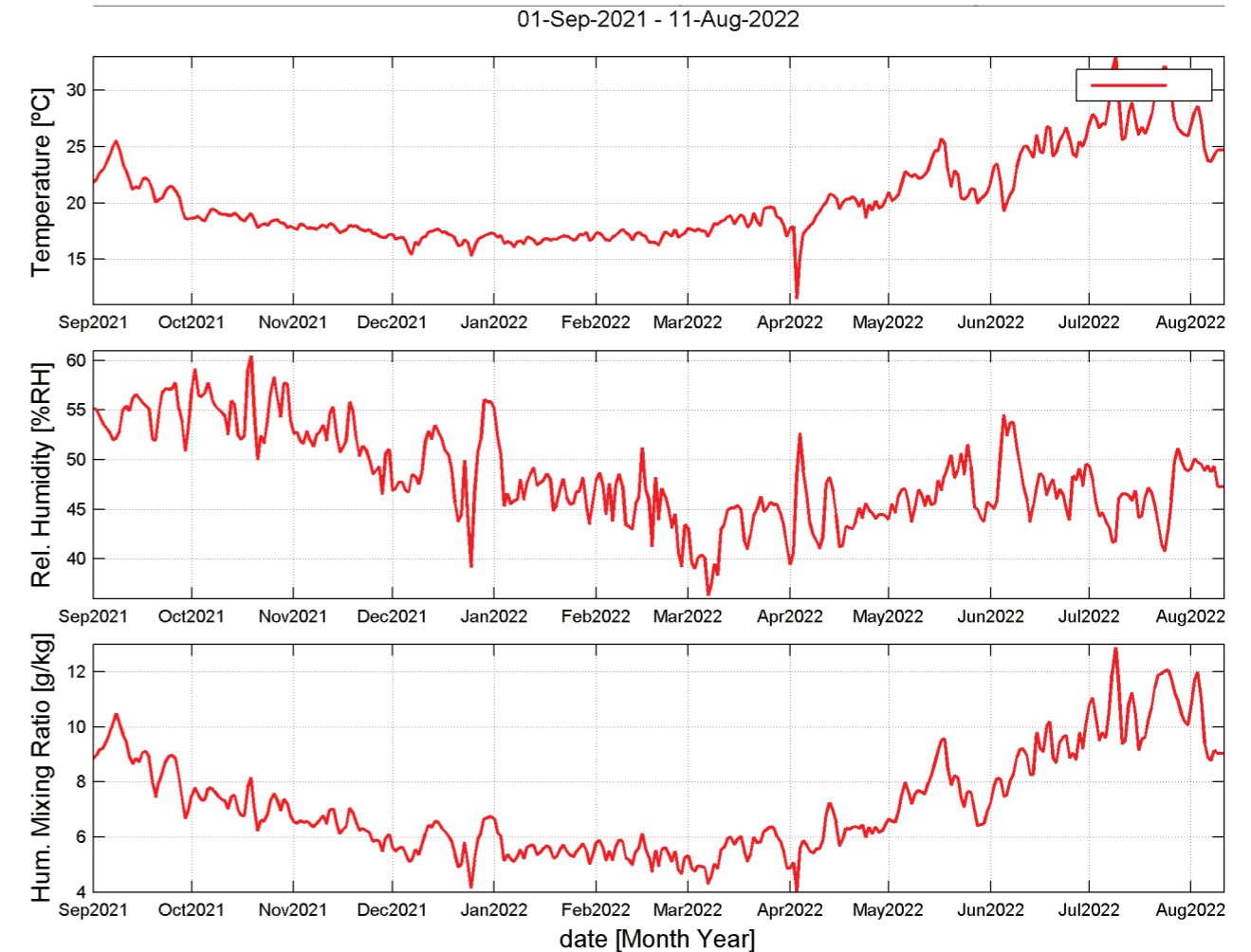


Fig. 25. Graphs of the average operative temperature, relative and absolute humidity in the Belvedere zone (Smulders & Martens, 2014).

fluctuations in relative humidity can cause more damage than temperature fluctuations, stated by ASHRAE (2019), so additional monitoring indicators are introduced to bring the relative humidity fluctuation into view. These indicators are taken from Climate class B by AHSRAE (2019) and are also used by the reference project of the Bourbaki Panorama in Luzern, Switzerland (Frei Wüest Expert Ingenieurbüro, 2021).

Additional monitoring: yearly indoor climate fluctuation indicators

- Days per year of RH fluctuation > 10 %/24hr
- Maximum RH fluctuation [%/24hr]
- Days per year of T fluctuation > 5 °C/24hr
- Maximum T fluctuation [°C/24hr]
- Days per year of T fluctuation > 3 °C/24hr

These indicators give an overview of the size of fluctuations in temperature and relative humidity and the frequency of occurrence per year. These indicators are not stated as requirements, but can be used for comparative analysis of for example annual measured data. The objective is to minimize the values of all indicators, because that would indicate of a yearly indoor climate with minimal daily fluctuations. This would increase the quality of the indoor climate for preservation of art objects, such as the Panorama Mesdag painting.

The yearly indoor climate fluctuation indicators are combined with the outer limits for temperature and relative humidity into a table, with the indicators ranked in importance for preserving the panoramic painting. The results for the measured period of September 2021 to September 2022 are given in Table 8.

Yearly indoor climate outer limits for operative temperature and relative humidity and the fluctuation indicators	Behind Painting (set nr. 1)				Open space in Rotonde (set nr. 4)
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%]	23.6	25.8	23.2	29.0	33.5
Maximum RH [%]	62.6	65.3	63.7	63.7	62.0
Minimum T [°C]	15.1	13.7	14.0	14.3	9.6
Maximum T [°C]	28.3	33.2	36.1	32.2	34.7
Days per year of RH fluctuation > 10 %/24hr	34	49	100	36	3
Maximum RH fluctuation [%/24hr]	19.7	18.1	20.0	16.6	11.0
Days per year of T fluctuation > 5 °C/24hr	3	18	75	16	24
Maximum T fluctuation [°C/24hr]	6.8	7.1	8.4	6.2	6.6
Days per year of T fluctuation > 3 °C/24hr	88	116	157	116	107

Table 8. Yearly indoor climate outer limits and fluctuation indicators for the Rotonde between September 2021 to September 2022 (source: own).

In conclusion, the objective for the indoor climate of the Rotonde of the Panorama Mesdag is to minimize daily or short-term fluctuations in temperature and relative humidity during the summer to ensure preservation of the artwork. During the winter season the objective is to sustain the current indoor climate, but to decrease the energy demand for heating with passive solutions, as is stated in 'F: Previous Research and Ambitions'.

Thermal Buffering

Thermal buffering is the phenomenon of heat being stored temporarily in an object and being released again at a later moment. This process can help to reduce the energy demand of buildings, because it can fulfil both a cooling and heating function (Sarbu & Sebarchievici, 2018). In winter, when there is a heating demand, heat from the sun can be transferred to the material and be released at night, decreasing the heating demand. In summer periods the material can take up heat during the day from internal sources in the space and store them, decreasing the cooling demand. At night the heat is released, which also results in less temperature fluctuations between night- and daytime. The decrease of temperature and relative humidity fluctuations per day is particularly interesting for exhibition spaces with fragile pieces that are often vulnerable to short-period fluctuations, such as the Panorama Mesdag painting.

This chapter elaborates on the different thermal buffering processes, materials and installations that have been realised before. Next, the possibilities of the implementation of a thermal buffering system is explored based on the possible locations, the capacity of different installations and the risks on the monumental exhibition and building. A comparative analysis will help define the most suitable thermal buffering system for the Rotonde of the Panorama Mesdag museum.

Thermal buffering processes

The process of heat being stored and released can differ and three process types are distinguished. The first process is sensible heat storage which uses a solid or liquid material to store heat, such as water or concrete. The medium can store heat by increasing its own temperature and it is dependent on the amount of storage material, the temperature change, and the temperature of the medium itself (Sarbu & Sebarchievici, 2018). It is a relatively simple process where no phase changes occur, there is a small risk

on chemical substance release, and it is considered as a cheap option.

The second process is storing the heat in latent energy, also known as phase-change storage. During this process the medium that stores and releases the heat, changes phase, which allows for a high-energy storage density. The advantage of this process type is that it has a large heat storage capacity at an almost similar temperature range. The materials that function according to this process are also called phase-changing materials (PCMs).

The third thermal buffering process is heat being stored in a medium by changing its chemical structure (Tenpierik & van Kranenburg, 2012). This change is reversible for the medium to release the heat. The advantages of this storage process are the high storage capacity, allowing for the heat to be transported. Also, some of the techniques following this process can control humidity in a space.

Thermal buffering materials

The materials that are used in thermal buffer installations are dependent on the type of process they follow, but also the circumstances of space and the heat source. Choosing a suitable material should be done carefully and it is essential to match the characteristics of the material to the intended space.

Material characteristics

The following characteristics are important for defining a suitable material for a heat storage medium (Sarbu & Sebarchievici, 2018).

Optimal temperatures

This is usually a temperature range in which the medium performs best. For PCMs the point for a phase change lies within this temperature range [°C].

Specific heat

This is the amount of heat that is needed to raise the temperature of one kilogram of storing medium by one °C [J/kg x K].

Thermal conductivity

This is rate in which a material is able to transfer heat through conduction [W/(m x K)].

Density

This is the weight of a material per cubic meter [kg/m³].

Phase segregation (specific for PCMs)

The phenomenon in a PCM where an area of the material is in a different phase than the remaining area and will not change phase. This is a result of degradation of the material.

Commonly used materials per heat storage process

For thermal buffering techniques that follow the sensible heat storage, materials are used that can be in solid or liquid form. The most popular material is water, but also sand and concrete are commonly used in sensible heat storing installations (Sarbu & Sebarchievici, 2018). The working temperature of sensible heat storage lies between 0 and 1200 °C, depending on material type. For an installation in buildings, working temperatures below 100 °C are sufficient. Water is considered to be very efficient for sensible heat storage in buildings, because of its relatively low density, high specific heat and low costs.

PCM's used in latent heat storage can be in gas, liquid, or solid form. The most used phase change in PCM's is between solid and liquid states, because it doesn't require a large volume variation,

such as between liquid and gas states. This would pose a problem for the container in which the PCM is stored. A suitable PCM has a melting point in the temperature range that is similar to the temperature of the space the heat storage will function in (Tenpierik & van Kranenburg, 2012).

Within solid-liquid PCMs there are three categories of materials: organic, inorganic and eutectics and every category has specific dis- and advantages. Organic PCMs are often paraffin waxes, but also different materials such as alcohols and fatty acids are suitable. Within organic PCMs there is a large range of options with variable properties, but the main advantages are that they are non-corrosive and have low phase segregation. A disadvantage of organic PCMs is that most of them are flammable (Rubitherm, 2022). Inorganic PCMs that are often used are salt hydrates and metallics. These materials function most efficiently at high temperatures, such as in solar application.

The main disadvantage of these materials is that they can be unstable and require maintenance regularly. A eutectic medium is a combination of multiple material with similar properties, such as melting points. This type of medium can be adapted to the requirements of the thermal storage installation, which makes them suitable for many applications.

In a chemical energy storage thermo-chemical materials are used. Heat applied to the material creates a reversible reaction where the material is split into two components. This reaction can store heat and release it again when the two components are merged again. This reaction can also be used in the advantage for humidity control. A thermo-chemical material can be chosen in which water vapour is one of the produced components from the reaction (Geyer, et al., 2018). The water can be absorbed again during the process of forced condensation. This process can help with controlling the humidity in a space.

The working temperatures of most thermo-chemical materials ranges from 200 to even 1200 °C and their storage capacity is high, compared to other storage medium. The high temperatures and the

storage of multiple components result in a complex heat storage installation which required regular maintenance.

Thermal buffering Installations

The combination of the material type, heat storing process and the type of installation technique shape the thermal buffering installation.

Installation characteristics

The following aspects are important for defining a suitable heat storage installation (Sarbu & Sebarchievici, 2018).

Thermal buffering capacity per cubic meter

The amount of energy that can be stored within the installation

Power

The speed in which the heat can be stored in and released from the storage, also known as charging and discharging.

Efficiency

This is the amount of energy that is provided after discharging compared to the amount of energy needed to charge the storage. Efficiency can decrease after several cycles of dis- and charging and the number of cycles depends on the type of medium.

Storage period

The period that heat can be stored within the installation. This can range from hours to months.

Charge and discharge time

The time that is needed for heat to be stored in and released from the storage.

Cost

The cost of the installation depends on multiple factors, such as the lifetime and the costs for maintenance. The costs are often compared to the capacity or the power of the installation.

Installation types

A heat storage installation is optimized to heat storing process and for this reason the installation types are categorized.

Sensible heat storage

A commonly used heat storing installation is a water tank, found in most households. Water is heated, stored within the tank and a connection to a floor heating installation or radiators transports the heat to the intended space.

Another common installation that functions through sensible heat storage is an underground storage. Those installations often use the ground as a source, which can be soil, sand, rock or clay (Sarbu & Sebarchievici, 2018). The advantage of this installation type is that cold and heat is stored within the ground. A common installation is a heat pump, which uses tubes filled with water, or another fluid that can transport heat, running through the soil to subtract heat or cold. A disadvantage is that the system needs to be located on a substantial depth for the installation to be efficient throughout the year.

A less commonly applied, but promising, installation type is a packed bed heat storage. This is a volume filled with bulk granulate or pebbles that is loosely packed, so a fluid medium can circulate through the bed. There is a variety of material choices for the pebbles, such as a type of rock, brick or basalt. A packed-bed installation is usually combined with a consistent air flow through the bed. Hot air flowing down through the installation will cool the air while the pebbles take up the heat.

Later the air flow's direction is switched, and cold air can be heated when flowing through the bed and released into a space that needs heating.

The advantages of these installations are that they can also fulfil a structural function, can be combined to a solar collector and with the right medium choice the fire risk, leakage risk and harmful substance release risks are low. This makes this installation suitable for a location within a building.

Phase-change storage

The type of installation with a PCM depends on the containment of the material. Containment is needed to decrease the risk for PCM leakage and direct incorporation of PCM in building elements is not advised (Jelle & Kalnæs, 2017). There are three containment types: bulk, macro and micro containment. Bulk containment is usually a tank storage, but this is not considered as an efficient method, because it needs more extensive heat transfer compared to other tank heat storages (Sarbu & Sebarchievici, 2018).

Macro-containment is usually a tube, sphere or panel larger than 10 mm in which the PCM is stored. These elements can then be processed within building material, but also function on themselves. The disadvantage of this type of containment is that PCM tends to melt or solidify only at the edges in these dimensions, which decreases the efficiency of the installation. Also, the size may pose a larger risk of leakage and needs further protection when incorporated into a building.

Micro-containment is often in very small granulate smaller than 1 mm wide, which then can be processed in a building element, such as a panel, but also concrete and gypsum. This PCM type can be processed in fluid or powder form (Jelle & Kalnæs, 2017). The disadvantage of micro-contained PCM in building elements is that it has a relative low heat storage capacity per square meter, compared to pure PCM.

Within PCM installations there are also two categories of active and passive installations. Both installation types can use different sources of heat, such as solar energy, internal sources or soil energy. Active installations are used to improve the efficiency of storing heat in a building and actively control the

indoor climate during peak conditions (Sarbu & Sebarchievici, 2018). These active PCM installations are often an addition to a HVAC system that has a high degree of control over the indoor climate. Examples are the use of PCM in second-skin ventilated facades or heat pumps that use PCM to increase the efficiency of heat transfer.

Passive PCM installations often are used to increase the total heat buffering capacity of a building by using the naturally available heat sources to improve the indoor climate quality. The use of mechanical HVAC systems is minimized in these installations. An example of a passive PCM installation is the incorporation of micro-contained PCM in concrete building structures.

Thermo-chemical storage

The installations that use thermo-chemical storage, often follow the reversible process of adsorption. Thermo-chemical storage media have a high storing capacity which makes them suitable for long term storage that is compact (Sarbu & Sebarchievici, 2018). Solar energy or internal heat sources can be used as the energy source. After storage, the energy that is released can be transported to water or air.

An example of such a system is an installation that facilitates a reaction between silica-gel and water. During the summer, the installation is charged by solar energy through solar collectors that initiate the desorption reaction of the gel and water to be separated. During the winter, the water can be merged with silica-gel and the absorption reaction is started, which releases heat (Geyer, et al., 2018).

Conclusion

Overall, in terms of capacity the systems based on thermo-chemical storage have the highest efficiency and possible best impact on indoor climate. However, installations are often complex, expensive and require lots of maintenance and supportive mechanical system, which increase energy consumption.

Techniques	Storage Capacity [kWh/t]	Efficiency [%]	Costs [€/kWh]
Sensible heat storage	10-50	50-90	0,1-10
Phase-change storage	100 [kWh/m ³]	75-90	10-50
Thermo-chemical storage	max. 250	75-99	8-100

Table 9. : characteristics of thermal storage techniques (Adapted from Sarbu & Sebarchievici, 2018).

Sensible heat storages have the lowest capacity of the options, but seem to be most stable, have the lowest costs and small risks on damaging building or any interior elements. The properties of PCM installations are generally average in terms of thermal storage capacity and costs, compared to both sensible and thermo-chemical storage installations. PCM installations can be implemented with a wide range of materials which makes it a suitable option for a custom-fit installation. However, instability due to variations in temperature and volume create a risk of leakage. Some PCMs also come with a substantial fire risk. If PCMs are used for a custom installation design, the containment is the most crucial design part. An overview of average properties per technique is given in Table 9.

Thermal Buffering Solution in the Rotonde

In this chapter the possibilities for a thermal buffering system in the Rotonde of the Panorama Mesdag museum are explored. First the potential locations will be discussed, then the suitable techniques per location are presented and a comparative analysis will help determine the most suitable thermal buffering system

Potential Locations

Within the Rotonde there are four locations that could be suitable for application of a thermal buffering installation, shown in Fig. 26, because they comply with the spatial requirements defined by the organisation of the museum (Fig. 17). The potential location include an underground area, the

space in between the canvas and the scaffolding, the space between the scaffolding and the interior side of the façade and the glass roof.

Underground Storage

This location seems a suitable option, because the current sand base already has a thermal buffering effect in the Rotonde, as mentioned in chapter ‘Current Indoor Climate in the Rotonde’. The sand could be excavated and replaced with a material or installation with a higher efficiency and thermal buffering capacity, to increase the effect. However, the potential volume is restricted to the area between the perimeter of the façade and the interior spaces, such as the depot. Underneath these elements, respectively, a brick foundation and concrete floor construction are present and cannot be affected.

Also, a monumental rails is located on the sand base and it’s the foundation of settled sand cannot be impacted (de Bruin, Personal communication, 2022). This is also the case for the foundation of the scaffolding structure. For this reason every few meters an area underneath these structures cannot be changed to ensure stability of the foundation for the rails and scaffolding (Fig. 27).

<i>Estimated area</i>		
550 m ² - 100 m ² (foundation)		450 m ²
<i>Estimated volume</i>		
0,5 m depth: 450 * 0,5 =		225 m ³
1,0 m depth: 450 * 1 =		450 m ³

The replacement of the current sand base with a more efficient thermal buffering system is likely to increase the thermal buffering effect during the summer and winter. During the winter the bottom level of the Rotonde is currently the level with the

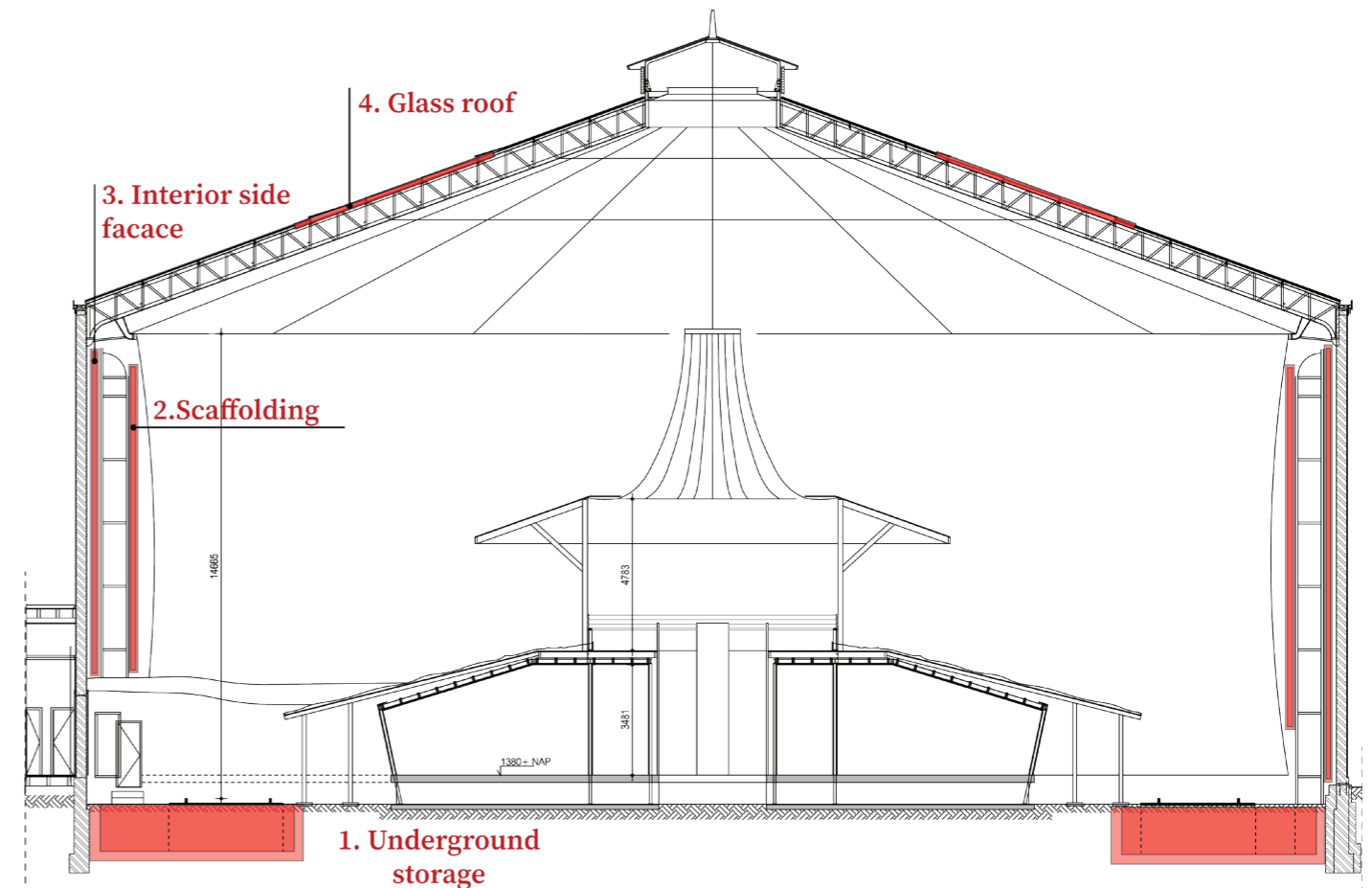


Fig. 26. Section of the Rotonde with potential locations for a thermal buffering system (source: own).

highest measured temperatures and could increase more with the implementation of a thermal buffering system. During the summer in the bottom level currently the lowest temperatures are measured and this effect could also be enhanced. This could have a negative effect on the temperature variation over the canvas, but because of the large surface of the base it is also expected to heat or cool the Rotonde evenly.

Besides, during summer periods the base of the Rotonde experiences sun exposure, as is shown in a sun path analysis (Panorama Mesdag BV, 2022), which is the main source of heat gain. Placing a thermal buffering system at a location with a large heat gain is an effective way of capturing and storing heat when there is a cooling demand.

Potential thermal buffering installation

The potential installation could be a packed-bed installation with an additional ventilation installation, making it an active system based on the

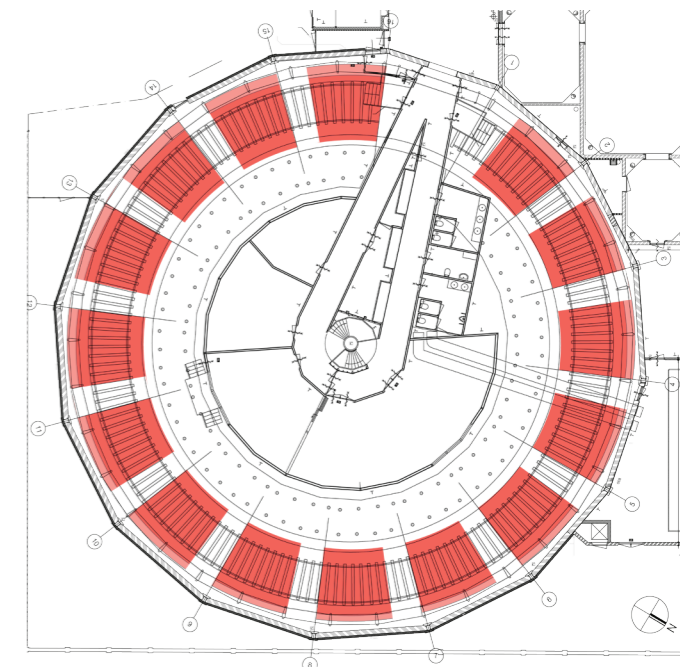


Fig. 27. Plan of the Rotonde with the area of the potential underground storage location (source: own).

sensible heat storage. The whole area could be used because the bed can fulfil a structural function. Air could be transported through the bed with

mechanical ventilation using some of the current air ducts. The capacity of the installation is defined using the following equation and properties.

Density basalt	3000 kg/m ³
Porosity	0,33 (average)
Sensible heat capacity	800 J/kgK

$2000 \cdot 800 = 1.6e6 \text{ J/m}^3\text{K}$. In totaal 720 MJ/K.

For the packed bed installation the following assumptions are taken. The basalt comes in pheres with a diameter of 100 mm and the available area in the Rotonde for a packed bed is 450 m² with a height of 1 meter.

Packed bed with spheres

R	radius sphere [m]
A	total surface area bed [m ²]
L	length packed-bed [m]
ε	porosity of packed bed (average 0,33)

Total number of spheres in packed-bed

$$M = \frac{3(1-\varepsilon)AL}{4\pi R^3}$$

Number of spheres in packed-bed per m³

$$N = \frac{3(1-\varepsilon)}{4\pi R^3}$$

Surface of spheres in packed bed per m³

$$a = \frac{3(1-\varepsilon)}{R} \quad [\text{m}^2/\text{m}^3]$$

With these equations the density of the basalt packed bed is defined as 2000 kg/m³ and the surface of basalt spheres is 40 m²/m³ and in total 18.000 m². This gives the packed bed a heat capacity of 1.6e6 J/m³K and in total 720 MJ/K.

Effective thickness of the packed bed installation

$$d = ((1-\varepsilon))/a \quad [\text{m}]$$

The effective thickness is 0,01675 m.

Heat transfer within packed bed: basalt to air

Heat transfer between packed bed and air

A_{bed}	Total surface of spheres in packed bed [m ²]
a_{con}	Convective heat transfer coefficient [W/m ² K]
U	Heat transfer [W/K]

Heat transfer from basalt to air in packed bed

$$U = A_{\text{bed}} a_{\text{con}} \quad [\text{W/K}]$$

a_{con} is estimated to be 1,7 W/m²K for basalt spheres of 100 mm diameter with an air velocity of 0,05 m/s. This results in a heat transfer of 30.000 W/K. Sufficient ventilation through the packed-bed is needed to transfer the heat from the installation to the air in the Rotonde. The area of the Rotonde is 1200 m² and 30.000 W/K needs to be transferred.

$$30.000/1200 = 25 \text{ m}^3/\text{s}, \text{ or } 90.000 \text{ m}^3/\text{h}.$$

For a air velocity of 0,05 m/s and a ventilation rate of 25 m³/s the following flow surface is needed.

$$25/0,05 = 500 \text{ m}^2$$

The packed-bed installation in the Rotonde has an area of 450 m², so this is sufficient.

Flow through a packed bed

A sufficient air flow through the packed bed is needed to transfer the heat from the air within the packed bed to the air in the Rotonde.

x	Diameter of sphere [m]
ρ_f	Density of air [kg/m ³]
μ	Dynamic viscosity of air [Pa.s]
ε	Porosity of packed bed (average 0,33)
Q	Volumetric flow rate of air [m ³ /s]
A	Cross sectional area of packed bed [m ²]
L	Height of packed bed [m]

Reynolds number for flow through a packed bed

$$Re^* = \frac{xU_s\rho_f}{\mu(1-\varepsilon)}$$

Superficial fluid velocity [m/s]

$$U_s = \frac{Q}{A}$$

Packed bed friction factor

$$f^* = \frac{150}{Re^*} + 1,75$$

Ergun equation, pressure drop through a packed bed [Pa]

$$\Delta P = H f^* \frac{\rho_f U^2 (1-\varepsilon)}{x\varepsilon^3}$$

These equations give a pressure drop over the packed bed in the Rotonde of approximately 1,45 Pa.

Advantages of the application of this technique is that during the winter when the storage discharges, the heat is distributed evenly throughout the space, similar to floor heating. The heat source is the indoor air, but possible outdoor could be transported at night through the installation to amplify the cooling effect during the summer.

A variation to this installation could be filling the bed with a PCM, because this would increase the storage capacity. Further research is needed if these options could increase the impact on the indoor climate and are worth the risks. Also, a supplementary analysis on the foundation of the Rotonde is needed to define how deep the soil can be removed and replaced by the installation. If this design seems to be the most suitable option simulations can be run to help optimize the design.

For sensible heat storage a single-phase simulation can be run with computational fluid dynamics (Flaischlen & Wehinger, 2019). For PCM use, a simulation of two-phase models is advised, such as the Schumman's model or concentric dispersion models (de Gracia & Cabeza, 2017). The more advanced modes require complex software and longer simulation times but tend to result in more reliable results. DesignBuilder could be a possible software for running these simulations (DesignBuilder Software Ltd, 2022).

Also, experiments can be done to test the influence of solar energy on the packed-bed installation in situ, which means there is a layer of sand present on top of the installation. Experiments can be executed in a climatized box to test the behaviour of the installation in combination with this sand layer. Furthermore, an in-situ experiment

can be done to test the impact of the solar energy that is received by the installation in the Rotonde.

Scaffolding

Between the painting and the façade is the scaffolding structure and around this structure a substantial volume is unused (Fig. 28). An installation could be secured to the scaffolding structure on the side closets to the painting, so the painting is not affected. The advantage of using this location is that it is adjacent to the canvas and can help manage the microclimate evenly over the whole area of the painting. Besides, the scaffolding structure is an additional structure and not part of the monumental exhibition or building. The scaffolding, and any system secured to it, is reversible.

A sidenote for this location is that any installation with fluids is not preferred, however the current heating installation behind the canvas does also contain water is located. Fluids close to the canvas pose leakage risk and the risk of damage on the canvas is increased. Another disadvantage of this location is that the structural capacity of the scaffolding structure and it's foundation are limited.

Estimated area

Length of scaffolding unit	3,1 m
Total length	108,5 m

Available space between

scaffolding - painting	0,3 - 0,55 m
Surface	1575 m ²
Thickness	0,2 m

Estimated volume

Between scaffolding - painting	315 m ³
--------------------------------	--------------------

Potential thermal buffering installation

A possible installation is a PCM system, because of its high storage capacity per cubic meter material (Tenpierik & van Kranenburg, 2012). The disadvantages of a PCM system close to the canvas is the risk on damage on the painting and monumental

façade due to leaking. In Fig. 31 the capacity of a PCM system of this location is presented, using information from reference PCM systems (Sharma, Sellami, Tahir, Mallick, & Bhakar, 2021).

The efficiency of the PCM system could be improved by an additional mechanical ventilation system behind the canvas, using the currently not functional ventilation ducts underneath the roof to transport warm air to the zone behind the canvas, where it can be stored in the PCM system.

Further research is needed to define the structural capacity of the scaffolding and elaboration on the leakage risks, flammability and toxicity of PCMs should be executed. If this thermal buffering system seems most suitable, further optimization can be done by simulations, as explained in paragraph 'A. Underground Storage'.

Interior Side of the Façade

Between the scaffolding structure and the façade space available if the current heating tubes are removed (Fig. 28). This location is also close to the painting, so any installation with fluids could potentially harm the painting.

Estimated area

Available space between scaffolding and façade:	0,8 – 0,25 m
Surface	1700 m ²
Thickness	0,15 m

Estimated volume

Between scaffolding – façade 255 m³

This potential location has similar advantages as the option of a system on the scaffolding structure, however with less risks. A thermal buffering on this location can help manage the microclimate around the canvas evenly. The façade has a larger structural capacity than the scaffolding structure which results in more possibilities in terms of types of system and the weight of materials.

Also, since the space between the façade and the canvas is at least one meter, any leakage of a

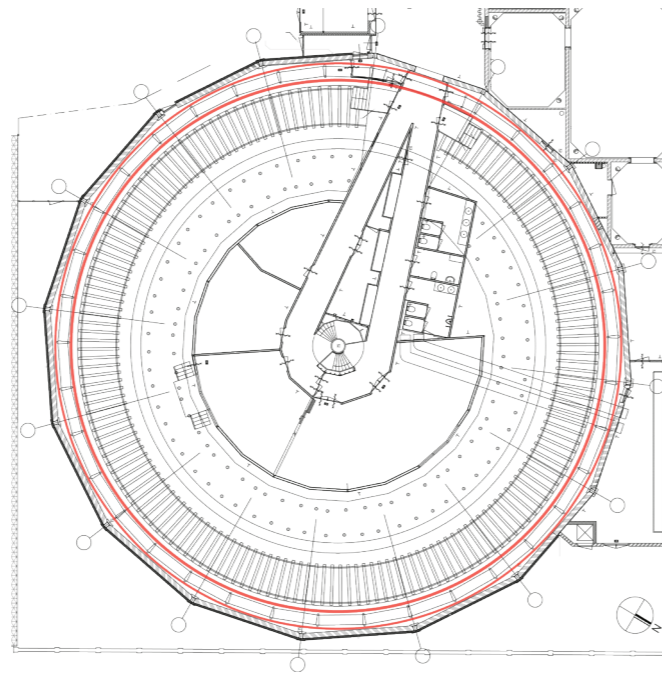


Fig. 28. plan of the Rotonde with the area used for an installation connected to the scaffolding and the interior side of the façade (source: own).

system will be less harmful compared a system on the scaffolding structure.

Potential thermal buffering installation

There are two potential techniques that are suitable for this location. The first option is a packed-bed installation using sensible heat storage. A second option is a PCM-system. Both options require sufficient air flow around the material and this could be increased with an additional mechanical ventilation system, as is explained in paragraph 'B: Scaffolding'. In Fig. 31 these possible thermal buffering systems are presented with their characteristics.

A risk of the implementation of system on the interior side of the façade is that it has a similar effect as an interior insulation layer, which is shown to increase the indoor temperature drastically during the summer (NIAG, 2020). Further research is needed to determine if the cooling capacity of the system is able to decrease this effect.

Glass Roof

The skylights in the roof could be a potential location for a thermal buffering system and in particular a PCM system. The products by GlassX (2022) are used as reference, because the windows contain a translucent PCM, that potentially match the spatial requirements set by the organisation of the museum regarding natural daylight incidence.

Estimated area

Skylights: 418,6 m²

Through the skylight the solar heat is able to enter the Rotonde, so capturing the heat locally at this location could be an efficient way of decreasing the indoor temperature. The panes would use the sun exposure as heat source, but also the air, because in the area underneath the glass roof the highest temperatures in the Rotonde have been measured

The products by GlassX (2022) are complete curtain wall elements with a variation of glass configurations (Fig. 30). The PCM used are inorganic salt-hydrates that are able to store and release heat while changing form, respectively from solid to fluid and fluid to solid. Disadvantages of these skylights are the risks on leakages and the changing visual transmittance during a phase change.

Characteristics of GLASSX product

Type of PCM: inorganic, salt hydrate.

Visual light transmittance (solid/liquid): 38/55 %

Heat storage capacity: 1185 Wh/m²

Phase change temperature: 26-30 °C.

Estimated heat capacity

Applied in the Rotonde over the whole glass roof area: 496 kW

Further research is needed to determine if other PCMs with different melting and freezing temperatures are suitable for application in the curtain wall elements.

If this installation type seems most suitable as a thermal buffering system in the Rotonde, simulations can be run in DesignBuilder which allows PCM material characteristics to be added within the simulation (DesignBuilder Software Ltd, 2022). The expected indoor climate with the application of this installation can be determined.

Also, experiments are advised to be executed to define the impact on visual light transmittance of the PCM behaviour. For the product the visual light transmittance of both liquid and solid state is known, but the stage during transformation is unclear, such as local shadow creation from uneven phase change throughout a panel (Fig. 29). These experiments can be repeated in situ in the Rotonde to gather information about the time span of the phase change and the impact on the incidence of light on the painting. The hypothesis is that during the process of phase change the glass PCM panels create shadows when light falls through the skylights. This creates the negative effect of shadows on the panoramic picture and for that reason this application seems less suitable for the Rotonde.

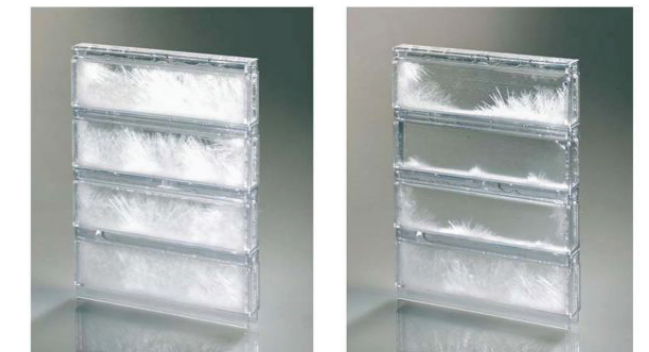


Fig. 29. GlassX PCM panels during phase change (GLASSX, 2022).



Fig. 30. Section of a PCM curtain wall element (GLASSX, 2022).

Risks analysis of thermal buffering systems

A risk analysis is presented in Table 10 of the potential thermal buffering systems in the Rotonde, which will help to compare the options and define the most suitable option. In the risk analysis the following aspects are taken into consideration; the risks of damage on the canvas, the complexity and costs of the materials and installations and the impact the system could have on the monumental exhibition, the building and the users of the building.

The indicators that are mentioned are negative factors and total score of thermal buffering options are presented at the bottom of the table. The largest negative value for the total score means that the concerning thermal buffering system is expected to have the lowest risks, costs and impact on the Rotonde, the exhibition and its users. The results of the analysis shows that an underground storage

with a passive sensible heat process, using for example brick or basalt, is expected to have the lowest risks on the canvas while it is also a low cost intervention with a small impact on the canvas, building and its users. The thermal storage capacity of a underground packed-bed is lower than a PCM system.

However, the advantage of a system based on sensible heat storage compared to PCM is that there is no temperature range in which the system functions. The basalt packed-bed will be storing heat at all temperatures whereas any PCM system is only active when the indoor temperature falls within the temperature range for phase change.

The systems that have the least positive outcome in the analysis are the scaffolding PCM system and the PCM incorporated skylights. Both the systems use PCMs and are located in a position that could potentially harm the exhibition when leakages occur. Also, the costs of the PCM and the

Thermal Storage Capacity and Feasibility Analysis	Underground Packed-bed	Scaffolding PCM	Facade Packed-bed	Façade PCM	Glass Roof PCM
Thermal Capacity					
Volumetric Heat Capacity [MJ/m3]	8	140-500	8	140-500	213.3
Volume available [m3]	450	65	200	68	8.5
Thermal Storage Capacity of total installation [MJ]	3,600	9,000 - 32,500	1,600	9,300 - 33,750	1800
Expected Efficiency [%]	80-90	75-90	80-90	75-90	75-90
Charge and Discharge Time [hr-days]	hrs	hrs	hrs	hrs	8hrs
Storage Period [hr-days]	hours-days	hours-months	hours-days	hours-months	hours-days
Risks [-/+]					
Leakage Risk	-	+	-	+	+
Overcooling	-	+	-	+	-
Installation [-/+]					
Supplementary installations	+	-	+	-	-
Energy demand	+	-	+	-	-
Weight inconvenience	-	+	+	+	+
Costs of technique	+	+	+	+	+
Installation difficulty	+	+	-	-	-
Installation costs (excavating/suppl. installations/etc.)	+	+	-	-	-
Impact on museum [-/+]					
Affecting monumental building	+	-	+	+	+
Affecting panorama exhibition	-	-	-	-	+
Inconvenience visitors	-	-	-	-	+
Inconvenience employees	+	+	+	+	+
Total	+2	+2	0	0	+2

Table 10. Risk and feasibility analysis of the potential thermal buffering systems in the Rotonde (source: own).

installation are substantial.

When comparing the packed-bed façade system with the PCM façade system the packed-bed system is expected to create less risks of damaging the canvas, so this could be preferred over a PCM system. However, when comparing the capacities of the systems, as in presented in Fig. 31, the capacity of the packed-bed system is estimated to be substantially lower. Also, additional installations with an energy demand are most likely necessary to bring the packed-bed system to its estimated efficiency. For these reasons the PCM-system is preferred over the packed-bed system on the façade.

In conclusion, a number of thermal buffering system seem feasible in the Rotonde, but most promising are the underground and facade PCM system. In this research the facade PCM system will be further researched to estimate the effect the system can have on the indoor climate of the Rotonde for preservation of the panoramic painting while also decreasing energy demand.

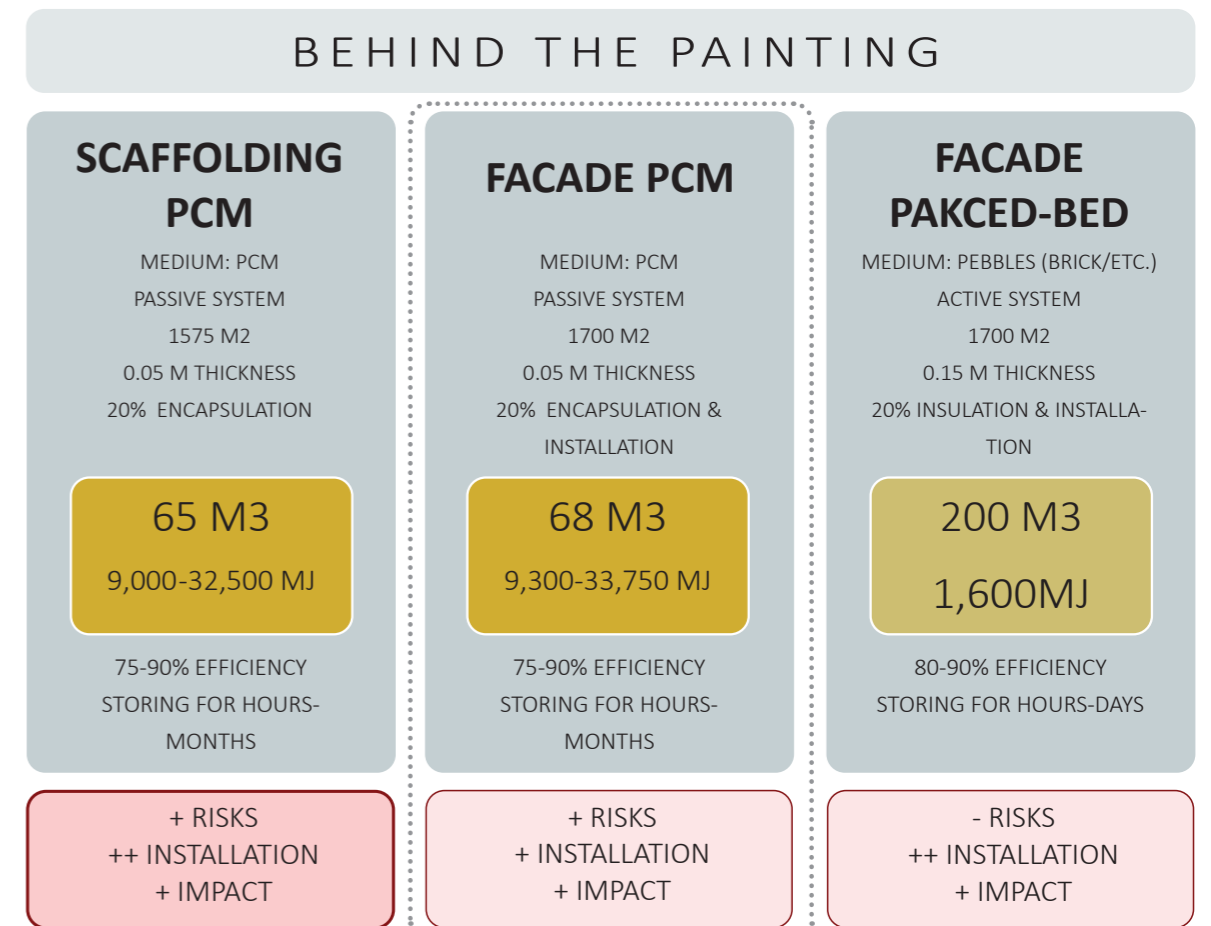
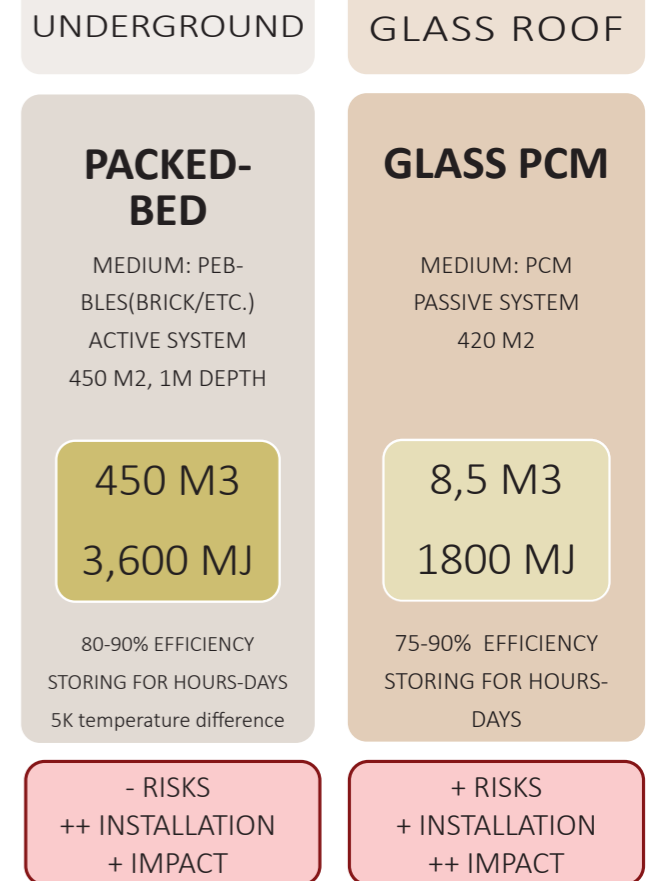


Fig. 31. Thermal buffering systems on the potential location and their characteristics (source: own)

PCM Façade system in the Rotonde

This chapter elaborates on the design process of the proposed PCM façade system in the chapter ‘Thermal Buffering Solution in the Rotonde’. PCMs are able to store a large amount of heat in a small volume when compared to conventional thermal buffering materials, such as water or brick (Sarbu & Sebarchievici, 2018). However, to design a PCM system that is able to function with high efficiency, the process of choosing the PCM type, which is mostly based on the optimal melting and freezing temperature of the PCM (Solarino, 2018). To define the suitable PCM an elaborate indoor climate analysis is done of the zone behind the canvas, which is the proposed location of the PCM system.

First, the design process of the PCM façade system is presented and afterwards the steps of the process are elaborated on per chapter. The steps include indoor climate analyses, a preliminary design, simulations run in DesignBuilder and their results. Finally, an optimised PCM façade system is presented with its estimated effect on the indoor climate of the Rotonde.

Design Process

The design process of a PCM system for the interior façade of the Rotonde is a complex process with a variation of aspects that are taken into account. A full overview of the design process is given in Appendix F. A simplified version is given in Figure 31.

The process starts with additional measurements and analysis of the current indoor climate of the Rotonde to define the vertical and horizontal variations within the zone behind the canvas. Next, a preliminary design is presented with zones and multiple strategies. A representative climate profile per zone is defined, which is used to calculate the optimal PCM types and their thickness. After the finalisation of the preliminary design, the design is implemented in a DesignBuilder base model of the Rotonde. Simulations are run and the efficiency of the different strategies is compared, from which the most effective option is chosen. This option is optimised through testing and the final design of the PCM façade system is presented. Finally, the effect of the final PCM system on the indoor climate of the Rotonde is determined together with the risks and feasibility of the design. An advice

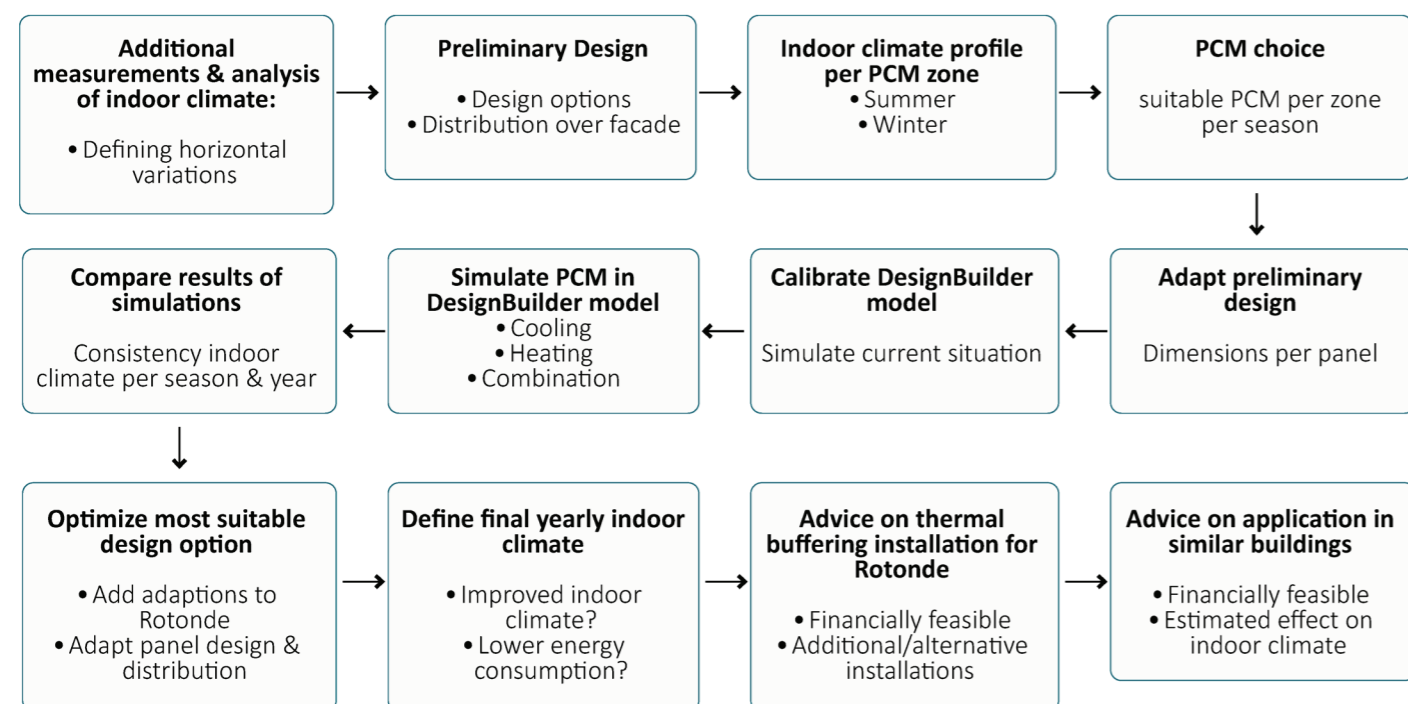


Fig. 32. Simplified design process for the PCM façade system in the Rotonde (source: own).

is presented for implementation of this system in the Rotonde of the Panorama Mesdag museum and reference projects.

Step 1: Additional measurements and analysis of indoor climate

Most PCM manufacturers mention the melting and freezing temperatures in a range of one or two °C (Rubitherm, 2022). For this reason, it is assumed that differences in air and surface temperature below one degree do not impact the efficiency of the PCM.

Choosing suitable PCMs relies on the current and the intended indoor climate, but to ensure that the measured current indoor climate is representative for the whole building, some additional measurements were done. The additional measurements aim to determine if there is a difference of indoor climate at the north side compared to the south side of the Rotonde.

First, the data from three measured locations at the north side are compared to data of three locations at the south side to determine if any horizontal zoning is needed in the final design with different PCMs. Next, the vertical differences in indoor climate at both sides of the building are compared. In the previous current indoor climate analysis, it is clear that the temperature rises when higher in the building at the north side. This analysis will determine if there is a substantial difference in the vertical temperature gradient and what the representative indoor climate behaviour is per zone.

Horizontal variation

The air and surface temperature at the south side have been measured by datalogger set number two and three, respectfully, during the summer of 2022. An analysis of the difference between the north and south façade is defined (Fig. 33). First the average interior façade surface temperatures at the north side are compared to the south side. A different daily

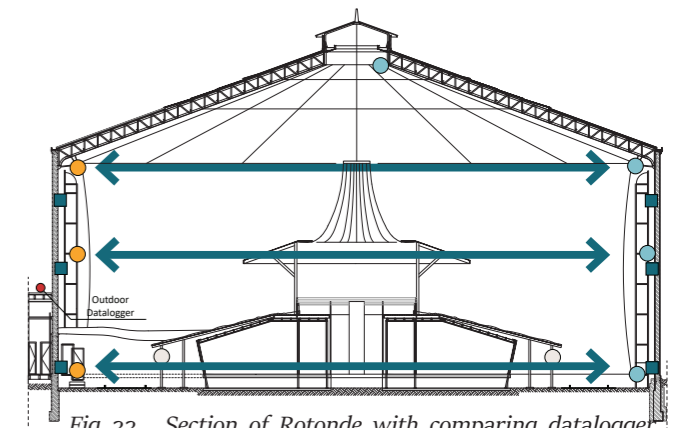


Fig. 33. Section of Rotonde with comparing datalogger set nr. 2 (south) to set nr. 3 (north) (source: own).

behaviour is expected, because of different sun exposure. The north façade shows an earlier maximum temperature in the day and the south side later because the sun rotates throughout the day.

For this reason, not the differences of a point in time are compared, but the average daily maximum and minimum temperatures are compared and their differences are determined (Table 11). The variation between the average maximum and minimum surface temperatures are determine for the month July 2022, a representative summer period. Because these variations are all below one degree centigrade no substantial horizontal deviation is found in surface temperature between the north and south side of the Rotonde.

Average daily variation between north and south facade in surface temperature (July 2022)	Bottom	Middle	Top
Variation daily minimum temperature [°C]	0,3	0,9	0,7
Variation daily maximum temperature [°C]	0,5	0,4	0,9
Variation daily average temperature [°C]	0,4	0,7	0,8

Table 11. Average variations in daily interior façade surface temperatures between the north and south side of the Rotonde during July 2022 (source: own).

Next, the air temperature at the north and south side are compared in a similar way. Table 12 shows the variations between daily air temperature of the north and south side and also in this case there are no variations larger than 1 °C. This means that no

Average daily variation between north and south façade in air temperature (July 2022)	Bottom	Middle	Top
Variation daily minimum temperature [°C]	1,0	0,4	0,5
Variation daily maximum temperature [°C]	0,3	0,3	0,9
Variation daily average temperature [°C]	0,8	0,3	0,6

Table 12. Average variations in daily air temperatures between the north and south side of the Rotonde during July 2022 (source: own).

substantial horizontal differences are found in air and surface temperature. For further design steps combined average values from the north and south side can be used, because these are best representative for the summer period of the whole building.

Vertical Variation

To determine if different PCMs should be placed over the façade in vertical direction, the variation between the top and bottom level datalogger of set 1 (Table 4) are determined. The daily average value for air temperature per datalogger is calculated and the difference between these values is defined. These differences are presented in average values per month. If this difference is larger than 1 °C a vertical distribution should be defined for different PCMs.

The results are given in Table 13 and in July a substantial variation is found between the top and bottom level behind the canvas in July. This means that a PCM system optimized for cooling should have multiple zones in vertical direction, two zones are most likely sufficient to for the 2,6 °C difference.

Variation between bottom and top level - behind the canvas	
Average variation July 2022 [°C]	2.6
Average variation January 2022 [°C]	-1
Average variation yearly [°C]	0.2
Max. variation (+)	6.1
Max. variation (-)	-2

Table 13. Temperature variation between the top and bottom level in the zone behind the canvas between September 2021 and September 2022 (source: own).

Step 2: Preliminary Design

Multiple factors of the PCM installation have to be defined to make simulations feasible. First the base of the design is explained and the different variations of designs that will be developed. Next, multiple factors of the preliminary designs will be defined, which will create PCM installations that can be implemented and tested in the simulations afterwards.

Base of preliminary design

The available area of interior façade of the Rotonde is defined and the total area is 1718,4 m². (Fig. 34). For the simulations three design options are developed, one focussing on PCM heating, one on PCM cooling and one option is a combination of heating and cooling PCMs. These three options will help determine the efficiency and capacity of the separate approaches. Afterwards, an optimised design will use the most efficient option or combination of both. Fig. 35 shows an elevation of one of the sixteen façade elements with the three design options. In the simulations it will be tested which option of the three designs performs best in terms of changing the indoor climate towards the intended climate.

For option number three it is presumed that the cooling PCM works best in the area where the highest temperatures are measured. Also, warm air rises within a space, so it is logical to place heating PCM at a lower location and the cooling PCM at a higher location. In this way the whole height of the Rotonde can profit from the heating installation. The amount of PCM for heating and cooling is in this phase presumed to be similar, so the border between the two PCM types is at the middle of the façade. The location of the border can change during optimisation of the design, because the amount of heating and cooling PCM is dependent on the characteristics of the chosen PCMs and their efficiency in the indoor climate of the Rotonde. For this reason, the needed amount of material per zone might be adapted to increase the impact of the total installation.

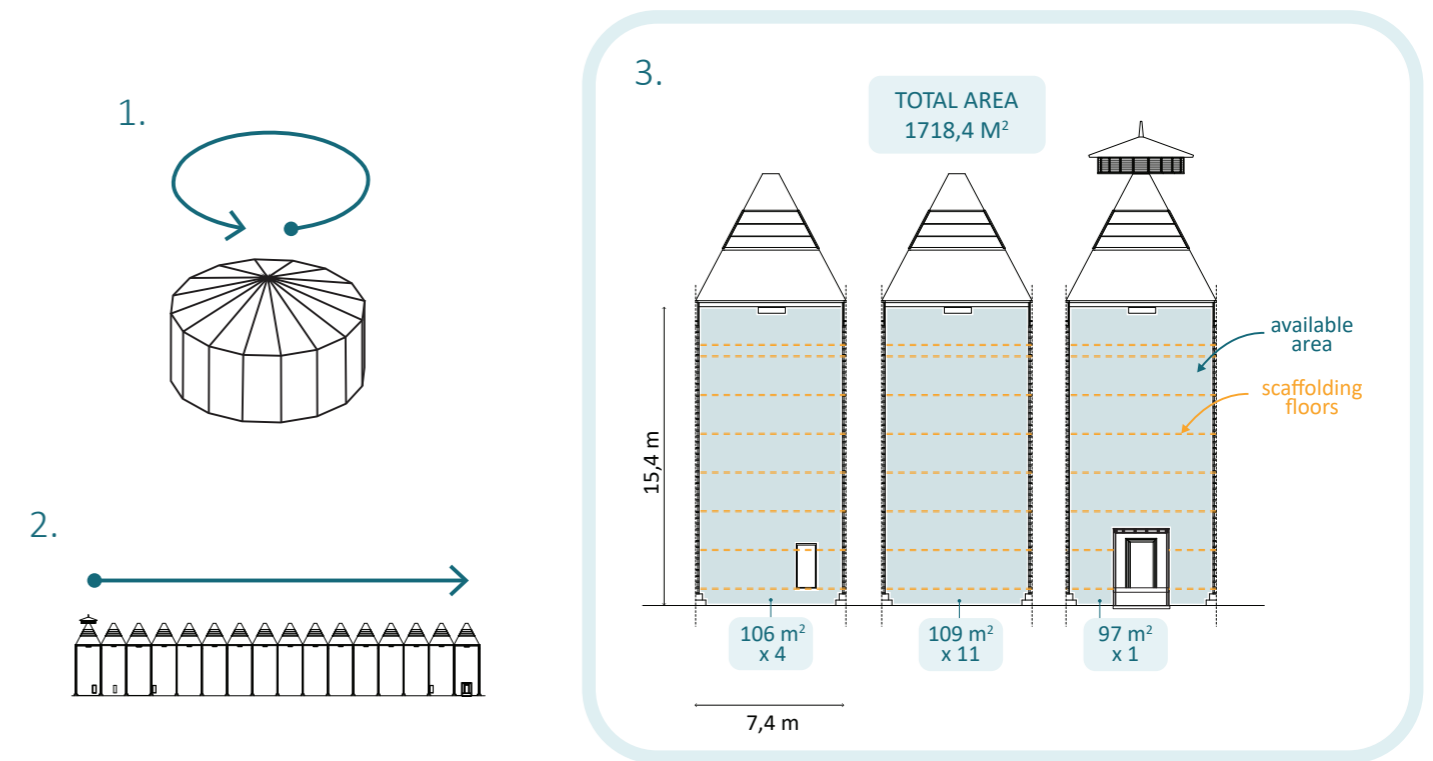


Fig. 34. Steps of defining the exact available area of the interior façade (source: own).

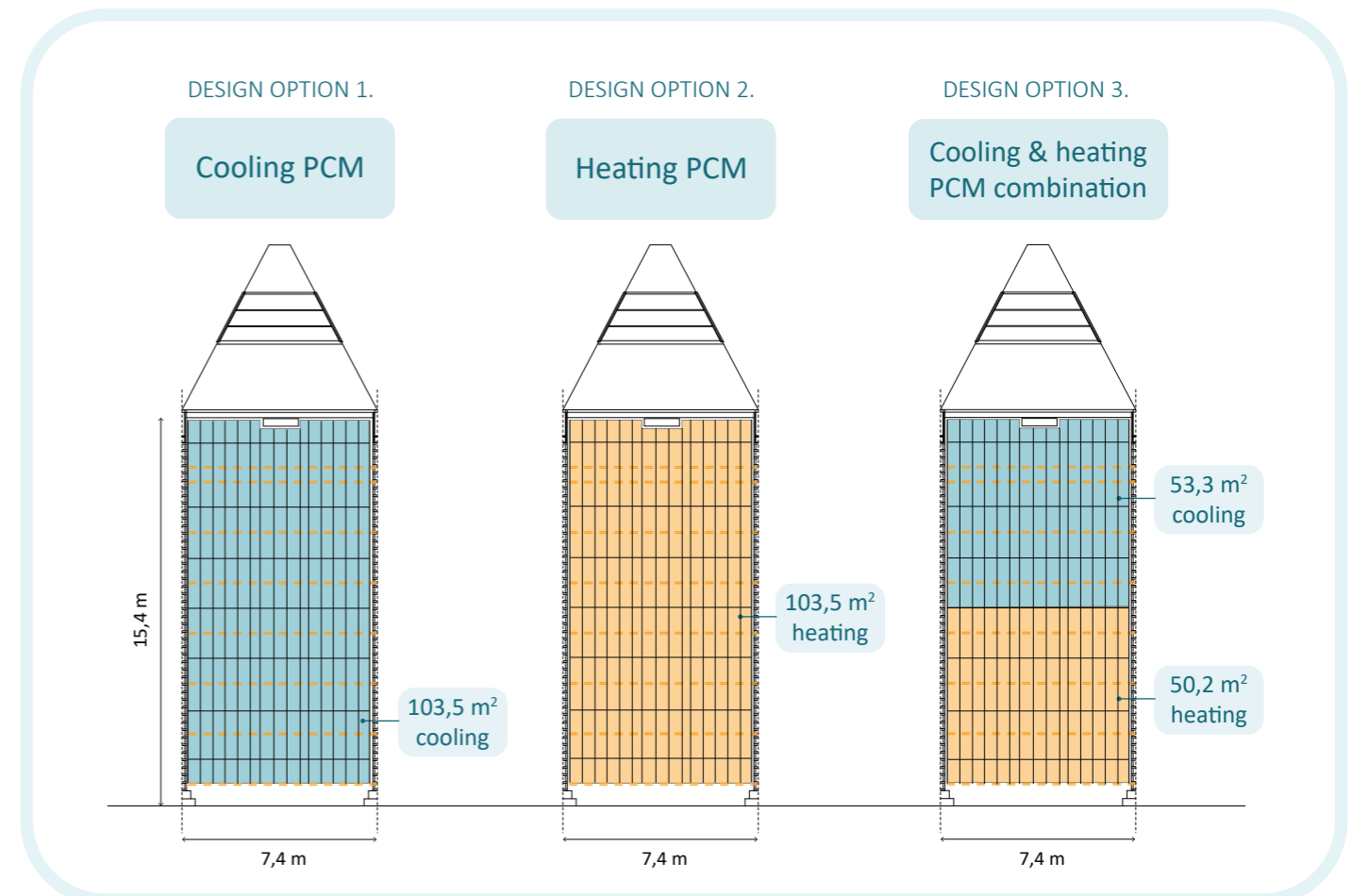


Fig. 35. Three design options of the PCM installation (source: own).

Climate per installation zone

Since the measured points are not distributed evenly over the determined zones, an additional step has to be done to determine representative temperature values per zone on which the PCMs choice will be based. This is done by determining the gradient over the measured temperatures and with this gradient, estimating missing temperatures are estimated. Figure 36 shows an example of the gradient over the façade, in this case the daily average temperature during July in 2022.

With the principle of a temperature gradient, the representative average temperatures per zones can be determined, so this process is repeated for the daily maximum and minimum temperatures per zone per season (Fig. 37). In Fig. 38 the representative climate profile for the top and bottom zone are presented of the average daily temperature behavior from the summer period, July 2022.

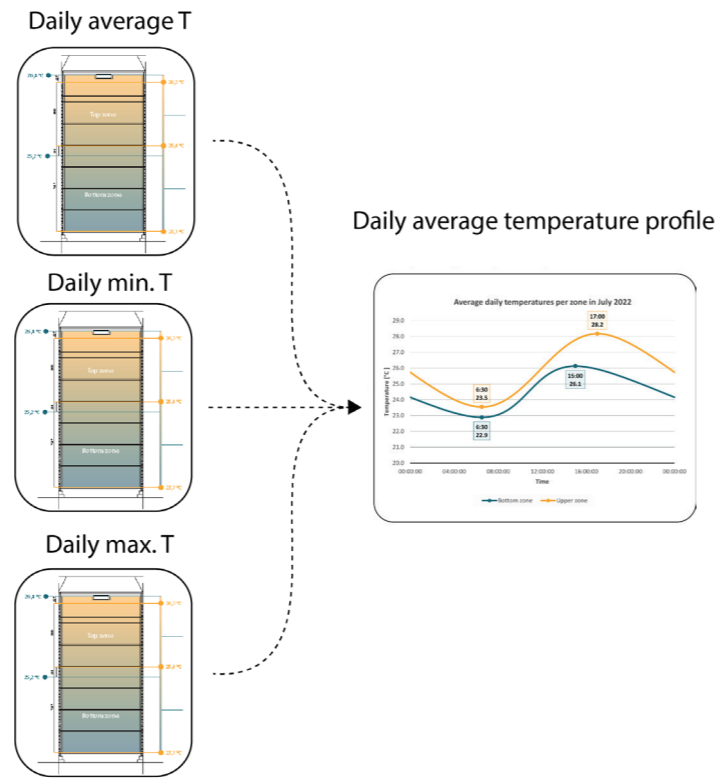


Fig. 37. Diagram of the process to determine the average climate profile per zone (source: own).

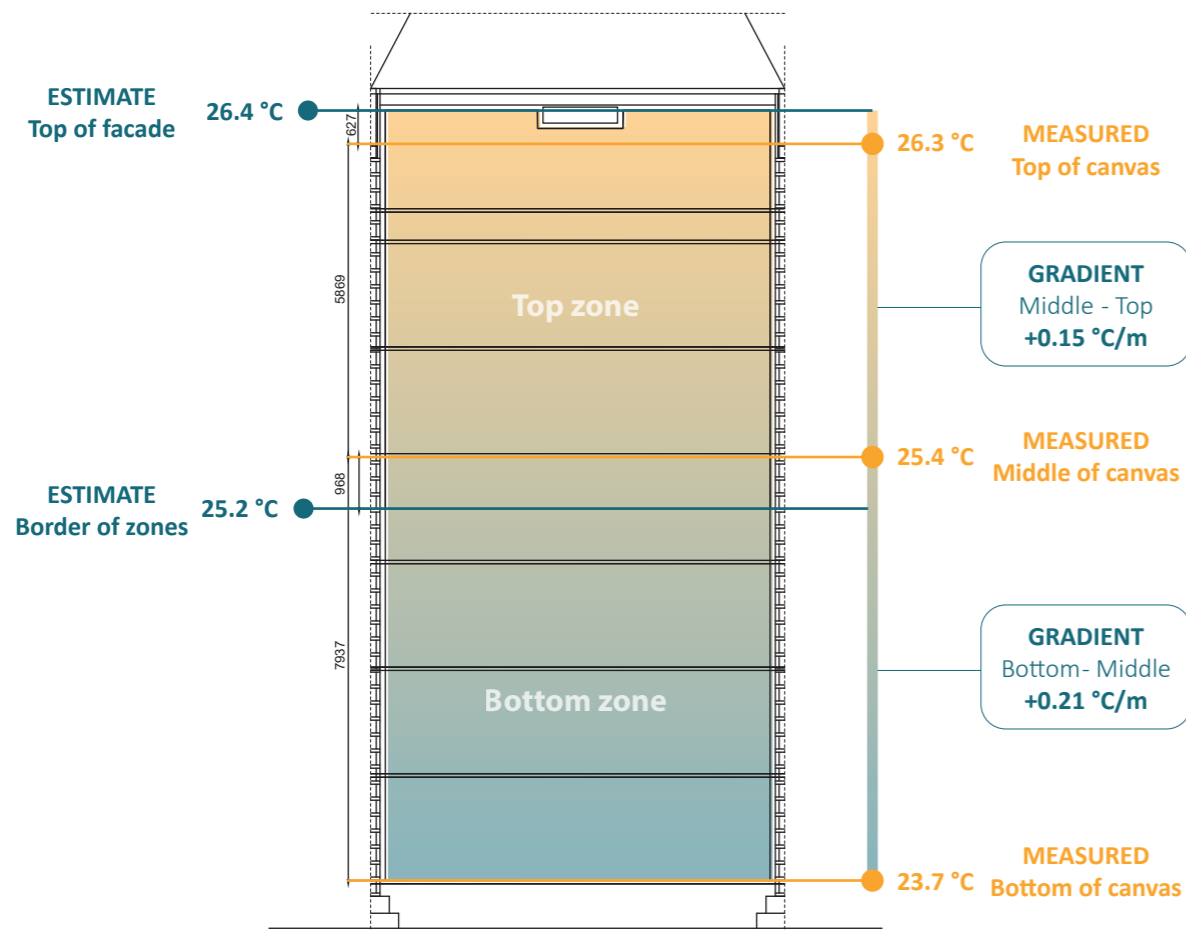


Fig. 36. Gradient of average daily temperature over the façade in July 2022 (source: own).

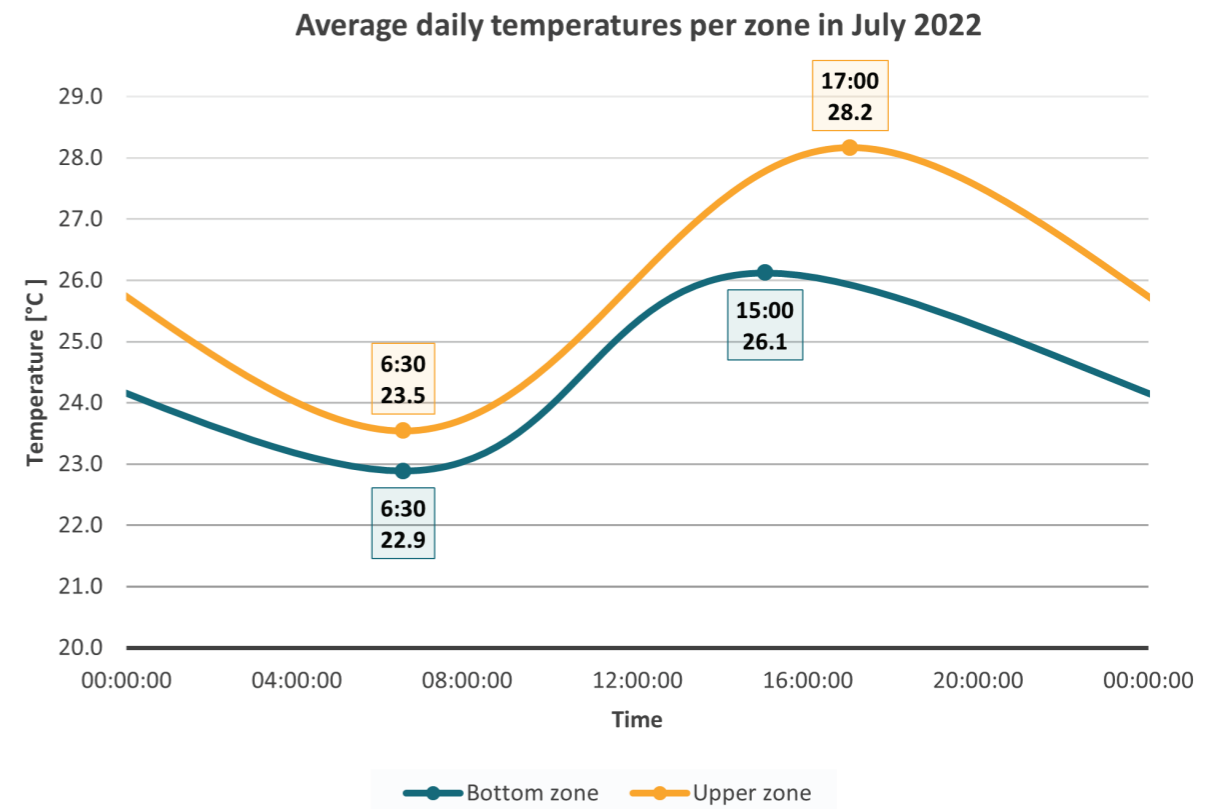


Fig. 38. Average daily temperature profile of the bottom and top zone during July 2022 (source: own).

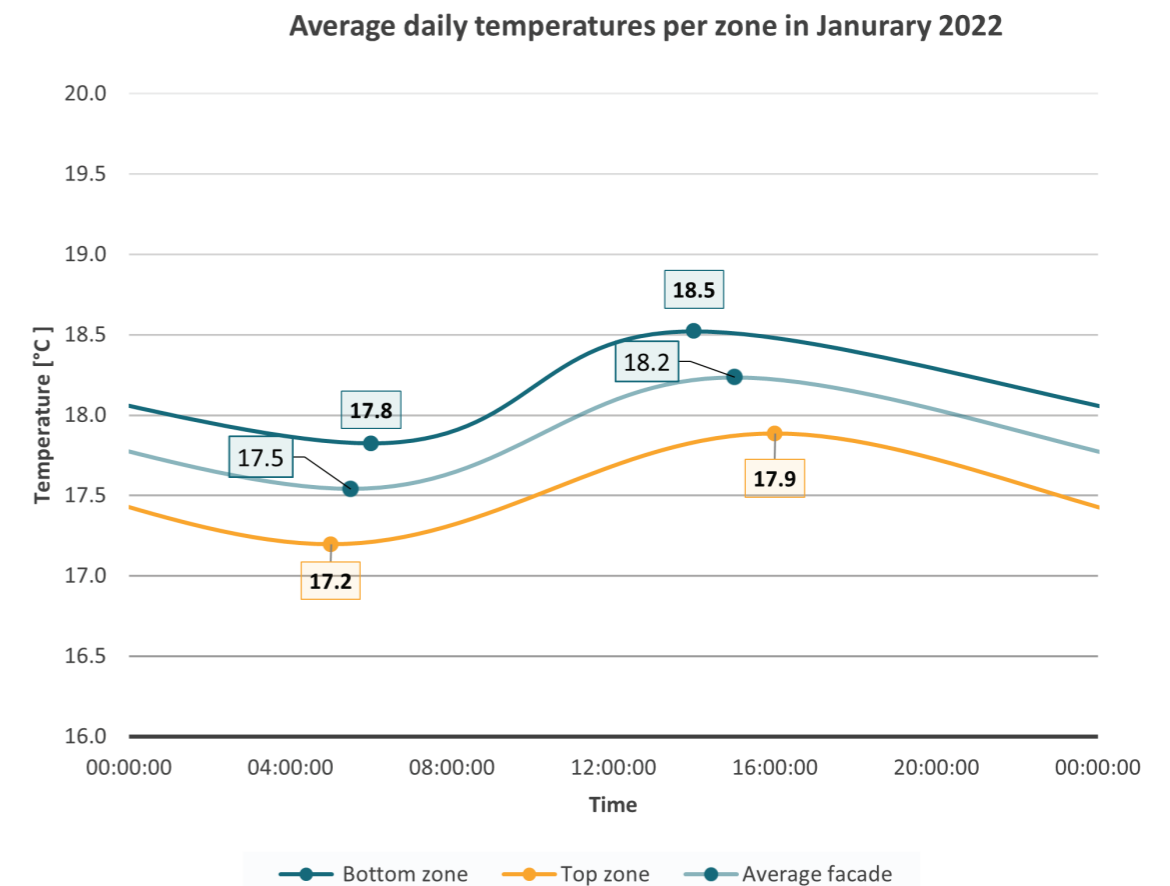


Fig. 39. Average daily temperature profile of the bottom and top zone during January 2022 (source: own).

For the summer period, as explained before, the average of data from the north and south side is used. For the winter period only data from the north side is available and this was measured when the heating installation behind the canvas was functional (Fig. 39). This does not represent the indoor climate behaviour when a PCM installation is installed, because the PCM will substitute the heating installation. An estimation of the indoor climate without heating installation behind the canvas is done by analysing a period from the measured data during a heating installation failure period in April 2022 and by simulations in DesignBuilder. Chapter 'C: Base model: no heating behind the canvas' elaborates on this process and average winter. The average January temperature profile of a simulation without heating system behind the canvas is given in Fig. 40.

Based on these climate profiles the desired behaviour of the PCM is projected onto the daily temperature behaviour. From the average climate profiles, the optimal melting and freezing temperatures of the PCMs can be defined. Other studies propose equations to define the optimal melting and freezing temperatures of a PCM based on a heat balance values. However, it is shown that the optimal melting temperature is closely related to the indoor temperatures (Solarino, 2018). Since a

large quantity of data of the indoor temperature is available of the Rotonde and less data is available for a heat balance equation, such as material characteristics, the optimal melting and freezing temperatures are defined using the temperature profiles per season. The daily PCM behaviour and the optimal PCM per zone is given in for all three design options.

Based on these analysis is it expected that cooling PCMs can have an effect on the indoor climate of the Rotonde, because daily temperature ranges in the summer have a size of 3 to 5 °C. This range is suitable for most PCMs to transitions from solid to liquid and vice versa and thus in theory would be able to charge and discharge on a daily basis.

However, the daily temperature range in the winter in the Rotonde is smaller than 1 °C and seems less suitable for a PCM to impact the indoor climate. PCM designed for heating purposes needs a heat influx at a certain moment in the day to charge and later to discharge this heat when needed. There seems to be a minimal heat influx during the day in the Rotonde and it is expected that the PCM will not fully charge nor discharge on a daily basis during the winter. Nevertheless, a PCM was found that somewhat matches the daily temperature range in the winter, so this design option will be simulated to validate the hypothesis.

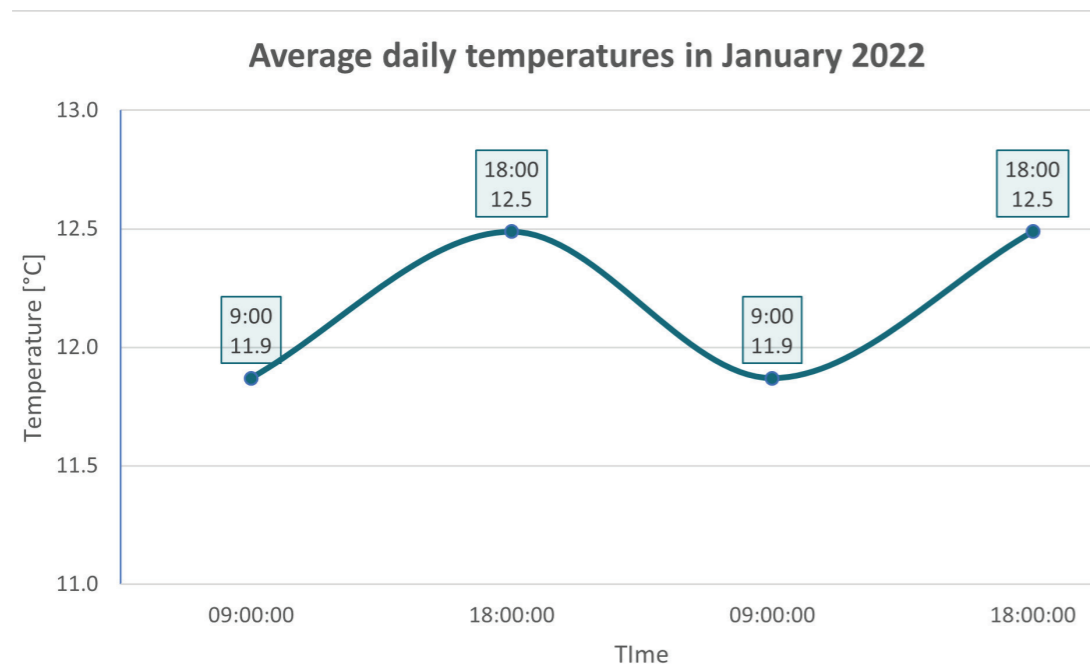


Fig. 40. Average daily temperature profile façade during January 2022 without heating installation behind canvas (source: own).

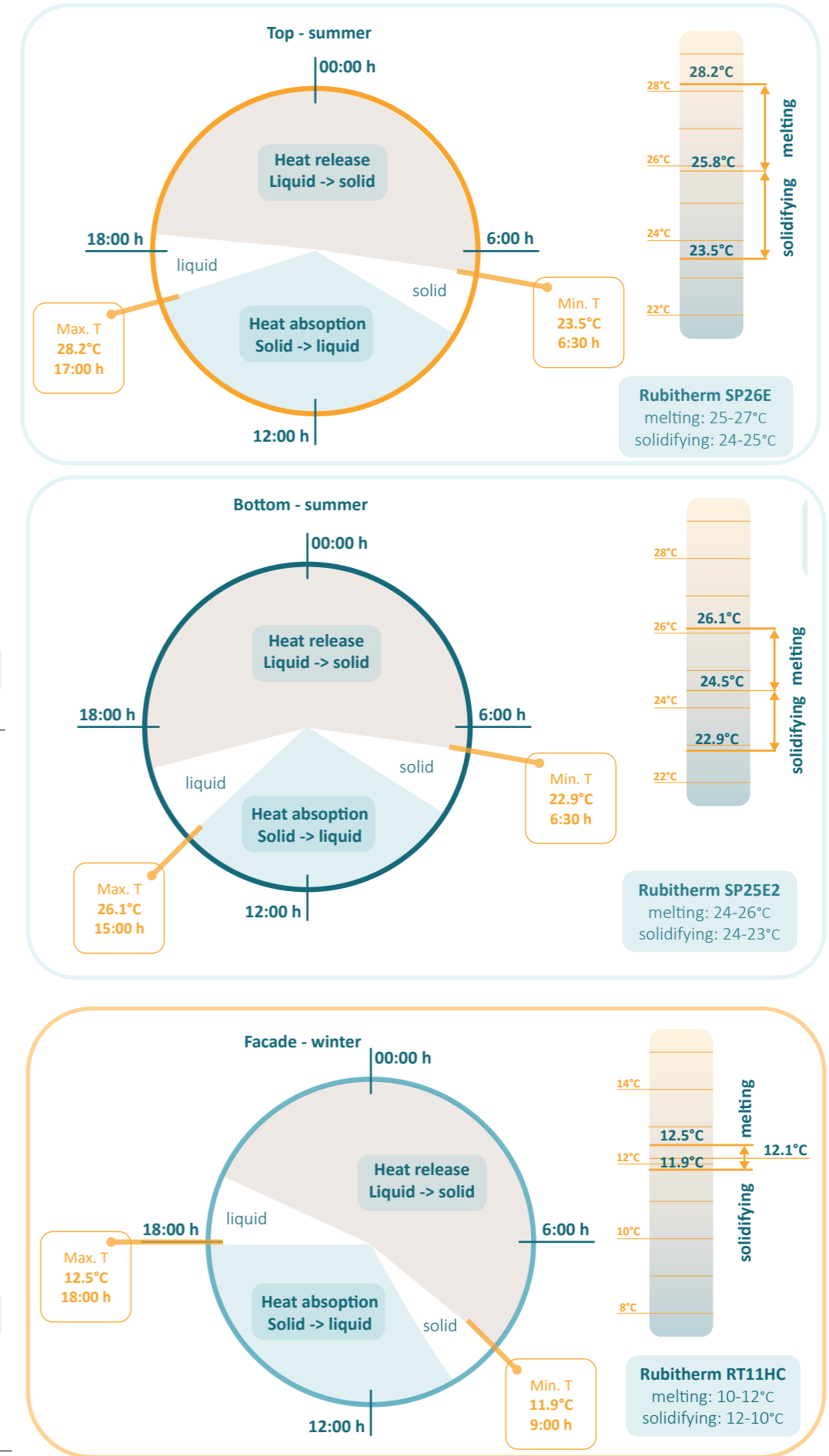
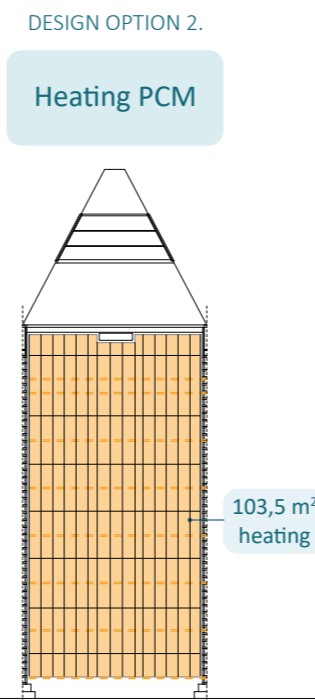
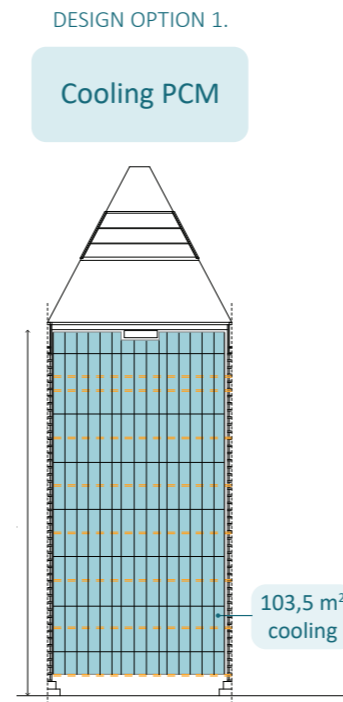


Fig. 41. The expected PCM behaviour and suitable PCM for the design options 1 & 2 (source: own).

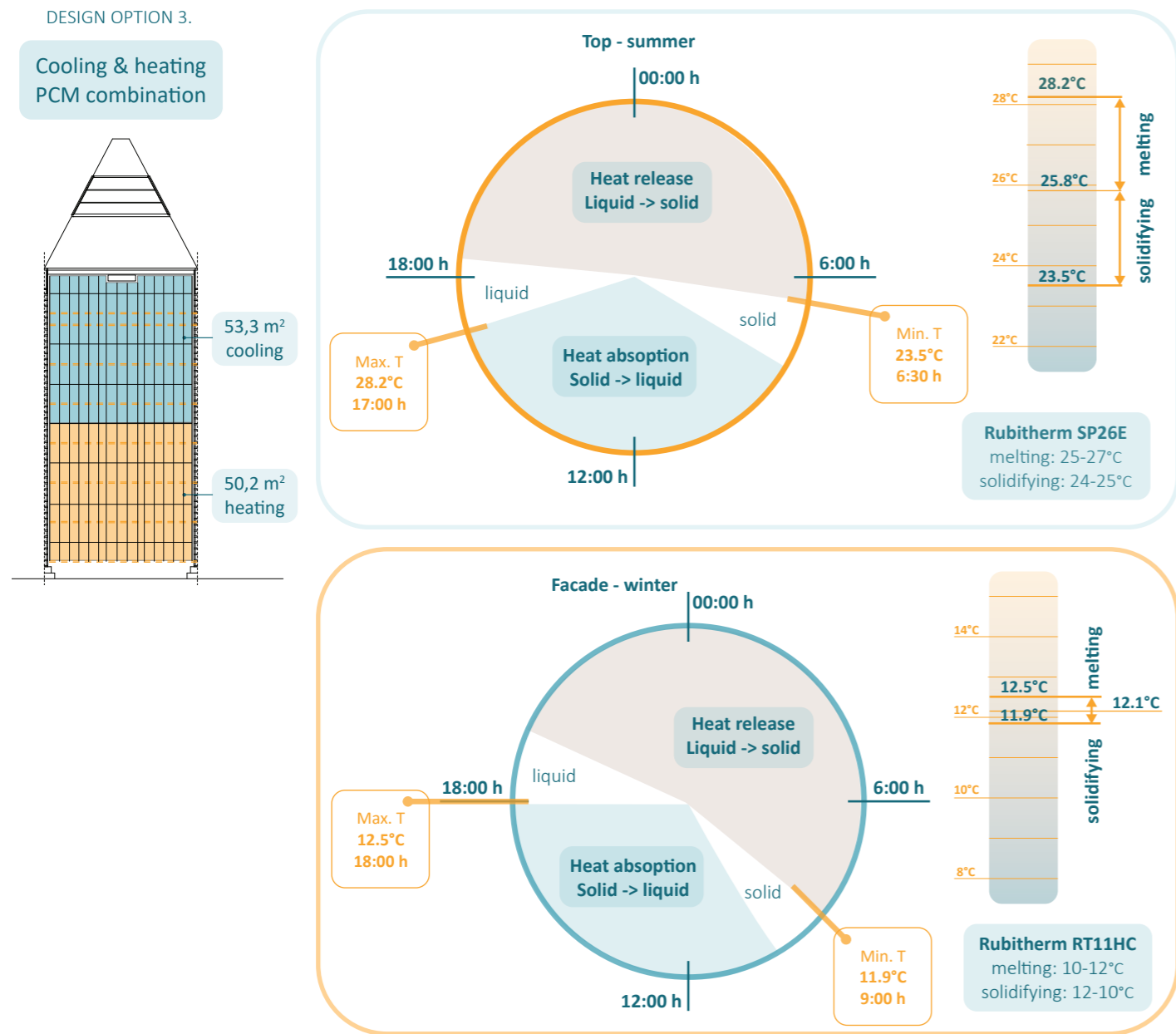


Fig. 42. The expected PCM behaviour and suitable PCM for the design option 3 (source: own).

The suitable PCMs are found in a PCM database with their characteristics (Turrin, 2019) and it has been expanded for this research. The types of PCM were filtered on melting and freezing temperatures and their characteristics on toxicity and flammability were checked. The chosen PCM types are all by Rubitherm (2022) and have low flammability and are non-toxic. The full overview of material characteristics of the suitable PCMs is given in Appendix G.

The SP-line by Rubitherm is the preferred PCM line, because it is non-flammable and the RT-line has a minimal flammability. The SP-line is made from non-organic salhydrates and has

a price of 2 to 5 euros per kg, but most materials have a higher density and have a corrosive effect on metals (Rubitherm, 2022). The RT-line is made from organic materials, hydrocarbons, and has a lower density and no corrosive effect on metal, but a higher price of 4 to 15 euros per kg.

Maximum weight of the panels

The monumental façade and foundation of more than 100 years old have structural limitations. For this reason, it is important to define a maximum amount of weight that is allowed to be added to the façade while not impacting the structural condition

or increase the risk of a subsiding façade.

Through previous research conducted by the organisation of the museum the maximum allowable weight on the facade is 20 kg per m² façade (Table 15). The weight of the masonry façade is estimated on 1600 kg/m³. With the thickness of 0,350 meter and the height of 15 meter, the weight of the façade per running meter is 8400 kg. By adding the maximum 20 kg per square meter façade, per running meter in total 300 kg could be added which is 3,6% of the original facades weight (A. Sluis, personal communication, August 23, 2022).

However, this estimation was broad, so it is expected that more weight could be added per m². The maximum allowable weight of 20 kg/m² will be used as a maximum value for solely the PCM material. Further research is needed to define the maximum allowable weight for the whole system including PCM, containers and support system.

Because the estimation by the construction engineer was broad, another way of estimating the maximum weight of the installation can be by determining the weight of the current heating installation on the façade, that will be removed. The jacketed piping used for the installation has a diameter of 350 mm and it's weight is estimated to 15 kg/m when filled with water. The weight of the whole installation is determined in a situation when it is filled with water and the results are shown in Table 14.

Also, the organisation of the museum has stated that it is necessary for a PCM panel to be installed manually by one person, because of the limited amount of space on the scaffolding. On average the maximum amount of weight that can be handled by one person is 23 kg. An object of more than 50 kg is not allowed to be handled manually, even when it involves multiple people (Ministerie van Sociale Zaken en Werkgelegenheid, 2022).

The weight restrictions will be taken into account when defining the dimensions of the PCM panel with the different types of PCM.

Weight restriction of new installation	
Max weight per m ² facade [kg]	20
Max weight per meter facade [kg]	300
Max. weight of total installation [kg]	34.368
Max. weight per panel [kg]	23

Table 15. Weight restriction of additional installations on the facade (surce: own).

Weight of current facade heating installation	
Weight per meter tube [kg]	21,5
Weight per meter facade [kg]	110,1
Weight per facade section [kg]	853,1
Weight of total installation [kg]	13.650
Weight carried per facade connection [kg]	42,7

Table 14. Weight of current facade heating installation (source: own).

Dimensions of a PCM panel

There are multiple factors that have an impact on the dimensions of the panels, such as the allowable weight, most efficient thickness of the panel, one person handling capabilities and minimizing the damage on the monumental façade.

First, an assumption about the optimal height of a panel is done which is one meter. This is dependent on the layout of the façade and the scaffolding and the distribution of the panels over the façade. To minimize damage on the monumental facade, the panels will be secured to the facade using the existing holes of the current heating installation. These holes are present every two meters in vertical direction. For this reason a supporting system is designed with a vertical distribution of 1 m with rails by which the 1 m tall PCM panels are supported (Fig. 43 & Fig. 45).

A suitable width for the PCM panel is set to 0,5 m, making them easy to handle on the narrow scaffolding. One panel has a surface of 0,5 m²

There are multiple factors that have an impact on the thickness of the panels, such as the available space, weight limitations and PCM efficiency. The usable space between the scaffolding structure and the façade ranges from 0,8 to 0,25 meters. With some margins the maximum thickness of the PCM installation is 0,15 meter in terms of usable space. However, a larger thickness does not mean a more efficient PCM installation, because the thickness of the panel influences the heat transfer efficiency and solidifying and melting process. The maximum weight per square meter PCM panel is defined as 20 kg (Table 15).

Next, the optimal thickness of a PCM panels is determined by using the equation of Figure X. For the equation a location specific heat gain value is needed and this value is acquired by the simulation of the base model explained in ‘Step 3: Calibrate base model in DesignBuilder’. In table X the optimal thickness of the different types of PCM per design option are given. Also, the maximum thickness per PCM type is given based on the maximum allowable weight per m² (Table 15) and the density of the PCM types (see Appendix G for full overview of the material properties of the PCMs).

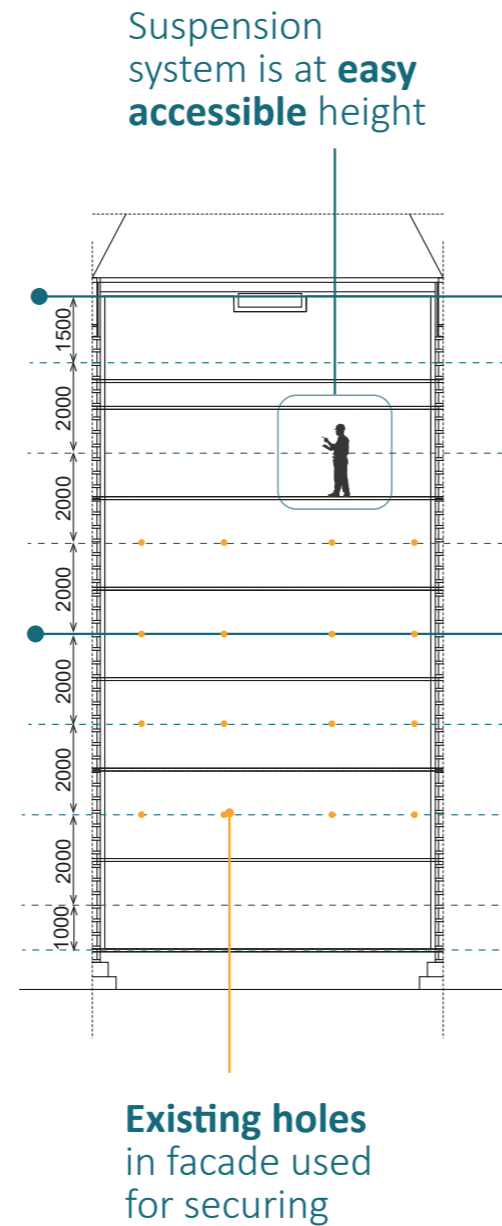


Fig. 43. Preliminary Design PCM panels (source: own).

$$t_{PCM,opt} = \frac{Q}{C d}$$

m OPTIMUM PCM THICKNESS
 kJ/m² HEAT GAIN LOCATION SPECIFIC
 kJ/kg LATENT HEAT PRODUCT SPECIFIC
 kg/m³ PCM DENSITY PRODUCT SPECIFIC

Fig. 44. Equation for defining the optimal thickness of a PCM panel in a specified location (Solarino, 2018).

PCM type	Optimal thickness [mm]	Maximum thickness [mm]
RT11HC (heating)	4	22.7
SP25E2 (cooling)	43.2	12.5
SP26E (cooling)	5	12.5

Table 16. PCM type and their optimal and maximum thickness for application I the Rotonde (source: own).

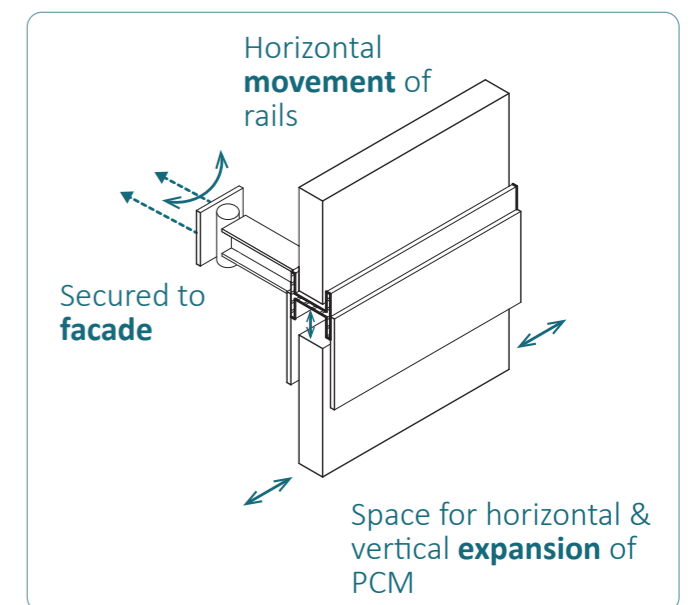
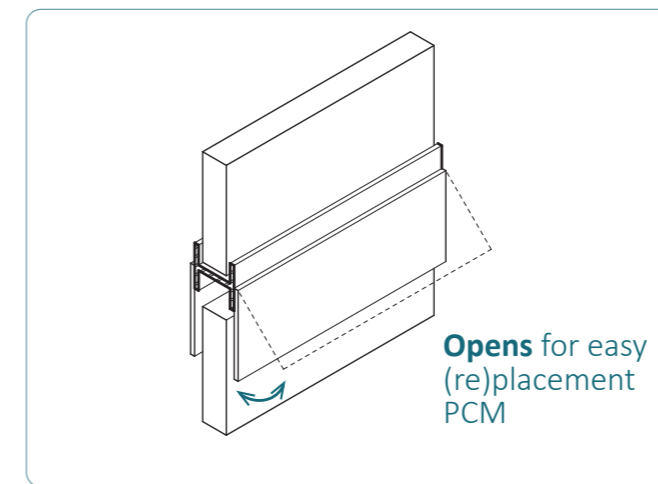
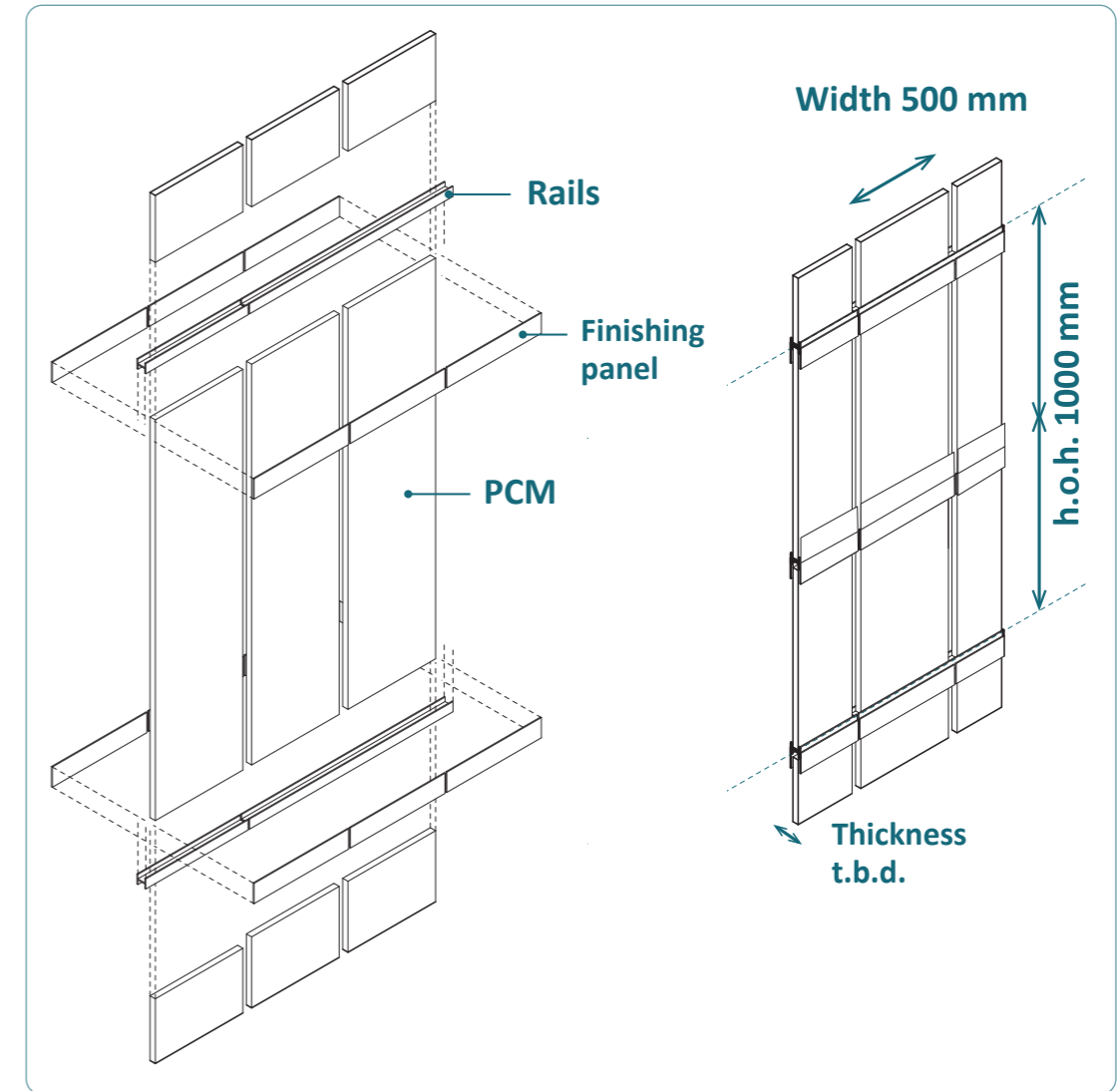


Fig. 45. Preliminary Design PCM panels (source: own).

Step 3: Calibrate base model in DesignBuilder

This chapter will elaborate on the simulations in the software DesignBuilder and how the digital model used for the simulation is made comparable to the building.

Input and settings

Detailed description will follow of the model, material characteristics, HVAC, weather file, climate zones and simulation settings.

Weather file

- Hourly weather data collected by KNMI Voorschoten from 01-09-2021 to 01-09-2022.
- Hourly outdoor air temperature: measured by an outdoor datalogger on the roof of the museum (Fig. 12).

HVAC

The HVAC system in DesignBuilder is designed to reflect the situation in the museum by using the

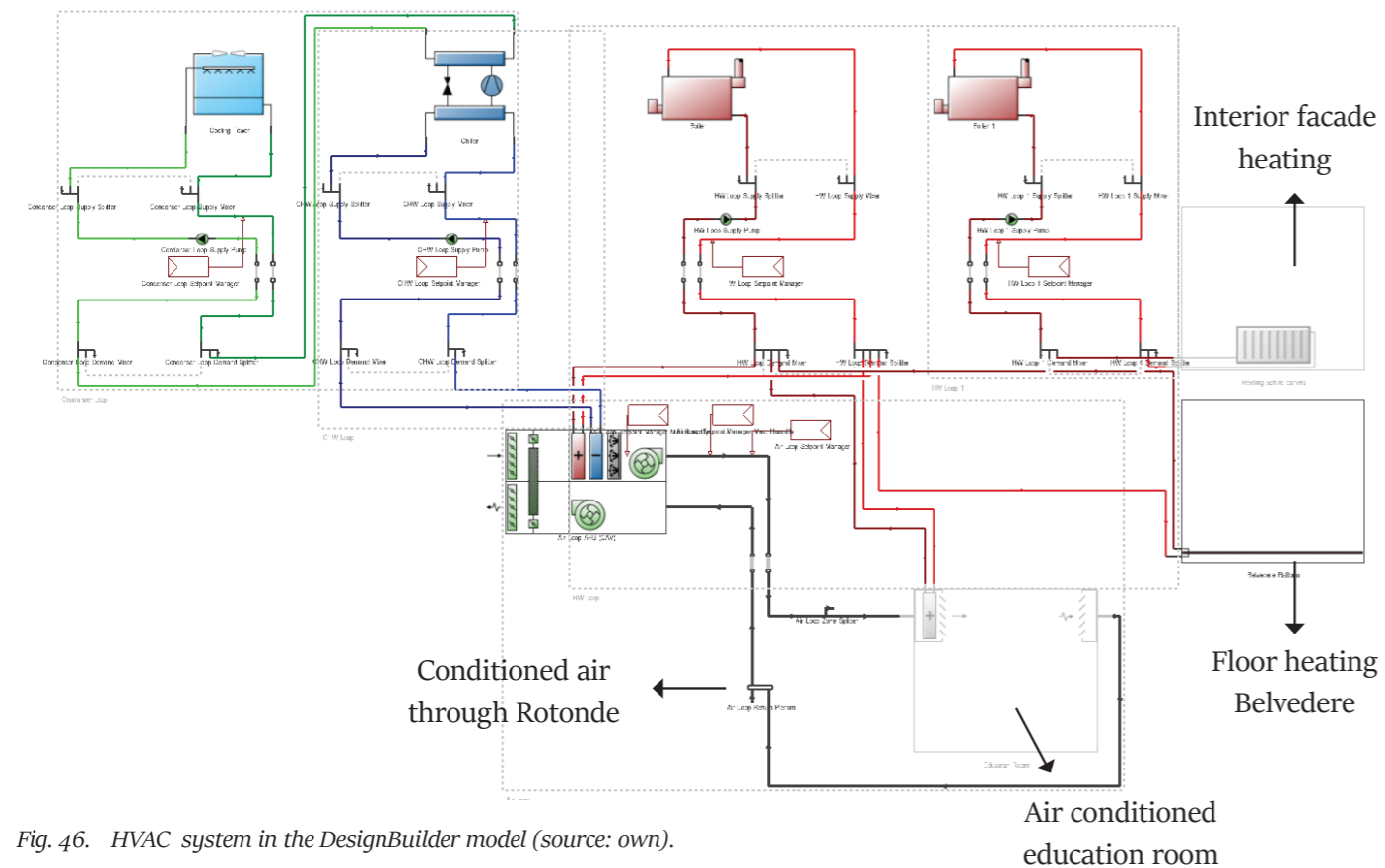


Fig. 46. HVAC system in the DesignBuilder model (source: own).

installations properties (Table 3). Only installations affecting the Rotonde are modelled in the DesignBuilder model. The additional cooling ventilation on the Belvedere was not modelled because of a lack of suitable system in DesignBuilder. However, the impact of this is expected to be limited, because of its relatively small capacity. Some installations are further explained if divergent from the situation in the building.

Model options

- HVAC: ‘2-Detailed HVAC Data’.
- Natural ventilation & infiltrations: ‘Calculated ventilation’ and airtightness method: ‘2-Crack template’.
- Interior facade heating: electric radiator is used with same capacity and setpoints as stated in Table 3.
- Overflow ventilation from educational space to Rotonde: a plenum space is added after ventilation extraction from the education space. The plenum is assigned to the zone: ‘Bottom_Rotonde’.

Surrounding buildings

The surrounding buildings of the Rotonde are modelled in the DesignBuilder (Fig. 47).

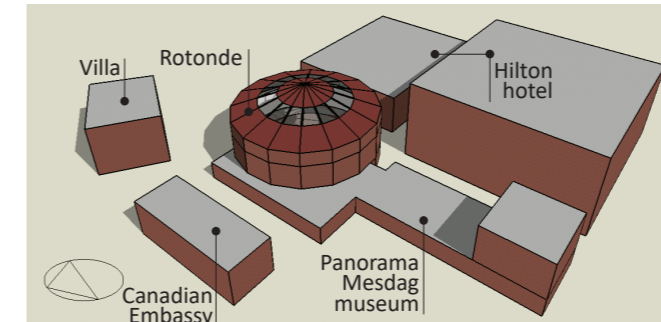


Fig. 47. Surrounding buildings of the DesignBuilder model (source: own)

Blocks and zones

The Rotonde is modelled according to drawings and dimensions provided by the organisation of the museum. The Rotonde is modelled in four building blocks: bottom, middle, top and roof block. This

distribution is used, because it aligns with the climate zones as explained in Fig. 13.

Within the bottom to top block there are two main zones, the zone behind the canvas and the zone of the open space. In the middle of the bottom block there are also zones for the closed rooms, such as the educational space.

All partitions between the blocks and zones are modelled as holes or virtual partitions to allow air flow between zones. The partitions that have material properties are the closed rooms and the canvas which is the partitions in the middle block between the zones behind the canvas and the open space.

This division in block and zones is used, because it is possible to analyse indoor temperatures and relative humidity per zone.

Material properties

The used materials for the model of the Rotonde are presented in Fig. 48.

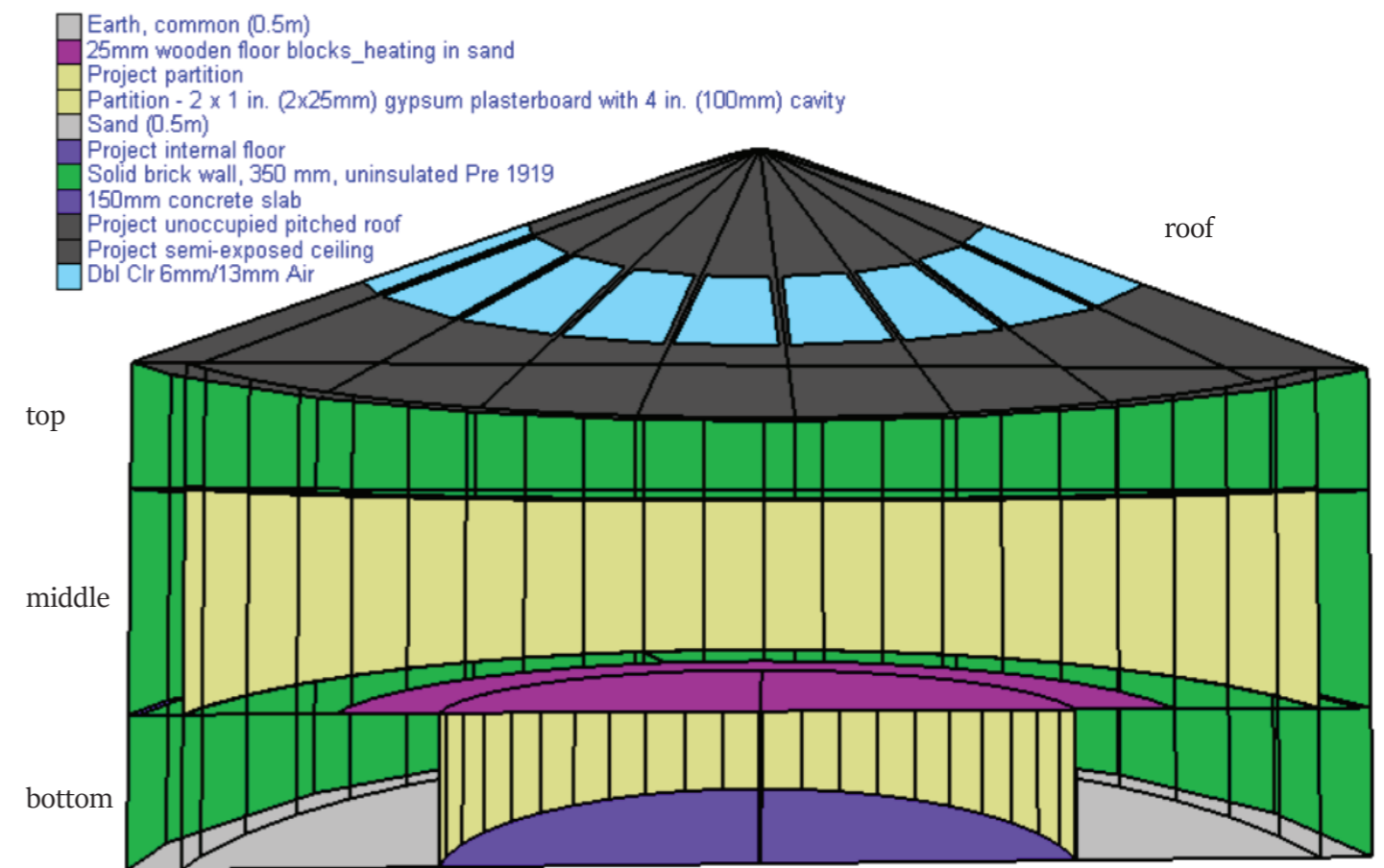


Fig. 48. Section of the DesignBuilder model (source: own).

Infiltration

The infiltration of the masonry facade is set through the crack-template for the concerning zones. The air tightness is set to 'Poor', which has the following properties.

'Poor', properties external walls

Flow coefficient 0.000200 kg/sm²@Pa
Flow exponent 0.7

These properties seem suitable for a masonry brick facade from the 19th century with some larger cracks, for example in the connection of facade to roof (Pleysier & Vos, 2017).

All other zones are set to the default 'medium' setting with the following properties

'Medium', properties external walls

Flow coefficient 0.000100 kg/sm²@Pa
Flow exponent 0.7

Model Options

1. Data
 - '2-Detailed HVAC data'
 - 'Calculated ventilation'
 - 'Air tightness method: 2-Crack template'
2. Advanced tab
 - Natural ventilation: check 'model airflow through holes and virtual partitions.'
3. Simulation tab
 - Simulation options: from 1 Januari to 31 December
 - Time steps per hour: 4
 - Solar: check 'include all buildings in shading calculations'
 - Solar distribution: '3-Full interior and exterior *advanced*'
 - Solar: check 'Check for non-convex zones?'
 - Solution algorithm: '5-EMPD
 - Inside convection algorithm: '6-TARP'
 - Outside convection algorithm: '6-DOE-2'

Simulation of current situation

The current situation of the Rotonde is modelled DesignBuilder and a simulation is run according to paragraph 'Input and Settings'. An analysis is done of the difference between the measured data and simulated data. The yearly indoor climate indicators and the average daily indoor climate in January and July 2022 are compared and the difference is presented in Fig. 49 and Table 17

From the results it is clear that the operative temperature behind the canvas from the DesignBuilder model matches the measured data relatively well throughout the year considering the average daily. However, the daily temperature fluctuation is smaller in size in most zones and occurs more frequently in the simulation compared to the measured data.

The relative humidity between the measured and simulated data seems to differ substantially. The simulated relative humidity is approximately 10 % higher throughout the year and there is an increased frequency and size of daily fluctuations. For this reason the simulated relative humidity is poorly comparable to the measured data and an additional analysis is given concerning the absolute humidity, which is the mass of water vapour in the air mixture in g/kg in (Nguyen, Schwartz, & Dockery, 2013). The absolute humidity, or humidity mixing ratio, shows more comparable data, because it defines the absolute weight of water vapour.

Relative humidity shows the percentage of water vapour in the air, but this is also relative to the air temperature. Since the simulation and measured operative temperatures show differences, it is expected for the relative humidity to differ too.

Also, the model is less detailed than the actual building concerning interior objects, so it is not able to simulate the exchange of moisture between all object in the Rotonde and the air. the For this reason, the absolute humidity is in this case more appropriate for a comparative analysis between the measured and simulated data of the current situation.

Fig. 50 and Fig. 51 show comparable data

between measurement and simulations, because in both cases the summer absolute humidity is approximately 6 g/kg and during the winter close to 10 g/kg. This means that the basis of the humidity simulations is comparable to the actual situation that was measured. The behaviour of the relative humidity in the simulation is comparable, but of a higher value and with larges fluctuations.

Because the measured data and the simulated data of the current situation are not fully comparable, it is estimated that any further simulations with the

representative absolute values. It is also expected that the relative humidity results will contain larger daily fluctuations and diverge more from the base model simulation than compared to measurements of PCM implementation.

From the results of this comparative analysis, between the measured data and the simulation of the current situation, the method for data comparison is defined for the simulations where PCMs are implemented in the DesignBuilder model. Instead of comparing the absolute values of operative

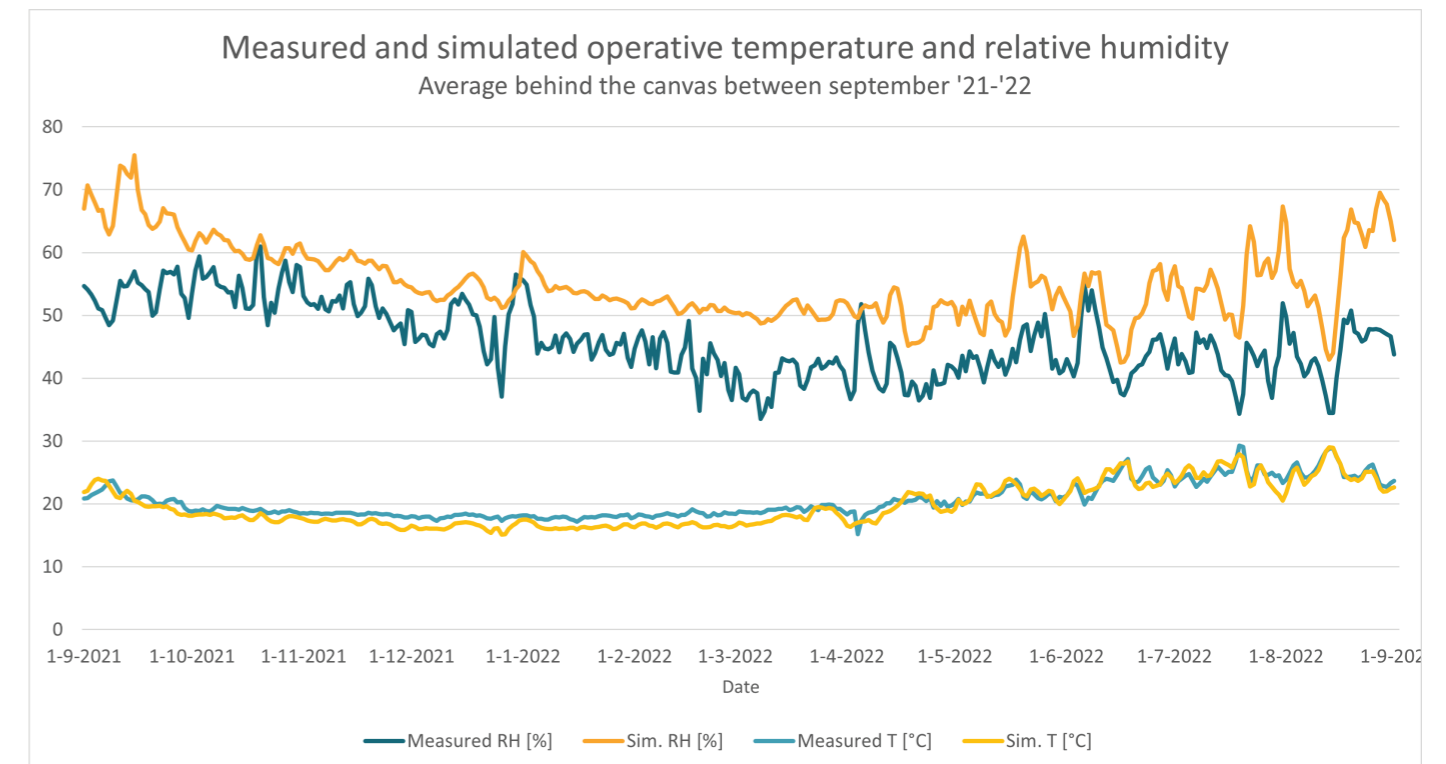


Fig. 49. Graph of the measured and simulated daily average operative temperature and relative humidity in the space behind the canvas of the current situation from September 2021 to September 2022 (source: own). implementation of PCM will not result in completely temperature and relative humidity of the simulations

Difference of yearly indoor climate indicators: measurement and simulation data	Behind canvas				Open space
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%]	15.5	11.5	12.4	8.4	5.7
Maximum RH [%]	16.0	13.1	14.8	14.6	16.6
Minimum T [°C]	-2.1	-0.9	-2.3	-1.7	5.4
Maximum T [°C]	-0.1	-2.9	-1.1	-1.7	-7.6
Days per year of RH fluctuation > 10 %/24hr	184	210	203	221	215
Maximum RH fluctuation [%/24hr]	-2.4	1.8	-0.7	2.2	6.3
Days per year of T fluctuation > 5 °C/24hr	-3	-13	62	-16	-24
Maximum T fluctuation [°C/24hr]	-3.1	-1.1	0.5	-1.3	-2.9
Days per year of T fluctuation > 3 °C/24hr	-73	73	172	81	-59

Table 17. Difference of the simulation data of the current situation compared to measurement data of the yearly indoor climate indicators (source: own).

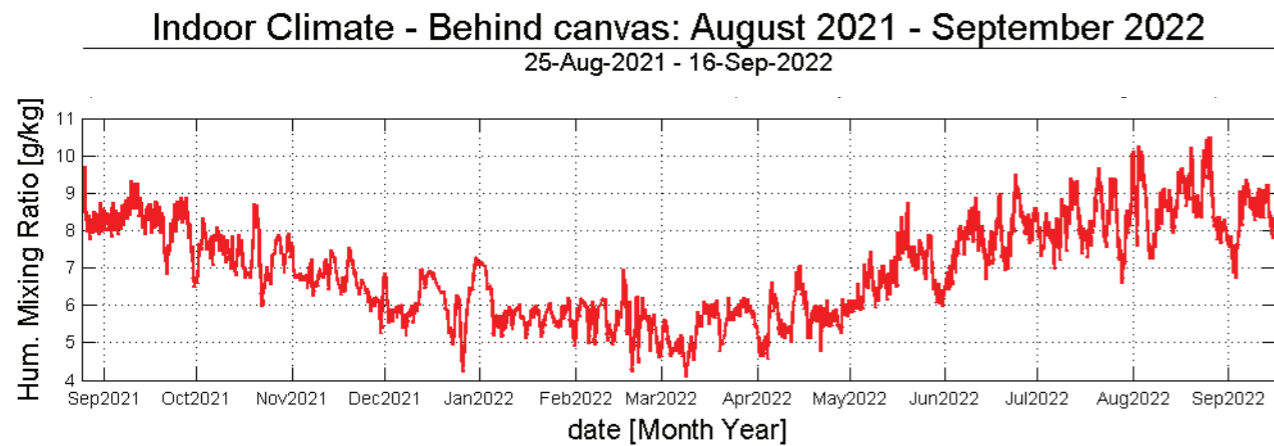


Fig. 50. Absolute humidity from measurement data behind the canvas from August 2021 to September 2022 (source: own).

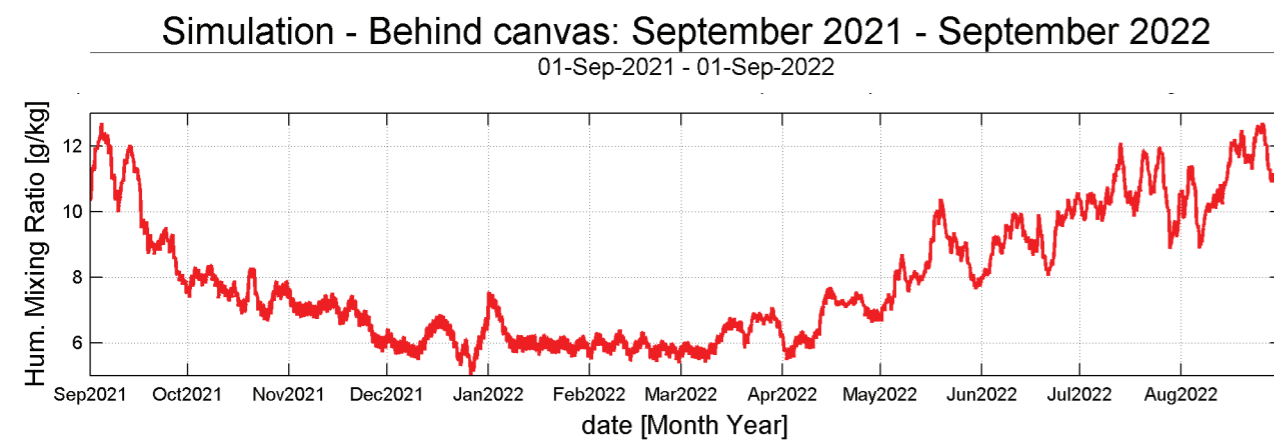


Fig. 51. Absolute humidity from simulation data of the current situation behind the canvas from August 2021 to September 2022 (source: own).

with PCMs to the measured data, the effect on the indoor climate is first defined between the simulations. These effects are derived from the difference between the results of a base model simulation and an alternative model simulation with PCMs. These differences estimate the effect that a PCM installation can have on the indoor climate of the Rotonde. If desired, an estimated new indoor climate with the implemented PCM can be calculated with these differences.

Simulation base model: no heating behind the canvas

In a possible future situation where a PCM installation is functioning in the Rotonde, the current heating installation behind the canvas will have been removed. However, measured data of the operative temperature and relative humidity in the Rotonde of this situation are not available, so a

simulation is used to estimate the indoor climate in this alternative situation without the specific heating installation. This version of the model without heating will be referred to as the base model for further simulations. The base model is created by removing the radiator heating from the zone 'middle block: behind the canvas' from the HVAC system in the model of the current situation in DesignBuilder. A simulation is run according to "Input and settings" on page 64 and the results from the simulations of the current situation model with heating and the base model without heating are shown in Fig. 53 and

As expected, during the winter season the daily average values for the operative temperatures are lower and the relative humidity are higher, because there is less heating capacity in the Rotonde. There is still a floor heating installation active in the sand layer of the Belvedere, but the capacity of this installation is not large enough to impact the

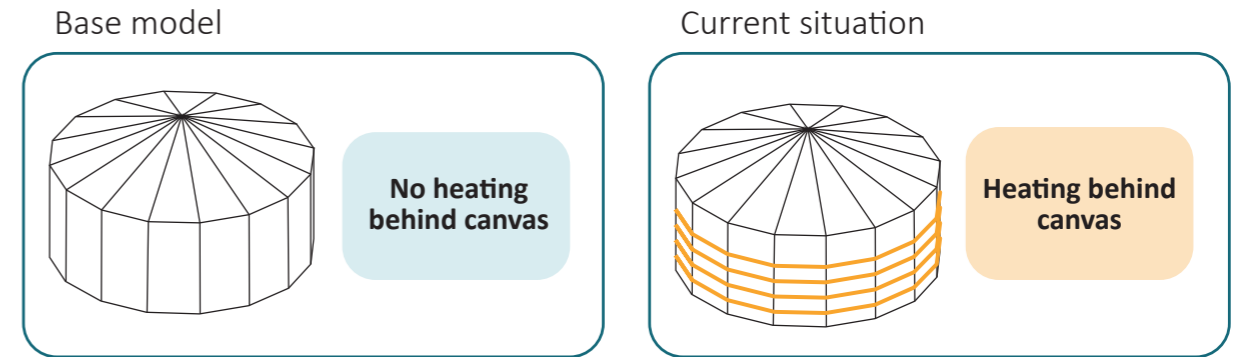


Fig. 52. Characteristics of the base model and current situation model (source: own).

temperature throughout the whole Rotonde. The simulation results of the operative temperature during the winter season seem realistic, because they are comparable to measured operative temperatures in April 2022, when a heating installation failure left the Rotonde unheated for two days. During these days the outdoor temperature was between 5 to 10 °C and the indoor operative temperature behind the canvas stabilized around 9 to 10 °C while all heating installations were down, including the floor heating, heating installation behind the canvas and the heating installation in the HVAC system. Graphs of this measured data is given in appendix B. For this reason an average temperature of 12 °C during the winter season is expectable when

the HVAC and floor heating in the Rotonde are functional, because it is higher than a situation without any heating, but lower than a situation with heating behind the canvas.

An interesting conclusion that can be drawn from the difference between the yearly fluctuation indicators is that the indoor climate in a model with less heating installations is more consistent than the current situation with a heating installation behind the canvas. The explanation for this is that the heating installations follow a setpoint during opening hours of the museum, given in Table 3 and during these hours the temperature can rise quickly and the relative humidity reacts to this by decreasing. During the night the heating installation follow a

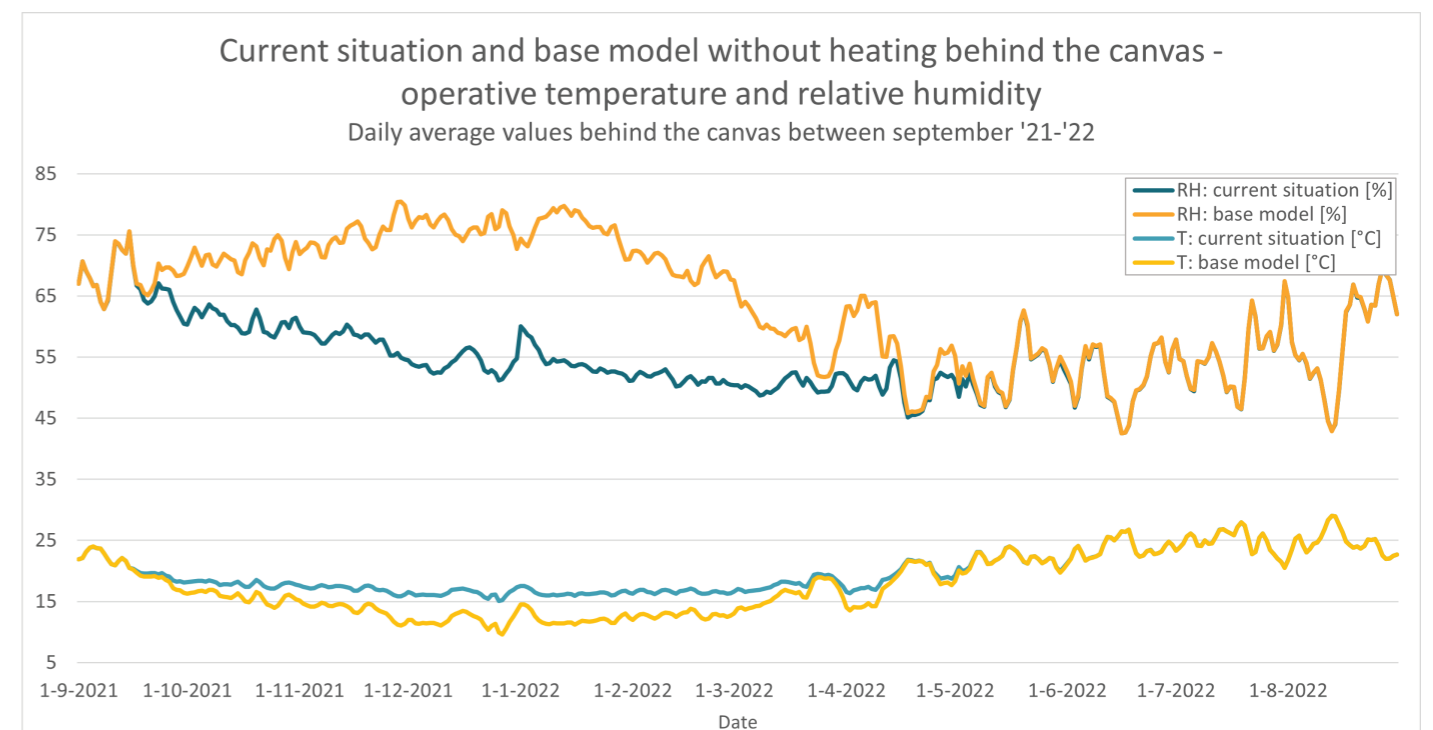


Fig. 53. Graph of the daily average operative temperature and relative humidity in the space behind the canvas from simulations of the current situation model with heating and the base model without heating (source: own).

Yearly indoor climate fluctuation indicators: average behind the canvas	Behind the canvas		
	Current situation model	Base model	Difference of base model to current situation model
Minimum RH [%]	37.4	37.5	0.1
Maximum RH [%]	78.3	81.8	3.5
Minimum T [°C]	12.6	9.2	-3.4
Maximum T [°C]	30.5	30.6	0.1
Days per year of RH fluctuation > 10 %/24hr	257	71	-186
Maximum RH fluctuation [%/24hr]	18.8	17.7	-1.1
Days per year of T fluctuation > 5 °C/24hr	0	0	0
Maximum T fluctuation [°C/24hr]	4.88	4.6	-0.3
Days per year of T fluctuation > 3 °C/24hr	197	62	-135

Table 18. Yearly indoor climate fluctuation indicators from simulations of the current situation model and base model and their differences (source: own).

lower setpoint and the temperatures decreases again while the relative humidity rises, which creates large daily fluctuations.

In Table 18 the differences of the fluctuation indicators are given and seven out of nine indicators show a more consistent indoor climate from the base model simulations. However, the yearly indoor climate of the base model without additional installations is not preferred over the current situation, because the daily average temperature and relative humidity values of the base model are less compliant with the climate class C by ASHRAE (2019) than the current situation. The results of a base model simulation seem realistic and this version of the model will be used as a base for implementation of the PCM designs.

Step 4. Inserting PCM panels in DesignBuilder

To test the impact of the PCM designs, the different PCM materials are inserted into the base model. It is essential that the base of the model is similar in all versions with different PCMs to ensure representative data that can be used for a comparative analysis of the indoor climate.

First, partitions are inserted in a copy of the base model that will represent the PCM panel system of the preliminary design. The partitions are located

parallel to the interior side of the façade on a distance of 100 mm from the façade to ensure air flow in the zones between the façade and the partitions.

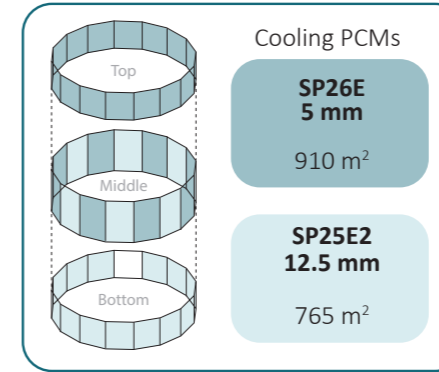
Secondly, holes are inserted into the partitions that represent the 50 mm spacing between two panels. This ensures air flow between the zone between the façade and the partitions and the zone between the partition and the canvas. Then, multiple copies of this version of the model are made and per copy the material properties of the PCM panels are assigned per design option. ... gives an overview of the different design options that are simulated and what PCM is assigned in the top, middle and bottom zone. The material properties per PCM type are given in appendix G and the defined optimal and maximum thickness is used (Table 16).

In design option one and three the panels in the middle zone with different types are not distributed vertically, as is defined in the preliminary design, but horizontally. This is done because the simulation in DesignBuilder follows the average values within a zone, so there is no vertical temperature distribution within a zone. For this reason placing the different PCMs above each other will not show deviating results from a horizontal distribution.

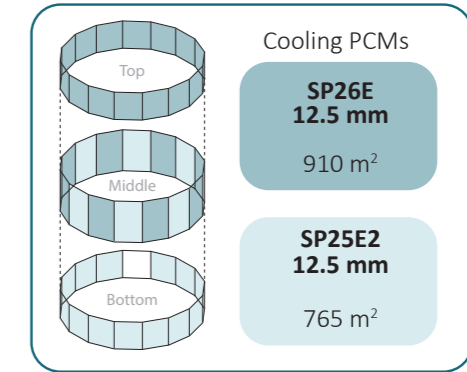
Furthermore, some setting of ‘Model options’ in the paragraph ‘Input and settings’ on page 66 are changed for simulation with PCMs.

COOLING

Design Option 1.1

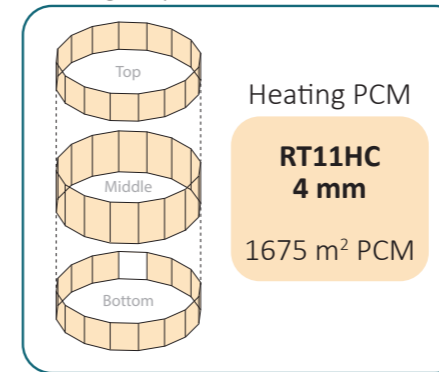


Design Option 1.2

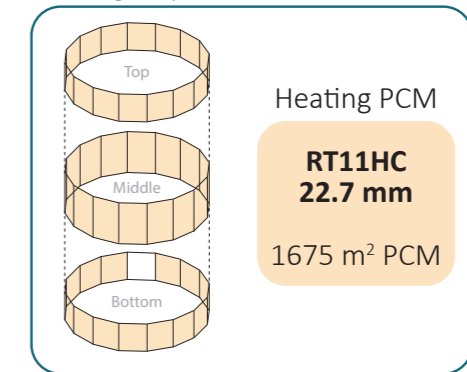


HEATING

Design Option 2.1

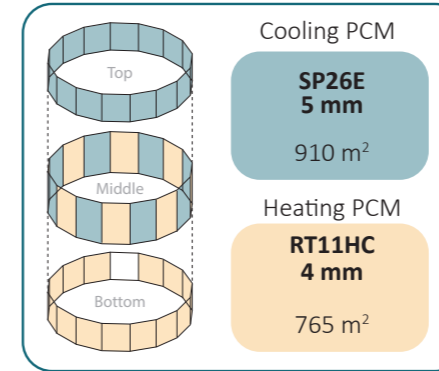


Design Option 2.2



COMBINATION

Design Option 3.1



Design Option 3.2

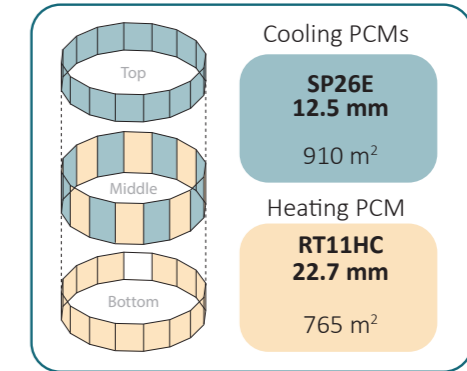


Fig. 54. PCM panel design options with the assigned PCM per zone in the DesignBuilder model (source: own).

3. Simulation tab

- Solution algorithm: ‘2-Finite Difference’

Step 5. Simulation results

Six simulations of the different design options (Fig. 54) are run according to paragraph “Step 4. Inserting PCM panels in DesignBuilder” on page 70 and the results are given in appendix H with graphs of the daily average operative temperature and relative humidity and tables of yearly indoor climate fluctuation indicators. To compare the effectiveness of the design options on the indoor climate, the differences between the simulation results are defined. The differences are only defined for the average values in the zone behind the canvas, because this value is most representative for the climate around the canvas. In appendix H also results of other zones are given. The differences of the simulated indoor climate are discussed per season, so the impact of heating PCMs on the indoor climate during the winter and the impact of cooling PCM during the summer.

Comparing simulation results: winter season

The winter season is commonly dominated by heating demand while autumn and spring have a lower demand of heating. The impact of the PCMs on the operative temperature in the space behind the canvas from autumn until spring are given in Fig. 55. As mentioned in the chapter C: ‘Base model: no heating behind the canvas’, there is a substantial difference between the operative temperature of the current version and the base model without heating installation on the façade. This graph shows that all the PCM design options increase the operative temperature compared to the base model, but no PCM type is able to match the temperatures of the current situation with heating installation.

In the graph it is also clear that there is a minimal difference of the operative temperatures between the PCM design options with varying thicknesses. This shows that the equation used for defining the optimal thickness for the PCM, presented in Fig. 44, is accurate and a larger thickness does not result in substantially more efficient PCM panels at this location.

Furthermore, the most relevant finding that can be seen in the results of operative temperatures is that there is a minimal difference between heating PCMs and cooling PCMs. This could suggest that the heating PCMs have a minimal impact and the effect that is seen for all design options is related to the insulating capacity of a PCM panel. An assumption is that any panel, with or without a PCM, increases the insulation of the façade and therefore higher temperatures are reached during the winter. Also, with this insulating layer on the façade, the radiative heat transfer from the facade is lower to the space and the canvas itself.

When comparing the relative humidity results of simulations without PCM or heating to the simulations with PCM implemented, it is clear that the PCMs decrease the relative humidity substantially, on some days with approximately 15% compared to the base model without heating. This is a positive outcome, because it is expected for the relative humidity to reach high levels outside the climate class C ranges without heating.

The month January is used as a representative month for an in depth view on the average daily behavior of the indoor climate. In Table 19 the differences in the daily indoor climate of the January are given and the values in green show that the difference is a positive effect on the indoor climate. These results show that all PCM installations have a positive effect on the daily fluctuations in January when compared to the situation with the current heating installation. This shows that PCMs can increase the quality of the indoor climate during the winter by decreasing fluctuations in relative humidity and operative temperature.

However, any of the PCM designs is not able to reach the temperature of the current situation of 16 °C. This is most likely not because of a low capacity of the PCM, but the low heat gain in the space during the winter. A PCM is not providing additional heat to the space, but spreading out the release of the heat over a longer period and therefore an average operative temperature that matches the current situation with a heating installation is not realistic.

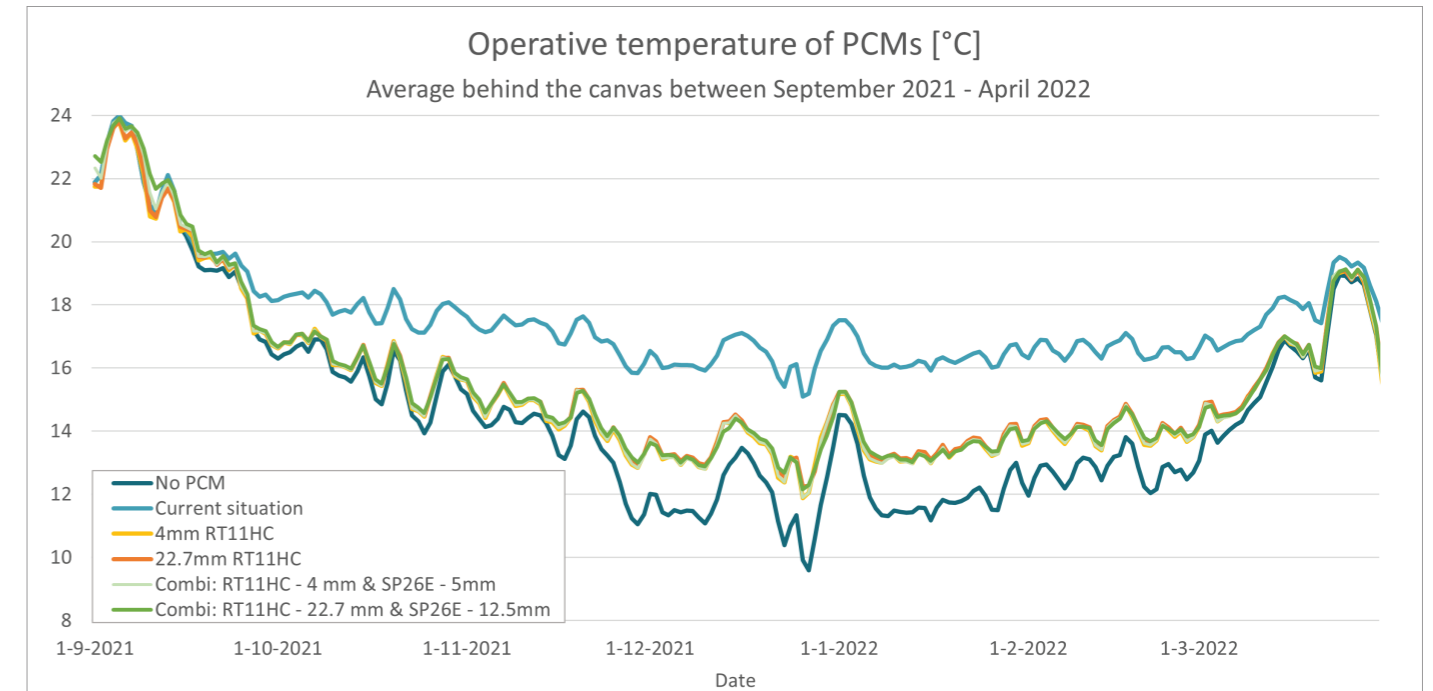


Fig. 55. Graph of the daily average operative temperature between September 2021 and April 2022 from simulations of heating PCMs (source: own)

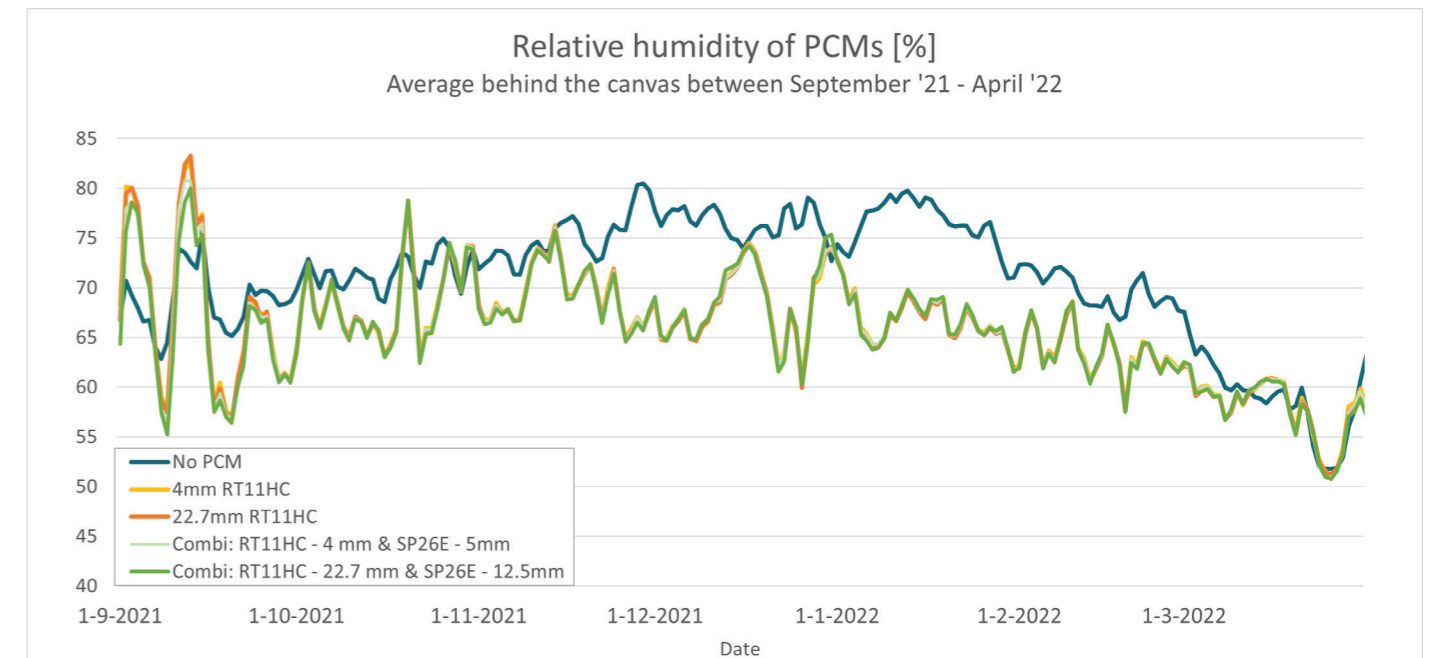


Fig. 56. Graph of the daily average relative humidity between September 2021 and April 2022 from simulations of heating PCMs (source: own)

January: differences daily indoor climate - Current situation with heating (SIM) vs. PCMs	Current situation (SIM)	Heating: RT11HC - 4mm	Heating: RT11HC - 22.7mm	Cooling: SP25E2 - 12.5mm & SP26E - 5mm	Cooling: SP25E2 - 12.5mm & SP26E -	Combi: RT11HC - 22.7 mm & SP26E - 12.5mm	Combi: RT11HC - 4 mm & SP26E - 5mm
Average daily RH fluctuation [%/24h]	15.7	-8.3	-9.2	-8.7	-9.0	-9.0	-8.7
Average daily T fluctuation [°C/24h]	3.6	-1.6	-2.0	-1.8	-1.9	-2.0	-1.9
Average daily RH [%]	54.3	12.6	12.5	12.6	12.5	12.6	12.7
Average daily T [°C]	16.4	-2.8	-2.8	-2.8	-2.8	-2.8	-2.8

Table 19. Differences in daily average operative temperature, relative humidity and fluctuations of the simulation results with PCM compared to the simulation results of the current situation of January (source: own).

From these results it could be stated that the heating PCMs have a minimal effect and are therefore not suitable as a heating system.

Comparing simulation results: summer season

The results of the summer period of the cooling PCM (Fig. 57) show the effect that the PCM have on the indoor temperature in the Rotonde. The temperature shows less fluctuations when within the active range of the PCMs, as expected. The cooling PCMs store the heat in the Rotonde during the day and slowly release the heat when the indoor temperature decreases, showing a temperature curve with a similar average value, but with smaller fluctuations.

However, the cooling PCMs have a negative effect when the indoor temperature is outside the active range of the PCMs. This is most likely caused by the insulating capacities of the PCM panels, as discussed in paragraph “Comparing simulation results: winter season” on page 72. The increased insulating capacity of the façade causes more heat that enters through the skylights to stay within the building increasing the indoor temperature of the

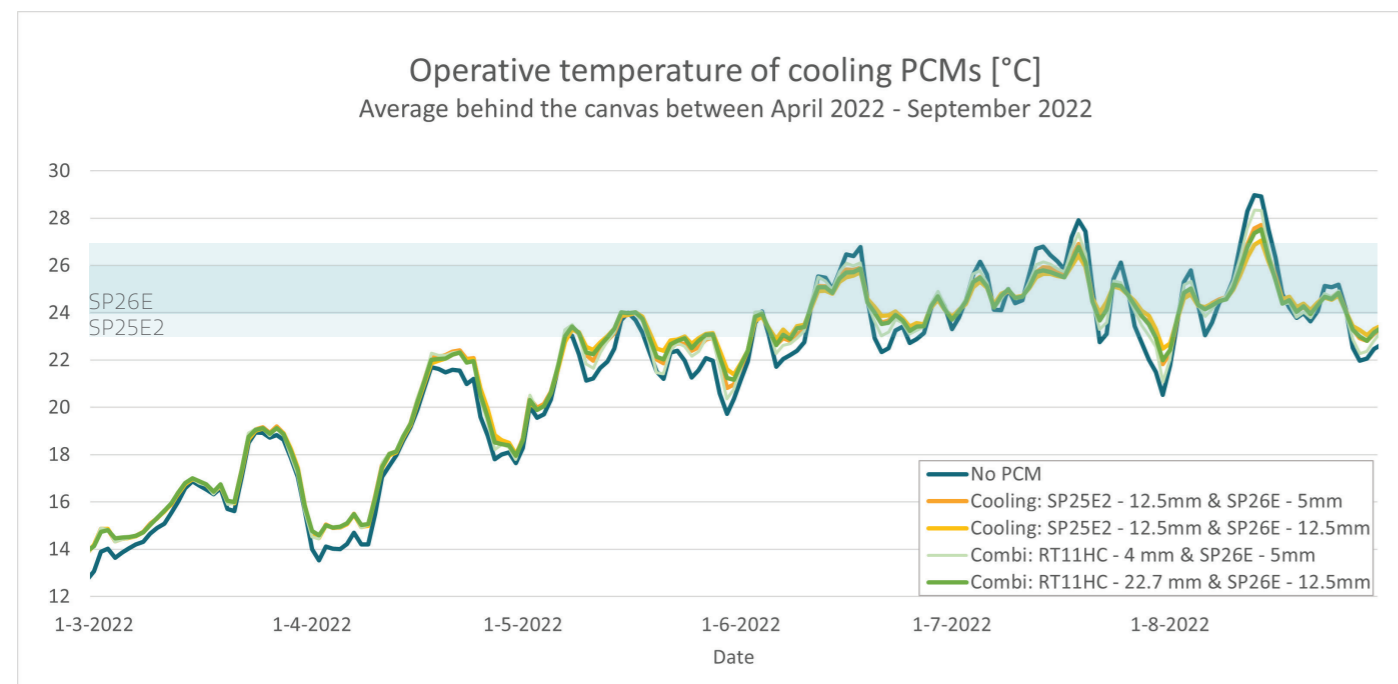


Fig. 57. Graph of the daily average operative temperature between April 2022 and September 2022 from simulations of cooling PCMs (source: own)

Rotonde. This insulating effect is present for all PCM design options.

The effect of the cooling PCMs on the relative humidity (Fig. 58) is as expected when the indoor temperature is outside the active range of the PCM. The indoor temperature is higher than currently, which results in lower relative humidity levels. However, the relative humidity results are not as one would expect when the indoor temperature is within the active range. As mentioned, the temperature shows smaller daily fluctuations and is therefore more stable. A more stable relative humidity is also expected in this situation, however the results show larger daily fluctuations than the current situation. These results are most likely not representative of the expected situation in the Rotonde and it might be related to the less representative simulation of relative humidity in the DesignBuilder model (“Simulation of current situation”, pages 66-68).

Besides, the yearly indoor climate indicators of most PCM options do not show better results than the current situation (Table 20), which means that the indoor climate with the PCM design could pose a risk of damage on the panoramic painting. The indicators of the heating and cooling PCM design options show negative development in indicators

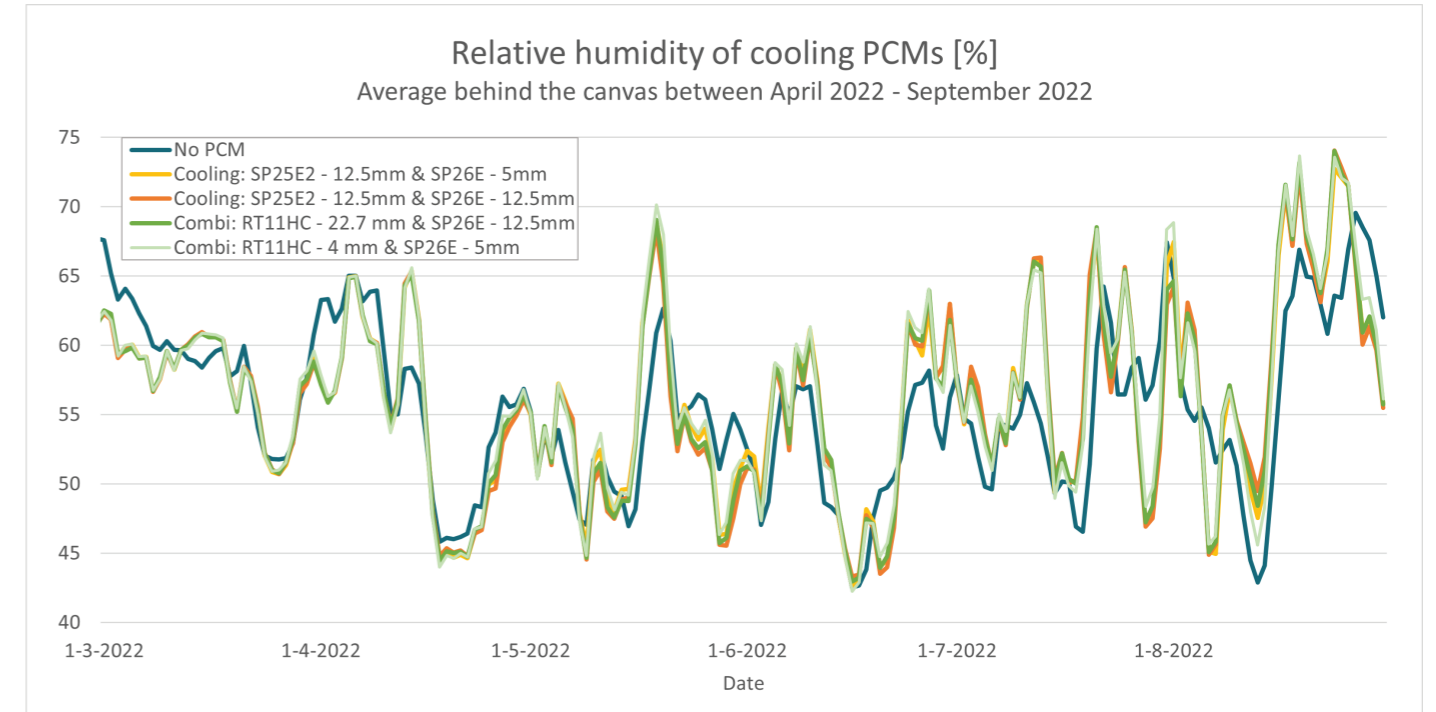


Fig. 58. Graph of the daily average relative humidity between April 2022 and September 2022 from simulations of cooling PCMs (source: own)

Differences of yearly indoor climate indicators: current situation vs PCM design options: average behind the canvas	Behind the canvas						
	Current situation (sim)	Heating: RT11HC - 4mm	Heating: RT11HC - 22.7mm	Cooling: SP25E2 - 12.5mm & SP26E - 5mm	Cooling: SP25E2 - 12.5mm & SP26E - 12.5mm	Combi: RT11HC - 22.7 mm & SP26E - 12.5mm	Combi: RT11HC - 4 mm & SP26E - 5mm
Minimum RH [%]	37.4	-4.3	-3.4	-0.8	0.8	0.0	0.0
Maximum RH [%]	78.3	13.0	12.9	9.9	6.7	0.1	0.1
Minimum T [°C]	12.6	-1.8	-1.2	-2.0	-1.9	-0.1	-0.1
Maximum T [°C]	30.5	1.3	0.9	-0.3	-1.8	0.0	0.0
Days per year of RH fluctuation > 10 %/24hr	257	-52	-87	-114	-131	-1	0
Maximum RH fluctuation [%/24hr]	18.8	12.3	10.8	3.9	2.9	0.2	0.4
Days per year of T fluctuation > 5 °C/24hr	0	64	42	2	0	0	11
Maximum T fluctuation [°C/24hr]	4.9	2.2	1.5	0.2	-0.2	0.0	0.2
Days per year of T fluctuation > 3 °C/24hr	197	-22	-42	-105	-136	-1	0

Table 20. Differences in daily average operative temperature, relative humidity and fluctuations of the simulation results with PCM compared to the simulation results of the current situation of January (source: own).

and the combination PCM options show similar results as the current situation. It seems that the PCMs are not active on a sufficient amount of days per year to have a convincing positive effect on the yearly indoor climate of the Rotonde and for this reason are not advised to be implemented according to any of these designs.

Conclusion

The improvement of the PCM design seems to be dependent on increasing the amount of days that

the PCM system is active. There are multiple options to achieve this effect. The first option would be to choose a cooling PCM with a large active temperature range, so the PCM would be active on more days per year (Fig. 59). The disadvantage of this option is that most days the indoor temperature fluctuation is not large enough to fully charge and discharge the PCM on a daily basis. A consequence of this could for example be that the PCM system is already fully charged on a warm summer day and is not able to store more heat, because the PCM was not able to discharge the heat at night from the day before. This

would decrease the efficiency of the PCM system and is therefore not a preferred option.

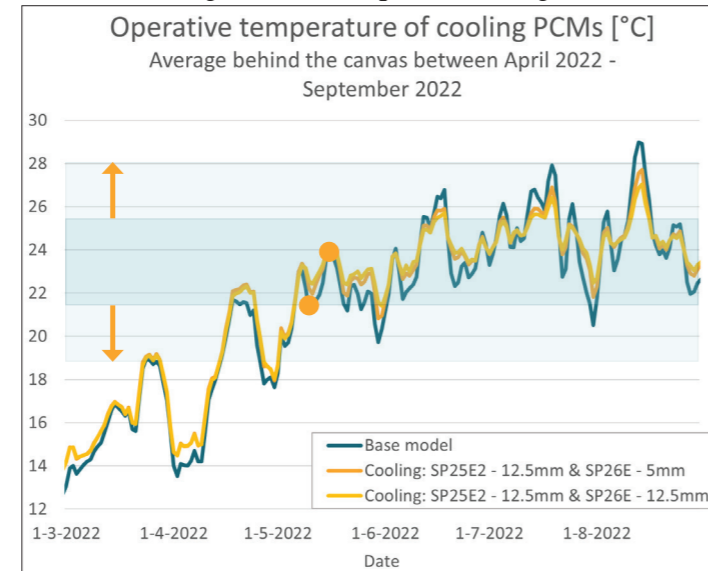
The second option is to apply multiple types of cooling PCM with different active temperature ranges, to enlarge the active PCM range of the total system (Fig. 59). Through this option a part of the PCM system is expected to be active on most summer days. However, the disadvantage is that per day the capacity of the active PCM is decreased to for example 25% when four different PCM types are applied. Therefore the expected effect of this option is minimal and also not a preferred option for implementation in the Rotonde.

The third option lies in increasing the quality of the building envelope of the Rotonde and not the PCM system. If the indoor climate of the Rotonde is more consistent during the summer, the cooling PCM system is expected to be active on more days per year than what the simulation results show. A more consistent indoor climate means that more days per year have a similar average temperature with a similar fluctuation size. The size of the fluctuations do not need to decrease, but should occur within a smaller range (Fig. 59). By realising this, the PCM system is expected to be active more days per year and have a convincingly positive effect on the quality of the indoor climate.

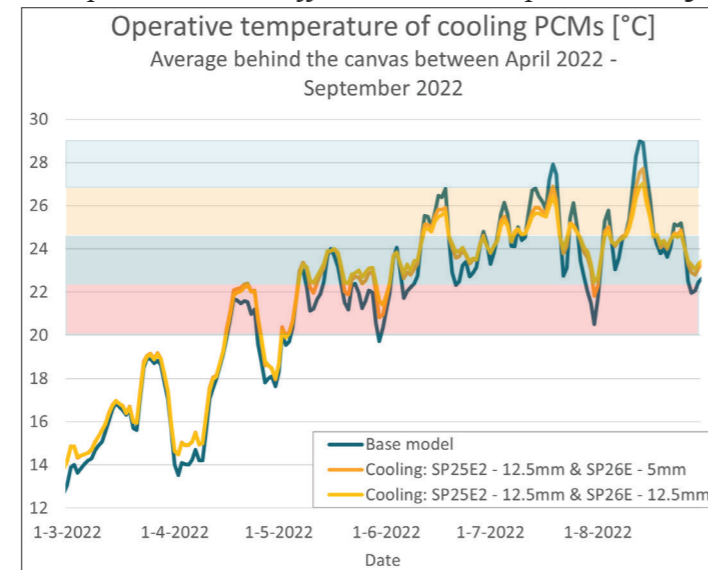
Optimized design

As mentioned previously, the organisation of the museum have considered adding interior insulation to the façade of the Rotonde, but this had a negative effect on the indoor climate in the summer. Also, it is planned to install new glazing for the skylight with a solar block film. These two adjustment to the Rotonde will increase the temperature during warm days, as is stated by NIAG (2022), but it might help to stabilize the indoor climate during the summer, which is beneficial for the efficiency of a PCM installation, because of the more narrow temperature range in the Rotonde. For this reason additional simulations are run of this better insulated situation. One simulation is run of the base model with the

PCM with a larger active temperature range



Multiple PCMs with differemt active temperature range



Increase consistency of daily temperature fluctuations

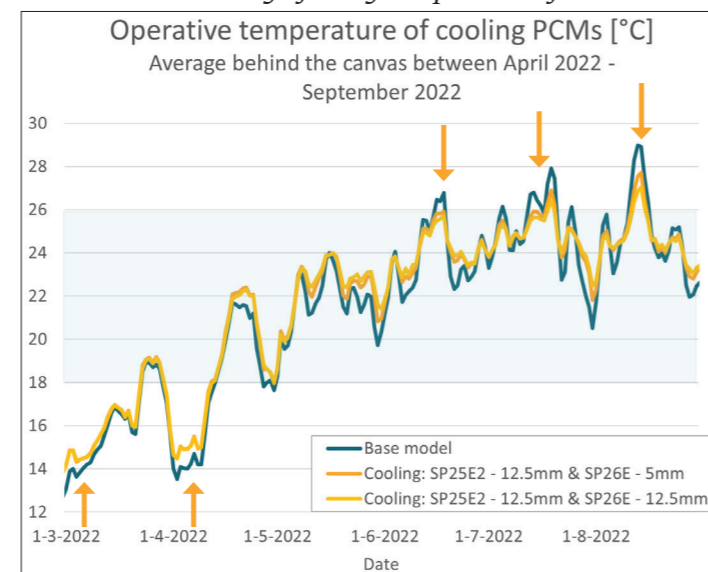


Fig. 59. Options for optimising the efficiency of the PCM system (source: own).

Alternative situation

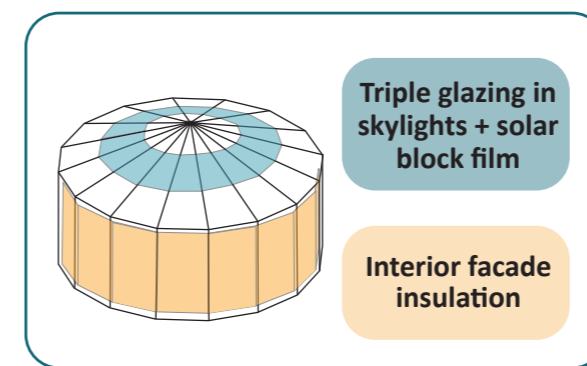


Fig. 60. Characteristics of the alternative situation model (source: own).

proposed interventions, also referred to as the alternative situation, and another simulation is run with a PCM installation is added to this alternative situation (Fig. 60). This simulation will help determine the impact of a PCM installation on the indoor climate in a situation with more consistent indoor temperatures during the summer than what the building currently experiences.

Simulation of the alternative situation

The glazing and insulation type used for the simulation are matched to the suggested interventions by the museum and the technical details of the insulation and new glazing are given in

Table 21 and Table 22. The organisation of the museum has defined that the visual light transmission of any new glazing is preferred to stay as close to the current glazing as possible, so there is no change in daylight exposure on the exhibition. At the same time is it necessary for the total solar transmission to decrease to allow less solar heat to enter the Rotonde.

Since a layer is added to the interior side of the façade in the simulation, the infiltration value of the façade would decrease in the actual building, because of the capacity of PUR foam to fill holes in the existing masonry façade. So, the crack template value in the simulation, which is a value for the infiltration level of an element, is changed from 'poor' to 'medium' (paragraph "Input and settings" on page 66).

The results of the simulation of the alternative situation are shown in Figure 55 and Table 18. From the graph the impact of the insulation and triple glazing is apparent. The operative temperature is stabilized throughout the year, because it is higher during the winter and lower during the summer when compared to the base model, which is a positive outcome. The relative humidity however has not been stabilized and shows even more fluctuations.

Because of the added insulation layer on the façade, the infiltration value has decreased and as a

Glass characteristics	Current glass in the Rotonde	Triple glazing with solar block film
Thermal transmittance [W/m2K]	2,976	1,757
Total solar transmission	0,745	0,358
Visible light transmission	0,798	0,535

Table 21. Characteristics of the current and alternative glazing in the Rotonde (source: own).

Facade layer characteristics	Current facade the Rotonde	Insulated facade
Layer 1	Cement plaster	Cement plaster
Layer 2	350 mm brick masonry	350 mm brick masonry
Layer 3	Cement plaster	Cement plaster
Layer 3	n.a.	50 mm polyurethane foam
U-value of facade [W/m2K]	1,6	0,4

Table 22. Characteristics of the current and alternative façade of the Rotonde (source: own).

result there is less ventilation. This causes a moisture built up and results in higher values of the relative humidity and more fluctuations, especially during the summer period. However, the yearly climate indicators given in Table 18 shows some positive effect on the consistency of the indoor climate with these additions compared to the current situation. The alternative situation has less days with large relative humidity fluctuations on a yearly basis than

the current situation. Also, the operative temperatures maximum value has decreased and the frequency of small fluctuations has decreased. This suggest a more consistent indoor temperature on a daily basis, however the size and frequency of large fluctuations in temperature has increased. This aligns with the findings of NIAG (2020) and the hypothesis that a more consistent daily behaviour of operative temperature during the summer can be

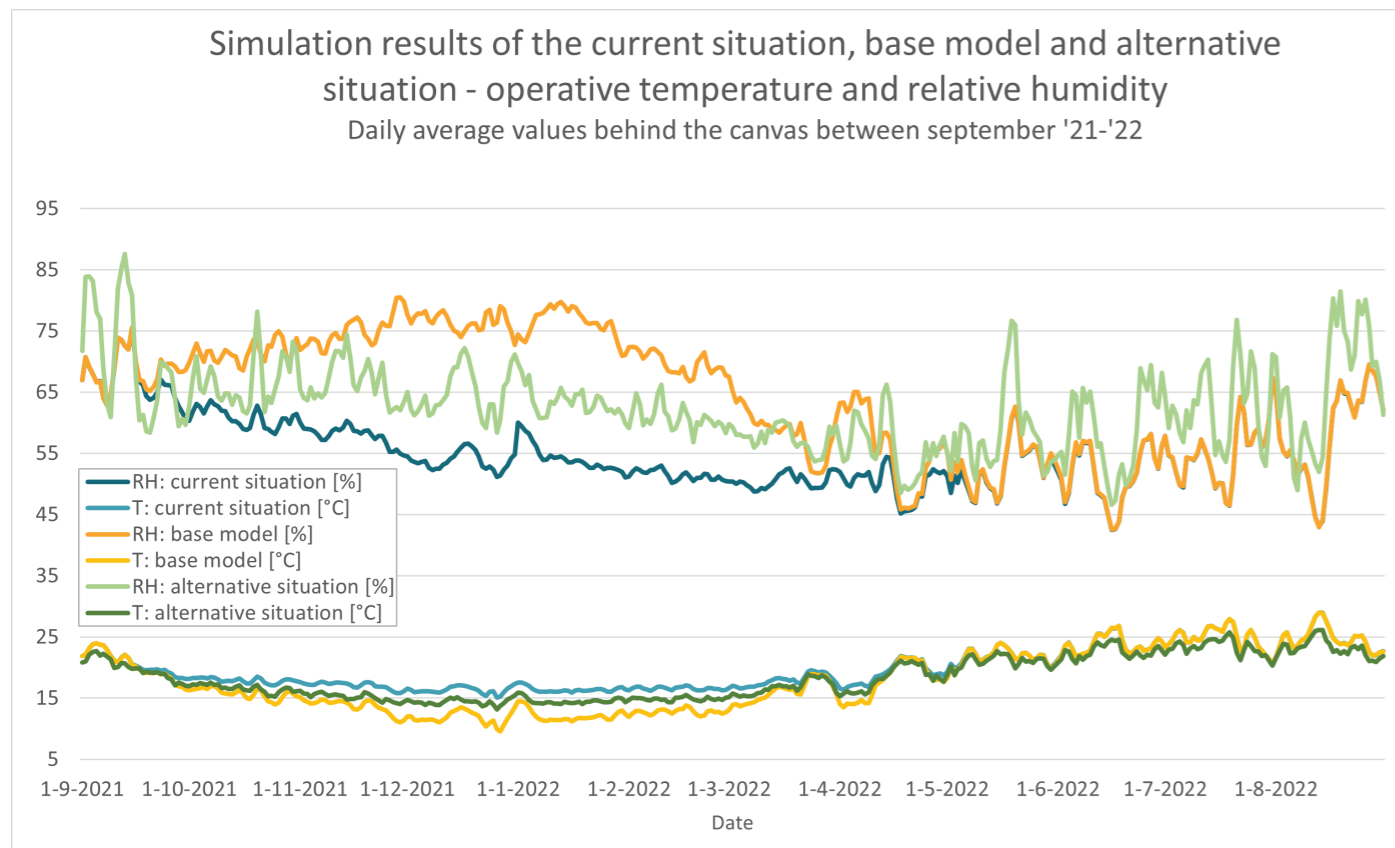


Fig. 61. Simulation results of the current situation, base model and alternative situation of the operative temperature and relative humidity in the space behind the canvas from September 2021 to September 2022 (source: own).

Yearly indoor climate fluctuation indicators: average behind the canvas	Behind the canvas				
	Current situation model	Base model	Alternative situation: insulation and triple glass	Difference of alternative situation to base model	Difference of alternative to current situation
Minimum RH [%]	37.4	37.5	37.3	-0.2	-0.1
Maximum RH [%]	78.3	81.8	97.3	15.5	19.0
Minimum T [°C]	12.6	9.2	11.8	2.6	-0.8
Maximum T [°C]	30.5	30.6	29.4	-1.2	-1.1
Days per year of RH fluctuation > 10 %/2	257	71	234	163	-23
Maximum RH fluctuation [%/24hr]	18.8	17.7	32.4	14.7	13.6
Days per year of T fluctuation > 5 °C/24h	0	0	82	82	82
Maximum T fluctuation [°C/24hr]	4.88	4.6	7.4	2.8	2.5
Days per year of T fluctuation > 3 °C/24h	197	62	180	118	-17

Table 23. Yearly indoor climate fluctuation indicators the simulation results of the current situation, base model and the alternative situation and their differences (source: own).

achieved with insulation and triple glazing in the Rotonde, even though the maximum temperature values have increased.

Simulation of the optimized PCM design

A simulation is run of the alternative situation with a PCM system implemented that is customized to activate during the summer season. From the analysis of the indoor climate of the alternative situation, the optimal melting and freezing temperature and optimal thickness is defined, given in Fig. 62, using the similar process as explained in paragraph “Climate per installation zone” on page 56 and the optimal thickness of 12,5 mm is defined as explained in paragraph “Dimensions of a PCM panel” on page 61. In this situation one PCM type is used for the whole façade and is not divided into a bottom and top zone. The hypothesis of this method is that because the PCM is defined on a representative indoor climate of the whole façade, the PCM will be active more frequently on a daily basis than the PCMs in design options 2 and 3 that were based on the data of specific zones of the façade.

A simulation was run according to paragraph “Input and settings” on page 64 and the results are given in Fig. 63 and Table 24. In the graph the impact of the optimized PCM design on the temperature

during the summer is visible. During summer months the temperature of the situation with the cooling PCM is substantially more consistent than the current and alternative situation, because of less fluctuations. This shows that a cooling PCM system functions efficiently in an indoor climate with more consistent summer temperatures than the current situation. Also, the PCM definition method used for this summer design option could have helped with defining a suitable PCM that is active more frequently and efficiently than previous design options.

Also, the relative humidity of the optimized design simulation shows lower values and smaller fluctuations compared to the alternative situation, especially during the summer season. This shows that the relative humidity react to the more consistent temperatures. Nevertheless, the average daily values of the relative humidity are higher than the current situation, because of the decreased ventilation.

In Table 24 the differences of the yearly indoor climate indicators are given and the green values indicate that the difference is a positive effect on the quality of the indoor climate for preservation of the canvas. When the optimised PCM design fluctuations are compared to the alternative situation, the optimised PCM design has increased the quality of all the indicators. When compared to the current situation almost all indicators show a positive effect of the optimised PCM design, except

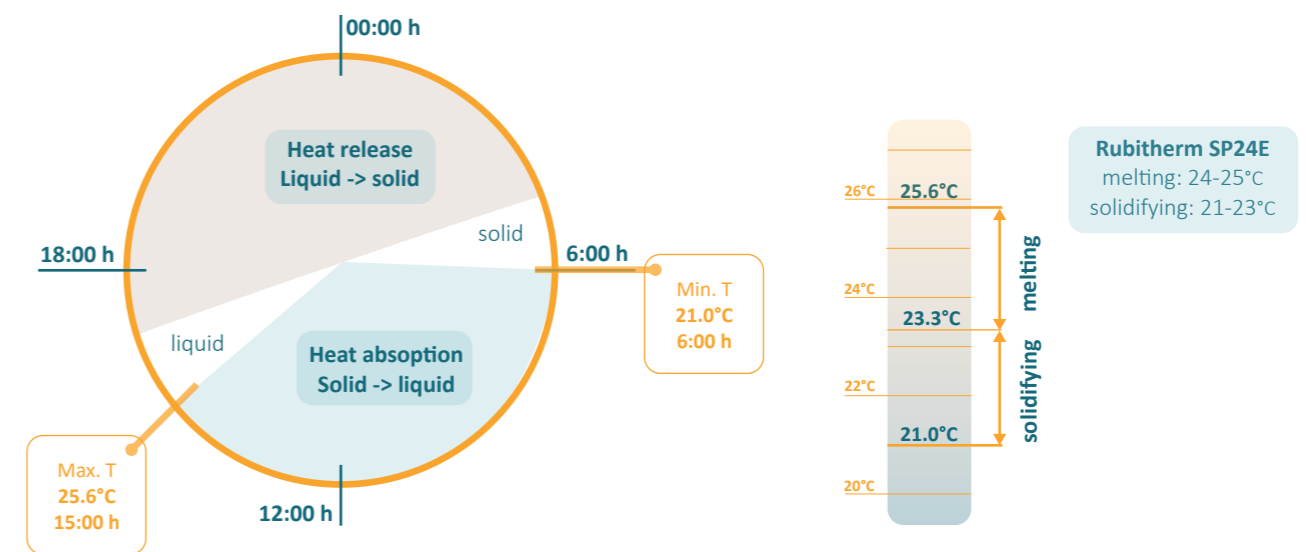


Fig. 62. Daily summer indoor climate profile of the alternative situation and the defined PCM (source: own).

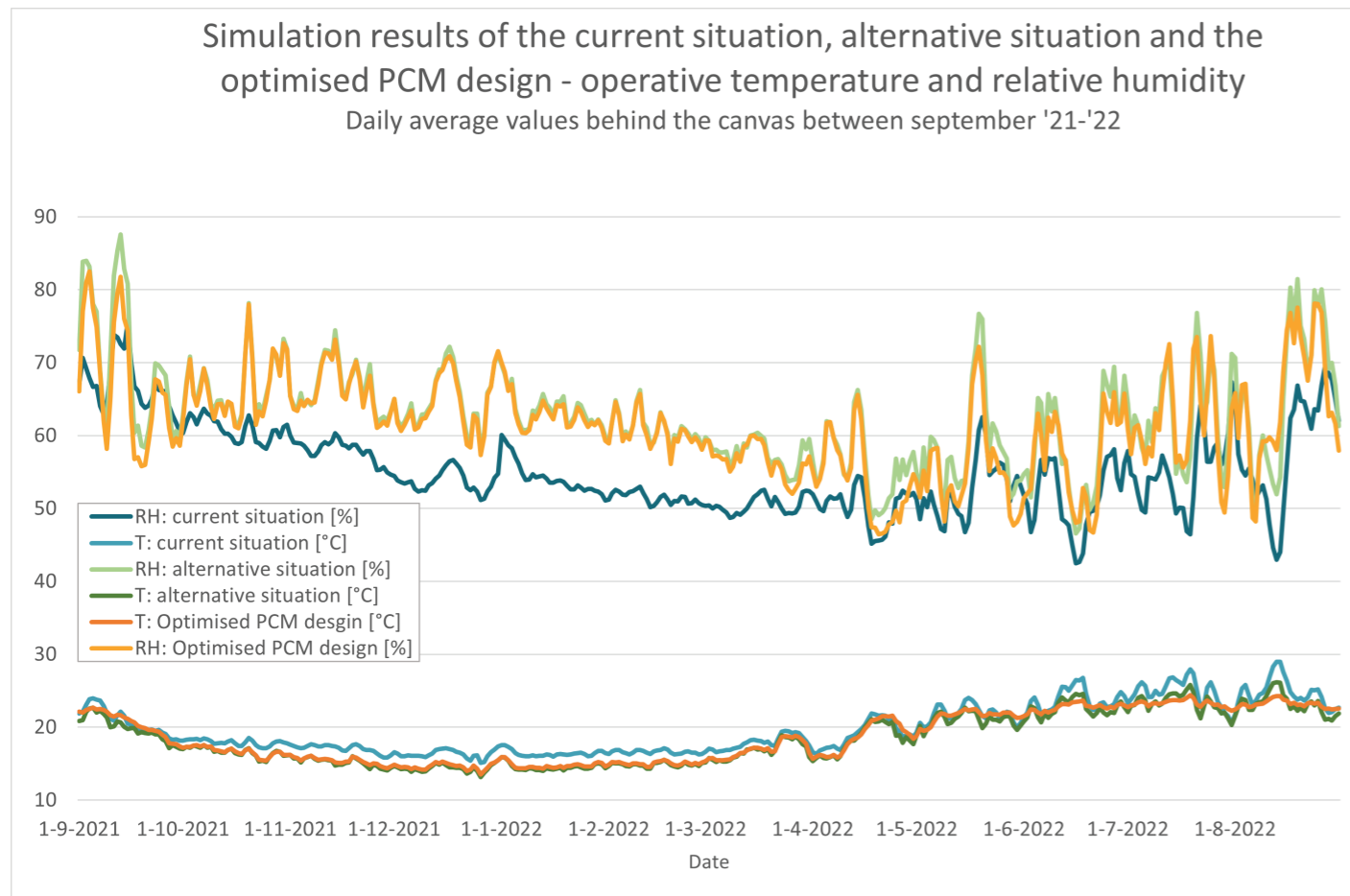


Fig. 63. Simulation results of the current situation and alternative situation and the optimized PCM design of the operative temperature and relative humidity in the space behind the canvas from September 2021 to September 2022 (source: own).

Yearly indoor climate fluctuation indicators and their difference: average behind the canvas	Behind the canvas				
	Current situation	Alternative situation	Optimised PCM design: SP24E	Difference of optimised design to alternative situation	Difference of optimised design to current situation
Minimum RH [%]	37.4	37.3	42.2	4.9	4.8
Maximum RH [%]	78.3	97.3	88.2	-9.1	9.9
Minimum T [°C]	12.6	11.8	12.4	0.6	-0.2
Maximum T [°C]	30.5	29.4	25.7	-3.7	-4.8
Days per year of RH fluctuation > 10 %/24hr	257	234	104	-130	-153
Maximum RH fluctuation [%/24hr]	18.8	32.4	18.8	-13.6	0.0
Days per year of T fluctuation > 5 °C/24hr	0	82	0	-82	0
Maximum T fluctuation [°C/24hr]	4.88	7.4	3.6	-3.8	-1.3
Days per year of T fluctuation > 3 °C/24hr	197	180	13	-167	-184

Table 24. Yearly indoor climate fluctuation indicators of the alternative and current situation and the optimised design and their differences (source: own).

for a higher maximum relative humidity and a lower minimum operative temperature. However, these values are expected, because of the removed heating installation and the decreased ventilation on the model.

However, these values might be neglectable, because the size of the temperature difference is small and the relative humidity simulations are not entirely representative of the measured data, which is discussed in Step 3. B: Simulation of current situation. This means that the combination of insulating the façade, replacing the skylight with triple glazing and implementing cooling PCM panels in the Rotonde, can result in an indoor climate that has a lower heating and cooling demand while also increasing the quality of the indoor climate for the preservation of the canvas.

Estimated indoor climate

The simulation results of the optimised PCM design are translated to the measured data, to create an estimated indoor climate of the Rotonde with the implementation of the optimised PCM design. This is done by multiplying the measured data with the differences in percentage between the simulation of the current situation and the optimised PCM design. With this estimated indoor climate it can be defined if the indoor climate of the optimised PCM design complies with climate class C and the requirements by the museum.

Also, with these results the decrease of heating and cooling demand can be estimated and the financial consequences can be determined. However, the estimated indoor climate of the optimised PCM design is not an accurate display of the actual indoor climate, because of the slight differences in indoor temperatures between what is measured and simulated. The effect of the PCM is defined based on the simulation indoor temperatures, but the PCM would react differently in the actual building.

Also, the measured data contains unrepresentative days, such as the heating installation failure in April 2022, which was not

simulated and therefore is the estimated indoor climate not accurate on these days.

The estimated annual operative temperature of the final PCM design is given in Fig. 64. The temperatures during the summer months show substantially lower values and smaller fluctuations compared to the current situation and the temperature of the final design does not exceed the maximum range of 25 °C on majority of summer days. This shows the impact a PCM cooling system in combination with triple glazing skylight can have on the indoor climate of the Rotonde. The estimated indoor climate of the final PCM design does not comply with the temperature requirements of climate class C, however it is a significant improvement compared to the current situation.

During the winter the temperature is lower than the current situation, because of the removed heating installation. However, the insulation and PCM panel have decreased the heating demand substantially, which is shown in Fig. 64. Without any heating installation the indoor climate of final PCM does comply with the climate class C temperature requirements during the winter.

The estimated annual relative humidity of the final PCM design is presented in Fig. 65. During the summer months the average value of the estimated indoor climate is increased compared to the current situation and follows the optimal curve more closely.

However, during the winter months the relative humidity has increased compared to the current situation and this is a negative development, since the measured values are already higher than the optimal curve. This rise in relative humidity in the final PCM design indoor climate is most likely caused by the low average temperature. An additional heating installation could decrease this effect by increasing indoor temperature or a moisture buffering system.

The yearly indoor climate fluctuation indicators are given of the measured data and the estimated indoor climate of the final PCM design in . These indicators portray the outer limits of the relative humidity and the operative temperature and the size and frequency

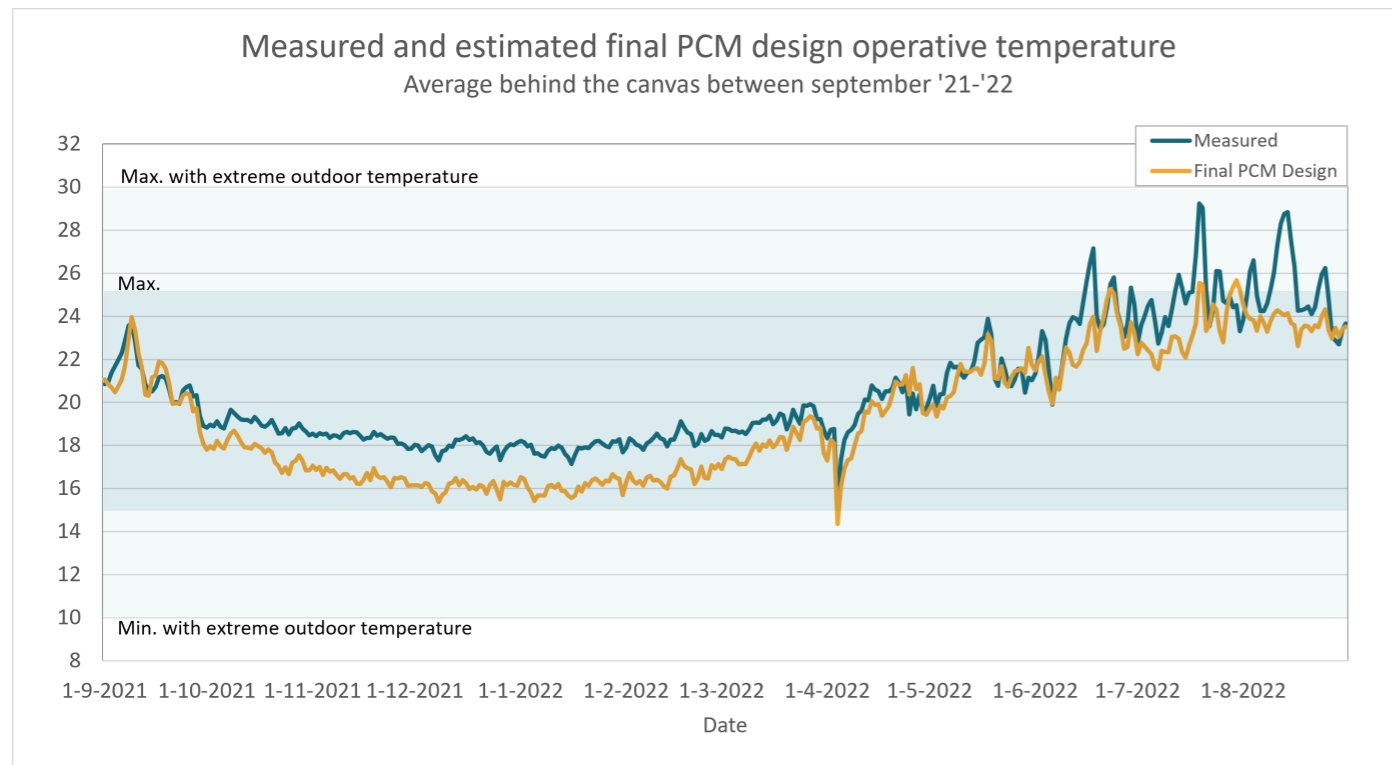


Fig. 64. The measured and estimated of the final PCM design operative temperature in the space behind the canvas between September 2021 and September 2022 (source: own).

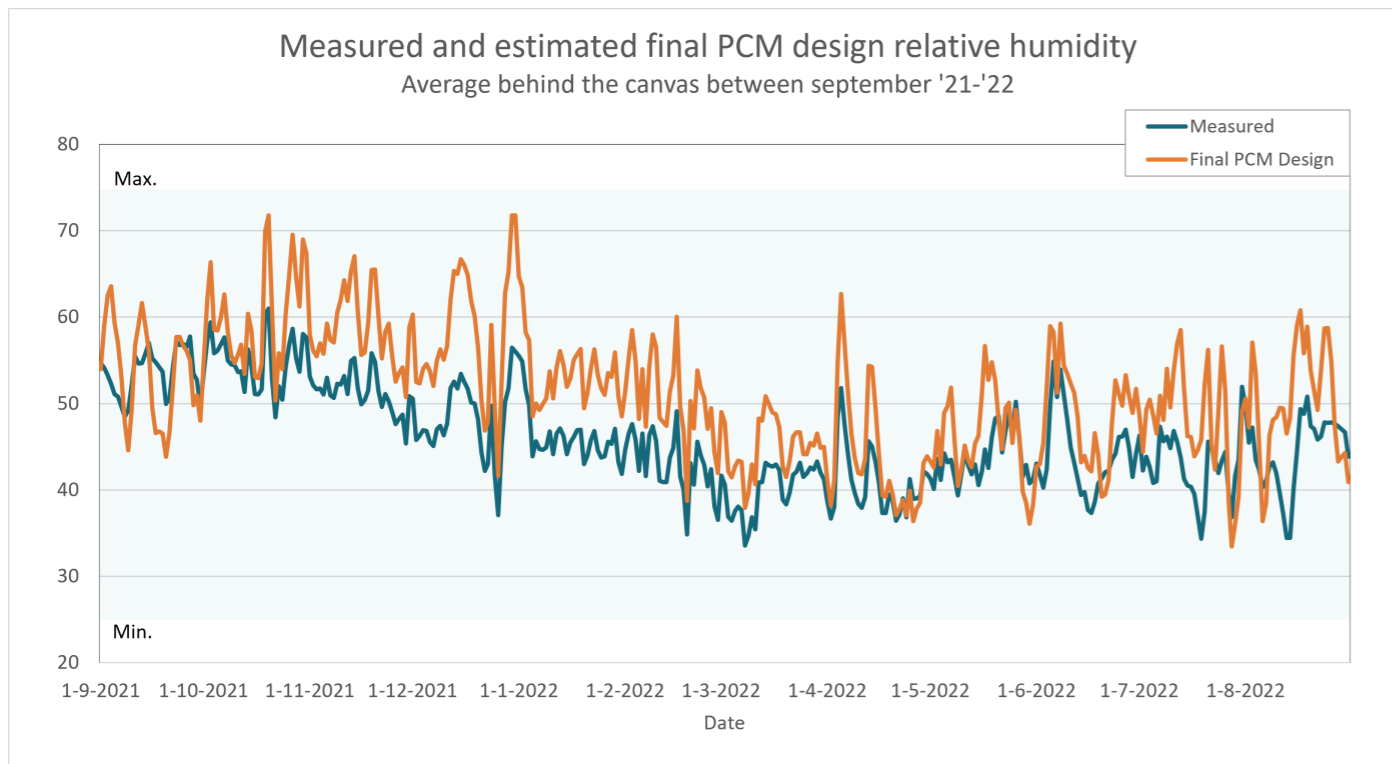


Fig. 65. The measured and estimated of the final PCM design relative humidity in the space behind the canvas between September 2021 and September 2022 (source: own).

of their fluctuations. More indicators of the final PCM design indoor climate comply with the requirements of the intended indoor climate compared to the measured data or have improved. This means that less and smaller fluctuations occur and that some outer limits have moved towards the optimal value. Therefore, according to the indicators, the final PCM design can be applied without an increased risk of damaging the panoramic canvas. It could be argued that the indoor climate of the final PCM design poses less damage risks on the canvas, because the estimated indoor climate is more consistent than the current situation.

Simulations with climate reference data

Previous simulations in this research were conducted with measured data from the years 2021 and 2022 (“Input and settings” on page 64.), but this climate data might not be representative of others climate years of the Netherlands. To account for these differences climate data of a representative year is used according to (NEN 5060:2018+A1:2021, 2021)

for the hourly weather data of a simulation of the current situation (“Simulation of current situation” on page 66) and the final optimised PCM design (“Simulation of the optimized PCM design” on page 79).

The results of the simulations are presented in Fig. 66 and Fig. 67. The optimised PCM design is able to decrease the temperature peaks during the summer with approximately 2 degrees, while not increasing the temperatures on days where the indoor temperature is not within the active range of the PCM. Both the results of the current and optimised PCM design simulation show that the temperature during the winter months reaches levels below the minimum temperature of 15 °C. However, as is discussed in paragraph ‘ref’ are the simulated winter temperatures approximately 1 °C lower than measured and the relative humidity are less representative.

The results of the relative humidity simulation with the reference climate data show that the levels of the optimized PCM design exceed the maximum range of 75% during the summer months while the current situation simulation reaches levels above 70%. However, measurements

Yearly indoor climate fluctuation indicators: average behind the canvas	Behind the canvas		
	Measured	Estimate of final PCM Design	Required indoor climate
Minimum RH [%]	29.0	32.7	25
Maximum RH [%]	63.7	71.8	75
Minimum T [°C]	14.3	14.1	10
Maximum T [°C]	32.2	27.1	30
Days per year of RH fluctuation > 10 %/24hr	36	14.6	0
Maximum RH fluctuation [%/24hr]	16.6	16.6	10
Days per year of T fluctuation > 5 °C/24hr	16	0	0
Maximum T fluctuation [°C/24hr]	6.2	4.6	5
Days per year of T fluctuation > 3 °C/24hr	116	7.7	n.a.

Complies with intended indoor climate		
No, but improved	No	Yes

Table 25. Yearly indoor climate fluctuation indicators of the measured, estimated indoor climate of the final PCM design and the required indoor climate (source: own).

(Appendix B) show levels below 50% during the summer months. This means that the measured outdoor data of 2021 and 2021 is not representative of the general climate data in the Netherlands or the relative humidity simulations are not representative.

The yearly indoor climate indicators (Table 26) show that both situations do not meet the required climate indicators. However, the optimised

PCM design is an improvement for the indicators and is for that reason the preferred indoor climate for preservation of the panoramic painting.

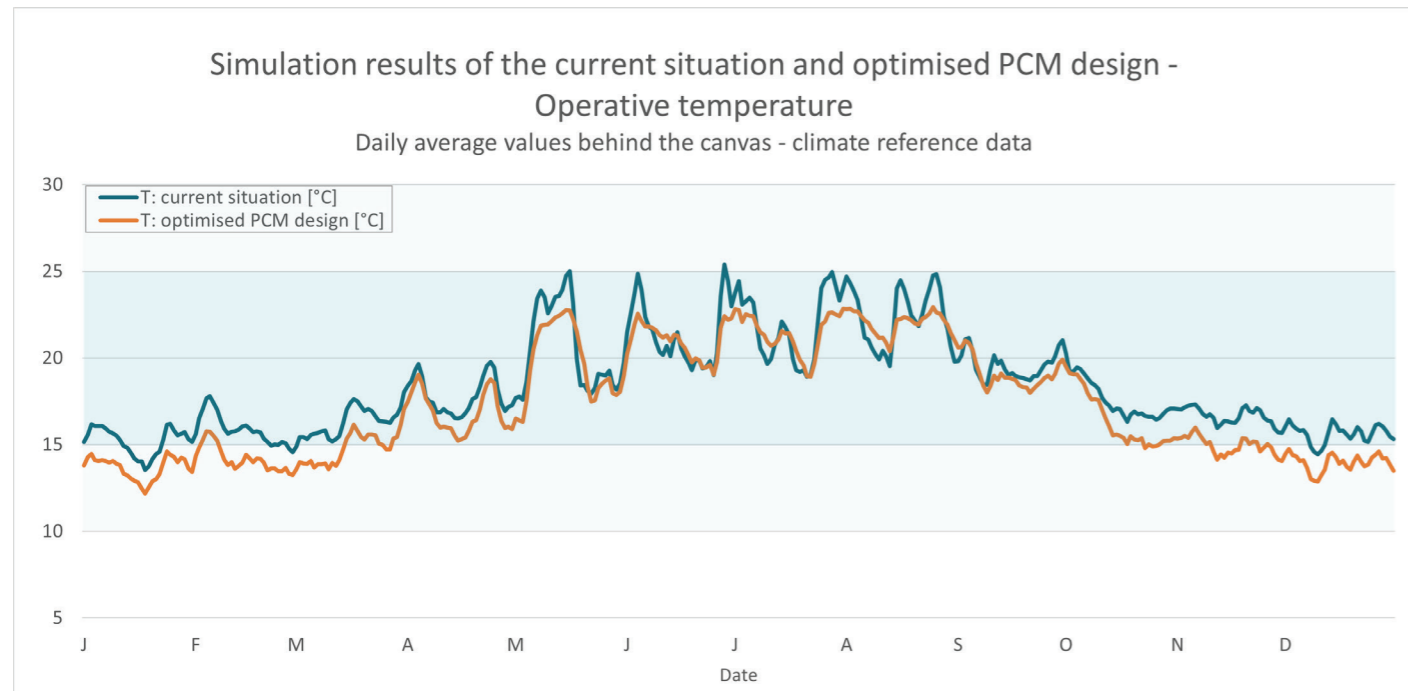


Fig. 66. Simulation results of the current situation and the optimized PCM design of the operative temperature in the space behind the canvas with climate reference data (source: own).

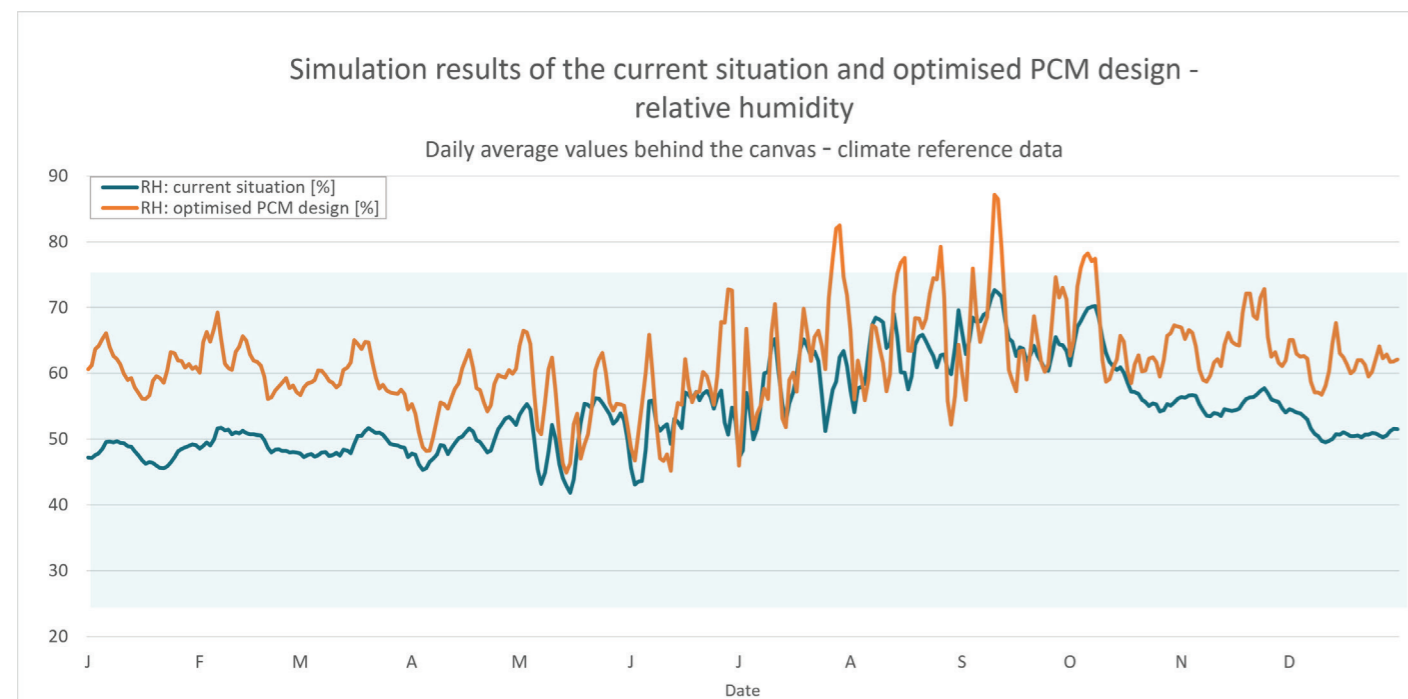


Fig. 67. Simulation results of the current situation and the optimized PCM design of the relative humidity in the space behind the canvas with climate reference data (source: own).

Yearly indoor climate fluctuation indicators: average behind the canvas - climate reference data	Behind the canvas		
	Current situation	Optimised PCM Design	Required indoor climate
Minimum RH [%]	36	40.3	25
Maximum RH [%]	77.6	95	75
Minimum T [°C]	10.8	10.7	10
Maximum T [°C]	27.1	24.4	30
Days per year of RH fluctuation > 10 %/24hr	257	62	0
Maximum RH fluctuation [%/24hr]	20.5	26	10
Days per year of T fluctuation > 5 °C/24hr	19	0	0
Maximum T fluctuation [°C/24hr]	6.1	4.2	5
Days per year of T fluctuation > 3 °C/24hr	229	21	n.a.

Complies with intended indoor climate		
No, but improved	No	Yes

Table 26. Yearly indoor climate fluctuation indicators of the indoor climate of the current situation and final PCM design with climate reference data and the required indoor climate (source: own).

Energy demand and financial consequences

To get an understanding of the advantage of implementing the final PCM design in the Rotonde of the Panorama Mesdag museum, an estimation is made of the energy consumption and financial consequences. As mentioned in paragraph “Estimated indoor climate” on page 81 the average temperature in January of the current situation with heating is 17,4 °C and without heating this temperature is estimated to be 12,1 °C. This means that the heating installation is able to increase the temperature with 5,3 °C. If in a situation with the final PCM design implemented, the average indoor temperature should also reach 17,4 °C, the heating will have to increase the temperature with 2,7 °C from 14,7 °C. This is a difference of approximately 50% and therefore a simplified estimation is that the heating demand is decreased with 50% with the final PCM design implemented. The decrease in heating demand is most likely even larger, because of the reduced heat loss of the insulated façade and triple glazing. An elaborate heating demand estimation of the final PCM design situation is needed for a more accurate estimation on heating

demand decrease and financial consequences and could be conducted in further research.

Currently the annual demand for heating of the Rotonde is 400.000 kWh, which costs €76.000,- with the current gas prices, given in appendix I. If the heating demand is lowered by implementing the final PCM design, with 50% to 200.000 kWh, the annual price is approximately €35.500,-, if a similar heating installation is installed with comparable efficiency. However, currently there are more efficient heating installations on the market that could also use an alternative sustainable heat source, instead of a gas fueled boiler.

Table 27 presents the material costs of the final PCM design, including PCM, insulation and triple glazing prices. This table also mentions the number of years the final PCM design will need to function before it earns back the material investments, which is currently more than 6 years. This actual number is most likely lower than, because of larger energy demand as mentioned before and optimization of the final PCM design. With the optimization of the final PCM design the PCM thickness and the efficient amount of square meters of panels could be decreased.

PCM	Price of Rubitherm SP24E [€/kg]*	€ 5
	Weight of PCM in final design [kg]	33500
	Total price of PCM	€ 167,500
INSULATION	Price of insulation (PUR foam) [€/m2]**	€ 25
	Area of insulation in final design [m2]	1700
	Total price of insulation	€ 42,500
TRIPLE GLAZING	Price of triple glazing [€/m2]***	€ 110
	Area of triple glazing in final design [m2]	320
	Total price of triple glazing	€ 35,200
CONTAINMENT & SUPPORTING SYSTEM	Price of PCM containment & supporting system [€/m2]	t.b.d.
	Area of containment & supporting system [m2]	t.b.d.
	Total price of containment & supporting system	t.b.d.
TOTAL	Total price of materials for final design [€]	€ 245,200
	Decrease of annual energy costs [€]	€ 35,500
	Years to earn back material investments	6.9

Table 27. Material costs of the final PCM design (sources: * (Sharma, Sellami, Tahir, Mallick, & Bhakar, 2021), ** (Homedeal, 2022), *** (Hage, 2020).

Alternative system: basalt packed bed

An alternative thermal buffering system is simulated in DesignBuilder which is also a promising option (Table 10): a basalt packed bed as an underground system in the Rotonde. The system is modelled according to paragraph “Underground Storage” on page 44 with the base setting explained in paragraph “Input and settings” on page 64. The following adaptations are done to the ‘base model’ to represent the basalt packed bed system.

Inside convective algorithm: 2-Simple

This algorithm ‘2-simple’ gives an convective heat transfer of 3.1 W/(m2K), which is too high, because 1.7 W/(m2K) is representative for a packed bed. For this reason is the surface decreased with factor 0.55 to lower heat transfer. Also, the effective thickness is increased from 0.01675 m to 0.061 m to ensure a similar volume of packed bed installation.

Internal thermal mass: zone rotonde
Surface: 9,900 m2

Basalt packed bed:
Thickness: 0.061 m

Material properties
Specific heat: 800 J/kgK
Density: 3000 kg/m3
Thermal absorptance (emissivity): 0.001

The results of the simulation are presented in Fig. 68 and Fig. 69. The results of the operative temperature show that the packed bed system is able to reduce the daily fluctuation sizes during the summer, but the cooling effect is not as promising as the optimised PCM design. The packed bed however does show promising results in terms of heating during the winter, when compared to the temperatures of the base model. This shows that the basalt packed-bed installation is a promising option for heating, when combined with other interventions, such as façade insulation.

The relative humidity results of the packed bed simulation diverge from the other options. It seems that the packed bed increases the relative humidity substantially while it has a minimal effect

on the indoor temperature, so this effect is not expected. Further research is needed to seek the source of the diverging relative humidity values during the summer to define the reliability of the simulation results.

The yearly indoor climate indicators show improvements in temperature and relative humidity fluctuations compared to the current situation (Table 28). This means that applying the basalt packed bed system could be beneficial for the

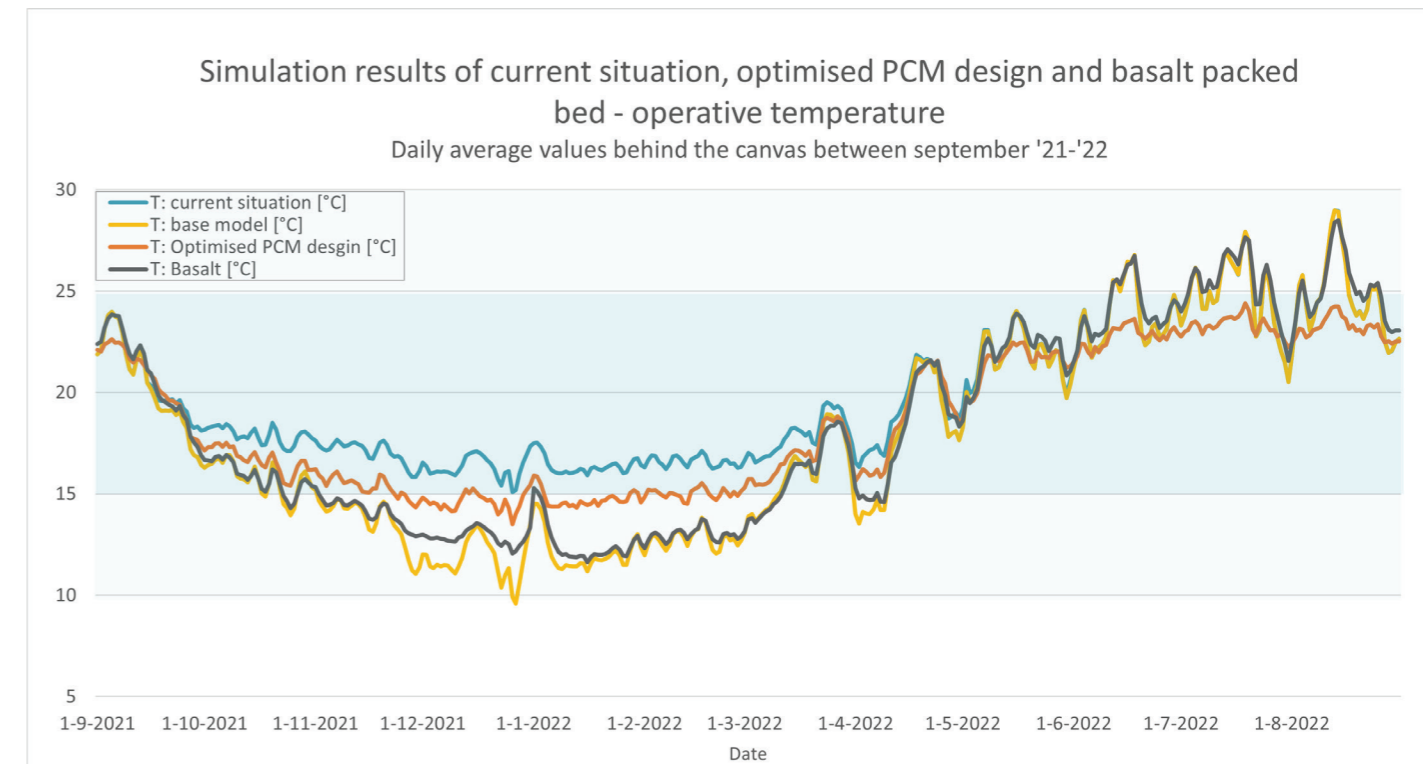


Fig. 68. Simulation results of the current situation, base model, the optimized PCM design and basalt packed bed of the operative temperature in the space behind the canvas (source: own).

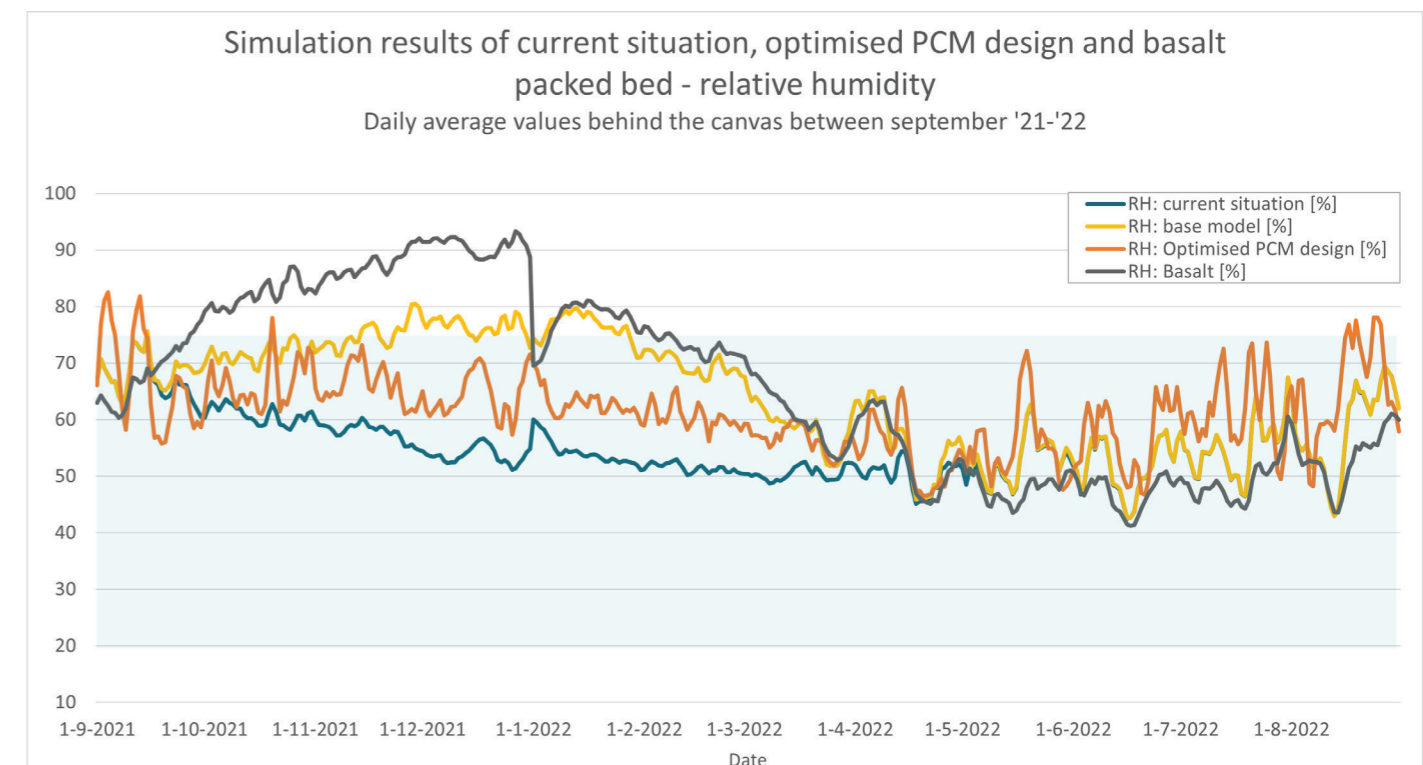


Fig. 69. Simulation results of the current situation, base model, the optimized PCM design and basalt packed bed of the relative humidity in the space behind the canvas (source: own).

preservation of the painting. However, the diverging relative humidity results need to be further examined, because high levels of relative humidity could be damaging to the painting.

Further research is needed to explore the potential of a basalt packed bed installation, because as a sole intervention it does not have a convincing effect. Combining the system with other interventions, such as façade insulation and triple glazing could create an effective passive climate system that ensures preservation of the panoramic painting while also decreasing the energy demand of the building.

Yearly indoor climate fluctuation indicators: average behind the canvas - climate reference data	Behind the canvas		
	Current situation	Basalt packed bed	Required indoor climate
Minimum RH [%]	37.4	38.5	25
Maximum RH [%]	78.3	94.5	75
Minimum T [°C]	12.6	11.4	10
Maximum T [°C]	30.5	29.9	30
Days per year of RH fluctuation > 10 %/24hr	257	0	0
Maximum RH fluctuation [%/24hr]	18.8	7.8	10
Days per year of T fluctuation > 5 °C/24hr	0	0	0
Maximum T fluctuation [°C/24hr]	4.88	3.5	5
Days per year of T fluctuation > 3 °C/24hr	197	14	n.a.

Complies with intended indoor climate		
No, but improved	No	Yes

Table 28. Yearly indoor climate fluctuation indicators of the indoor climate of the current situation and basalt packed bed and the required indoor climate (source: own).

Reference Panorama

This chapter discusses the theoretical application of the final PCM design in the reference project Bourbaki Panorama in Luzern, Switzerland. First, an elaboration is given on the reference project including the exhibition, building, installation and the indoor climate. Afterwards, the feasibility of the implementation of the final PCM design in the Bourbaki Panorama will be defined based on building and the indoor climate comparison to the Panorama Mesdag museum.



Fig. 70. photo of the Bourbaki-Panorama building in Luzern, Switzerland (Kümmerli, 2017)

Bourbaki Panorama Luzern

The Bourbaki Panorama Museum is located on a busy square in the city Centre of Lucerne, Switzerland (Fig. 7050). Besides the exhibition on the top floor, the building houses a café, library, shops, and a cinema on the lower floors, creating a lively public indoor space (Bourbaki Panorama, 2022). The Bourbaki exhibition is centred around the panoramic painting of a scene during the Franco-Prussian war around 1870 where the French army led by General Bourbaki was just defeated and travelling through neutral Switzerland (Bourbaki Panorama, 2022). In 1876 Swiss painter Edouard Castres, who had travelled with the French army as a medical volunteer, was asked to paint the panoramic work by the Belgium Panorama Society. The painting was first exhibited in Geneva in 1881 but was relocated to Luzern in 1889.

The building has changed owner multiple times who did not prioritize the preservation of the exhibition. The painting was cut twice in the 20th century losing about one third of its original height and the faux terrain and visitors platform were removed to create space for additional levels for other functions, such as parking space. From 1977 the exhibition was a priority again and the painting was restored (Bourbaki Panorama, 2022). With old photos the faux terrain was being recreated and as many as possible original exhibition elements were kept. Soon the building was expanded and renovated, and cultural functions settled in the lower floors. The current building opened in 2000 and is

welcoming about 40.000 visitors per year.

A close monitoring plan is used for the painting because it is in a fragile state (Helm & Marty, 2021). The approach of the museum is to do as little interventions as possible on the painting, so relining to increase its structural behaviour is unsuitable. Also, previous interventions and repair efforts will not be reversed.

Building Construction

From 1996 the rectangular expansion was built around the existing circular panorama building. The original roof and the largest part of the original façade are still present. In Fig. 711 the original façade and roof structures are shown with the renewed glazing units. In both structures insulation is not present.

Climate management

The climate within the building is closely monitored, however the control over the climate and its consequences on the painting is minimal.

Indoor climate sensors

Air temperature and humidity: Measured at four locations throughout the exhibition space at low and high locations.

UV exposure: measured at one location on the top part of the painting.

Approach

The climate control approach is described as minimizing the daily and seasonal relative humidity and temperature fluctuations. This is done by heating, cooling and (de-)humidifying the air when needed before it is used to ventilate the building with an air conditioning unit. The organisation of the museum is aware that full climate control with an HVAC system is not feasible or sustainable in combination with the non-insulated roof.

Relative humidity and air temperature targets

RH: 45 - 55 %.

T: 18 - 25 °C

Sidenote: RH values above 60% are not acceptable, because it will make the high/low pH deposits on the painting active and create degenerative processes.

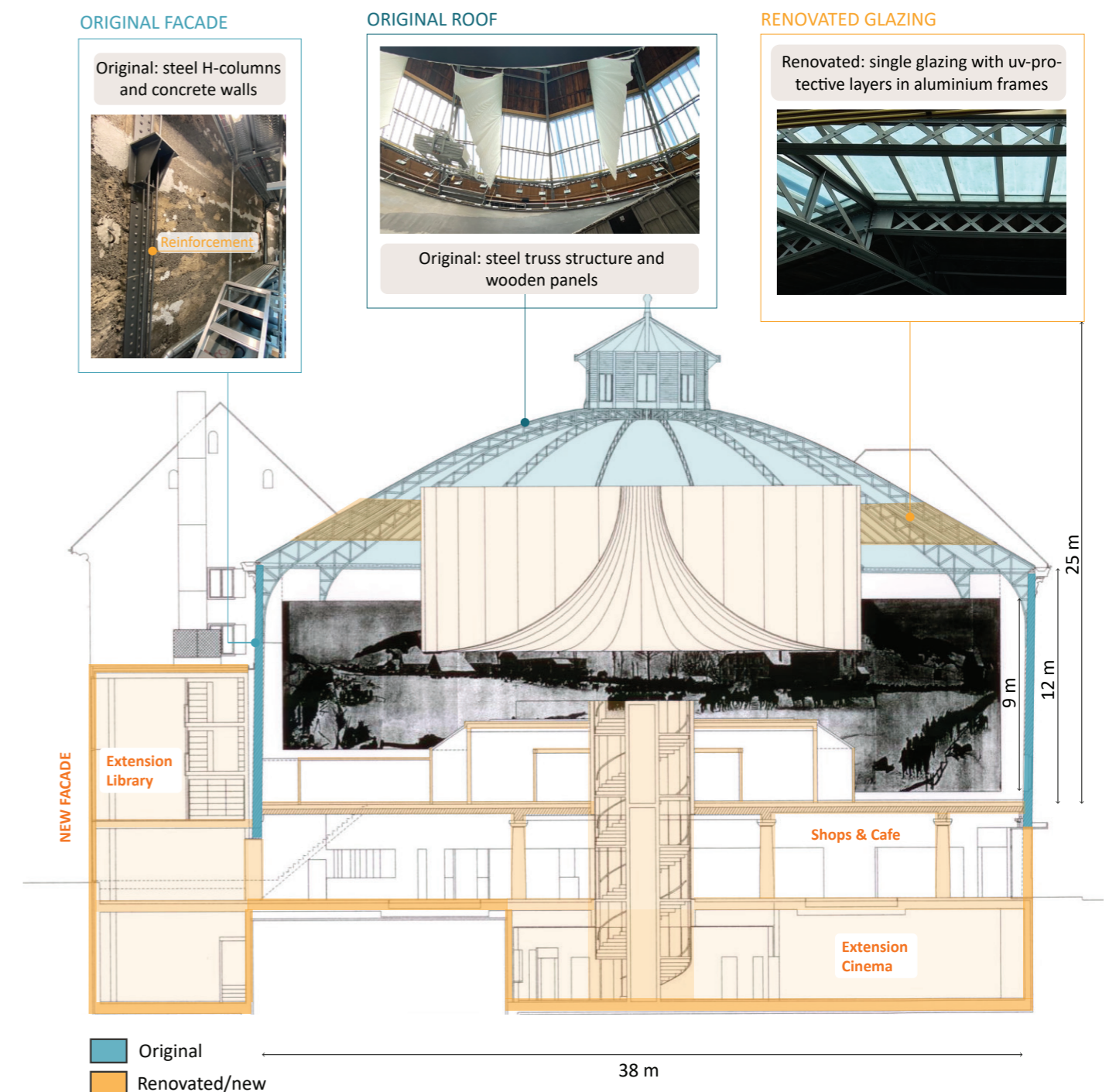


Fig. 71. Section of the Bourbaki Panorama museum and the renovated and original elements (source: own).

Relative humidity and air temperature in Bourbaki Panorama 2021

The results of the relative humidity and air temperature measurements in the Bourbaki Panorama in 2021 are shown in appendix J. The RH targets are not met, because during the winter and spring months the RH are below the minimal RH. During the summer and autumn, the RH values are mostly within the targets. The RH has not exceeded the 60% throughout 2021. The T targets are mostly met throughout the year, except for the summer months. The air temperature seems to be consistently above 25 °C during the day, especially at higher locations in the space. This is most likely the cause of the large glass surface in the roof which allows for lots of solar energy to enter the building.

Comparing the Bourbaki Panorama and the Panorama Mesdag

The buildings of the Bourbaki Panorama and Panorama Mesdag are comparable, according to Fig. 72, except for the insulated building elements. Also, the installations of both museums are different with the Bourbaki museum using only a HVAC system to control the indoor temperature and relative humidity, while the Panorama Mesdag uses also water heating systems in the Rotonde.

The overall climate challenges of both the panorama exhibition buildings is similar with the daily and seasonal fluctuations of indoor temperature and relative humidity. However, the exhibition space of the Bourbaki Panorama is able to contain a higher indoor temperature during the winter, even without additional heating installation and a HVAC system with a low air change rate. This is most likely caused by the better insulated façade and the newly built museum extension that is adjacent to the exhibition space.

In Table 29 the yearly climate fluctuation indicators are given of the Rotonde, behind the canvas, and the Bourbaki Panorama. The values of the Bourbaki Panorama are measured in the space behind the canvas, as is presented in appendix J,

including a yearly relative humidity and temperature graph. The maximum and minimum values of the Bourbaki Panorama are less extreme values than the those of the Rotonde, meaning that the range of temperature and relative humidity that the painting is exposed to, is smaller in the Bourbaki exhibition space. However, in the Bourbaki Panorama the relative humidity is below the minimum requirement of 45%, especially during the winter and spring. The temperature exceeds its maximum requirement mostly during summer months.

Also, the size and frequency of fluctuations are very similar of the two panorama exhibition spaces. In the Bourbaki Panorama even more fluctuations in temperature per year have been measured than in the Rotonde. This can be harmful for the canvas, because the relative humidity reacts to temperature inconsistency with substantial daily fluctuations.

When zooming in on the summer period on the yearly indoor climate graph in appendix J, it also clear that a temperature difference is measured at the bottom and top of the canvas of a few degrees at one point in time. The estimate of the daily temperature fluctuation per measuring locations is approximately 5 °C.

Conclusion

The characteristics of the Bourbaki Panorama indoor climate's outer limits and fluctuations seem suitable for a PCM system that is optimised to decrease temperature fluctuations during the summer. The daily 5 °C fluctuation is a sufficient temperature range for a PCM, because most PCM types melt and freeze within a temperature range of 3 to 4 °C (Rubitherm, 2022). An elaborate indoor temperature analysis, especially of the daily summer behaviour, is needed to confirm this estimation.

Next, the available space on the interior façade is determined to define if a PCM system can be implemented at this location. The space between the canvas and the interior side of the façade varies, but is at least 800 mm wide (Helm & Marty, 2021). A similar scaffolding structure as in the Rotonde is

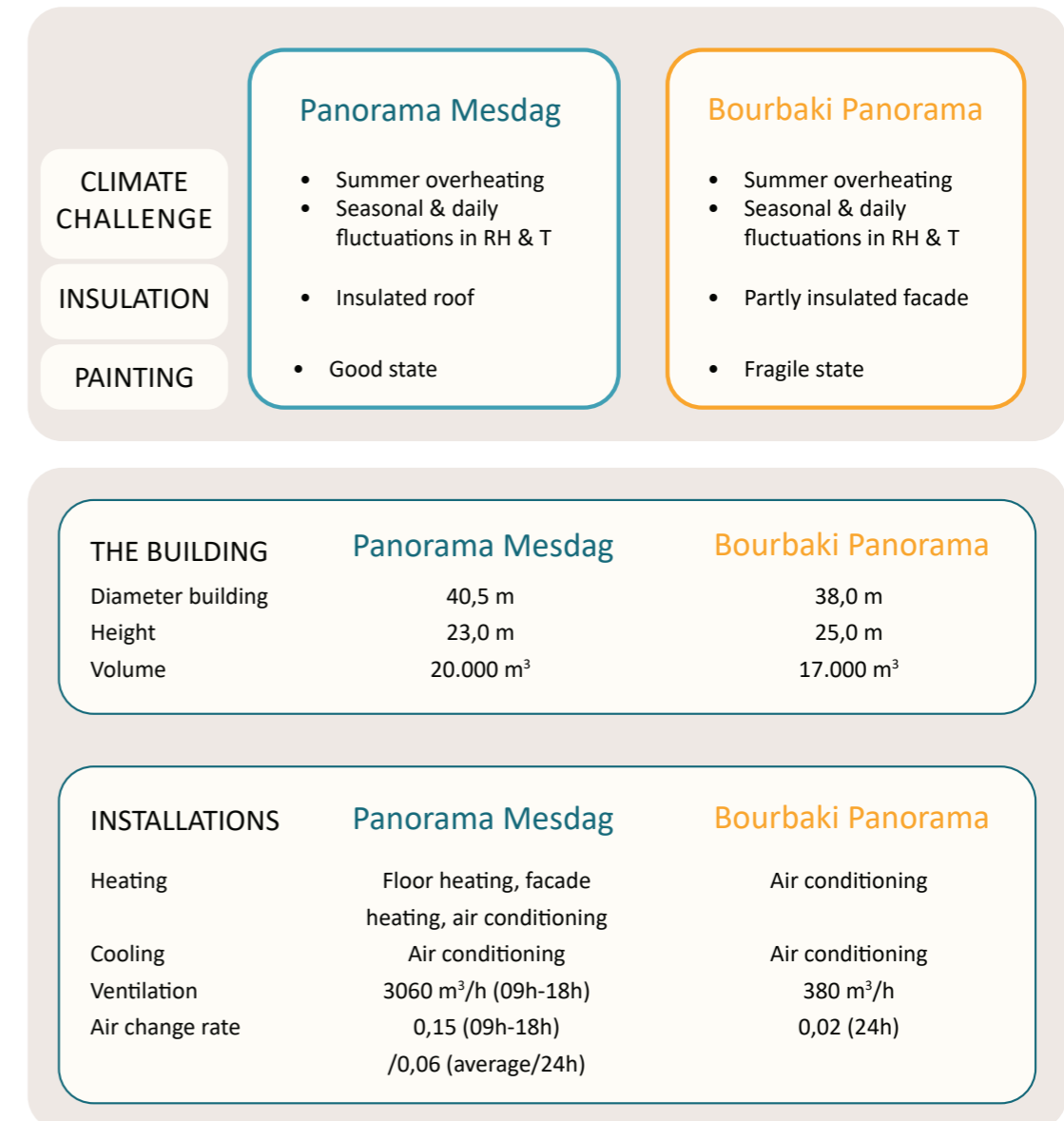


Fig. 72. Comparison of the Panorama Mesdag in the Hague and Bourbaki Panorama in Luzern, Switzerland on building, installation and painting characteristics (compiled from Frei Wüest Expert Ingenieurbüro (2021), NIAG, (2021)).

Yearly indoor climate fluctuation indicators	Behind the canvas	
	Rotonde (measured)	Luzern
Minimum RH [%]	29.0	36.4
Maximum RH [%]	63.7	61.3
Minimum T [°C]	14.3	15.9
Maximum T [°C]	32.2	30.8
Days per year of RH fluctuation > 6 %/24hr	172	144
Maximum RH fluctuation [%/24hr]	16.6	15.8
Maximum T fluctuation [°C/24hr]	6.2	6.1
Days per year of T fluctuation > 3 °C/24hr	116	171

Table 29. Yearly indoor climate fluctuation indicators of the Rotonde of the Panorama Mesdag museum and the Bourbaki Panorama museum (Frei Wüest Expert Ingenieurbüro, 2021)

located in the space behind the Bourbaki Panorama canvas (Fig. 73). The scaffolding structure is 600 mm wide, so it is estimated that at least 100 mm space is available between the scaffolding and the façade. Next, analysis should be done to determine more precisely what space is available on the interior façade and where a PCM system could be implemented.

Then, an additional indoor climate analysis should be executed, as explained in paragraph “Climate per installation zone” on page 56, to define if multiple zones are necessary with different types of PCM within the available space. From then the steps explained in the chapter

The results of the analysis shows that an underground storage with a passive sensible heat process, using for example brick or basalt, is expected to have the lowest risks on the canvas while it is also a low cost intervention with a small impact on the canvas, building and its users. The systems that have the least positive outcome in the analysis are the scaffolding PCM system and the PCM incorporated skylights. Both the systems use PCMs and are located in a position that could potentially harm the exhibition when leakages occur. Also, the costs of the PCM and the installation are substantial.

When comparing the packed-bed façade system with the PCM façade system the packed-bed system is expected to create less risks of damaging the canvas, so this could be preferred over a PCM system. However, when comparing the capacities of the systems, as in presented in Table 10, the capacity of the packed-bed system is estimated to be substantially lower. Also, additional installations with an energy demand are most likely necessary to bring the packed-bed system to its estimated efficiency. For these reasons the PCM-system is preferred over the packed-bed system on the façade.

In conclusion, a number of thermal buffering system seem feasible in the Rotonde. When comparing their risks and impact on the exhibition and building to the thermal buffering capacity, a PCM system located on the interior side of the façade is expected to be the most suitable, because of its



Fig. 73. Photo of the space behind the canvas in the Bourbaki Panorama museum in Luzern, Switzerland (source: own).

relatively low impact on the exhibition and high efficiency and heat capacity (Table 10).

PCM can be followed to define if a suitable PCM system can be achieved in the exhibition building of the Bourbaki Panorama with the available PCM on the market.

If a sufficient amount of PCM and a suitable type of PCM can be installed in the space behind the canvas, the system has the potential to decrease temperature fluctuations during the summer period which stabilises the relative humidity. A consistent behaviour of relative humidity is preferred, because it will minimize the risk of damage on the canvas. However, it is important to examine the effect of the PCM system on other aspect of the indoor climate, such as the relative humidity during the winter. This might occur, as is expected in the Rotonde, due to the increase of insulation of the façade. If there is any indication of worsening the quality of the indoor climate, for example by worsening the yearly indoor climate fluctuation indicators, implementation of the PCM system is not advised.

However, the application of a PCM system in the Bourbaki Panorama should not be discarded too quickly, because new PCM types are available on the market every year and a more elaborate indoor climate measurement plan could result in diverging suitable PCMs. Also, the combination of a PCM system with other interventions could achieve the intended indoor climate, as is presented in paragraph “Simulation of the optimized PCM design” on page 79.

Conclusion

This research explores the possibilities of increasing the thermal buffering capacity of the exhibition building of the Panorama Mesdag museum while not interfering with the monumentality of the building and the experience of the Panorama Mesdag painting. Sub questions have been introduced to help answer the main question and are answered as follows.

What is the current state of the monumental Panorama Mesdag exhibition, including the painting, the building, and the indoor climate?

The exhibition building of the Panorama Mesdag museum, also called the Rotonde, is in a good state. The building, including the panoramic painting by Mesdag, is more than 140 years old and most elements of the building envelope have not been touched by renovations. This is also the cause of the estimated high level of infiltration and the low insulating capacity of the façade, which impacts the indoor climate. During the winter months the indoor climate is good based on temperature and relative humidity values, but this is at the cost of a high energy demand that is needed to keep the Rotonde at the acceptable levels of temperature and relative humidity.

During the summer the canvas is exposed to high temperatures, large daily fluctuation and variations over the canvas due to the large solar heat gain through the glass roof. Based on the age and the good state of the painting, it seems to be able to sustain these conditions. However, minimizing daily fluctuations in relative humidity and temperature could increase the lifetime of the canvas, which is a main objective for the preservation of cultural heritage.

What are possible techniques for increasing the thermal buffering capacity of a building and which one is most suitable to establish a more consistent indoor climate in the Rotonde of the museum?

Increasing the thermal buffering capacity of a building can be done by implementing a material with a large thermal buffering capacity. There are multiple types of materials and ways the material can be implemented in a building, also referred to as installation types. The most suitable installations for the Rotonde, without impacting the spatial requirements set by the organisation of the museum, are an underground storage, a panel system behind the canvas secured to the façade or scaffolding structure and a translucent system replacing the current skylights. Some of these installation function more efficiently when combined with a mechanical ventilation system.

One of most suitable types of materials are solid materials that use sensible heat for storage, such as brick and basalt, because of their high thermal buffering capacity and low risks to their environment. Another type of material are phase change materials, PCM, that are able to store a substantially larger amount of heat during a phase change, compared materials that use sensible heat.

However, these materials are expensive and could potentially harm the monumental canvas with a risk on leakages. Also flammability and toxicity can be a problem with these innovative smart materials.

However, after comparing the potential installations suitable for the installation based on their capacity, risks and feasibility, a PCM system secured to the façade is the most promising option for implementation in the Rotonde. This option has the potential to manage the microclimate behind the monumental canvas with a small amount of material.

How can the most suitable thermal buffering technique for the Rotonde be applied without interfering with the monumentality of the building and the experience of the permanent panorama exhibition?

The PCM system can be applied in a panel system secured to the façade in a minimal invasive way to prevent harming the monumental façade. The PCM is encapsulated by inflammable containers that also minimize the risk of leakages. In order for a PCM to achieve improvement of the indoor climate, additional interventions to the building envelope are necessary, which include an insulation layer on the interior side of the façade and triple glazing in the skylights with a solar heat blocking film. These interventions help to increase the temperature during the winter and decrease during the summer.

Also, the daily temperature fluctuations are more stable and this creates a smaller temperature window that occurs more frequently over a year. This is beneficial for a PCM, because every type is able to store and release heat within a specified temperature range. This consistent and small daily temperature range is less apparent in the current state of the Rotonde, without the additional interventions and therefore was any PCM type not able to stabilize the yearly indoor climate.

The most suitable type of PCM is the SP24E with a temperature range between 21 and 25 °C for the heat storage and release process. The optimal thickness for application in the Rotonde has been defined as 12,5 mm, limited by weight, and the panels are distributed over the whole area of the interior façade. The proposed PCM façade system in the Rotonde is able to decrease large daily fluctuations in relative humidity by 50% while also decreasing the medium to large daily fluctuations in temperature by respectively 90% and 100%. These improvements tackle the aspects that are most harmful to the monumental canvas.

However, the average values for relative humidity are increased compared to the current situation during the winter season and this is a negative development. This is most likely the cause of the lower average temperature in this period by lack of heating installation. For this reason an additional heating installation is advised for the zone behind the canvas.

Can the application of the thermal buffering solution for the Rotonde be relevant for other monumental panorama buildings or any monumental building with a similar building envelope?

The application of the proposed PCM façade system has the potential to help other exhibition buildings create a more stable indoor climate for the preservation of art works. The Bourbaki Panorama in Luzern, Switzerland is used as reference project throughout this research, because the building and the exhibition have similar characteristics. The Bourbaki Panorama has similar indoor climate challenges of minimizing daily fluctuations in temperature and relative humidity during summer months and a PCM installation that can decrease these fluctuations would be beneficial for the preservation of the panoramic painting. The daily summer temperature range of 5 °C is suitable for the PCMs currently on the market to go through a complete process of melting and freezing while storing and releasing heat. If a sufficient amount of PCM panels can be implemented in the exhibition space, the frequency of large temperature and relative humidity fluctuations can be decrease with 90%.

Elaborate research is needed to determine the suitable type of PCM within the space and determine if the thermal buffering system does not have a negative impact on other aspect of the indoor climate. For the preservation of art pieces it is important that the indoor climate stays within the current outer limits and fluctuations frequency and size when executing any modification to the building that might affect the indoor climate. Otherwise potential harm can be done to the art work by the indoor climate.

For other monumental buildings with challenges of indoor climate fluctuations, a PCM system can be a suitable option. For a single type of PCM to function efficiently, the consistency of the daily temperature fluctuation is important. If the indoor temperature shows too many differences from day to day, a strategy with multiple panel

configuration containing different types of PCM types could be explored. However, sufficient capacity per PCM type is needed for a substantial impact on the indoor climate, since only one type of PCM will most likely be active per day.

In cases of a too inconsistent indoor climate for a PCM system to function effectively, systems based on sensible heat, such as a packed bed are more suitable, because materials that store sensible heat do not function within a specific temperature range. A basalt packed bed for example will store and release heat throughout the year and might result in a more effective system on a yearly basis.

A advantage of passive climate systems using thermal buffering is that often no additional active installation is needed. Therefore it can be used locally without a connection to the water or electricity grid through wiring and tubes. This creates the possibility to apply thermal buffering systems locally. An example is the use of a PCM panel where needed in a relatively invisible manner, for example close to or behind an artwork, such as the Panorama Mesdag canvas.

The main question of this research is as follows.

How can the Rotonde of the Panorama Mesdag Museum be adapted to increase the thermal buffering capacity of the building while not interfering with the monumentality of the exhibition building and the experience of the permanent Panorama Mesdag exhibition?

There are a variety of possibilities to increase the thermal buffering capacity of the Rotonde, of which one option has been further explored in this research, a PCM façade system. Different varieties of this option have been simulated to test their impact on the indoor climate of the Rotonde and it is shown that a PCM system can increase the quality of the indoor climate of the Rotonde. However, after the simulation analysis it became clear that there needs to be taken a step back when trying to realise a consistent indoor climate with installations. The current indoor climate is too inconsistent daily for a

passive PCM system to function efficiently on a sufficient amount of days per year. For this reason additional active system would be necessary to increase efficiency, such as mechanical ventilation. However, adding an installation to an installation seems to defeat the purpose of this research to search for a passive system to create a more consistent indoor climate.

An alternative option is a basalt packed bed as an underground storage in the Rotonde, that is less impacted by the inconsistent indoor climate than a PCM system. This system also brings less fire and leakage risks compared to the proposed PCM system on the façade. The underground packed bed is however expected to impact the monumental exhibition, because for the installation the original rails of the movable work platform needs to be moved.

Because of the risks and limited effect of the additional climate system, it is advised to the organization of the museum to first explore the possibilities to increase the insulating quality of the building envelope and decreasing the solar heat gain. This will help make the indoor climate more consistent throughout the year. If the indoor climate still shows too many inconsistencies after these interventions for a PCM system to function effectively, it is clear that an active system is a more favourable option. Most active systems can adapt according to the indoor climate of that day and this is potentially a more effective strategy.

An example of an active system that still uses the advantages of the PCM façade system designed in this research, is a water system incorporated in the panel design and connect to a ground source heat pump. This heat pump uses the thermal buffering capacity of the ground underneath the Rotonde as a heat source and transports it to the panels behind the canvas. In theory this option could still be considered as increasing the thermal buffering capacity of the Rotonde when the perspective is expanded. The temperature of the water and the speed with which it flows through the panels impacts the heating or cooling capacity of the system. The downside of a similar system is the risk

of leakages that could harm the canvas and the large amount and length of tubes that will be installed.

Discussion

The methods used in this research seem suitable for the main research question that focusses on an installation in the exhibition building of the Panorama Mesdag museum, because indoor climate data measured in the Rotonde was used and simulations were run in a model comparable to the Rotonde. From the simulations the yearly indoor climate fluctuation indicators and yearly indoor climate graphs were produced, which were the objective products needed for comparing the current indoor climate to alternative situations.

However, the interpretation of the measured data and the input for material characteristics could be improved. For the process of defining the suitable PCM types for multiple steps the average value of temperature was used, while another value could be more representative of the measured data. For example when defining the representative daily temperature fluctuation the values were defined per day and then an average value for a month based on the day values was defined. However, for a PCM to function efficiently, the temperature range is important. A more representative daily fluctuation value would be determined by counting the most occurring daily temperature fluctuation.

The fact that the average daily temperature fluctuation might not be the most representative value for the measured data was found when the results of the simulations for design option one to three did not show an increase in the quality of the indoor climate. In fact, some of the results showed a worse indoor climate and the reason was that the chosen PCM was not functional for enough days per year to have a positive effect on the indoor climate.

A similar effect on the results of the simulations is caused by the lack of knowledge about the material characteristics of the building envelope and in particular the façade. From literature research and cooperation with the organization of the museum no technical details were found about the Rotonde, so most of the characteristics were estimated by the organization of the museum or during the course of this research. When using the estimated values of for example the insulation and

infiltration values of the façade, as input for the simulations, the results will be less reliable. To prevent this from happening in future simulations of the Rotonde, measurements could be executed to define a more precise value of the material characteristics.

The limitations of this research are based in the case study that is used, which is a rare and unusual building typology built around an unique artwork. For this reason are the results of the effect of a PCM system of the indoor climate mostly, and potentially only, valid for the case study of the Rotonde. The effects of the PCM system might be similar to other non-insulated large open space buildings. However, if there are no strict indoor climate requirements for preservation of art, other intervention in those type of buildings are probably more suitable and efficient.

The limitations of this research concerning the monitoring of the indoor climate for the preservation of artworks is that it is mostly focused on long term fluctuation of seasons and short term daily fluctuations, but no monitoring values were determined for short-term fluctuations of multiple days or weeks. The main sources for climate requirements are ASHRAE (2019) and the Bourbaki Panorama in Luzern (Helm & Marty, 2021), and no short-term fluctuations of more than 24 hours are mentioned. However, when analyzing the yearly graphs of relative humidity and temperature these type of short-term fluctuations seemed to have increased with the proposed PCM system, while the daily fluctuations have increased in frequency and size. Monitoring the short-term fluctuation of more than 24 hours gives a better overview of the potential harm on the artworks and there are more indicators for comparing the quality of indoor climates.

The results of this research implicate that with passive systems using thermal buffering the temperature during summer months can be stabilized in the exhibition building of the Panorama Mesdag museum. This system would be required to be applied in combination with insulating interventions in the building to reach the desired

effect on the indoor climate for preservation of the artwork. If the indoor climate of the Rotonde is not stabilized during the summer it can have a negative effect on the lifetime of the panoramic painting by Mesdag.

Further research on the application of PCM systems to manage the microclimate around vulnerable art pieces could be executed, to define if a smaller scale PCM system can have a similar effect on the indoor climate with the objective to increase the quality of the indoor climate for preservation of the art piece. In particular the relative humidity is an important factor for the preservation of art and this research has focused on stabilizing the relative humidity by stabilizing the indoor temperature. However, also PCM types that influence the relative humidity directly, and not through the temperature, have been researched currently. These type of PCMs have the potential to be valuable for the preservation of art for passive systems and more research could be carried out to define the suitability of the application of moisture managing PCMs close to art pieces.

Recommendations

In this chapter the recommendations of further research for the case study of the Rotonde are presented. A first step that could be taken is conducting more elaborate measurements for better monitoring and an in depth indoor climate analysis. A set of measurements could be conducted defining the near surface temperature and relative humidity of the canvas, on both sides of the canvas (Kompatscher, 2021). These measurements will help to determine the effect of the local indoor climate, for example the zone behind the canvas, on the canvas itself. This research has previously used local indoor climate data to estimate the effect it has on the painting. Broadening the used data that is more representative of the so called, object indoor climate around the panoramic painting can help to estimate effects of proposed climate systems and help with monitoring for preservation of the painting.

As mentioned in the conclusion, the first step for increasing the quality of the indoor climate and to reduce energy demand is to increasing the insulation value of the building envelope and to decrease the solar heat gain. A study could be done on finding a suitable insulating method for the façade while not impacting the relative humidity and increasing the temperature during the summer. Currently, through the estimated high infiltration of the façade, there is minimal moisture built up. When insulating the façade, the moisture balance could be disturbed and the relative humidity rises throughout the year. Research could be conducted to find a suitable insulation material with a possible air cavity, moisture barriers and additional ventilation. Also, variations in air cavities could be researched as an option to prevent overheating during the summer. For example, an air cavity that is not ventilated through the winter season to increase the insulating value of the façade and ventilating the cavity during the summer when a high insulating value would trap the heat inside the Rotonde. Also, a potential layer of PCM could be added to this proposed façade layer concept.

Another intervention that could be researched is the replacement of the current skylight

with better insulating glass with a solar block film. Simulations with this intervention have been run in this research and the results are promising with lower temperature during the summer. However, more research is advised to define the effect on the visual light entering the Rotonde and falling onto the panoramic picture. The natural daylight entering the building is a key aspect of the illusional effect of the panoramic exhibition and should not be impaired.

Any of these interventions in the building elements of the Rotonde have the potential to impact the heating and cooling demand substantially, while also increasing the quality of the indoor climate for preservation of the panoramic painting. These interventions are preferred over adding any additional active or passive installations to the building

Furthermore, alternative systems could also be researched for implementation in the Rotonde, including a water system connected to a ground source heat pump or other options (Fig. 74). The estimation of the effect of the systems can be done by software simulations. An important aspect of simulating the water system is the settings and setpoints used for the system to manage the indoor climate in the Rotonde.

A plan is made for the Rotonde of steps that could be taken to increase the quality of the indoor climate while decreasing energy demand (ref). The plan and the sequence of steps takes into account that every steps could be executed separately and would not harm the building or painting. Further research is needed to finalize the total intervention plan, specifically the façade insulation. It is advised to reevaluate the indoor climate of the Rotonde after implementing one of the steps to properly define the suitability of the following step.

Further research on the application of PCM systems to manage the microclimate in buildings around vulnerable art pieces could be executed, to define if a smaller scale PCM system can have a similar effect on the indoor climate with the objective to increase the quality of the indoor climate for

preservation of the art piece. In particular the relative humidity is an important factor for the preservation of art and this research has focused on stabilizing the relative humidity by stabilizing the indoor temperature. However, also PCM types that influence the relative humidity directly, and not through the temperature, have been researched currently. These type of PCMs have the potential to be valuable for the preservation of art for passive systems and more research could be carried out to define the suitability of the application of moisture managing PCMs close to art pieces.

Roadmap Panorama Mesdag museum

This advice is a step by step intervention plan that aims to increase the quality of the indoor climate of the Rotonde of the Panorama Mesdag museum, while also decreasing energy demand (Fig. 75). It is important that cooling interventions are executed before applying façade insulation, to prevent overheating during the summer.

Step 1.1 – 1.4: cooling interventions

Step 1.1

Triple glazing and solar block film

This will allow less heat to enter Rotonde during the summer and less heat loss during the winter. Due to the low tilting angle of the skylights, minimal solar heat enters the building during the winter in current situation, so this intervention it is expected to have

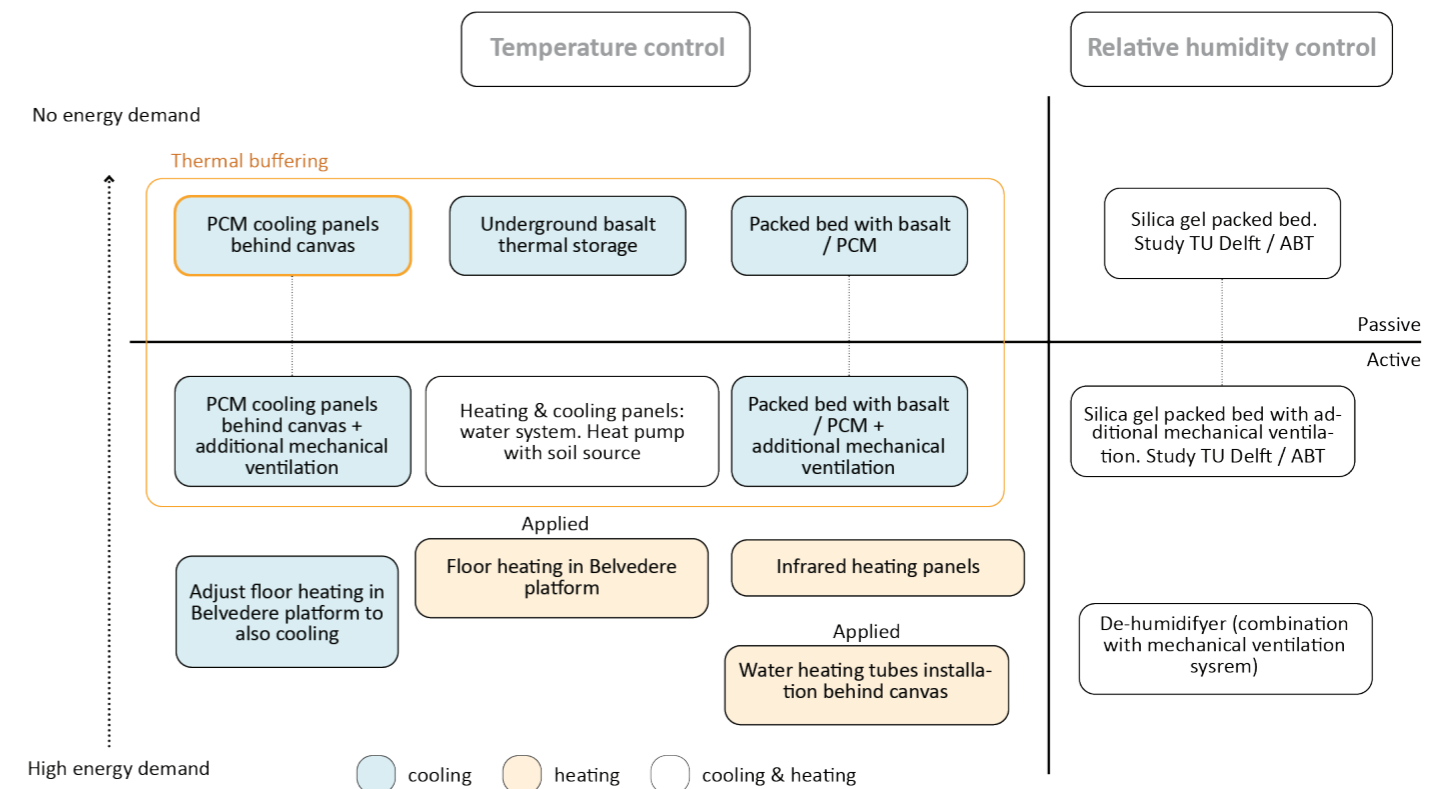


Fig. 74. Overview of alternative climate system for the Rotonde (source: own).

minimal impact on heat gain during winter. However, triple glazing will decrease the amount of heat loss through the skylight, because of the higher insulation value.

Step 1.2

Change color of roofing to lighter color

A light colored material absorb less heat than the current black roofing. It is expected that the roof will reach a lower temperature than currently and transfer less heat to the inside of the Rotonde, decreasing the indoor temperature.

The color of the roofing can be changed by painting the current roofing material or by replacing the current roofing with a different material. A reflective material is not advised due to risk visual discomfort by glare for occupants of surrounding buildings, such as the Hilton hotel (Baker & Steemer, 2002).

Step 1.3

Roof ventilation outlets

To extract warm air during warm summer days, the ventilation concept of the Rotonde could be changed by temporarily disable the mechanical ventilation extraction from the Rotonde to the HVAC system (Fig. 11) and opening ventilation outlet at a higher location in the Rotonde, such as in the roof or the currently unused vents openings at the top of the façade.

Instead of extracting cool air at the bottom level of the Rotonde, warm air at the top level is pushed out of the building by overpressure. This is expected to lower the indoor temperatures throughout the Rotonde. The ventilation outlets would open mechanically and need to be air tight when closed to prevent outdoor contamination to enter the Rotonde, which could be damaging to the painting.

Step 1.4

Outdoor sun screens.

This intervention can decrease the solar heat gain during the summer at peak solar loads. The screen

can be applied according to a reference project by (Helioscreen, 2021). The project is a renovated monumental museum and the roof on which the screens are located has a similar tilting angle as the skylights of the Rotonde. The screens would be controlled by indoor temperature and relative humidity levels, closing the screens when temperatures are too high and relative humidity too low during the summer. The screens could also be closed during a peak of solar heat gain which could create large fluctuations in temperature and relative humidity, but would be decreased by the sun screens, which is beneficial for the preservation of the painting.

Further research is needed to define the feasibility of outdoor screens on the roof of the Rotonde. Besides, indoor lighting is advised to be activated when sun screens are closed to ensure sufficient lighting on the panorama exhibition. To prevent an energy usage increase, it is advised to replace the current lighting installation in the Rotonde with LED-lights that are dimmable. The LED-lights could react to the amount of natural daylight in the Rotonde and ensure a stable amount of lighting on the exhibition for visitors comfort.

(step 2 if suitable: basalt packed bed floor construction)

Step 2.1:

Façade renovation: insulation, moisture control, PCM cooling panels (Fig. 76).

This combination of interventions will have to be executed all together, because the current heating installation on the interior façade will be removed prior to this step 2.1. These interventions aim to insulate the Rotonde to a level where additional heating is no longer necessary.

Insulation and moisture control

Material: insulating, moisture controlling, low flammability, reversible mounting to façade
Thickness: 50 mm

Example: Calcium Silicate (capillary-active)

Heat transfer coefficient: 0.06 (λ) [W/mK]

Roadmap for the Rotonde of the Panorama Mesdag museum

Steps 1.1-1.4 are interchangeable, because of no risk on damage. However, steps are in order of size of expected impact (large to small).

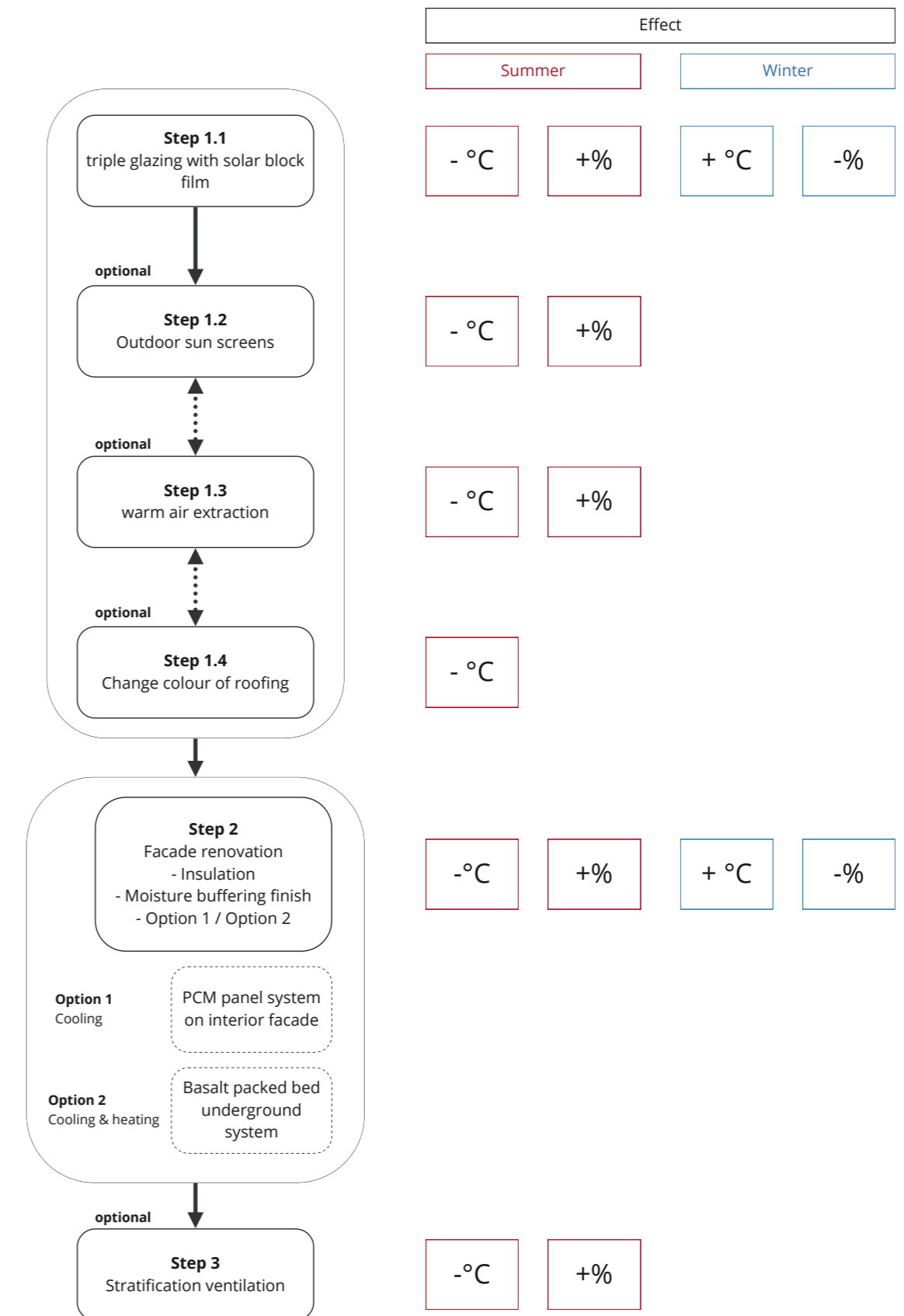


Fig. 75. Steps of the intervention plan for the Rotonde of the Panorama Mesdag (source: own).

Water vapor diffusion resistance factor: 6 – 9
 Water absorption coefficient: [kg/m²s^{1/2}]

Further research is needed to determine the suitability of this insulation material, but it is expected to be the most feasible option, because of the least damaging consequences. The previous research PUR foam from the optimised PCM design is advised to be combined with a water vapour barrier (Rijksdienst voor het Cultureel Erfgoed, 2020). However, the support system of the PCM panels will penetrate this barrier creating a risk of internal condensation in the façade.

For this reason seems a capillary-active

insulation the best option with least risk on damage on the monumental building. However, it is advised for the insulation to be secured tightly to the façade, because cavities could cause moisture damage. This means that the interior plaster layer on the façade is advised to be smoothed and a securing method should be applied that is reversible for the preservation of the monumental façade.

PCM panel support system

Vertical strut: metal (steel) structural connection of façade to horizontal rails supporting the PCM panels. Connection to masonry should be minimal invasive

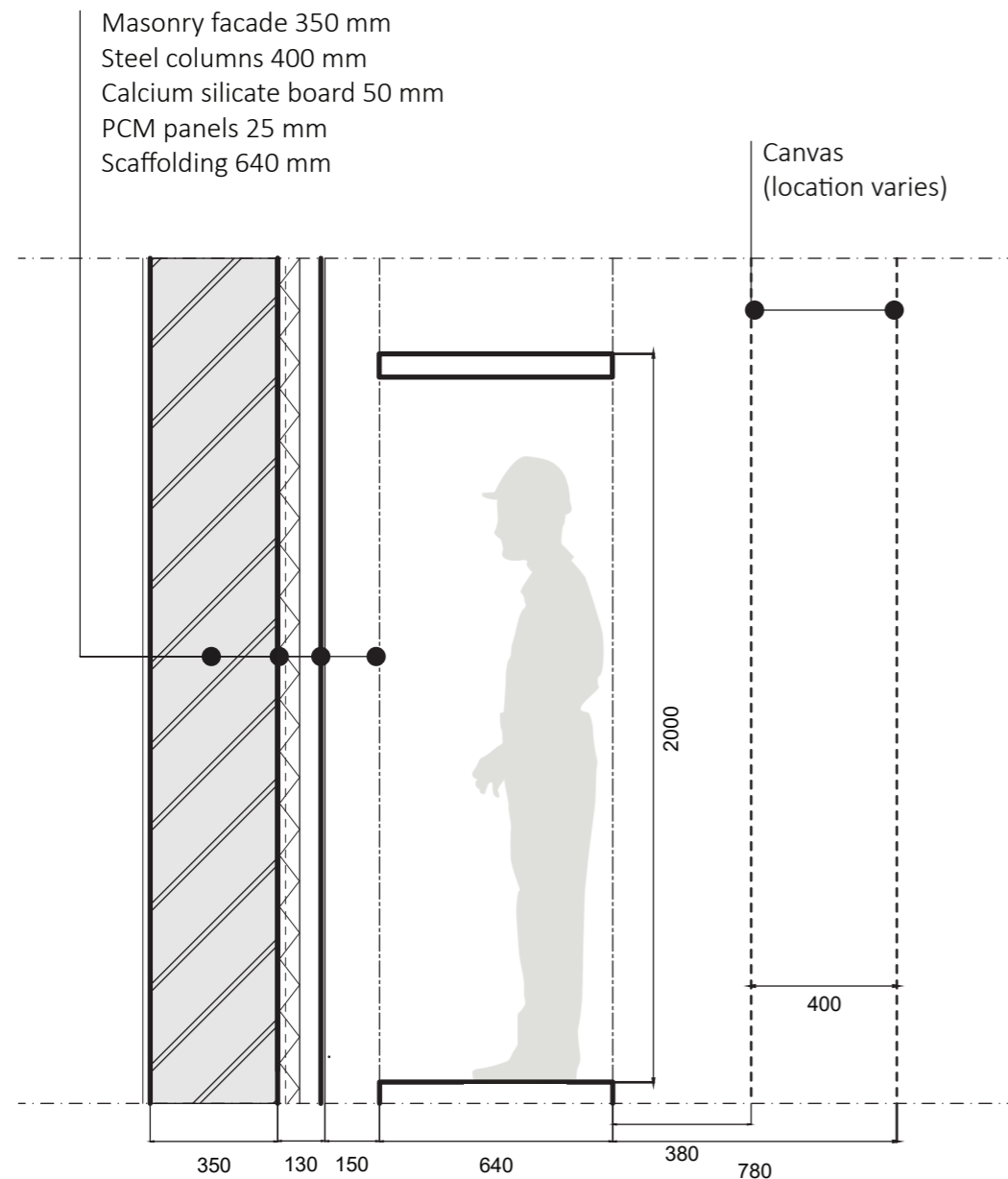


Fig. 76. Section of facade of the Rotonde with proposed interventions on scale 1 : 20 (source: own).

to the façade and have a cold-bridge interruption. Horizontal strut: non-metal (wood/composite) rails supporting the PCM panels while allowing for replacement of panels.

Maximum thickness: 40-50 mm

PCM panel

Container: lightweight and inflammable. Dimensions of the container should allow for expansion of PCM material within the container. The specific amount of expansion per PCM type is given in material properties datasheets. Examples of datasheet of the used PCMs in the simulations are presented in Appendix G.

Self-distinguishing materials of PCMs: self-distinguishing is often accomplished by forming a large residue (Sittisart & Farid, 2011). Residues of any kind near the panoramic painting are not advised, since it could damage the painting. Further research is needed to define a suitable inflammable container.

PCM type: for choosing (a) suitable PCM(s) for the Rotonde, the indoor climate needs to be reevaluated before step 2. Indoor climate measurements and data analysis of the indoor climate of the Rotonde is advised (paragraph 'Climate per installation zone' through 'Dimensions of a PCM panel') to be repeated to define a suitable PCM based on melting and freezing temperatures and other properties.

Maximum thickness: 50 mm

Step 3

Destratification ventilation

This intervention could be beneficial for the indoor vertical temperature distribution. Due to the insulation intervention it is expected that an extremer effect might occur of vertical temperature distribution during summer and winter. Measurements and data analysis is advised to be repeated after finalizing step 2 interventions to define the occurrence of vertical temperature distribution in multiple seasons ("Vertical Variation" on page 54).

A situation where stratification ventilation is

preferable is when the temperature at the top level of the Rotonde is multiple degrees higher than at the bottom level, because a too large difference in temperature can decrease the effectiveness of the PCM panels. In this case the warmer air at the top can be pushed to a lower level by the stratification ventilators increasing the efficiency of PCM panels. This is only necessary when the temperature range of the zone is within the active temperature range of the PCM type(s).

After the completion of these steps, it is expected that the indoor climate of the Rotonde is increased in quality for preservation of the painting, while using minimal energy for active climate installations. The indoor climate is expected to stay within the temperature and relative humidity requirements with minimal fluctuations. The indoor temperature is expected to stay within 15 to 25 °C without any additional active climate installation than are currently present.

During the winter it is also expected that the indoor relative humidity will be higher than currently, which is preferred, because of slightly low measured values. Relative humidity of higher than 75% is not expected, because of the addition of moisture buffering materials.

During the summer the cooling PCM panels are expected to lower indoor temperatures in the zone behind the canvas with approximately 2 °C and preventing the indoor temperature from rising above 25 °C. Also, the relative humidity is expected to rise during the summer, because of lower temperatures. This is beneficial because the current humidity levels during the summer are below the ideal curve of relative humidity for monumental museums (Appendix C).

Reflection

The approach of this research is to design a climate solution that would help to create a more consistent indoor climate in the Panorama Mesdag exhibition while not interfering with the exhibition and the monumental building. From the start there was a focus on solutions based on the natural thermal buffering of materials, which is a passive approach that aligns with the sustainability of the museum and the general aim of decreasing the carbon footprint of the built environment. After a comparative analysis it was decided to proceed with a PCM based solution, because of the large thermal buffering capacities and the lack of research into the application of PCM in monumental buildings or museums. PCM's do meet the need of creating a consistent indoor climate, however they will to some extent have a negative impact on the exhibition, the monumental building and sustainability needs. Most inflammable PCM are non-biological materials that have a larger carbon footprint than biological materials and could be damaging to the environment. Besides, any leakage of these PCM's could damage the canvas and monumental building substantially. Also, introducing new materials to the monumental building could be considered as inappropriate.

However, implementing PCM's is one of the approaches that can prolong the lifetime of the rare panoramic painting which ways heavier than the monumentality of the building, since the building has always played a supporting role for panoramic painting. Therefore applying PCM's in this monumental museum is a suitable solution for creating a more consistent indoor climate.

The methods that were used for the design process were suitable considering the timeframe in which the research was executed. Firstly, the measurement data of the indoor climate that was used, was collected by the organisation of the museum before the approach of this research was defined. Therefore the data was not completely applicable for the data analysis in the design process and additional measurements are advised, if this research is continued, that will give a more representative image of climate profiles per zone

over the whole year.

Secondly, the simulation software DesignBuilder is a suitable software, because it is relatively simple to operate and it has qualitative air flow and humidity simulations, PCM implementation and customizable output settings. However, even more accurate simulations could be run by using CFD, computational fluid dynamics, which would help to define the air flow behind the canvas and around the implemented PCM panels on the façade. This option is available in DesignBuilder, but alternative software's also offer this option, such as IES (Integrated Environmental Solutions Limited, 2022).

The most relevant feedback that was given by the mentors was broadening the research with a reference project to gain a better understanding of the relevancy of this research. The Rotonde is a rare building and the last of its kind in the Netherlands, so the possibility to compare its state and performance with a similar building could be very useful. This aspect has been incorporated in the research by conducting a reference research including a site visit to the Bourbaki Panorama in Luzern, Switzerland. Through the research of the current state of the Rotonde, the current state of the Bourbaki Panorama building is also included to show the comparability between the two projects. At the end of the research a theoretical application analysis of a PCM installation in the Bourbaki Panorama is presented. This will show the relevancy of this research for other monumental museum buildings for creating a consistent indoor climate.

However, if the application is suitable, there is a possibility that a monumental building will not have this innovative installation implemented, because it clashes with the vision of the museum of minimal intervention to the monument and exhibition, which seems the case for the Bourbaki Panorama. For this reason it is even more important to show the possible impact of a PCM solution on the quality of the indoor climate.

Relationship MSc AUBS - building technology - graduation topic

The master programme of Architecture, Urbanism and Building Sciences aims to develop a more sustainable built environment by blending a variety of practices that answers the societal, design and technological questions. Within the building technology track passive climate approaches are widely researched, because it helps to create sustainable buildings with an effective indoor climate system. This research aligns with these approaches by answering the technological question of passive indoor climate systems, while also trying to answer the societal question of preservation of monumental objects, in this case built and art objects. The projected answer to these questions is a PCM solution, which is an innovative technology that has been researched more than it has been applied in the built environment and even less so in museums or monumental buildings.

Influence research - design/advice

The conducted research has influenced the design by determining the most important parameters of an effective PCM installation and incorporating these in the measurement plan and design process. Without focussing the scope of parameters many research paths are possible, but in this research the effectiveness of the installation on the indoor climate is the priority which rules out many other research and design directions.

The design requirements specific for this fragile environment of monumental objects have also impacted the research direction, because an emphasis is put on inflammable and non-toxic materials. However, it showed that the development of PCM's has its limitations, because researched showed that no PCM is currently available that consists of all the favourable characteristics. In this way the design has helped to clarify the limitations and possibilities of currently available PCM.

Value of approach & methodology

The value of the approach and methodology is based

on the transition from previously conducted research, the extension into new research options and the possibility to copy measurement and simulation results. All tools and resources used for this research are accessible and should not pose limitations for additional or new research.

Also, the final design of a PCM installation is customizable and therefore the methodology of this research could be used as a base for determining a suitable PCM installation for any other case that aims to achieve a more consistent indoor climate for buildings.

Academic and societal value, scope and implication including ethical aspects

The value of this research in the societal perspective is that this research aims to protect and prolong the lifetime of cultural heritage, such as art and monuments by researching innovative technologies and designing a customisable solution with a low carbon footprint. From the academic point of view this research creates a new academic pathway by combining multiple widely researched areas into an innovative solution. The scope in which this research could be relevant is the preservation of art pieces, monumental preservation and adaptability to general sustainability needs and the development and implementation of PCM in the built environment.

Transferability of project results

The final design of this research has been customised to the specific situation of the Rotonde of the Panorama Mesdag and its' transferability is therefore limited. However, the advice on the most suitable indoor climate installation to create a consistent indoor climate could be relevant for other cases with similar building characteristics, such as monumental building, museum and even more so the combination of these two.

The element of this research which is mostly transferable is the methodology. Because of the wide variety of PCM's the solution is customisable to other cases. For this reason the methodology together with the tools could be used to define a

suitable PCM installation for other situations.

Environmental impact

The environmental impact any research into passive system has is that it builds on the knowledge base for sustainable ways to create suitable and comfortable indoor climates without using any additional systems that require energy. The reduction of energy demand in buildings is one of the ways to decrease the carbon footprint of buildings and slow down climate change.

Especially the findings of this research show that innovative technologies, such as PCMs, can help with reducing energy demand while creating a suitable indoor climate. However, it also showed that increasing the quality of the building envelope is the first step that should be taken in any building with a similar objective. Additional systems and installations, passive or active, should be the follow-up step, because the most profitable solution would be if the building is able to manage its own indoor climate passively.

Feasibility

This research has helped to shine a more positive light on the feasibility of PCM application in buildings, because calculations and simulation have shown that with a thin layer of PCM, in some cases just 4 mm, an effective system can be designed. Similar systems showed in results not a substantial increase in effect on the indoor climate, so in terms of cost-effective approach a thin layer of PCM could be sufficient. The material costs for the amount of PCM used in a panel of a square meter and a thickness of 4 mm would cost approximately 40 euros. This helps to overcome the stigma that a PCM system is by definition expensive and is therefore often not considered as a feasible option for application in buildings.

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Appendix A

Existing panorama exhibitions

1. Eigenbrakel, Belgium. 'The Battle of Waterloo', (1912).
2. Brussel, Belgium. 'The Battle of Yzer' (1920). In storage.
3. Altötting, Germany. 'The Crucifixion of Christ', (1903).
4. Bad Frankenhausen, Germany. 'Early Bourgeois Revolution in Germany in 1525', (1981).
5. Salzburg, Austria. 'The Panorama of Salzburg', (1828).
6. Innsbruck, Austria. 'The Battle at the Isel Mountain in 1809', (1895).
7. Luzern, Switzerland. 'Bourbaki Panorama', (1881).
8. Einsiedeln, Switzerland. 'Jerusalem and the Crucifixion of Christ', (1892).
9. Thun, Switzerland. 'Panorama of Thun', (1814).
10. Pleven, Bulgaria. 'The Pleven Panorama', (1977).
11. Wroclaw, Poland. 'The Battle of Raclawice', (1893).
12. Moscow, Russia. 'The Battle of Borodino', (1912).
13. Sebastopol, Ukraine. 'The Siege of Sebastopol in 1855', (1905).
14. Volgograd, Russia. 'The Battle of Stalingrad in 1943', (1981).
15. Prague, Czech Republic. 'The Battle of Lipany', (1897).
16. Ste-Anne-de-Beaupré, Canada. 'Jerusalem on the Day of the Crucifixion', (1882).
17. Atlanta, United States. 'The Battle of Atlanta in 1864', (1886).
18. Gettysburg, United States. 'The Battle of Gettysburg in 1863', (1883).
19. The Hague, the Netherlands. 'Panorama Mesdag', (1880).

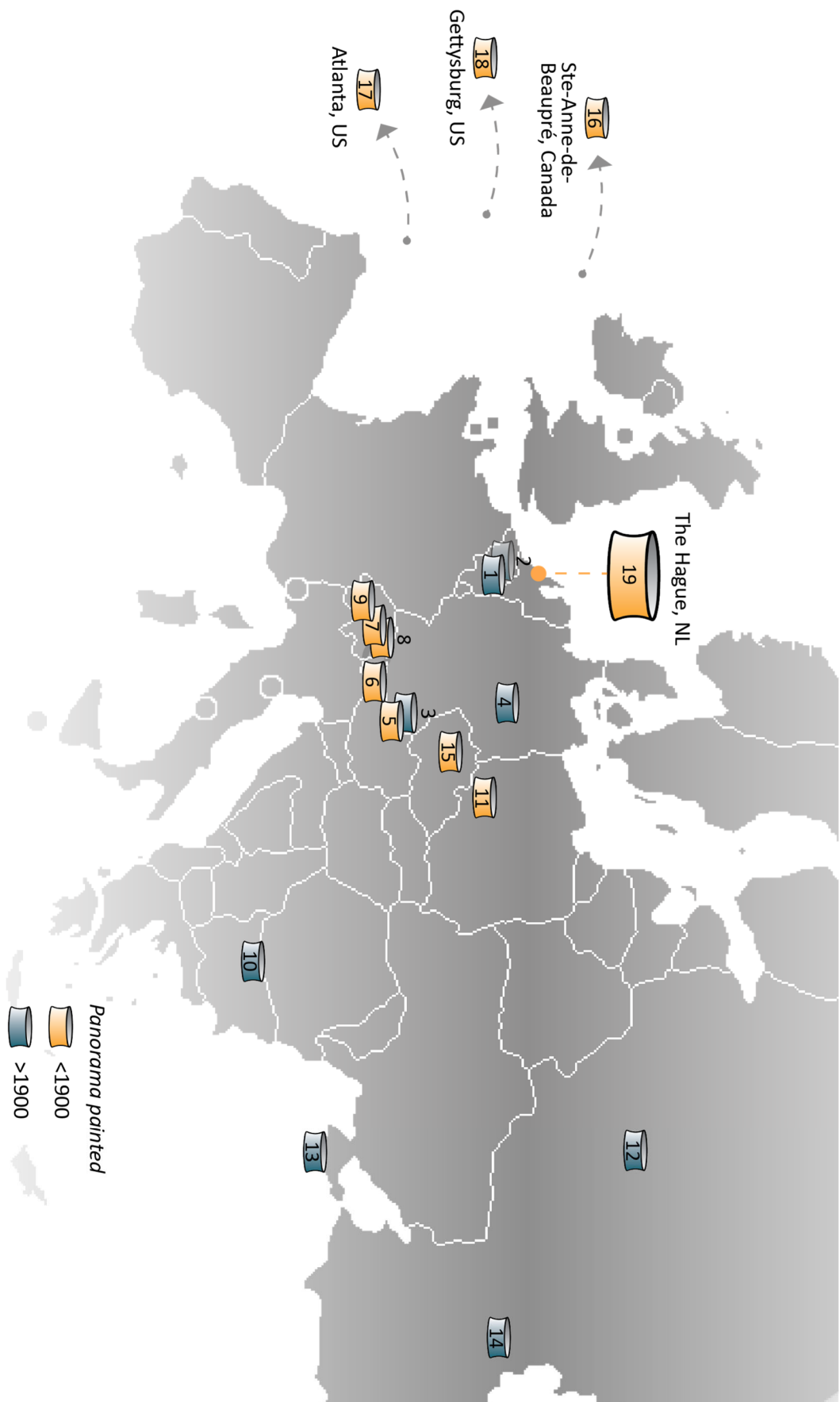


Figure A1.

Appendix B

Indoor Climate Analysis Graphs per season

Per season two graphs of temperature and relative humidity are presented of datalogger set 1 (Table 4). One graph contains the measured data from all dataloggers, and the other graphs shows the average from all measured dataloggers, resulting in a average temperature of the space.

The global horizontal irradiance (GHI) is measured at the KNMI station in Voorschoten 14 kilometres from the museum in the Hague. The GHI is a commonly used value to define the sun exposure. GHI is the total amount of light energy, also known as irradiance, received by a horizontal surface in W/m^2 .

Autumn: 01/09/2021 – 30/11/2021

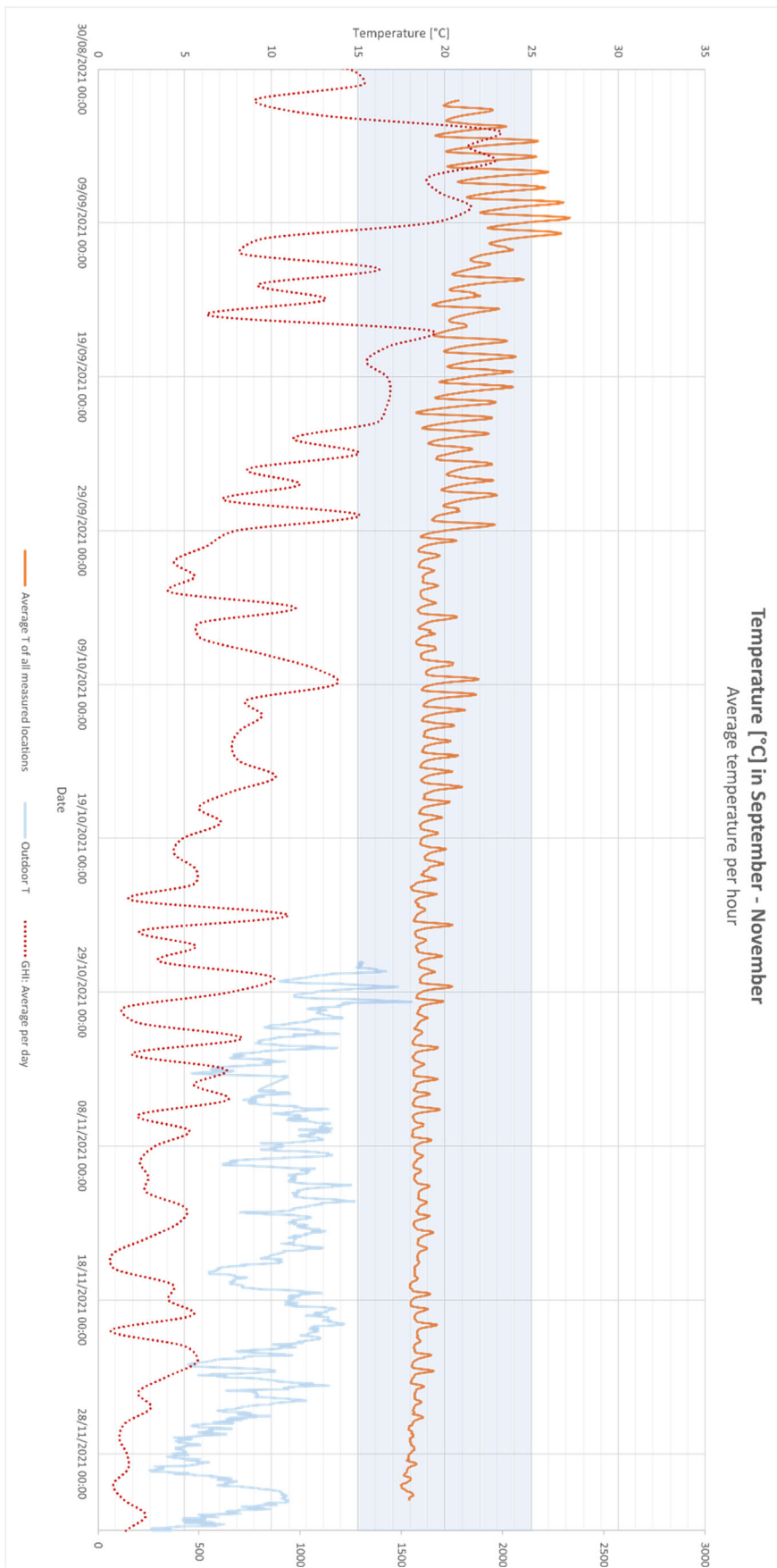


Figure B1.

Temperature [°C] in September - November Average temperature per hour

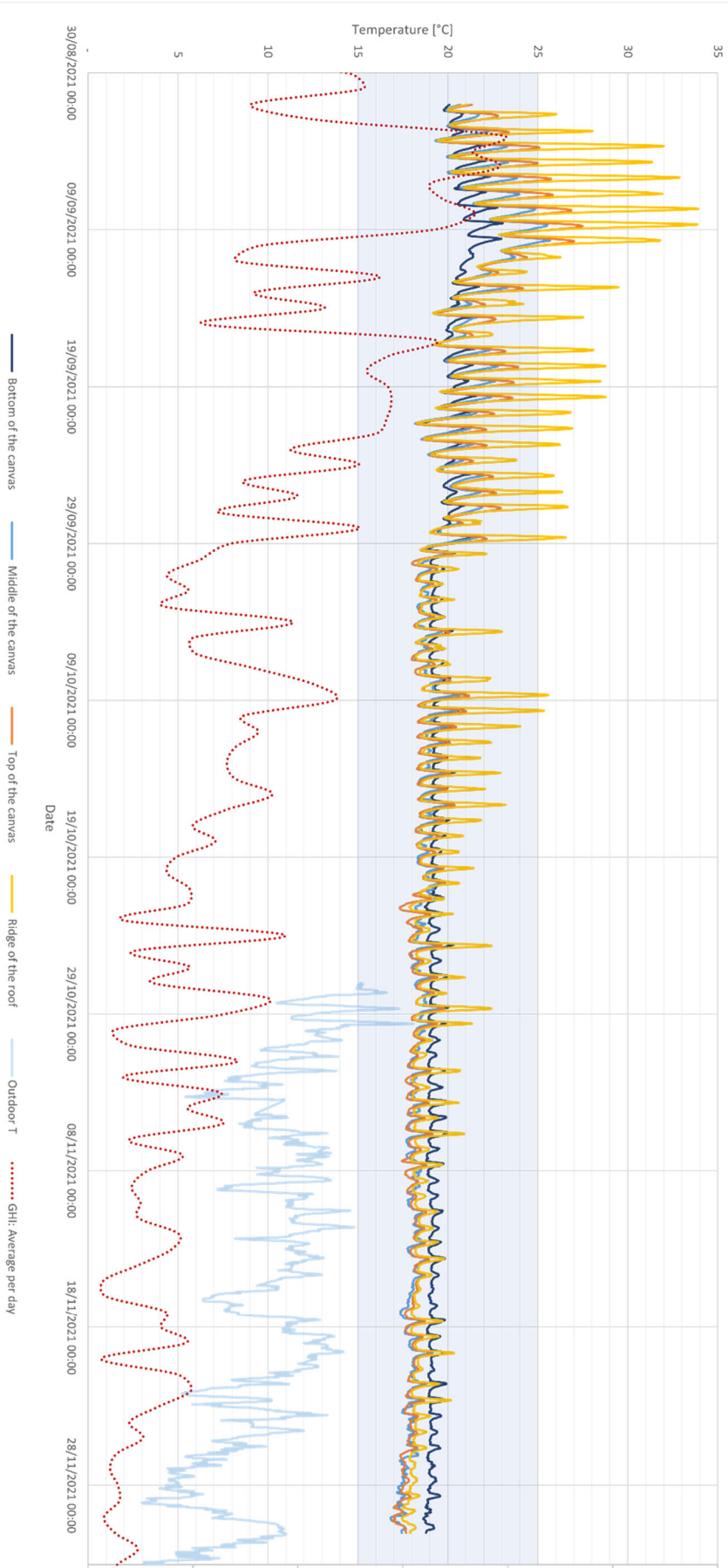


Figure B2.

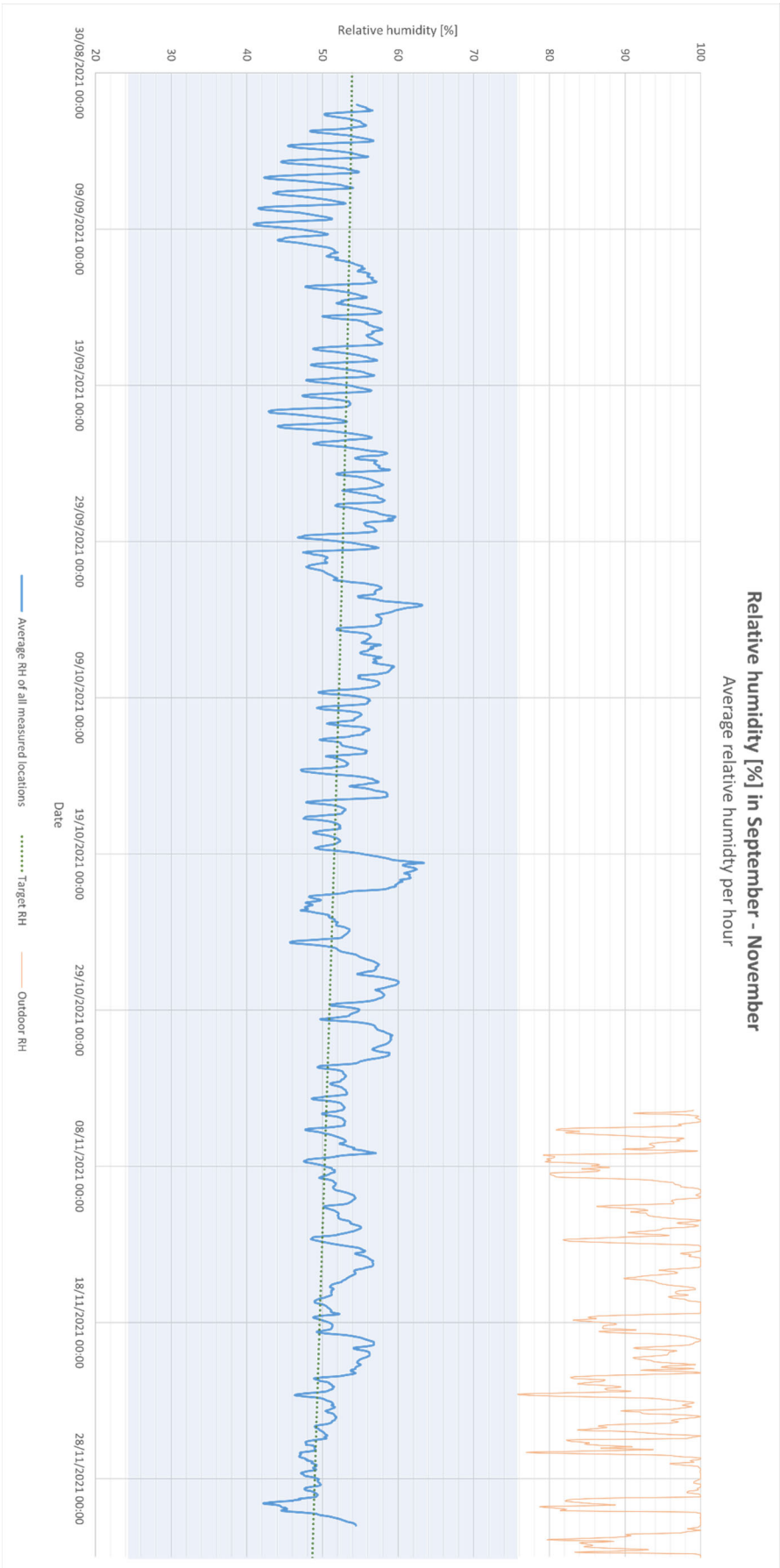


Figure B3.

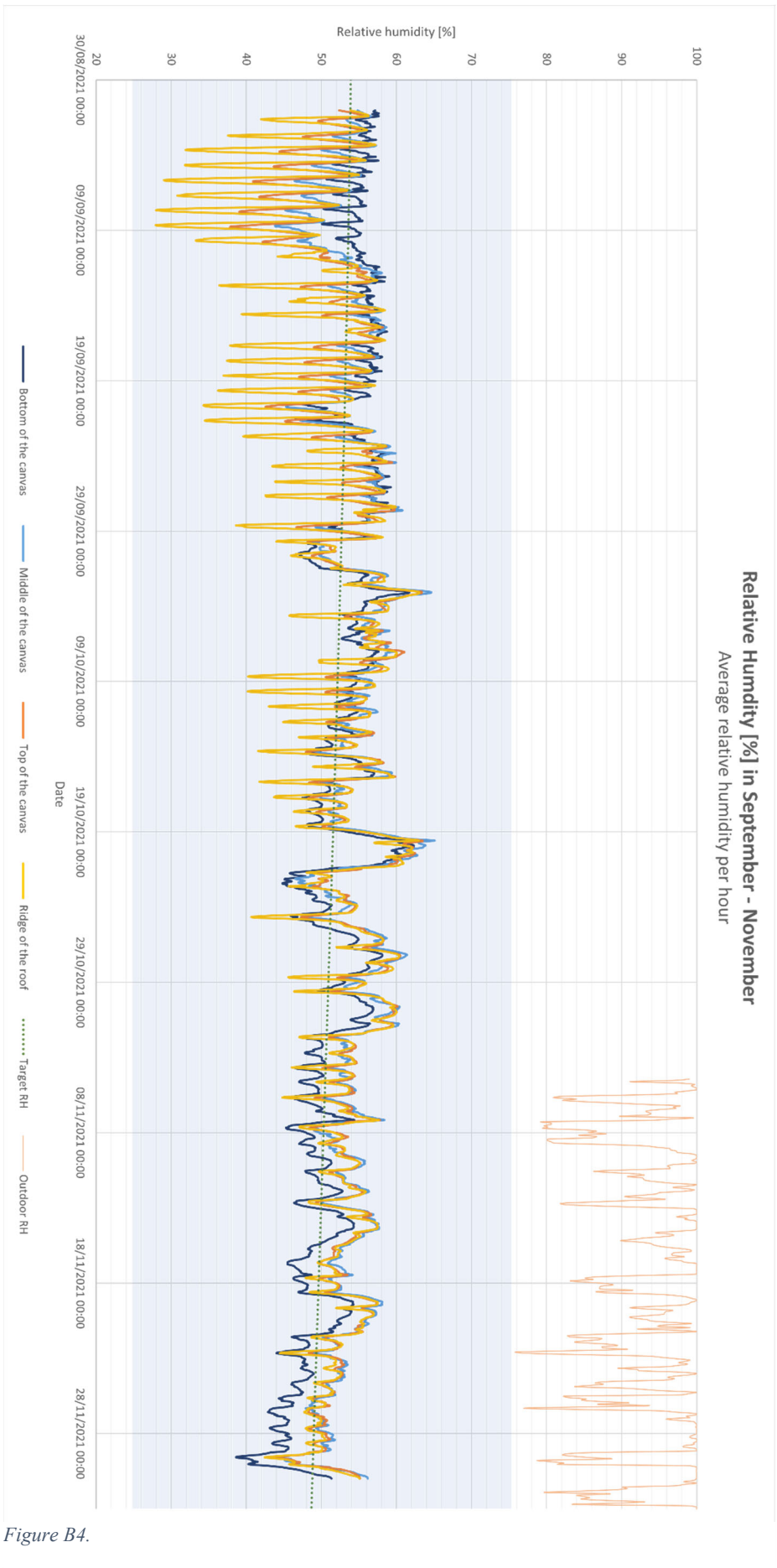


Figure B4.

Winter: 01/12/2021 – 28-02-2022

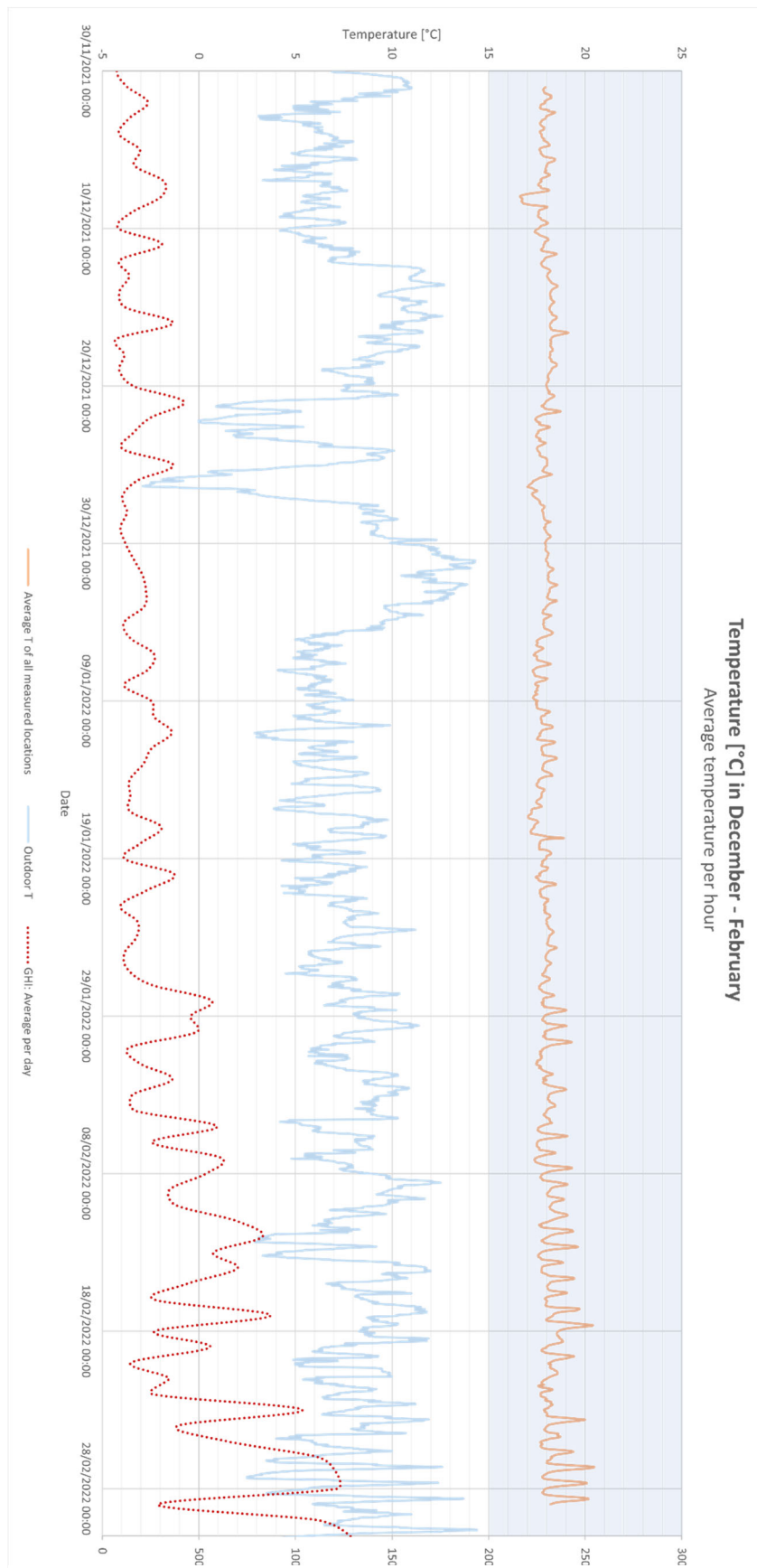


Figure B5.

Temperature [°C] in December - February

Average temperature per hour

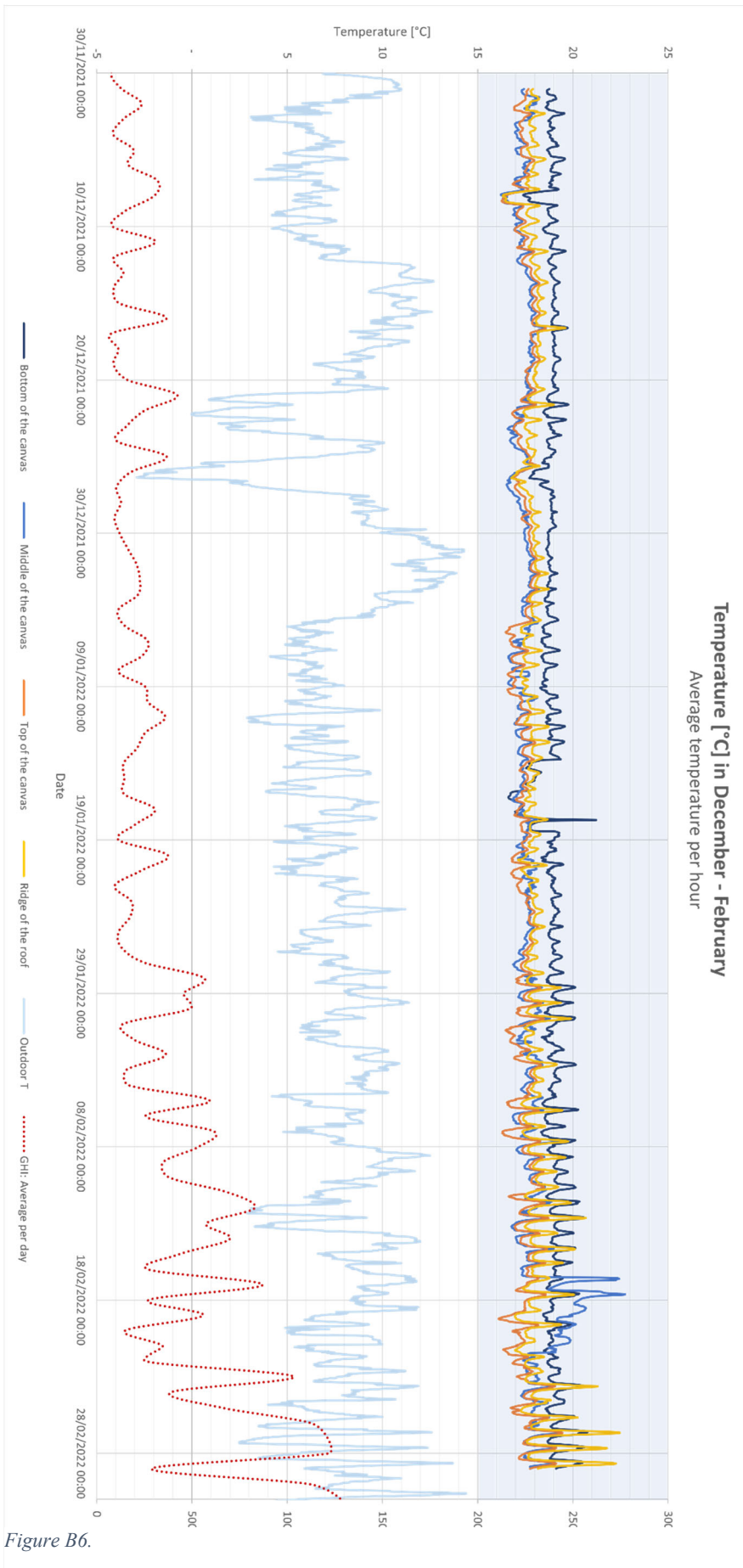


Figure B6.

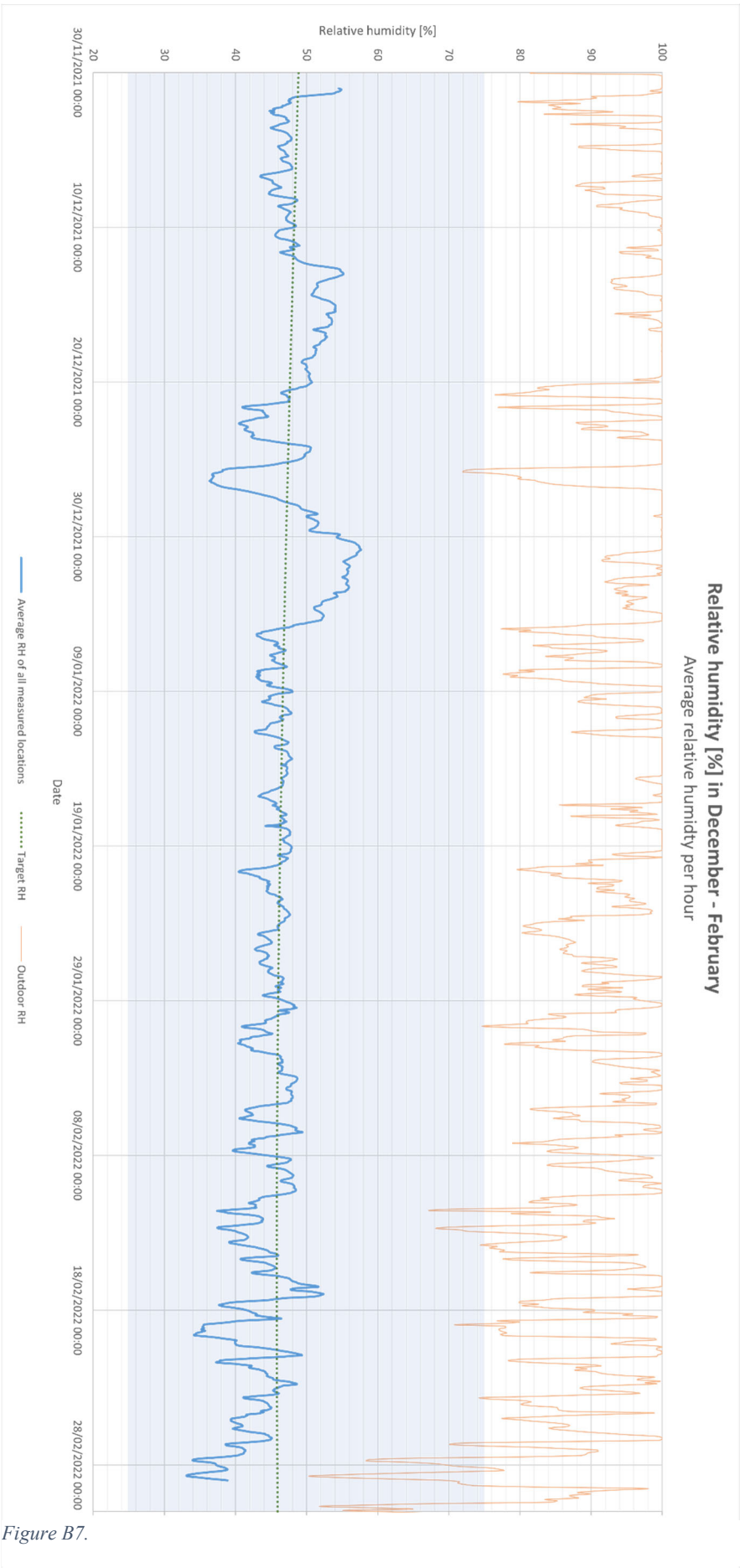


Figure B7.

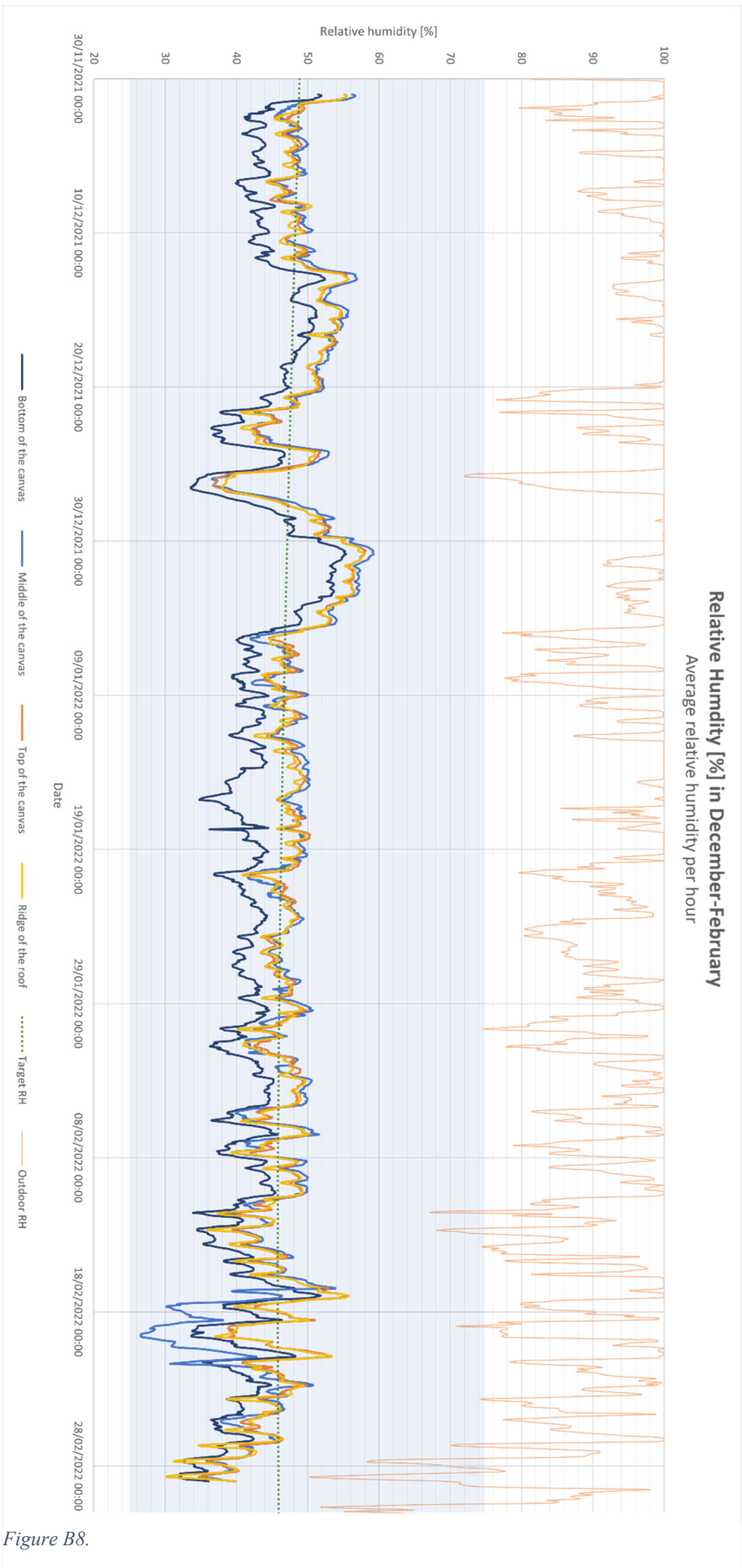
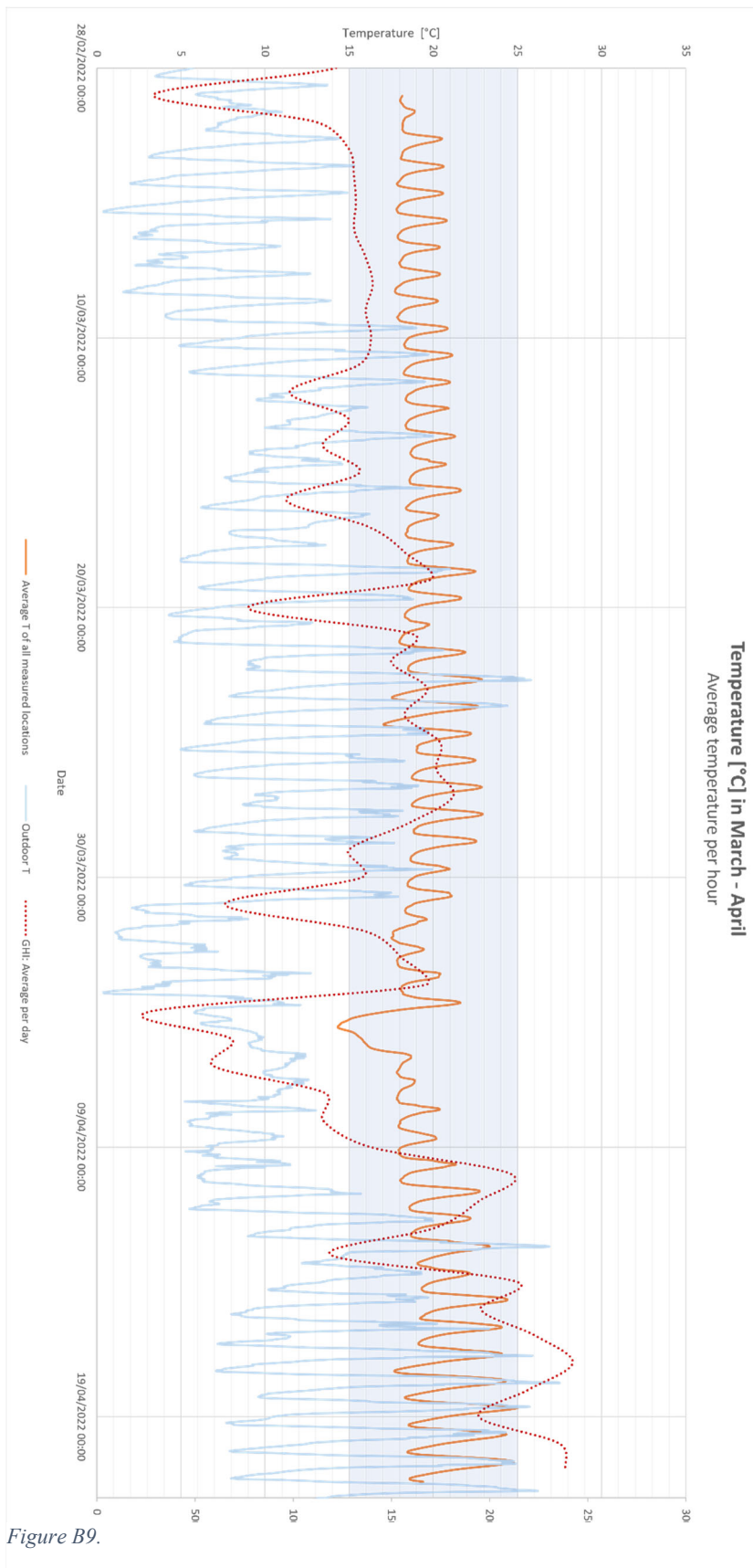


Figure B8.

Spring: 01-03-2022 – 21-04-2022



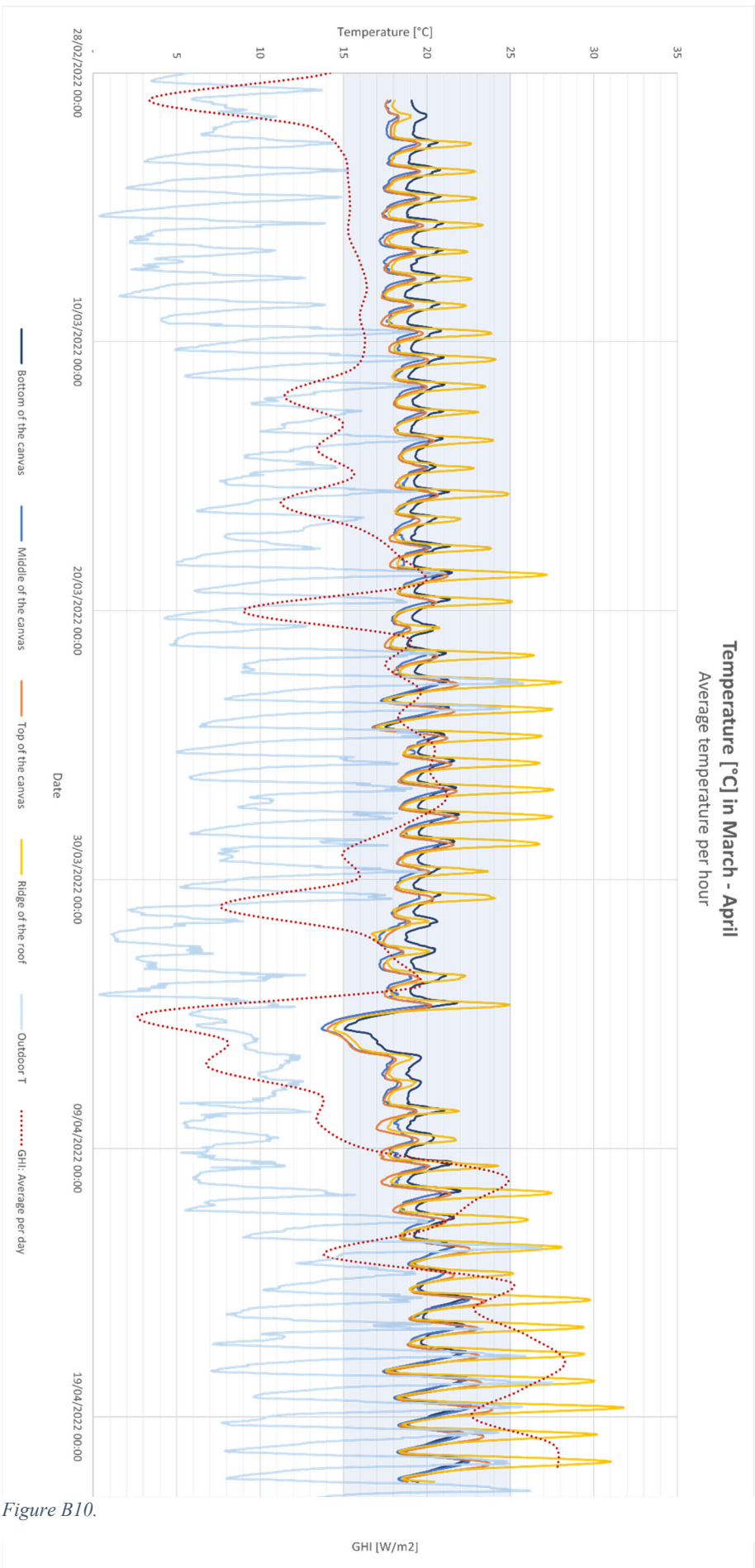


Figure B10.

GHI [W/m2]

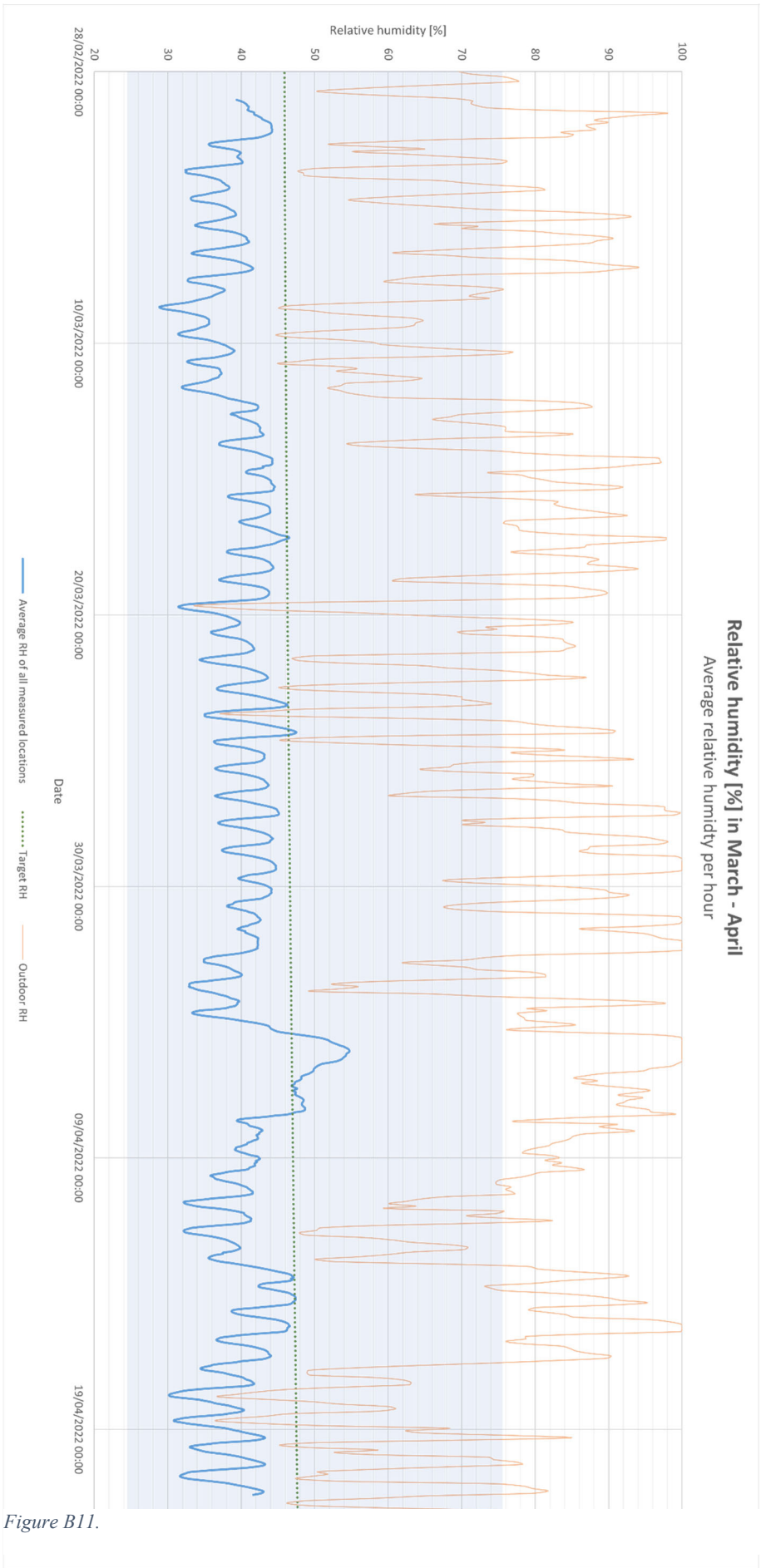


Figure B11.

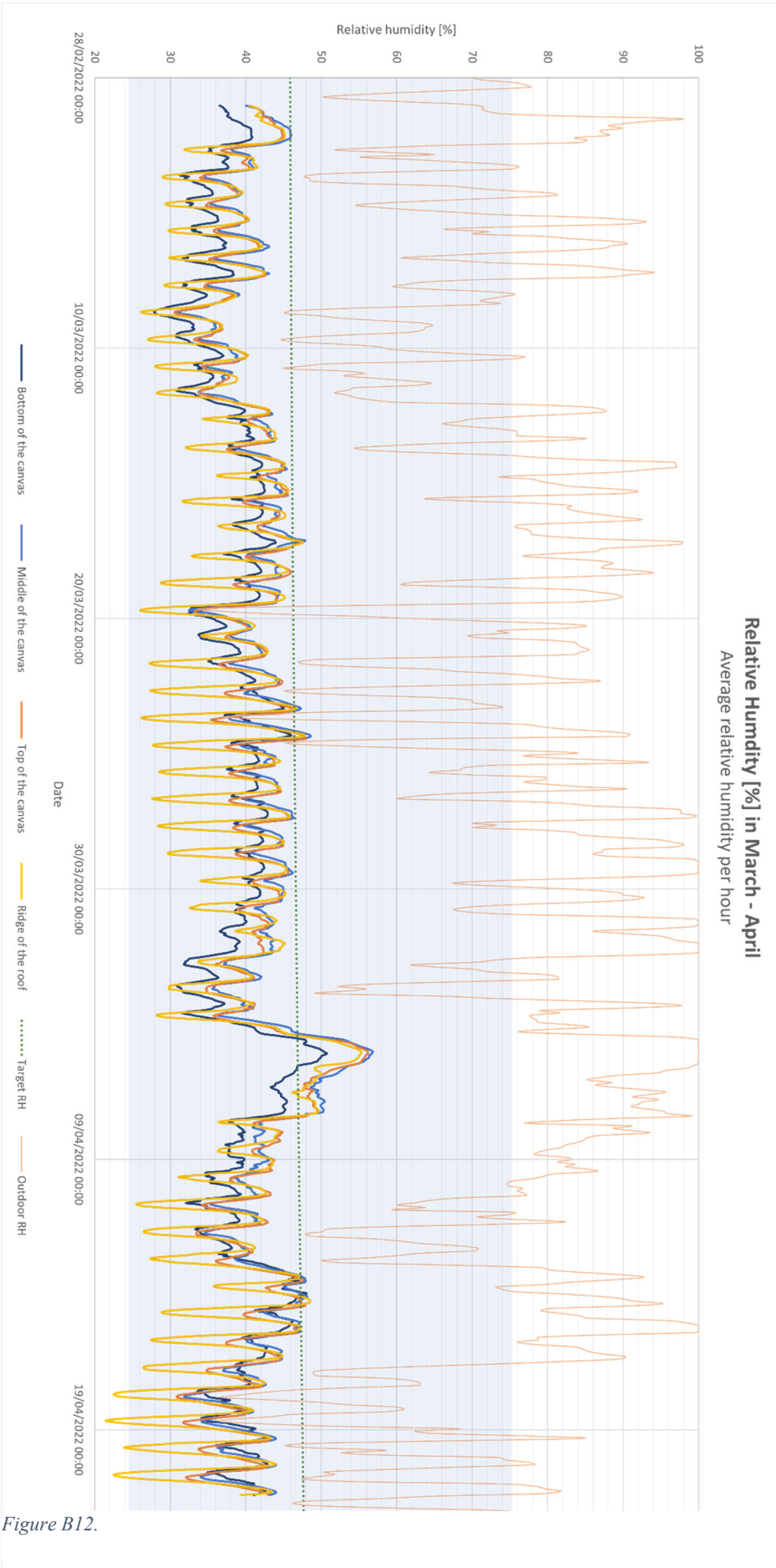


Figure B12.

Summer

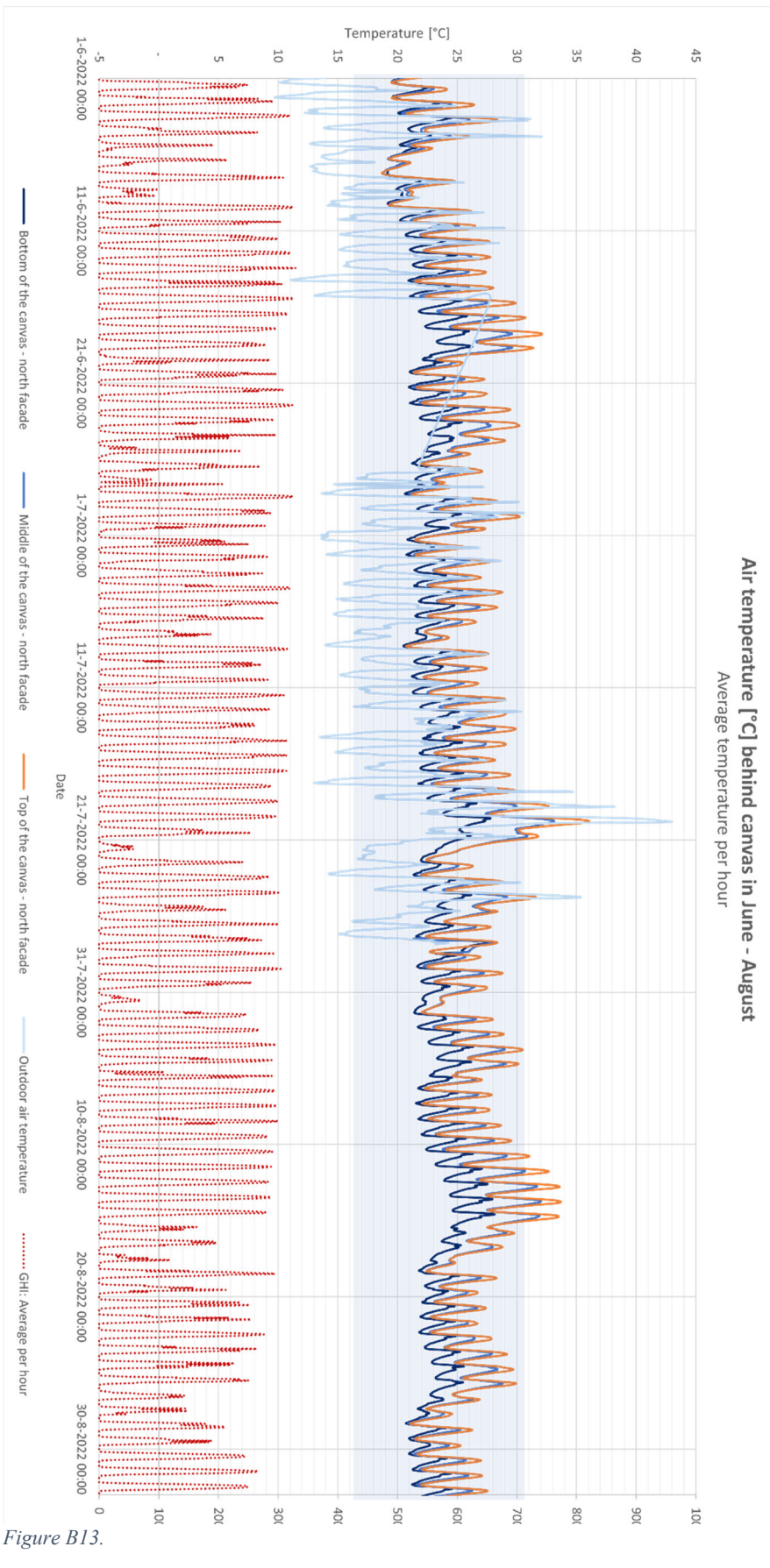


Figure B13.

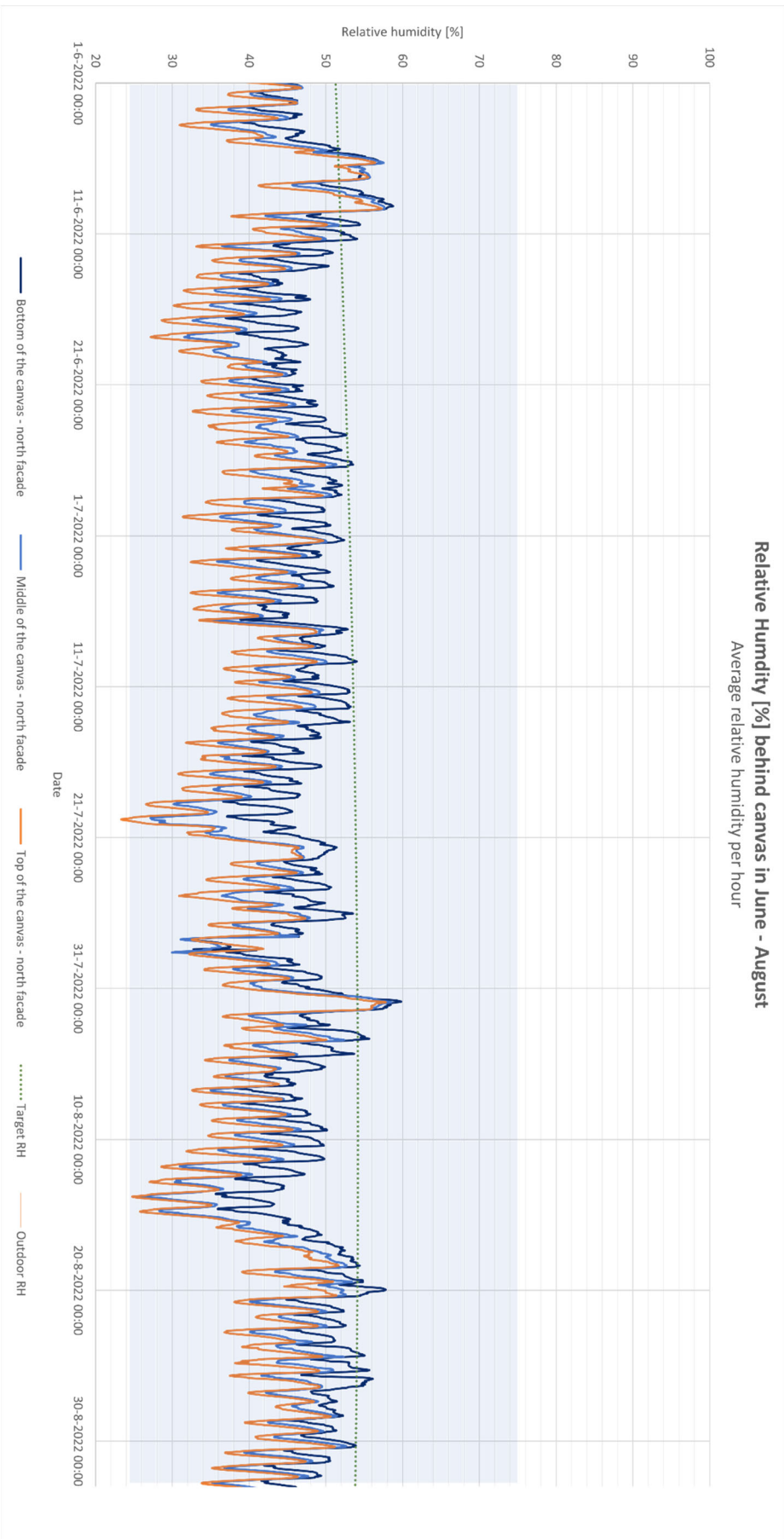


Figure B14.

Appendix C
Additional Indoor Climate Analysis Graphs: summer 2022 at the south façade

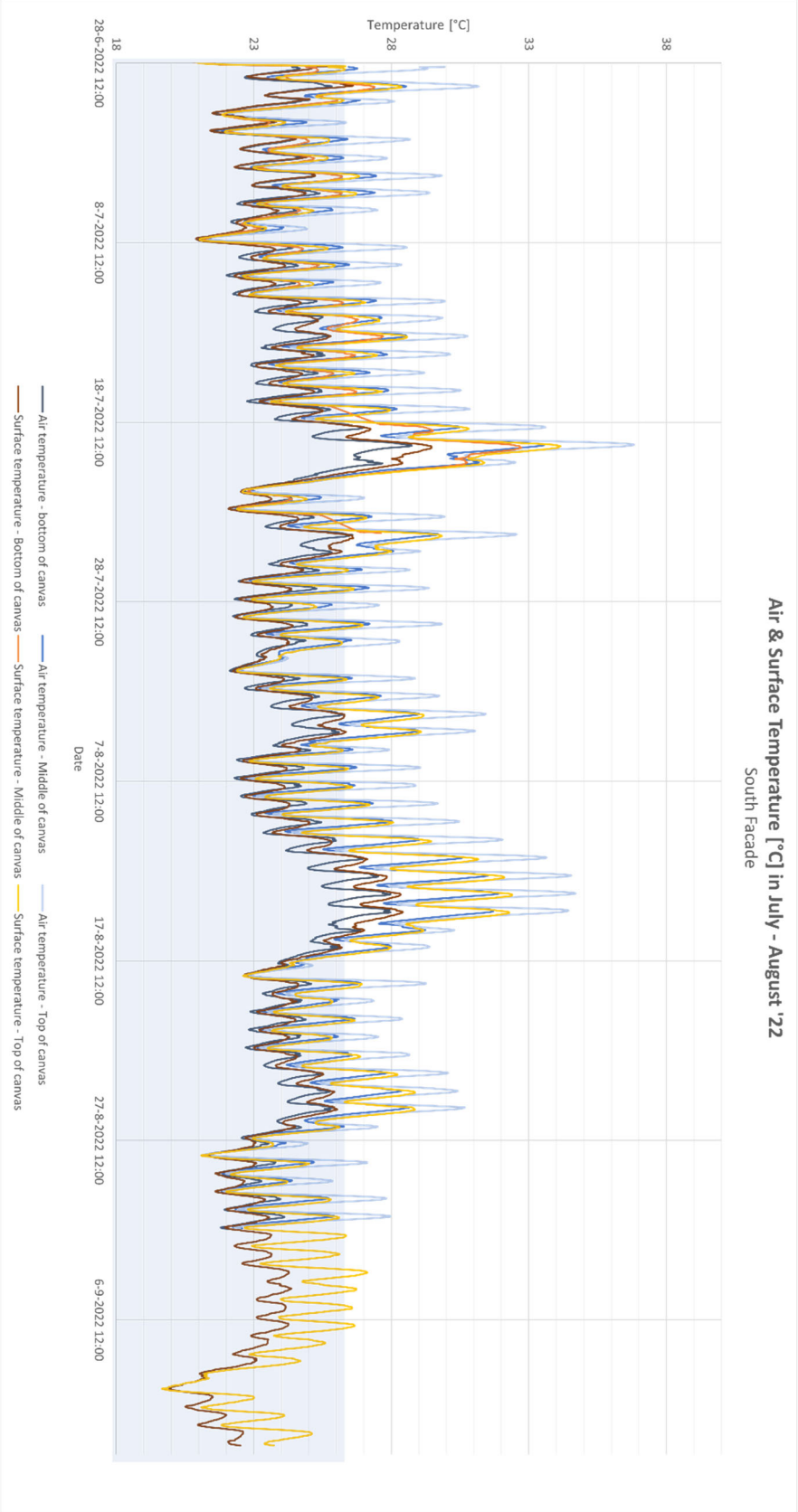


Figure C1.

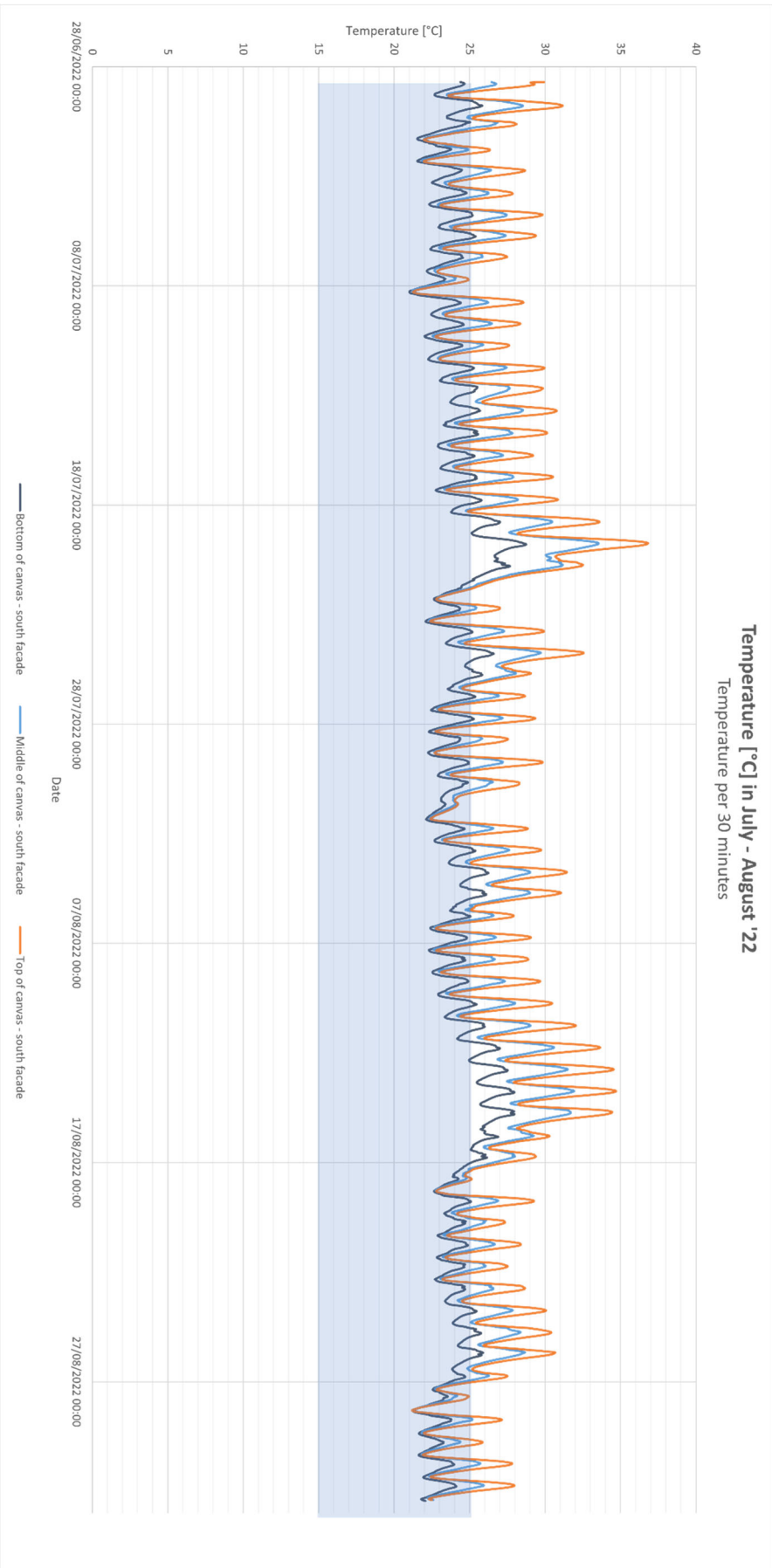


Figure C2.

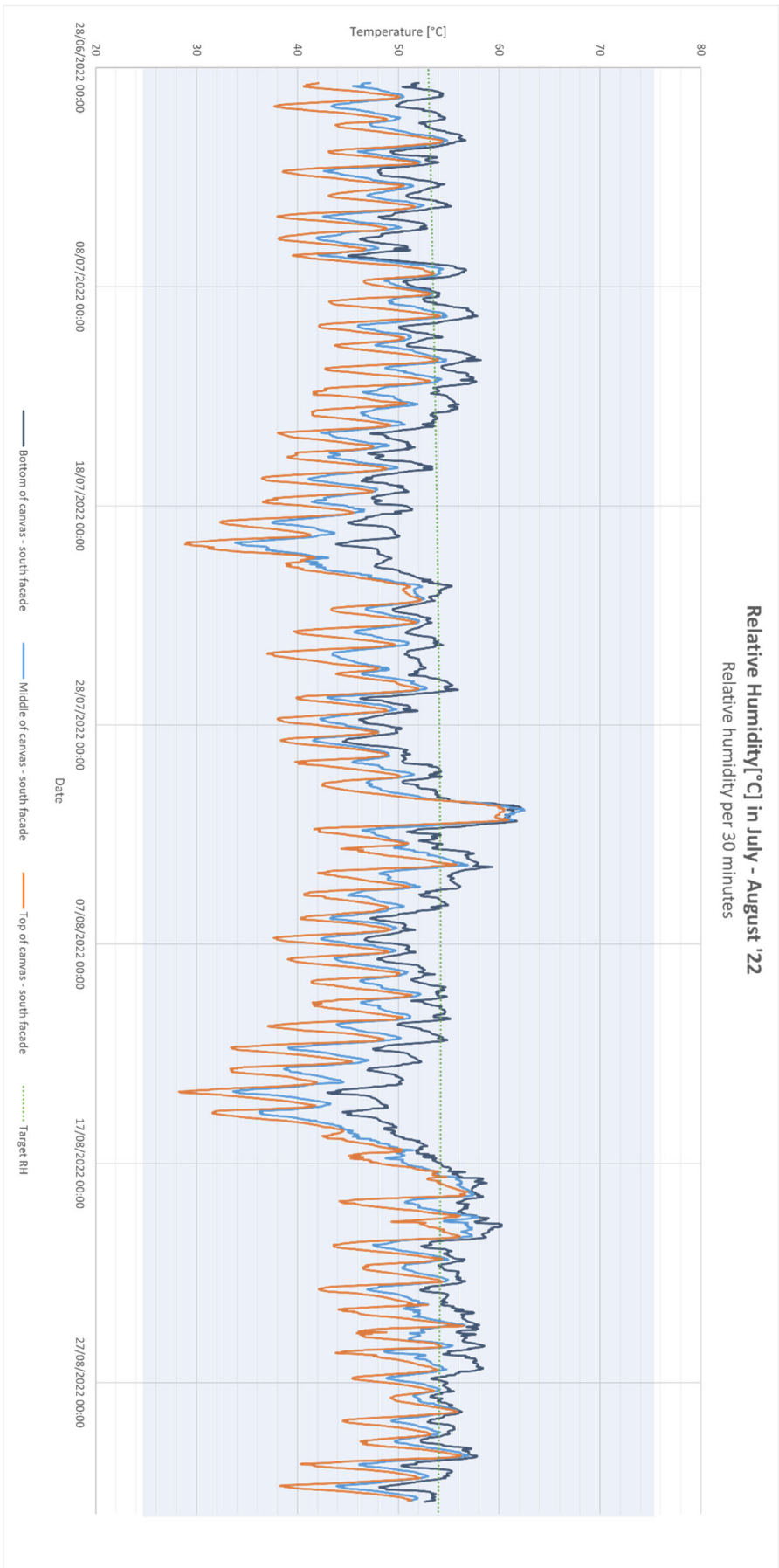


Figure C3.

Facade interior surface temperature [°C] in July - August '22
Average temperature per hour

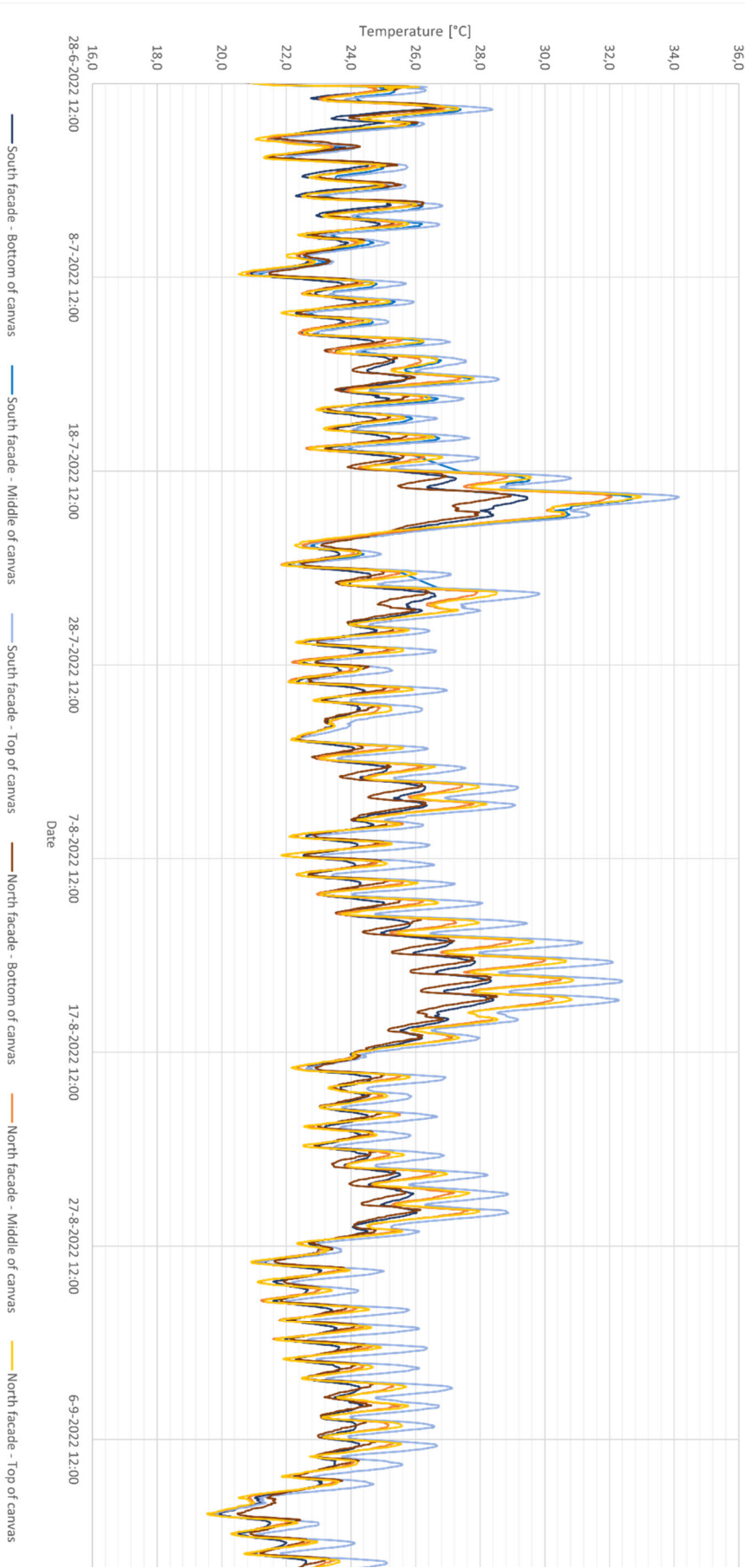


Figure C4.

Appendix D Plan of the Rotonde with datalogger sets and their locations

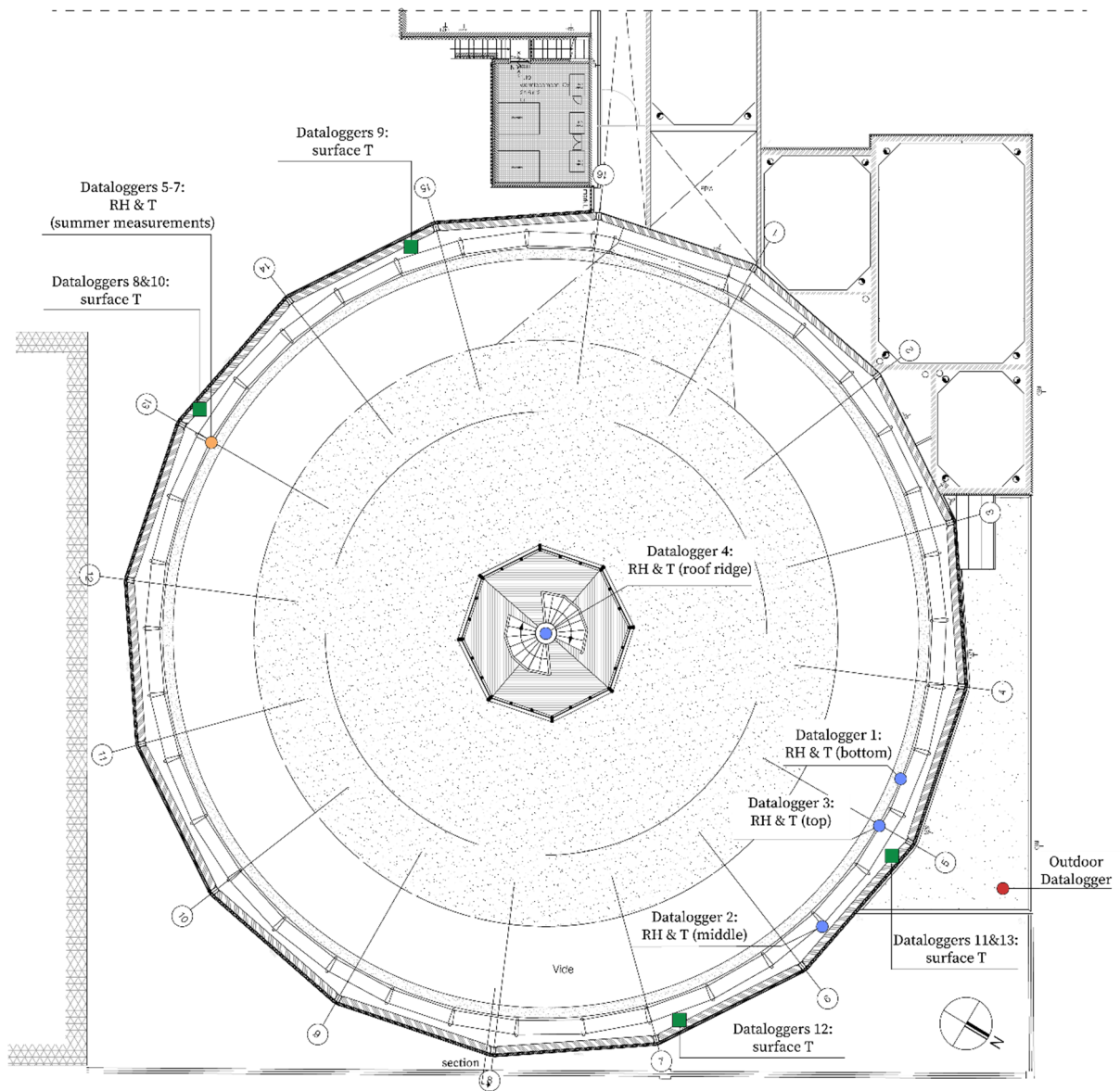


Figure D1.

Appendix E Yearly climate analysis and damage risk analysis

Zone: behind the canvas

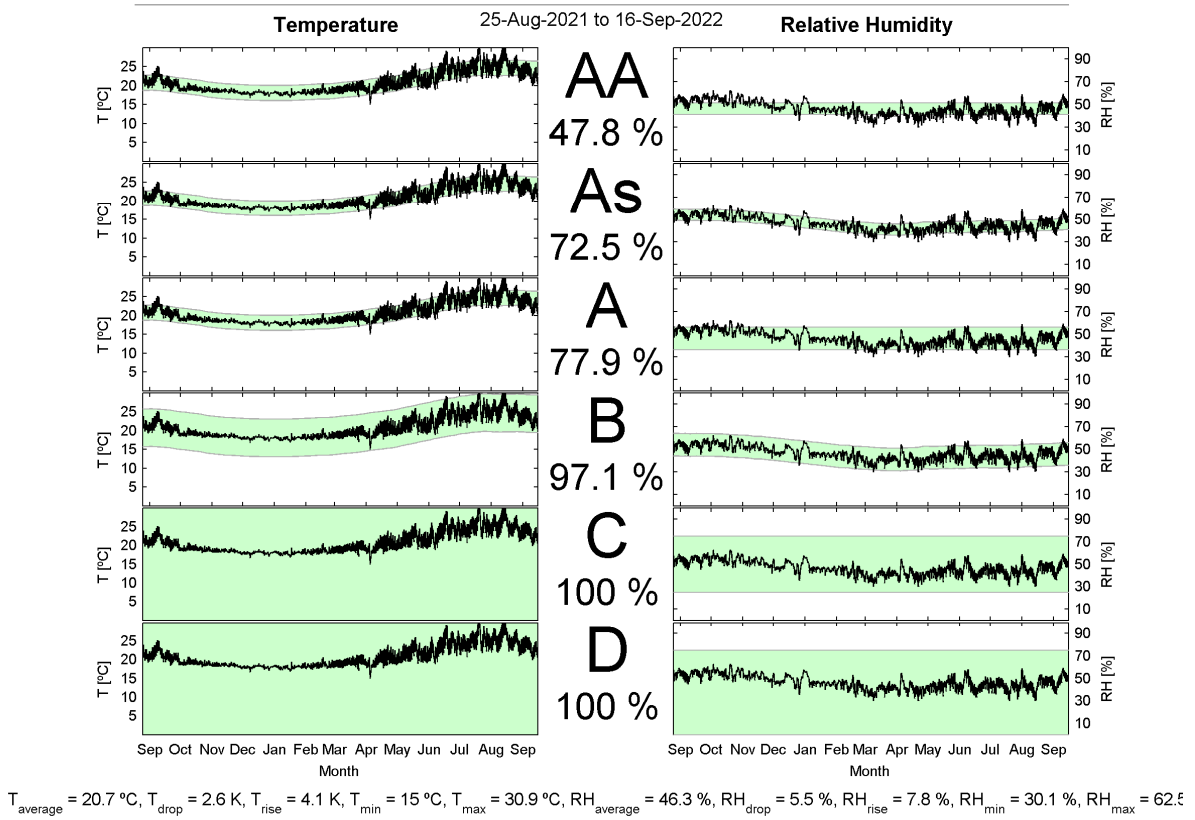


Figure E1.

25-Aug-2021 tot 16-Sep-2022

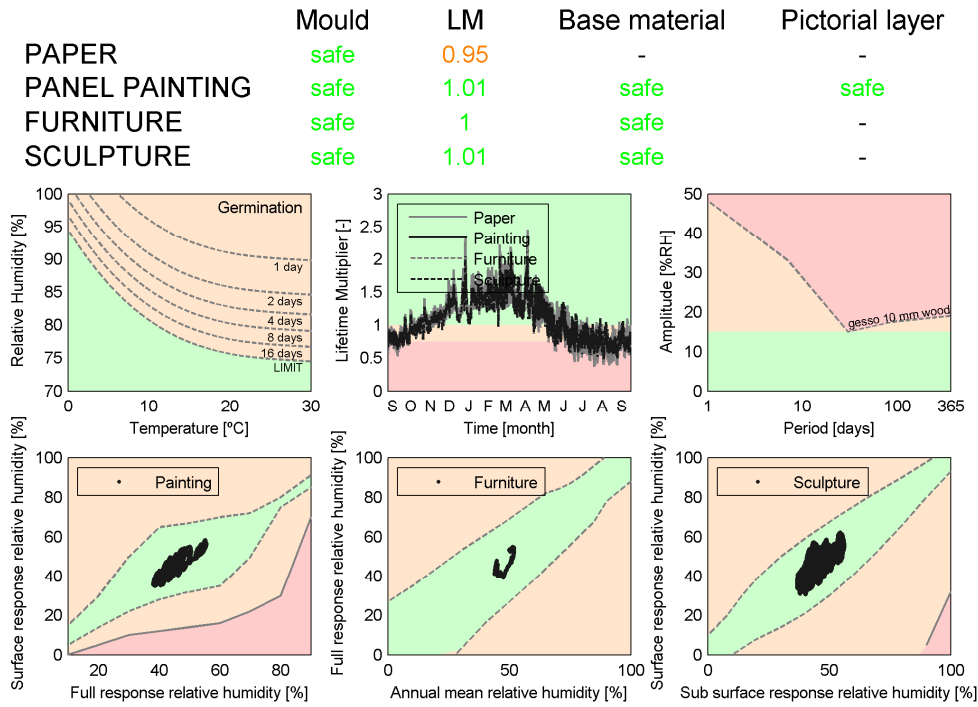


Figure E2.

Indoor Climate - Behind canvas: August 2021 - September 2022

25-Aug-2021 - 16-Sep-2022

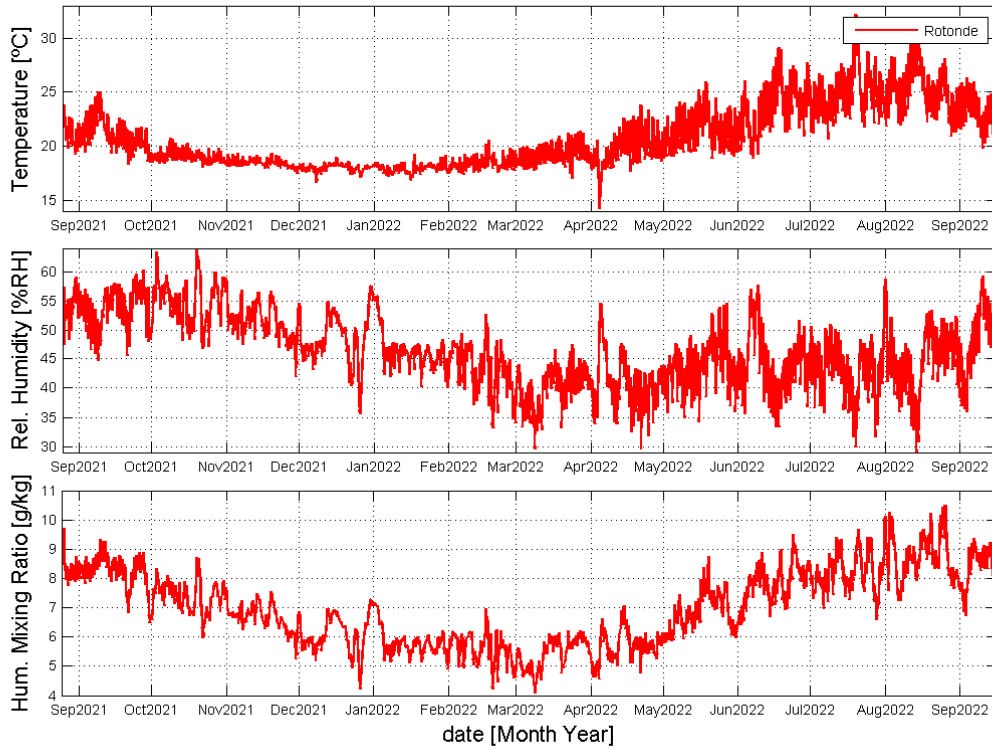


Figure E3.

Indoor Climate - Behind canvas: August 2021 - September 2022

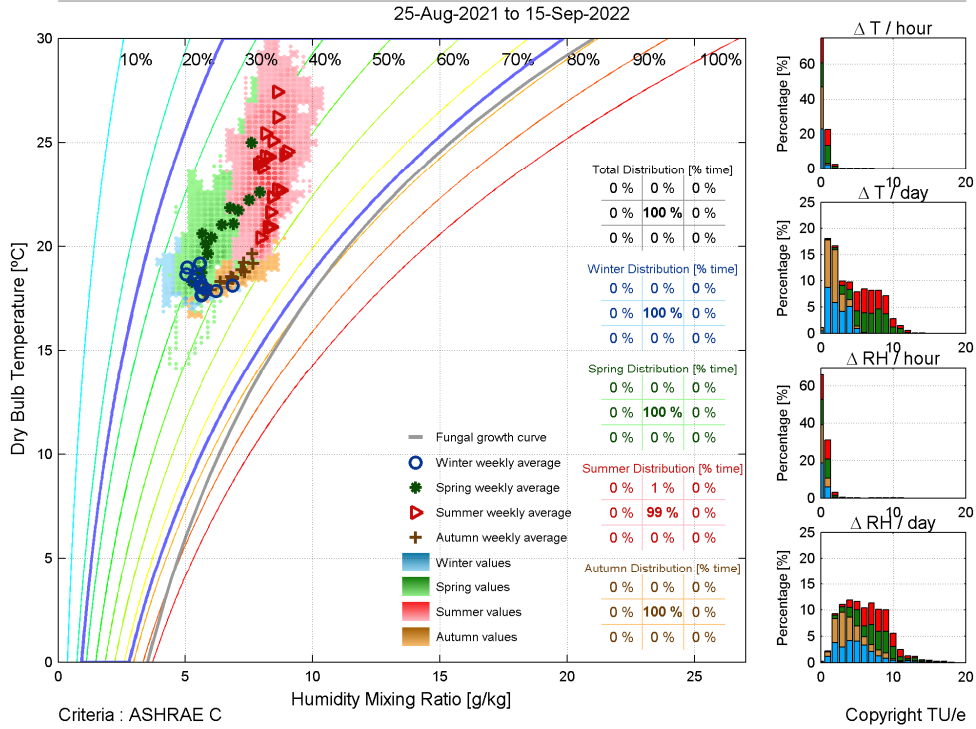


Figure E4.

Zone: Belvedere

Indoor Climate - Belvedere: September 2021 - August 2022

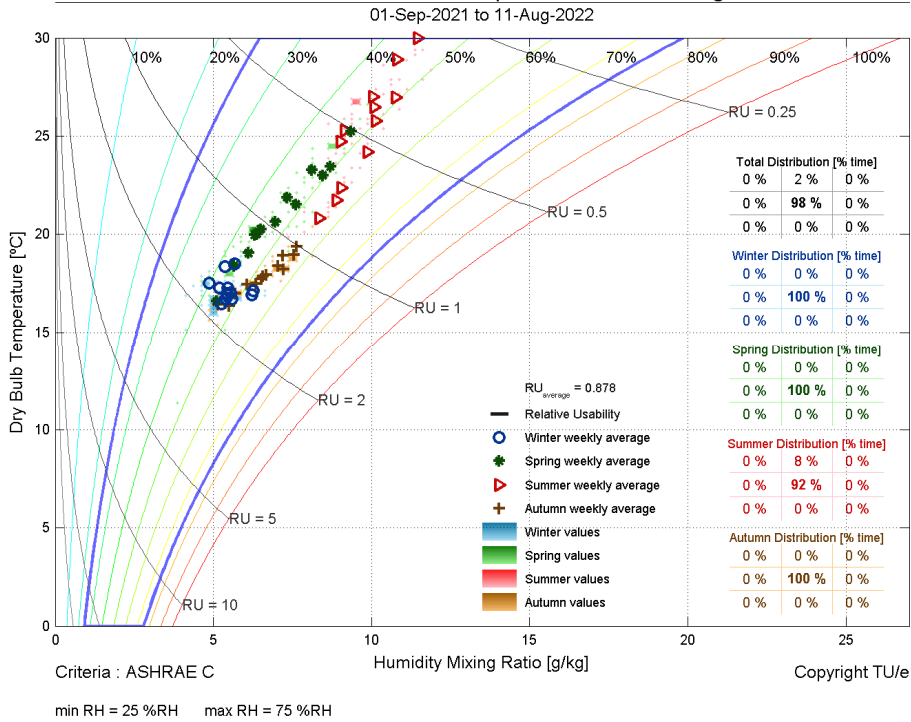


Figure E5.

Indoor Climate - Belvedere: September 2021 - August 2022
01-Sep-2021 - 11-Aug-2022



Figure E6.

Indoor Climate - Belvedere: September 2021 - August 2022
01-Sep-2021 tot 01-Sep-2022

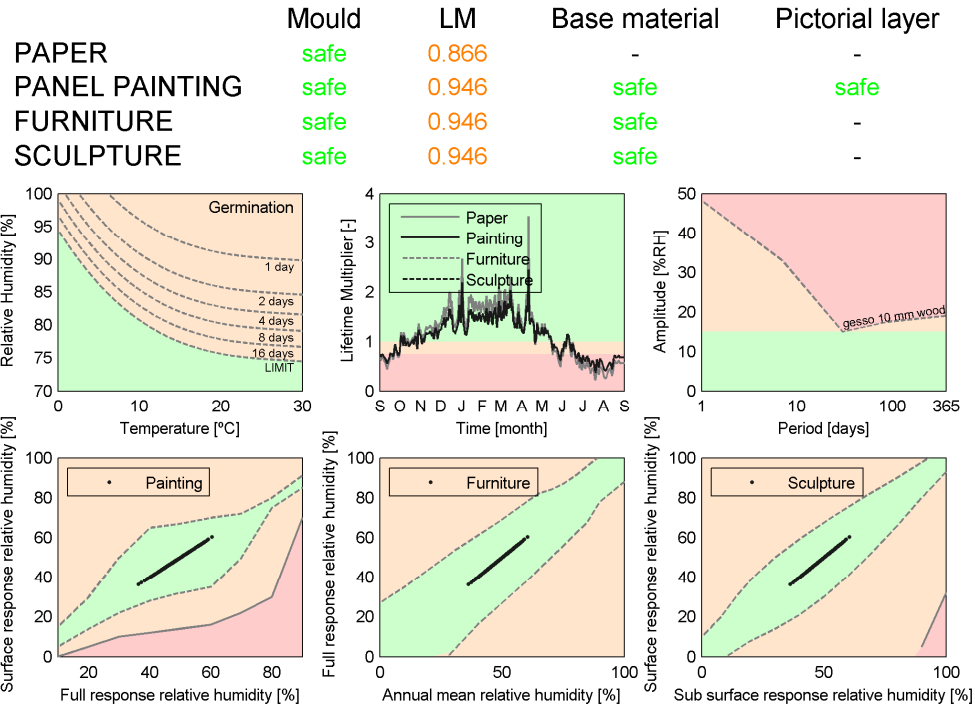


Figure E7.

Appendix F Design process of PCM façade system

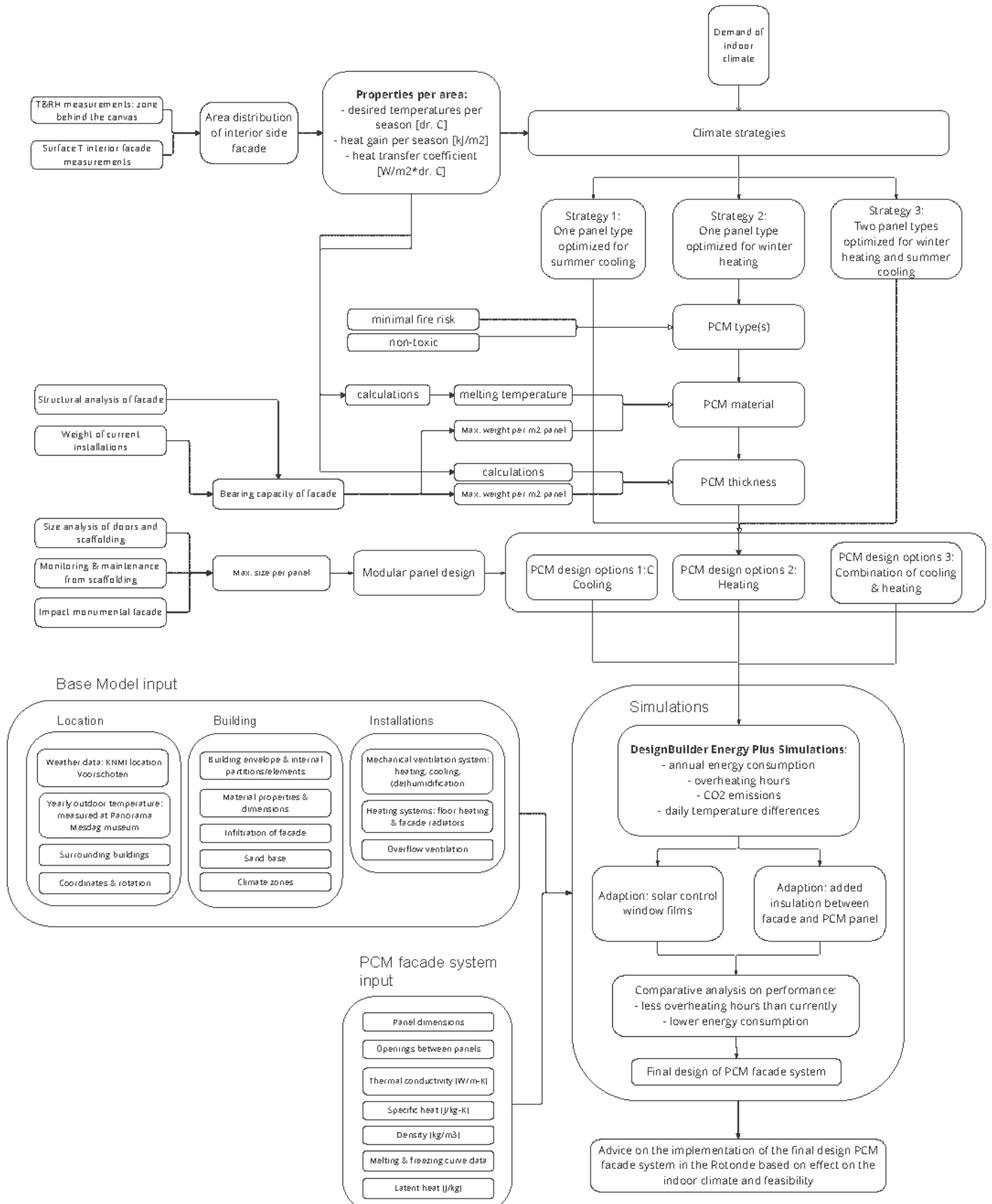


Figure F1.

Appendix G PCM Material characteristics

Data sheet



RT11HC



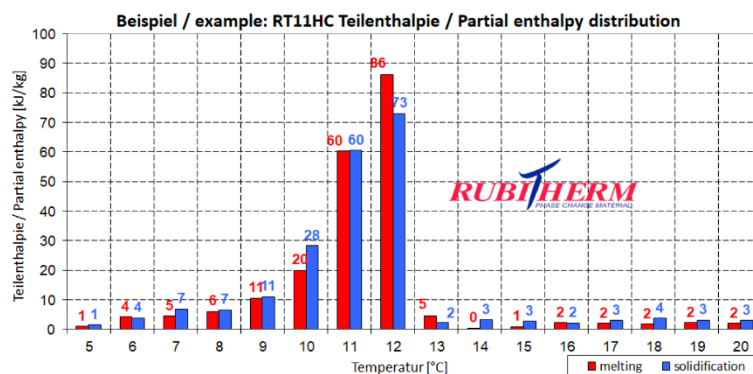
RUBITHERM® RT is a pure PCM, this heat storage material utilising the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature. The RUBITHERM® phase change materials (PCM's) provide a very effective means for storing heat and cold, even when limited volumes and low differences in operating temperature are applicable.

Properties for RT-line:

- high thermal energy storage capacity
- heat storage and release take place at relatively constant temperatures
- no supercooling effect, chemically inert
- long life product, with stable performance through the phase change cycles
- melting temperature range between -9 °C and 100 °C available

The most important data:

	Typical Values	
Melting area	10-12	[°C]
	main peak: 12	
Congeeing area	12-10	[°C]
	main peak: 12	
Heat storage capacity ± 7,5%	200	[kJ/kg]*
Combination of latent and sensible heat in a temperatur range of 5 °C to 20°C.	55	[Wh/kg]*
Specific heat capacity	2	[kJ/kg·K]
Density solid at 0 °C	0,88	[kg/l]
Density liquid at 20°C	0,77	[kg/l]
Heat conductivity (both phases)	0,2	[W/(m·K)]
Volume expansion	12,5	[%]
Flash point	130	[°C]
Max. operation temperature	40	[°C]



Rubitherm Technologies GmbH
Imhoffweg 6
D-12307 Berlin
phone: +49 (30) 7109622-0
E-Mail: info@rubitherm.com
Web: www.rubitherm.com

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Version: 08.10.2020

*Measured with 3-layer-calorimeter.

Figure G1.

SP24E



The creation of the latent heat material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components. RUBITHERM® SP is used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. air conditioners. We look forward to discussing your particular questions, needs and interests with you.

Properties:

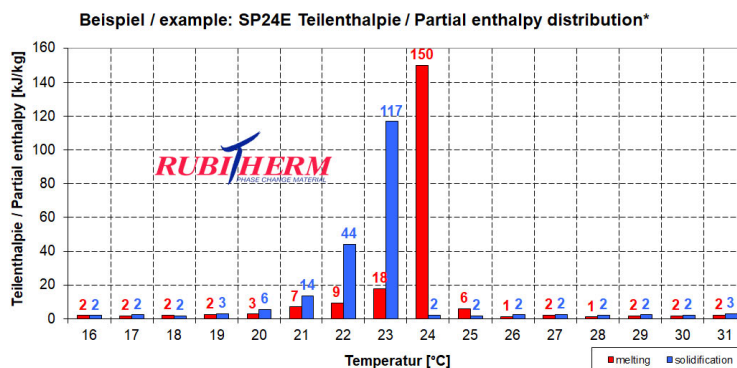
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K dependig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -50°C und 70°C are available
- encapsulation necessary, minimum volume: 50ml

The most important data:

	Typical Values	
Melting area	24-25	[°C]
	main peak: 24	
Congeaing area	23-21	[°C]
	main peak: 22	
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of 15 °C to 30°C.	180	[kJ/kg]
Specific heat capacity	50	[Wh/kg]*
	2	[kJ/kg·K]*
Density solid at 15°C	1,6	[kg/l]
Density liquid at 35°C	1,5	[kg/l]
Volume expansion	~6	[%]
Heat conductivity	~0,5	[W/(m·K)]
Max. operation temperature	45	[°C]
Corrosion	corrosive effect on metals	



The product must be initialized (melt, homogenize and cool to 0 °C) once before use to achieve the specified properties. SP-products may absorb release water if stored improperly. This can result in a change of the physical properties given. Storing in closed containers mandatory.



*Measured with 3-layer-calorimeter.

Rubitherm Technologies GmbH
 Imhoffweg 6
 D-12307 Berlin
 phone: +49 (30) 7109622-0
 E-Mail: info@rubitherm.com
 Web: www.rubitherm.com

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Figure G2.

SP25E2



The creation of the latent heat material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.

RUBITHERM® SP is used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. air conditioners.

We look forward to discussing your particular questions, needs and interests with you.

Properties:

- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K dependig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -50°C und 70°C are available
- encapsulation necessary, minimum volume: 50ml

The most important data:

Melting area

Congeaing area

Heat storage capacity ± 7,5%

Combination of sensible and latent heat in a temperatur range of 17 °C to 32°C.

Specific heat capacity

Density solid

at 15°C

Density liquid

at 35°C

Volume expansion

Heat conductivity

Max. operation temperature

Corrosion

Typical Values

24-26 [°C]

main peak: 25

24-23 [°C]

main peak: 24

180 [kJ/kg]

50 [Wh/kg]*

2 [kJ/kg·K]*

~1,6 [kg/l]

~1,5 [kg/l]

~6 [%]

~0,5 [W/(m·K)]

45 [°C]

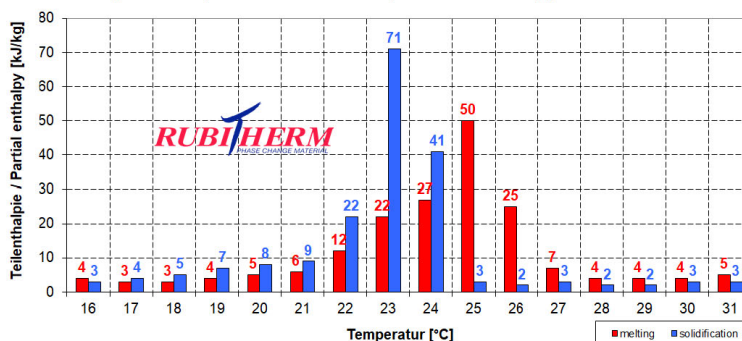
corrosive effect on metals



The product must be initialized (melt, homogenize and cool to 0 °C) once before use to achieve the specified properties.

SP-products may absorb release water if stored improperly. This can result in a change of the physical properties given. Storing in closed containers mandatory.

Beispiel / example: SP25E2 Teilenthalpie / Partial enthalpy distribution*



*Measured with 3-layer-calorimeter.

Rubitherm Technologies GmbH
 Imhoffweg 6
 D-12307 Berlin
 phone: +49 (30) 7109622-0
 E-Mail: info@rubitherm.com
 Web: www.rubitherm.com

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Figure G3.

SP26E



The creation of the latent heat material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components. RUBITHERM® SP is used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. air conditioners. We look forward to discussing your particular questions, needs and interests with you.

Properties:

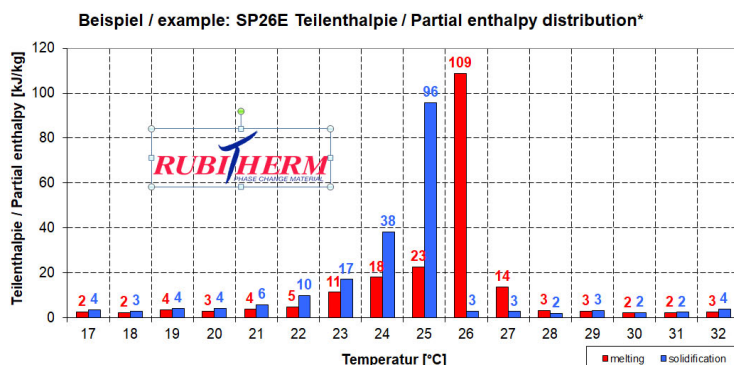
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K dependig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -50°C und 70°C are available
- encapsulation necessary, minimum volume: 50ml

The most important data:

	Typical Values	
Melting area	25-27	[°C]
	main peak: 26	
Congealing area	25-24	[°C]
	main peak: 26	
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of 17 °C to 32°C.	180	[kJ/kg]
Specific heat capacity	50	[Wh/kg]*
	2	[kJ/kg·K]*
Density solid at 15°C	~1,6	[kg/l]
Density liquid at 35°C	~1,5	[kg/l]
Volume expansion	~5	[%]
Heat conductivity	~0,5	[W/(m·K)]
Max. operation temperature	45	[°C]
Corrosion	corrosive effect on metals	



The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties. SP-products may absorb release water if stored improperly. This can result in a change of the physical properties given. Storing in closed containers mandatory.



*Measured with 3-layer-calorimeter.

Rubitherm Technologies GmbH
 Imhoffweg 6
 D-12307 Berlin
 phone: +49 (30) 7109622-0
 E-Mail: info@rubitherm.com
 Web: www.rubitherm.com

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Figure G4.

Appendix H Simulation results

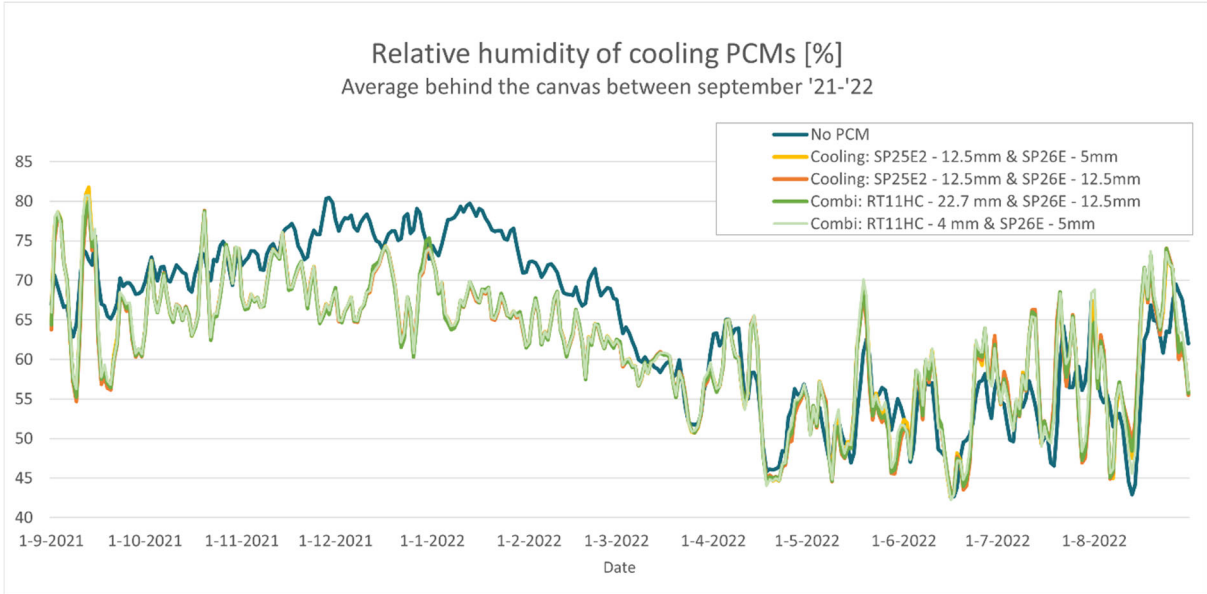


Figure H1.

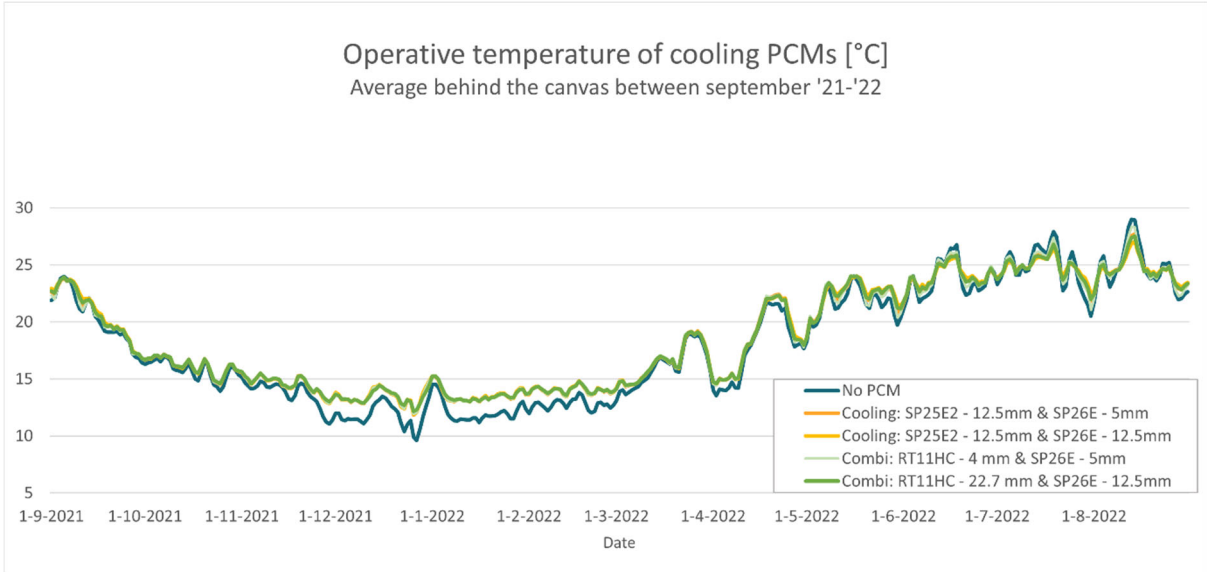


Figure H2.

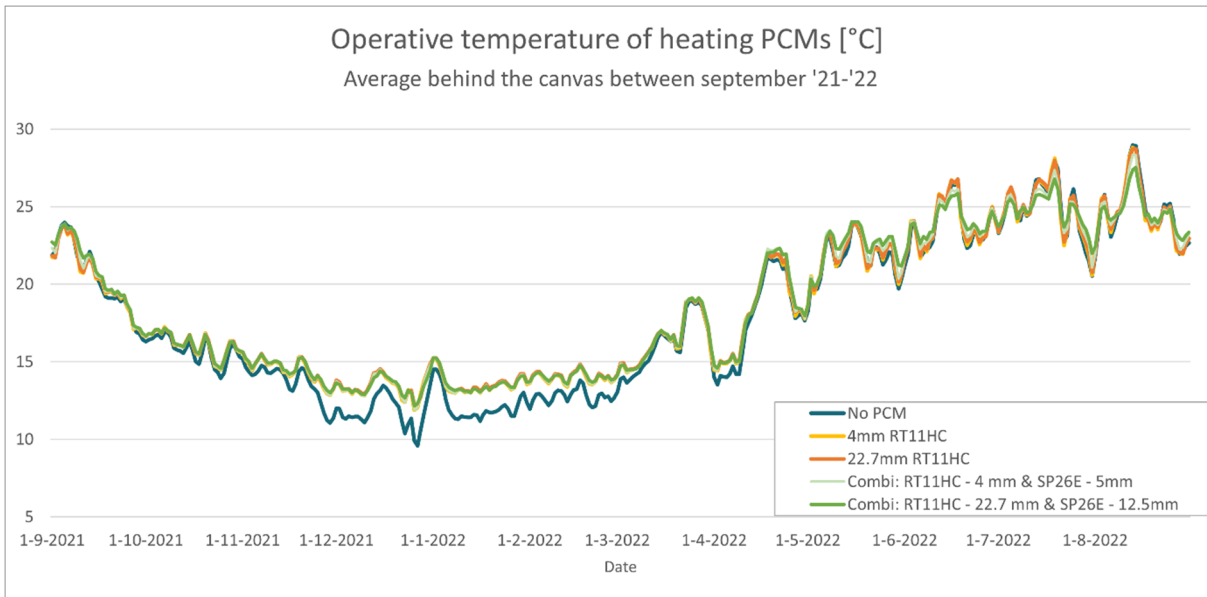


Figure H3.

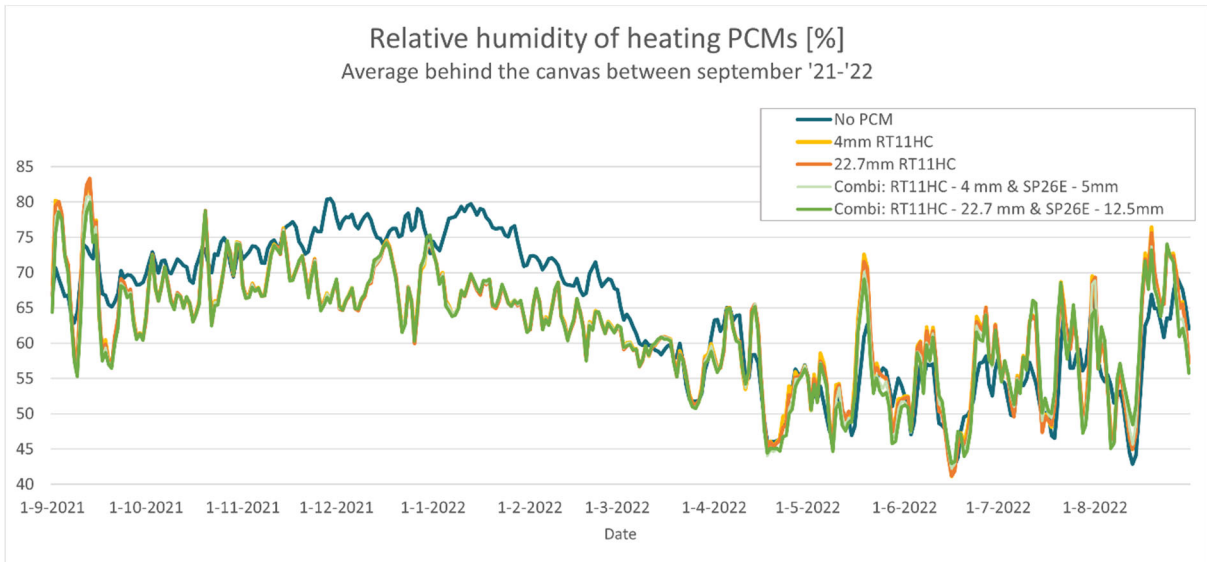


Figure H4.

Yearly indoor climate fluctuation indicators

Yearly indoor climate indicators: RT11HC 4mm. Design option 2.1	Behind Painting				Open space in Rotonde Belvedere
	Bottom	Middle	Top	Average	
Minimum RH [%/per day, month, season or year]	35.2	33	30.8	33.1	
Maximum RH [%/per day, month, season or year]	91.8	91.1	91.1	91.3	
Minimum T [°C/per day, month, season or year]	11.4	11	9.8	10.8	
Maximum T [°C/per day, month, season or year]	28.9	31.4	36.6	31.8	
Days per year of RH fluctuation > 10%/24hr	174	206	230	205	
Maximum RH fluctuation [%/24hr]	28.6	31.1	34.0	31.1	
Days per year of T fluctuation > 5 °C/24hr	0	35	193	64	
Maximum T fluctuation [°C/24hr]	4.4	6.2	12.6	7.1	
Days per year of T fluctuation > 3 °C/24hr	59	155	266	175	

Figure H5.

Yearly indoor climate indicators: RT11HC 4mm. Design option 2.2	Behind Painting				Open space in Rotonde
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%/per day, month, season or year]	36	33.9	31.7	34.0	36.1
Maximum RH [%/per day, month, season or year]	91.6	91	90.9	91.2	91.7
Minimum T [°C/per day, month, season or year]	11.8	11.5	10.6	11.4	13
Maximum T [°C/per day, month, season or year]	28.5	30.9	36.2	31.4	27.5
Days per year of RH fluctuation > 10 %/24hr	136	170	196	170	123
Maximum RH fluctuation [%/24hr]	27.6	29.5	32.3	29.6	27.8
Days per year of T fluctuation > 5 °C/24hr	0	9	177	42	0
Maximum T fluctuation [°C/24hr]	4	5.6	11.9	6.4	3.9
Days per year of T fluctuation > 3 °C/24hr	34	130	244	155	36

Figure H6.

Yearly indoor climate indicators: SP25E2 - 12.5 mm & SP26E - 5mm. Design option 1.1	Behind Painting				Open space in Rotonde
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%/per day, month, season or year]	38.5	36.5	34.2	36.6	38.6
Maximum RH [%/per day, month, season or year]	88.8	88.1	87.7	88.2	88.8
Minimum T [°C/per day, month, season or year]	11.3	10.7	9.5	10.6	12.7
Maximum T [°C/per day, month, season or year]	27.2	29.5	35.4	30.2	26.6
Days per year of RH fluctuation > 10 %/24hr	96	145	187	143	93
Maximum RH fluctuation [%/24hr]	21.4	22.7	24.8	22.7	21.5
Days per year of T fluctuation > 5 °C/24hr	0	0	126	2	0
Maximum T fluctuation [°C/24hr]	3.1	4.5	9.9	5.1	3.4
Days per year of T fluctuation > 3 °C/24hr	1	58	242	92	8

Figure H7.

Yearly indoor climate indicators: SP25E2 - 12.5 mm & SP26E - 12.5mm. Design option 1.2	Behind Painting				Open space in Rotonde
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%/per day, month, season or year]	40.2	38	35.9	38.2	40.1
Maximum RH [%/per day, month, season or year]	85.6	84.9	84.4	85	85.6
Minimum T [°C/per day, month, season or year]	11.3	10.9	9.7	10.7	12.8
Maximum T [°C/per day, month, season or year]	26.4	28.4	32.5	28.7	25.9
Days per year of RH fluctuation > 10 %/24hr	82	127	175	126	78
Maximum RH fluctuation [%/24hr]	20.9	21.7	22.9	21.7	21.1
Days per year of T fluctuation > 5 °C/24hr	0	0	87	0	0
Maximum T fluctuation [°C/24hr]	2.9	4.1	8.5	4.7	3.2
Days per year of T fluctuation > 3 °C/24hr	0	33	215	61	3

Figure H8.

Yearly indoor climate indicators: RT11HC - 4 mm & SP26E - 5mm. Design option 3.1	Behind Painting				Open space in Rotonde
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%/per day, month, season or year]	37.7	35.8	33.6	35.9	37.9
Maximum RH [%/per day, month, season or year]	87.5	86.9	89.9	87.1	87.6
Minimum T [°C/per day, month, season or year]	11.4	10.9	9.6	10.8	12.8
Maximum T [°C/per day, month, season or year]	28.4	30.7	36	31.1	27.2
Days per year of RH fluctuation > 10 %/24hr	112	158	195	157	114
Maximum RH fluctuation [%/24hr]	24.4	25.8	27.8	25.9	24.6
Days per year of T fluctuation > 5 °C/24hr	0	1	132	11	0
Maximum T fluctuation [°C/24hr]	3.7	5.1	10.2	5.8	3.6
Days per year of T fluctuation > 3 °C/24hr	22	91	243	119	18

Figure H9.

Yearly indoor climate indicators: RT11HC - 22.7 mm & SP26E - 12.5mm. Design option 3.2	Behind Painting				Open space in Rotonde
	Bottom	Middle	Top	Average	Belvedere
Minimum RH [%/per day, month, season or year]	39.7	37.2	35	37.6	39.5
Maximum RH [%/per day, month, season or year]	86	85.4	84.9	85.4	85.4
Minimum T [°C/per day, month, season or year]	12	11.3	33.4	11.2	12.9
Maximum T [°C/per day, month, season or year]	27.2	29	9.8	29.5	26.2
Days per year of RH fluctuation > 10 %/24hr	85	131	174	121	84
Maximum RH fluctuation [%/24hr]	22	22.9	23.7	22.6	22.0
Days per year of T fluctuation > 5 °C/24hr	0	0	92	0	0
Maximum T fluctuation [°C/24hr]	3.1	4.3	8.5	4.8	3.2
Days per year of T fluctuation > 3 °C/24hr	5	53	218	72	6

Figure H10.

Appendix I

Defining current energy consumption and comparative analysis to average

Base characteristics

Volume of Rotonde: 24.000 m³

Volume of Panorama Mesdag Museum (exclusive of Rotonde) [m³]: total area * average level height: 1480 * 4 = 5920 m³

Yearly visitors: 145.000

Yearly energy consumption	Average of museums	Total Panorama Mesdag museum	Rotonde
Electricity/area [kWh/m ²]	108,0	97,6	9,2
Electricity/visitor [kWh/visitor]	3,0	1,8	0,1
Building-related energy/area [Gj/m ²]	1,2	1,4	1,3
Gas/building volume [m ³ /m ³]	2,6	2,4	1,7

Figure 11.

	Totaal	Rotonde
Total energy consumption [kWh]	1.071.942	417.035
Energy consumption gas [m ³]	70.633	41.642
Energy consumption electricity [kWh]	261.627	11.070
Costs gas (average price 2022: 1,66 €/m ³ (CBS, 2022)) [€]	117.251	69.126
Costs electricity (average price 2022: 0,42 €/kWh (CBS, 2022)) [€]	109.883	4.649

Figure 12.

Appendix J

Relative humidity and indoor climate graphs of 2021 in the Bourbaki Panorama in Luzern

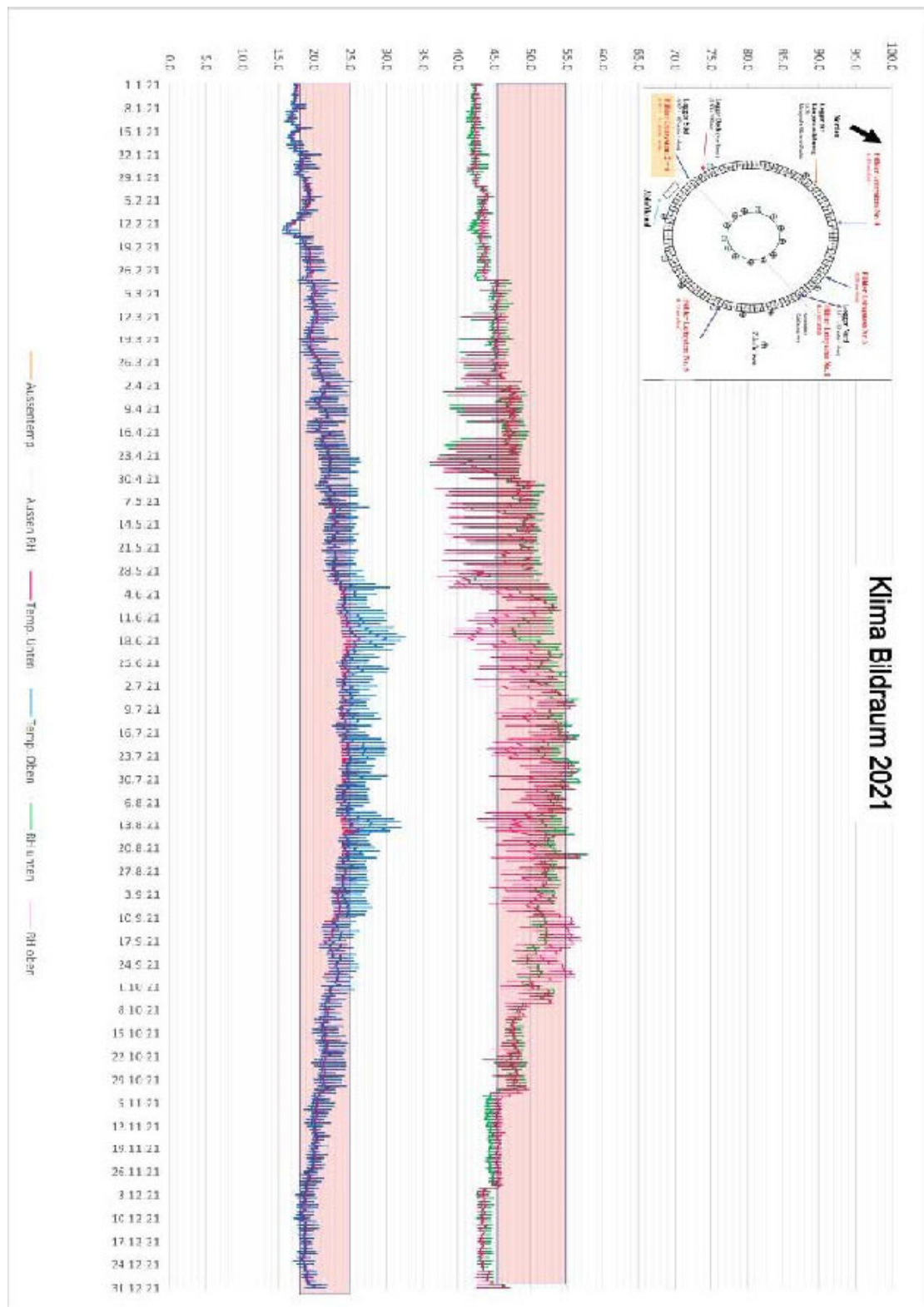


Figure J1.